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Reforestation Manual for California Conifers

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Foreword

The inspiration and impetus to develop this new publication documenting the latest reforestation practices for conifers in California came from several directions. In 1979, farsighted reforestation professionals held the first Forest Vegetation Management Conference, which fostered the exchange of ideas and information that played a central role in significantly improving reforestation practices used in California and elsewhere over the past 40-plus years. With many key practitioners on the cusp of retirement, a sense of urgency to share their mostly unpublished knowledge led to the creation of the organization's Forest Legacy Committee. The consequent development of this publication is a major addition to the legacy of this organization and its ongoing efforts.

Among the many individuals who contributed inspiration and guidance to this effort, the late Robert Powers, Ph.D., deserves special recognition. He spent many years as a soil scientist and silviculturist with the USDA Forest Service's Pacific Southwest Research Station in Redding, California. Bob Powers had that almost unique ability to look into the future and deter-

mine what questions practitioners of forest management would like answered and then design applied research that would provide those answers. His presence is sorely missed.

Another incentive to develop this publication came from an unlikely international source: the Association for Forests, Development, and Conservation of Lebanon. The association was formed in 1993 to promote reforestation, firefighting, and conservation work after a series of severe wildfires. Two of this publication's authors, Bob Rynearson and I, have provided assistance to the association's reforestation efforts since 2010. We were inspired by their efforts to publish reforestation guidance for Lebanon, which motivated and compelled us to begin this long overdue effort in California, another place with a challenging Mediterranean climate.

Tom Jopson, Chair
Forest Legacy Committee
Forest Vegetation Management Conference

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Chapter 1

Reforesting California

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With its publication in 1971, *Reforestation Practices for Conifers in California* by Gilbert H. Schubert and Ronald S. Adams (fig. 1.1) became the seminal reference for many young foresters in California facing unfamiliar new reforestation responsibilities. Prior to this time, planting efforts were sporadic and unpredictable. Private and public efforts were confined to the rehabilitation of previously forested brush fields and occasional wildfires, without well-established nursery,

handling, and planting techniques. As a result, uneven results were common.

The 1971 handbook compiled in one place the practical treatments identified as necessary for a successful program, and it presented them in an easy-to-understand fashion that was geared to operational practitioners. It covered reforestation activities such as seed collection and processing, nursery practices, mechanical and chemical site preparation, planting, and direct seeding. Details for these topics offered the best available science at the time but also included heavy doses of practical and operational experiences.

Since its initial publication major shifts have occurred in forestry practices. In the public sector, USDA Forest Service professionals in Region 5 (California) embarked on intensive forest management in the 1970s, which required considerable increases in reforestation. During this period, silviculture and reforestation personnel developed accordingly. An active USDA Pacific Southwest Research Station (historically known as the Pacific Southwest Forest and Range Experiment Station) conducted focused research, greatly advancing reforestation knowledge. However, a vocal environmental movement questioning this management direction, evolving public involvement authorized by the National Environmental Policy Act (NEPA), and new concerns about herbicide use and sensitive wildlife species (such as the northern spotted owl) all led to more limitations on forest management. By 1990 the Forest Service's emphasis on clearcutting and replanting had shifted nearly exclusively to thinning and uneven-aged management prescriptions with substantially reduced levels of reforestation. As time went on through the turn of the twenty-first century, even salvage harvesting and replanting after ever-larger

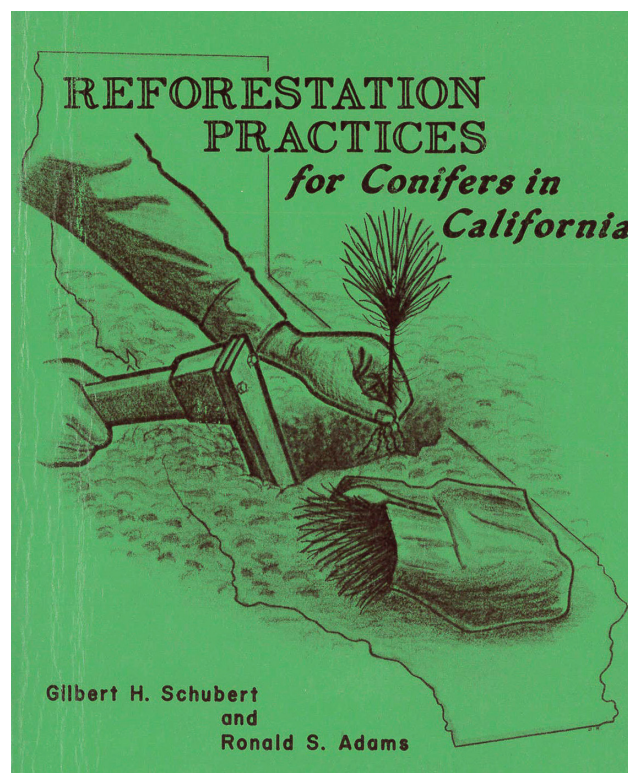


Figure 1.1. The original cover of *Reforestation Practices for Conifers in California*, published in 1971.

wildfire events were often legally challenged, and became less common on federal land. Meanwhile, federal agencies increasingly focused on the ecological role of fire in Western forests (Keeley and Safford 2016) with less emphasis on postfire reforestation. The net result over this period was a ramping up and then a dramatic deemphasis on reforestation infrastructure and funding.

A variety of entities are involved in reforestation of private and public forestlands in California (fig. 1.2). Along the North Coast, both smaller, private, nonindustrial forest ownerships and larger industrial forest ownerships dominate lands closer to the Pacific Ocean, with the Forest Service managing the more-inland areas of the Coast Range. A mix of large private ownerships, smaller forest ownerships, and the Forest Service is more common in the interior Cascade and Sierra Nevada regions. In general, the Forest Service owns more of the higher elevation forests, much of which is in reserve status, while smaller forest owners dominate in lower elevations immediately above the grasslands and woodlands of the Sacramento Valley. Unlike the northern part of the state, privately owned forests are limited in the southern Sierra Nevada and across Southern California.

As the public sector moved away from even-aged silviculture and its necessary reforestation component,

private industry was evolving in the opposite direction. While some coastal timberland owners continued even-aged forestry practices as they reentered second-growth stands in the 1970s, for decades much of interior California had traditionally used selective-type harvesting. The passage of the Z'Berg-Nejedly Forest Practice Act (1973) instituted the most comprehensive set of forest practice regulations in the nation. The law was a mandate for sustainable forest practices and immediate and successful reforestation after harvesting.

In the early 1980s, the Southern Pacific Land Company initiated an intensive forest management program on its ownership in northeastern California, and other companies found themselves dealing with the reforestation of both older and current wildfires. With the increasing use of even-aged management by interior landowners and the advent of more frequent and increasingly larger wildfires, industry programs utilizing regeneration foresters became more common until an active and sustainable statewide industry reforestation presence developed, which continues today.

Since publication of the 1971 handbook, the world has continued to change. Starting with the advent of computers, quantum leaps in technology have led to then-unimaginable but now routine changes in lifestyles. Our ability to capture, process, store, and share large quantities of data has resulted in the ability to organize and seek answers to questions not readily available before. Along with changes in silvicultural direction, this evolution has encouraged and enabled forest scientists and professionals to conduct studies specific to these reforestation activities.

Examples of this new or expanded work include long-term research, such as the Maximum Growth Study (also known as the “Garden of Eden” study) (Rabin et al. 2009) and the Long Term Soil Productivity studies conducted under the direction of Robert F. Powers of the Forest Service’s Pacific Southwest Research Station (Powers and Ferrell 1996; Powers and Reynolds 2000; Powers et al. 2005). In addition, since 2000 various landowner-, agency-, and university-supported research cooperatives such as the True Fir Management Cooperative in the 1980s and 1990s, Northern Sierra Tree Improvement Association from 1979 to present, and [Sierra Cascade Intensive Forest Management Research Co-op](#) have contributed to an expanding knowledge base. Major topics investigated in detail include vegetation management using selective herbicides, seedling performance, and plantation density. Developing practitioners not only encouraged and supported this focused research, but also experimented with and refined field practices. Since 1978, ideas have been commonly exchanged and practices shared through the annual [Forest Vegetation](#)

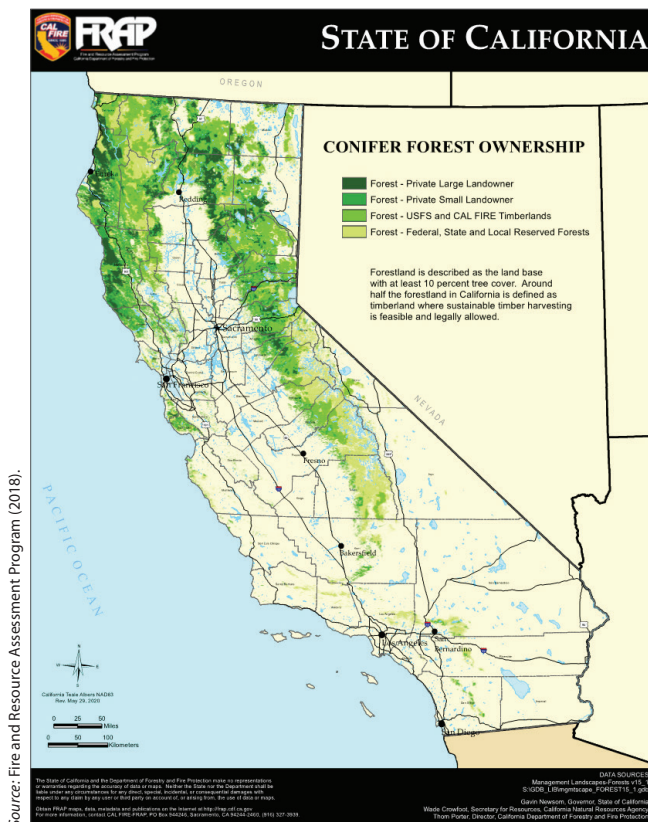


Figure 1.2. Private and public conifer forestlands in California.

Management Conferences and associated California Forest Pest Council Weed Committee field trips.

While much has changed in reforestation practices, many activities remain the same. Seeds are still collected, stored, and sown; seedlings are grown, packed, and stored; and new forests are regenerated one tree at a time. Since the original handbook was published in 1971, subsequent trial-and-error in the field and focused scientific research have rendered much of the original information outdated. For example, the original book included the now generally abandoned practice of direct seeding as a conifer reforestation tool in California and drier sites in the West.

Over the years new practices and principles have developed that are now commonly accepted and integral to successful and cost-effective programs. This is particularly true regarding the refined nursery techniques used to produce vigorous seedlings with ready-to-grow roots when planted, and the new and safer forest chemicals now available for site preparation and seedling release. Likewise, a greater recognition has emerged about the importance of timely vegetation management for successful reforestation, as well as the need to manage and monitor a reforestation program from the field and not just the office. Finally, reforestation professionals have focused on developing clearer definitions for each step and timing within reforestation plans, including stocking density levels, species selection and mix, protection from forest pests, and seedling handling, storage, and planting techniques.

Reforestation has developed into a recognized and well-respected career path. After being “thrown into the fire,” the early reforestation pioneers developed into ever-more-knowledgeable practitioners as planting efforts greatly expanded due to harvesting techniques and wildfire restoration. Seedling survival rates have greatly increased; new and focused manual, mechanical, and chemical treatments have been employed; labor pools have radically changed; and the previous barriers of timing and remote access have been challenged. However, just as the label “expert” emerged, new issues reinforced that constant learning and adaptation is always necessary. With time, reforestation specialists retire or take their expertise to other levels of responsibility. While the extension of their unique experience to different professional roles provides them with a broad and positive background, the loss of those battle-hardened reforestation skills in the field must be recognized and redeveloped. Opportunities for information exchange and training due to this natural professional turnover are critical to maintain high standards and avoid reinventing the wheel and repeating previous mistakes.

It is within this historical context that a group of past and current reforestation specialists recognized the importance of maintaining and transferring the current knowledge base. The ongoing exchange of personal information is vital, as are interactive workshops and seminars; but the focus of this publication is to provide a compilation of the wealth of operational knowledge garnered over the last half-century. While this publication is a sequel to Schubert and Adams’s original effort, it should be considered much more than a second edition, given the magnitude of changes. Hopefully it will contribute to continuing high standards by successors to the current generation of natural resource professionals and serve as a valuable resource for them as a building block of their own discoveries and advances.

Early history of California reforestation

Policy concerns about reforesting California go back to the end of the nineteenth century. In 1884, an interim State Forestry Commission reported to the governor the need to replant land “denuded of redwoods,” to plant “new land in suitable forest trees,” and to collect useful information on the “best mode of planting, caring for, thinning, and general treatment of growing timber trees” (Coleman et al. 1884). By 1887, the State of California was providing 150,000 seedlings of nursery stock and had established experimental plantations in all regions. However, “suitable forest trees” at that time were not always native species, and the State promoted exotics like eucalyptus and other potential new commercial species. Direct seeding of some conifer species began as an experiment on the San Bernardino Forest Reserve in 1901 and in northeastern California in 1908. Experiment stations were established to promote tree planting (Clar 1959). While concern was expressed about the focus on timber, which often were exotic species, these early efforts did not contribute significantly to reforestation success (Schubert and Adams 1971).

A state forest nursery was approved by the California legislature in 1917 and began production in Davis in 1922, with its stock initially limited for use at sites along highways or for public buildings. With the passage of the federal Clarke-McNary Act in 1924, joint federal-state attention was given to “the greatest possible incentive to commercial reforestation,” including authorizing cooperative forest nursery work (Clar 1959). Early federal efforts focused on growing and planting pine seedlings for California’s pine region (Show 1930; Corson and Fowells 1952). Considerable forest tree planting work was carried out by the Civilian Conservation Corps during the Depression of

the 1930s, with “tree and plant disease control” performed on nearly 800,000 acres of land in California (fig. 1.3; Merrill 1981). Forestry work included seed collection, tree seeding and planting, nursery jobs, and timber stand improvement.

The California legislature changed the focus of the state nursery in 1947, directing it to expand to provide a reliable source of quality tree seedlings for private forest landowners. The postwar lumbering boom helped accelerate this interest with 878 sawmills operating that year, reflecting the steep increase in California’s annual timber cut to 3.4 billion board feet (Arvola 1976). By 1952, California had established a significant system of public nurseries to produce timber species (Clar 1959), with four in operation by 1955. The California Reforestation Advisory Committee was tasked in 1957 with recommending reforestation methods and procedures and assisting the Division of Forestry in field studies and information exchange. State nursery production over the decades usually reflected harvesting rates and the availability of forestry assistance programs (Lippitt 1998).

To “repair the scars left by forest fires,” the Forest Service’s tree nursery at Mt. Shasta produced young trees for planting on the 17 national forests in California beginning in 1946 (Lanquist 1955). It grew 5 million seedlings, enough to plant 7,000 acres each year, although the burned acreage was usually much greater. The Forest Service estimated in 1955 that over a million acres of “unstocked forest soil” remained as a planting backlog on these forests. By 1960, several

more Forest Service nurseries had been added to expand the agency’s production capacity around the State. As table 1.1 shows, the potential for combined seedling production was about 36 million trees annually for federal nurseries while state nurseries had the capacity to grow about 11.5 million seedlings during peak production years. In contrast, private forest tree nurseries owned by industrial landowners and others did not begin operations in California until the 1970s.

Current reforestation needs in California

Forest regeneration has been a concern in California since the late nineteenth century. As a partial response to this concern, California revised its Forest Practice Rules in 1973 to require the successful reforestation of private lands following every timber harvest. Reforestation of lands deforested by harvesting activities prior to 1973 or by wildfires or other events is not legally required on private or federal lands. Current reforestation activities consist of required reforestation after timber harvests, voluntary reforestation of areas burned by wildfires, and voluntary restoration or rehabilitation of areas where historic tree cover has been replaced with shrubs or grasses. The State of California and the federal government provide some incentives in the form of cost-share programs and technical assistance to improve reforestation success for small landowners (see chapter 2, “Investing in reforestation”).



Photo: Wikimedia.org/USDA Forest Service.

Figure 1.3. California Conservation Corps crew carried seedling transplants to the field on the Shasta National Forest near Mt. Shasta in the 1930s.

TABLE 1.1. Public forest tree nurseries in California, 1921 to present*

Nursery	Owner	Years of operation	Maximum seedling capacity	County
L.A. Moran (Davis)	CAL FIRE	1921–2003, 2019–present	0.4 million	Yolo
Magalia	CAL FIRE	1952–2011	5–6 million	Butte
Ben Lomond	CAL FIRE	1945–1994	4–5 million	Santa Cruz
Parlin Fork	CAL FIRE	<1955–1970>	N/A	Mendocino
Mt. Shasta	Forest Service	1946–1970	5 million	Siskiyou
Placerville	Forest Service	1957–present	12 million	Placer
Humboldt	Forest Service	1960–1999	18 million	Humboldt
Oakdale	Forest Service	<1955–1963>	1.5 million	Stanislaus

Sources: Lanquist (1955); Lippitt (1998); J. Sherlock, personal communication (2018).

*As of 2023.

The scale of potential demand for reforestation in California depends on three major trends: the area harvested with even-age silviculture techniques, the extent of timberland experiencing severe wildfire damage, and new reforestation and afforestation (tree planting on areas without recent forest cover) projects. The most significant change in recent decades has been the increasing trend in areas affected by severe wildfires. While most California wildfires occur in grasslands and shrublands (Fire and Resource Assessment Program 2018), an estimated 400,000 acres of forests burned annually over from 2006 to 2015 (Brodie and Palmer 2020). Since 2015, record-breaking wildfires impacted forest areas in 2018, 2020, and 2021 (Wang et al. 2022). Federal forests, especially those with hotter and drier climates, will be the least likely to reforest without the successful application of reforestation expertise from similar sites in California.

The areas burned by wildfires that may need reforestation varies widely from year to year; losses in bad years are often twice the long-term average. Indications are that losses will increase over time unless significant changes are made to both fuels and fire management practices (Starrs et al. 2018). The extent of wildfires that have burned in forested regions over the past two decades is shown in figure 1.4. The forest area burned in wildfires is a mix of productive timberlands, reserves, and low-productivity forests. Expensive reforestation efforts are usually limited to more-productive timberlands as well as areas where forest cover is desired for recreational, residential, and aesthetic purposes.

Silvicultural practices data for nonfederal lands reported in California's Forest and Rangeland 2017 assessment indicate around two-thirds of recent private reforestation acres occur in planned harvest units (40,000 to 50,000 acres) and one-third are in postwildfire settings (20,000 acres). Even-aged harvesting and

subsequent reforestation occurs less often on federal lands, but severe wildfires have been more common on federal lands than on private lands. Of the estimated 80,000 acres of Forest Service timberlands burned annually in wildfires, only a small portion is replanted. Based on the reported certification of reforested acreage by Forest Service Region 5, less than 2,000 acres per year of reforestation planting with full site preparation has occurred on Forest Service timberlands from 2005 to 2015 in California, leaving the vast majority of

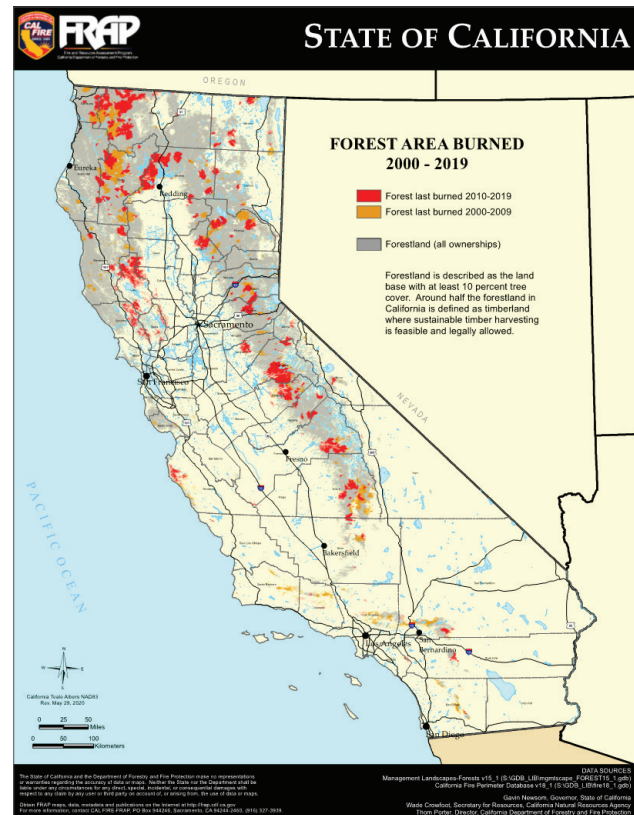


Figure 1.4. Fire perimeters: Wildfire perimeters and forests, 2000–2019.

Source: Fire and Resource Assessment Program (2018).

wildfire-affected areas dependent on natural regeneration (USDA Forest Service 2020b).

The success rate for natural regeneration in reestablishing conifer forests in California's Mediterranean climates is often low (Welch et al. 2016), and without planned and successfully implemented reforestation, conifer forest areas burned in severe wildfires are often dominated by shrub species for decades (Bohlman et al. 2016; Stephens et al. 2020). Use of the proven techniques presented in this manual could greatly increase the success rate in any type of reforestation effort.

Why plant forests?

The principles of best management practices for reforestation include technical and operational considerations developed and honed by practitioners in California and neighboring states over decades. Before exploring them, however, it is valuable to step back and consider why landowners should plant forests, where reforestation should happen, who should be involved, when it should take place, and what goals and constraints should be considered.

In his 2000 talk at the 21st Annual Forest Vegetation Management Conference in Redding, California, titled "The role of planted forests in a 'green certified' century," Robert F. Powers of the Forest Service—one of the guiding lights of modern reforestation—made a compelling case for planting forests (Powers 2000). "Planted forests simply are our best hope for meeting societal demands for wood while preserving the condition of natural forests," Powers said, and they are part of the solution to balancing society's need for wood products and the environmental benefits of sustainable natural forest cover. Powers said that world demand for wood could be met through the year 2050 with just 13 percent of the land base in planted forests under intensive forest management, with no need to harvest natural forests, and this approach only requires an average plantation productivity equal to the current average for planted forests in the Sierra Nevada region of California.

The State of California is the largest consumer of wood products in the United States with about 80 percent of the lumber and 90 percent of all wood products (such as lumber, wood panels, and paper products) used in the state imported from other regions of the United States and Canada (Fire and Resource Assessment Program 2018). Supplying this demand depends on sustainably managed forestlands in California as well as nearby states and Canadian provinces. Practices in all of these production areas have evolved such that successful reforestation is now one of the mainstays of productivity for forest landowners. Oregon has had a long-standing interest in ensuring

successful regeneration of their forests (Cleary et al. 1978), and Oregon State University Extension Service continues to publish useful technical publications on reforestation (Fitzgerald 2008, 2018; Huff 2014; Oester and Fitzgerald 2016).

Reforestation success is central to maintaining and increasing the productivity of timberlands. If not successful, brush species will likely become established on many forest sites, and in some cases, new conifer trees may not return for decades, if at all. Using the practices described in this manual, tree planting will result in a rapid return of well-distributed trees with the mix of species desired by the landowner. Seedlings begin growing the year they are planted and can be well-established on the site within a year or two. When using natural regeneration, it is true that the recruitment of seedlings can occur rapidly under the right conditions, but it also can be delayed by decades if shrubs or grasses fully occupy the site and suppress tree seedling growth.

When seedlings are planted, the spacing is planned so that they are evenly distributed over the entire site. This ensures that each planted seedling receives an equal share of resources without competing with neighboring trees, and that they have room to grow at their maximum possible rate. Natural regeneration often results in an unequal distribution of seedlings. Areas near seed trees where conditions are right may have too many seedlings, and areas where there are no seed trees or soils are lower quality may have too few. Only some of the crowded seedlings will make it to the sapling and tree stage, and then only over an extended period of time.

With tree planting, the landowner can also control the mix of species on the site to best reflect site conditions, management goals, and overall diversity. Natural regeneration does not generally offer the same flexibility, since the species mix is commonly determined by the species present that produce the most seed from cone crops, which only occur periodically. The prewildfire species mix is also influenced by the trees and vegetation that remain on-site after harvesting, fires, or other natural events that occurred in previous decades. For example, a forest historically dominated by pine may become a forest dominated by white fir if the pine is removed and the white fir that have naturally regenerated in the shade of the pine are left on the site. In such cases, specifically planting the historic species mix may be a better alternative. It can also avoid a subsequent site that is continually dominated by shade- and fire-intolerant species.

The benefits of planting are many, but the up-front costs of planting forests are high compared to relying on natural regeneration. The decision to plant

will ultimately depend on both the ability and the short- and long-term objectives of private landowners and government land-management agencies. The reality is that years of effort and expenditure are necessary before the eventual value of the regenerated forest stand is realized (see chapter 2, “Investing in reforestation”).

Where does reforestation take place?

Successful reforestation projects in California are based on planting seedlings grown from species native to the specific forest type. The tree species planted in a reforestation project are chosen to match species that have historically grown well in that region and will be able to continue to do so in the future. The current or potential forest type of a specific site determines the mix of species planted.

California has a diverse range of forest types containing different conifer species. Within the conifer forest area, active reforestation is typically concentrated in more-productive forests classified as timberlands, and it involves planting species that match those in the current forest types (fig. 1.2). Smaller reforestation projects and natural regeneration are more common where the future value of harvestable trees does not justify the cost of active reforestation.

The [Forest Inventory and Analysis program](#) of the Forest Service publishes the most statistically accurate forest-type data by ownership in California, based on a network of field plots. Table 1.2 summarizes the area of forest types that may require reforestation by different owner classes. The California mixed-conifer forest type represents about half of all timberland acres in California and is often the touchstone for forest policy or regulations requiring reforestation with a mix of species. However, tree species diversity within the mixed-conifer forest region varies, since mixed-conifer plots may intermingle with plots overwhelmingly

dominated by ponderosa pine or true firs. On the North Coast, plots of redwood, tanoak and laurel, and Douglas-fir are often the result of past management actions, and the species mix can change over time. On many sites the appropriate species to be planted will be those that have thrived on similar sites in the past, but on other sites the best decision may be to plant only one or two species. The decision on the appropriate mix of planted species should be made by the reforestation forester after considering which species have historically done well on the sites and which will thrive in the seedling and young tree stages of forest development.

It is important to note the significant differences in the portfolios of forest types for different owner groups, as this will affect which species they plant as well as their overall reforestation strategies. The California mixed-conifer forest and ponderosa pine types are the largest components for the Forest Service and corporate landowners. Family owners with smaller holdings have comparatively more coastal Douglas-fir, redwood, and other species. In addition, Forest Inventory and Analysis program data shows that around one-third of timberland area is currently dominated by stands with few, if any, commercial species. Some of these areas could be potential sites for reforestation projects with commercial conifer species if the economics of investing in such projects are favorable.

Who should be involved?

Who is involved in reforestation projects will be closely aligned with ownership patterns of the productive timberlands where investment in planting and tending seedlings will be rewarded with a rapidly growing forest. While forests and woodlands cover 32 million acres of California, reforestation projects primarily take place on the 16 million acres of managed timberlands where landowners can feasibly plant and manage conifer species appropriate for the local forest type and site

TABLE 1.2. Forest types on timberlands by owner group*

Forest type	Forest Service	Corporate	Family	Other government	Total
	<i>millions of acres</i>				
California mixed-conifer	4.2	1.6	0.5	0.1	6.5
Ponderosa pine	1.2	0.4	0.4	0.0	2.1
Douglas-fir	0.2	0.3	0.3	0.0	0.9
Fir/spruce/mountain hemlock	1.1	0.2	0.1	0.0	1.4
Redwood	0.0	0.4	0.2	0.0	0.7
All other species	2.2	1.3	1.5	0.2	5.1
Total timberlands	8.9	4.3	3.0	0.4	16.6

Source: Brodie and Palmer (2020).

*As defined by USDA Forest Service.

conditions (table 1.3). Forestlands that are not defined as timberlands either have low site and growing potential or do not allow for any planned commercial harvest of planted trees. Forestlands that are physically and legally able to sustainably grow trees for harvest and reforestation are generally called timberlands. The Forest Service's Forest Inventory and Analysis program further describes timberland as "forestland that has the potential to grow at least 20 cubic feet of wood per acre per year and is legally designated to allow mechanized vehicles and timber harvesting" (Waddell 2013). Unlike the vegetation cover maps available for California (Griffith et al. 2016; Fire and Resource Assessment Program 2018; USDA Forest Service 2020a), detailed maps of timberlands are not maintained by state or federal agencies. On the other 16 million acres of the forestland in California where potential productivity is too low to justify investing in reforestation, where federal or state reserved status precludes active forest management, or where natural recovery of the forest following disturbance is a management goal, natural regeneration rather than active planting is more commonly practiced.

The three basic types of landowners that must be involved in future reforestation efforts—small private, large private, and public agencies—each have their own goals, resources, and objectives. These can depend on site conditions, the size of the individual ownership, and the resources available for the project. The most significant variable in California, though, is whether the site is productive enough to be managed with long-term sustainable forest management. The higher growth rates of productive timberlands help justify greater initial investments.

Small private forest holdings are split between productive timberlands and less productive forests where noneconomic goals such as aesthetics, wildlife habitats, and fire safety near residences strongly influence decision-making. Ownerships of smaller landowners are concentrated in forests dominated by redwood,

Douglas-fir, and a mix of conifers and hardwood species in the Coast Range, as well as pine and mixed-conifer forests at lower elevations of the Sierra Nevada. Large private ownerships are primarily productive timberlands managed for their long-term sustainable economic values; they are concentrated in the highly productive redwood region in the Coast Range and mixed-conifer forests of the northern and central Sierra Nevada and Cascade regions. National and state forests in California are managed with a wide range of site qualities, goals, and objectives. National and state parks are primarily managed to maintain natural biodiversity and typically only use reforestation projects to achieve biodiversity goals that may have been negatively impacted by large and destructive wildfires.

Compared to other states, California's unique forests have a Mediterranean climate with long dry summers, which is better suited to shrubs and grasses than small tree seedlings. For all California landowners to have successful reforestation projects, following the best management practices outlined in this chapter and detailed in this manual is recommended.

Private forests: Large and small landowners

Private forestland ownerships are often classified by the dominant purpose of the owner. Large ownerships are sometimes referred to as industrial or corporate even though they may or may not own a sawmill and may be privately owned by a partnership, timber investment management organization, or family. Smaller ownerships in California are sometimes referred to as nonindustrial, noncorporate, family forests, or forest/ranch ownerships. We simply use the terms large and small ownerships.

Large ownerships control 60 percent of nonfederal timberlands in California, and they generated 88 percent of the 2005 to 2015 nonfederal timber harvest volume (Stewart et al. 2016). These owners typically have full-time forestry staff to conduct reforestation, timber harvest, and other forest management activities.

TABLE 1.3. Forestland ownership in California

Owner type	Timberland	Other forest	All forest	Timberland
	<i>millions of acres</i>			
Small private	3.0	4.4	7.4	41%
Large private	4.2	0.8	5.0	85%
State and local	0.15	0.9	1.1	32%
Other federal	0.3	2.8	3.1	10%
Forest Service	8.9	6.5	15.3	58%
Total	16.6	15.3	31.9	53%

Source: Brodie and Palmer (2020).

From a reforestation perspective, a huge advantage of having permanent staff is that they possess detailed knowledge of the property and can maintain a conifer seed bank for their lands—an activity upon which all reforestation depends. Large ownerships usually have demonstrated a commitment to successful reforestation, and, in most cases, have reforested commercial forestlands impacted by severe wildfires, even though they are not required to do so.

Small ownerships often have lower quality land and rarely have permanent forestry staff. Around two-thirds of the forest area in small ownerships is in parcels less than 500 acres where the income from sustainable timber harvesting is often not a dominant management goal (Ferranto et al. 2011). They may have an ongoing relationship with a consulting forester, but usually do not gather seed for major reforestation projects. Most prefer to use uneven-aged silviculture practices that leave harvested stands adequately stocked without the need for additional reforestation. However, small ownerships have the same exposure as their large ownership neighbors to wildfires, insect events, or severe droughts, which require active reforestation. These owners may not have sufficient capability to pursue reforestation without financial or technical assistance and may have different ownership priorities, such as wildlife and stream habitat, broad forest health concerns, or landscape aesthetics that influence their activities.

Recent trends in harvested acres across nonfederal land illustrates where reforestation projects may have been necessary for postharvest, postwildfire, or rehabilitation purposes (fig. 1.5). Even-aged harvests have declined over time to a relatively steady 30,000 to 40,000 acres per year, and all are reforested unless the land was approved for conversion out of forestland use. No additional reforestation is necessary for the

40,000 to 60,000 acres treated with uneven-aged silviculture, except for small areas of group selection if the owner does not want to depend on natural regeneration. Likewise, only a small portion of the annual 20,000 acres in the “other” category may require active reforestation. Of note, the fastest-growing component of harvest since 2012 has been the 30,000 to 50,000 acres of nonfederal timberland operated under emergency conditions following catastrophic wildfires or other mortality events. Much of this has been on large ownerships, and it nearly always has been actively reforested.

USDA Forest Service

Reforestation programs in the Western states have been integral to the mission of the national forests since the Forest Service’s inception as management agency in 1905, especially following large wildfires. The fiscal and operational challenges of reforesting large acres are substantial and have been the focus of numerous Congressional reviews and proposals to increase the rate of reforestation (Congressional Committee on Interior and Insular Affairs 1960). In response to public controversies over herbicide use on California’s national forests in reforestation projects, the Regional Forester in 1980 commissioned a task force on vegetation management to review “when and where various vegetation control methods could be used effectively, and with the overall consideration of prescribing in our site preparation and release treatments ‘no more and no less’ than those needed to achieve management objectives” (USDA Forest Service 1980). The task force reviewed the mechanical, manual, and herbicide methods in use at that time and found little published data on the relative efficacy and costs of different approaches. One result of this review was a 25-year effort by the Pacific Southwest Research Station to conduct experiments and publish results on the principles and challenges for conifer reforestation in interior regions of California (McDonald and Fiddler 2010). Data from this long-term research program formed the basis for many of the practices described in this manual.

The increase in extent of severe wildfires, especially on national forest timberlands in California since 2000, has substantially increased the need for successful reforestation projects in the state (Westerling 2016; Bedsworth et al. 2018; Starrs et al. 2018). There is evidence that more wildfire areas now experience near-total tree mortality (Eskelson et al. 2016), and federal forests with severe wildfire intensities increasingly experience less-successful natural regeneration (Thompson et al. 2007; Tepley et al. 2017; Zald and Dunn 2018). From 2008 to 2017, the Forest Service in California reported a total annual planted area of

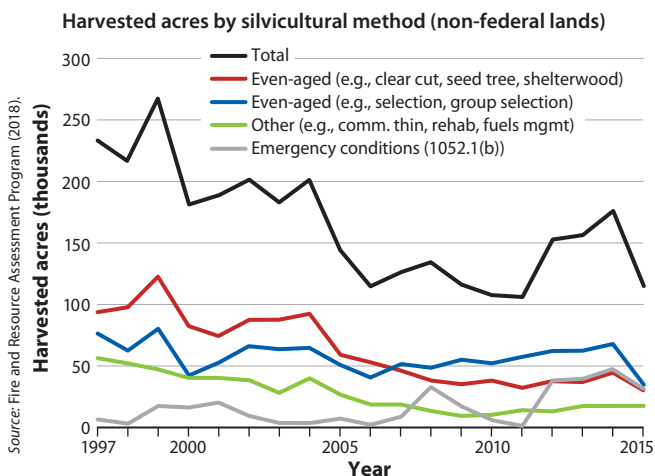


Figure 1.5. Potential reforestation acreage on private lands, 1997–2015.

13,000 acres with the majority being natural regeneration (USDA Forest Service 2020b). Annual rates of reforestation planting with site preparation and control of competing vegetation averaged less than 2,000 acres over the past decade (USDA Forest Service 2020b), which is low when compared with the approximately 80,000 acres of private land that is reforested annually. While current reforestation goals for national forests now place greater emphasis on restoring them to previous levels of forest complexity rather than just establishing a new cohort of conifer trees, successful reforestation of conifers still requires the same emphasis on conducting key steps in a timely fashion (USDA Forest Service 2022). Efforts are ongoing within the agency to train new personnel to successfully address evolving challenges.

Besides productive timberlands managed by the Forest Service, more than half of federal conifer forests in California are classified as designated wilderness areas, national parks, or have a low forest productivity rating. In these areas, natural regeneration will nearly always be the preferred approach to reforestation. Such regeneration after severe fires that kill potential seed trees may be quick, could slowly occur over decades, or may never happen for extended periods of time.

Other public and tribal lands

Other federal, state, and local public agencies manage forestlands, including the Bureau of Land Management, National Park Service, state forests, and state parks. While recreational uses and natural habitats may be the dominant management goals for some properties, managers of these public lands may need to engage in reforestation projects after either large or small mortality events such as wildfires, insect or disease outbreaks, or severe drought. As of 2018, four tribal reservations in California (Hoopa, Round Valley, Tule River, and Yurok) are being managed for timber production and other uses, based on their forest management plans (Fire and Resource Assessment Program 2018), with recent land transfers adding to the area of forests directly managed by tribes.

Forest seed collection facilities and forest nurseries

While federal forest nurseries in California have considerable production capacity, most of the seedlings produced in California are preordered and then produced in private nurseries. Millions of seeds from desired tree species must be collected, processed, and stored in seed banks to ensure that sufficient local seed will be available for future reforestation projects. Federal, state, and private seed collection, processing, and storing facilities are all parts of the larger reforestation process. Since 2012, reported seedling production

has varied from 13 million to 23 million trees per year (Harper et al. 2013; Haase et al. 2014, 2015; Hernández et al. 2016, 2017, 2018), with the differences resulting from changes in demand due to periodic wildfires and cycles in forest product markets. Unlike the rest of the United States, where bare-root seedlings make up around three-quarters of the total number of seedlings, experiences with harsher planting conditions in California have led to an industry where nearly all seedling production is from container stock (Hernández et al. 2018). If the Forest Service expanded reforestation efforts to address their existing backlog and new wildfire projects, it could potentially increase statewide demand by 10 million seedlings or more.

As covered in later chapters, expanding seedling production will also require a similar increase in the collection of viable seeds from the unique seed-collection zones of California. To ensure that planted seedlings grow well over many decades, the seeds used for seedlings must come from appropriate seed zones (Buck et al. 1970). Within each seed zone, collected seed is tracked by species, 500-foot elevation bands, and aspect to ensure that seedlings come from trees that were successful in the planting site. Figure 1.6 shows the seed zones, which are described in greater detail in chapters 5 and 9, as well as a close-up on one



Figure 1.6. California seed zones and site variability within one seed zone.

seed zone to illustrate the variability of elevation and aspect that also influence how well seedlings will adapt to their eventual planting site. To address potentially much-warmer future climatic conditions, consideration is being given to use seeds from higher elevation bands within current seed zones or from other seed zones where the current climate is similar to what is expected in future decades. Over time, California may increase collaboration with programs in Oregon, Washington, and British Columbia that have developed detailed protocols and tools to adjust seed collections to future climates (Mahony et al. 2018; Howe 2020).

Project timing

The timing of a reforestation project depends upon which of three general categories it falls into: 1) post-harvest, 2) postwildfire or other serious forest disturbances, or 3) rehabilitation or restoration of degraded forestland where conifer trees may have been absent for many years. In the first case, postharvest projects are usually scheduled to occur as soon after harvest as possible if stocking levels are inadequate to meet regulatory requirements and desired long-term growth. Since the scheduling of harvests is planned in advance, many of these sites can be planted in the fall, winter, or spring immediately following the completion of harvest activities. These reforestation activities should be planned to match site conditions and the owner's logistical limitations.

Planning for postwildfire projects should ideally begin immediately after the fire. This strategy allows for reestablishment of the new forest as soon as possible. In contrast, rehabilitation projects involve restoring conifer species to land that was forested in the past but is currently dominated by other types of vegetation. Examples include returning redwoods to land that was long ago cleared for agriculture or restoring conifers to old burns now dominated by brush species. These planned projects can be initiated at any time.

Chapter 3 ("Planning a reforestation project") describes the sequence of activities that will lead to the application and scheduling of the five principles of successful reforestation, described in sidebar 1.1, for each of the three reforestation categories. Some of the principles specified are common to all three types, but some are specific only to one. The exact timing of each practice may vary depending on planting site characteristics.

Getting started

Owners of timberland should evaluate their holdings to determine the need for reforestation. If reforestation then becomes the objective for particular sites, chapter 3 ("Planning a reforestation project") and chapter 4 ("Site assessment") are good places to start. Decades of

experience with reforestation projects in the often harsh Mediterranean climate across much of California's interior forests as well in other Mediterranean climates has led reforestation practitioners Bob Ryneerson and Tom Jopson to define five key principles that have proven critical to successful plantings.

It is important to emphasize that the first principle, using tree species from appropriate sources, is dependent on the availability of appropriate seed. Without seed banks with viable seed, no project is possible. The availability of seed may be dependent on an action that must occur many years prior to the actual need—the collection of seed from the either appropriate seed zones or specifically designed seed orchards. Both of these seed sources can require long lead times. As is described in detail in chapter 5 ("Seeds"), collectable conifer cone crops are sporadic and unpredictable in many areas. Landowners should seriously consider collecting or purchasing appropriate seed in years when cones are available and storing the seed until it is needed. Seed orchards are a more reliable source of seed once they are producing, but it can take 20 years or more to establish an orchard and obtain the first seed. Owners of seed orchards may be willing to sell seed if it is surplus to their reforestation needs.

Sidebar 1.1.

Five principles of reforestation

1. Plant species from known, appropriate seed sources (see chapters 4, 5)
2. Use quality seedlings (see chapters 6, 9)
3. Control competing vegetation (see chapters 7, 8)
4. Properly handle, transport, store, and plant seedlings (see chapter 9)
5. Protect plantings from damage by animal and insect pests, competing vegetation, and competition between trees (see chapters 8, 9, 10, 11)

Conclusion

Reforestation activities may be applicable at any time on approximately 16 million of the 32 million acres of private and public timberland in California. Since the publication of the Reforestation Practices for Conifers in California handbook in 1971, our understanding of the ecological principles of conifer reforestation has greatly expanded and reforestation tools have improved. Our ability to successfully regenerate forests has also improved dramatically in California as well as in other West Coast regions (Lavender et al. 1990; Huff 2014; Oester and Fitzgerald 2016). With increased

knowledge comes better insights into the complexity of designing and implementing successful reforestation projects. Research and experience have demonstrated new techniques to implement complex prescriptions to match challenging ecologic conditions (Powers et al. 2005; Zhang 2008; Ritchie et al. 2013).

At the same time, challenges to the long-term economic viability of forestry needed to justify investments in reforestation are multiplying. As wildfires intensify and fuels reduction efforts increasingly become a priority, clean air standards and liability concerns limit the use of controlled burning for fuel reduction on forestlands. Biomass energy facilities that once provided a market for wood, which otherwise would be left as fuel in the forest are disappearing due to the economics and politics of renewable and low-carbon energy sources. The use of herbicides on all landscapes is under constant scrutiny. The continued improvement and adaptation of forest management tools to maintain a social license for planted forests that are both productive and meet a wide range of environmental goals are the challenges of the future (Payn et al. 2015).

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California Forest Pest Council Weed Committee
caforestpestcouncil.org/weeds

Forest Vegetation Management Conferences
fvmc.org

Sierra Cascade Intensive Forest Management Research Co-op
ucanr.edu/sites/SCIFMRC

U.S. Forest Service, Forest Inventory and Analysis program
research.fs.usda.gov/programs/fia



Chapter 2

Investing in reforestation

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Decades of experience prove that successful reforestation cannot be done inexpensively but it can be done cost-effectively. Successful reforestation is challenging in California due to competing vegetation, hot summers, snow and frost, and many varied agents that can damage or kill seedlings. The necessary planning, implementation, and monitoring costs stretch out over years, and revenues and other benefits rarely occur within the first one or two decades of when the investments were made. However, experience shows that the full costs of not completing reforestation may be greater than the costs of undertaking the steps necessary for reforestation.

This chapter focuses on the investment decisions and actions that landowners should consider as they embark on a reforestation project. While the financial returns from individual reforestation projects are decades out, ensuring that forests maintain their productivity is essential to the long-term viability of sustainable forestry enterprises. In addition to the ensuring a future supply of wood products, young forests provide early seral stage wildlife habitats, vegetative biodiversity, greater carbon sequestration rates, and aesthetic benefits exceeding those of most fields of brush or invasive and nonnative plants. The numerous public benefits of successful reforestation investments are key justifications for federal and state governments to provide technical and material assistance, cost-share programs, and favorable tax considerations for reforestation expenses. Greater public support for reforestation on private and public forest lands can also improve the rate of successful reforestation in

California by reducing the immediate financial hurdles that impede action.

The chapter reviews the key steps of a reforestation project undertaken by private landowners or public agencies. While the mix of private and public financing will vary for different projects, having a clear view of the costs and benefits is critical when securing support from decision-makers to invest in reforestation. The key steps include estimating the costs of different reforestation management, planning, and operational activities; estimating potential revenues and noneconomic benefits; conducting a systematic economic analysis integrating the costs and benefits that occur across decades; and planning out the specific project steps.

Estimating costs and revenues

The first step in financing reforestation is estimating the potential range of project costs that must occur, decades before any revenue results from newly planted trees. The total costs will depend on how many acres will be reforested, how much emphasis is placed on forest growth rather than simply forest or vegetation cover, which treatments are chosen, how challenging the site is, and what logistical efficiencies can be achieved. Larger organizations typically have experience with and know the costs of similar, recently completed projects. To develop initial estimates for project costs, forestry consultants and landowners with more-limited reforestation experience should consult with local experts and review the reimbursable cost rates offered by the U.S. Department of Agriculture's

Natural Resources Conservation Service (NRCS) Environmental Quality Incentives Program and the California Department of Forestry and Fire Protection (CAL FIRE) California Forest Improvement Program. After developing a reasonable estimate of projected reforestation costs, the next step is to assess potential financing options. Finally, landowners should consider when revenues will be produced from reforested sites.

Assessing financing options

How reforestation projects are financed varies considerably across landowners. Large forest landowners and investment property owners typically treat reforestation as a long-term investment in a sustainable business that is judged by comparing the value of future returns to the more immediate costs that must be undertaken to bring seedlings to an age where they can be profitably and sustainably managed. Not every project will need a detailed economic analysis, especially if the landowners are invested in the long-term character of their forest enterprise and have confidence that standard procedures will be cost-effective. While it is rarely possible to borrow against future revenues to finance immediate restoration expenses, it is worthwhile to consider potential future revenues related to healthy and growing stands, including ecosystem services such as mitigation credits for certain habitats, conservation easements, recreational leases, and climate benefits.

Long-term investments on private lands will be taxed as capital gains and thus avoid the usually higher ordinary income tax rates. Tax rules that allow initial costs to be immediately deducted rather than amortized over a number of years vary for different types of private owners, and they can reduce the overall net cost of a project. The rules can change with revisions to the federal tax codes, so it is important to consult the most recent official information on taxation relating to forestlands. In addition, federal and state cost-share programs targeting small landowners may be available. Finally, publicly maintained resources such as seed banks and university-based technical assistance can often provide services to landowners at lower cost, allowing more favorable financing packages for private landowners.

Unexpected mortality events and reforestation after severe wildfires can place significant financial constraints on landowners, who may have also lost residences and other assets in the fire. Small-diameter trees burned in a wildfire have little value, and small landowners may find it very difficult to contract with loggers for salvage harvesting. After large wildfires, it is common for private owners of large forest areas to contract with the limited number of loggers in a region. Delays in initiating reforestation projects or

choosing more expensive reforestation practices can severely limit the number of successfully reforested acres that landowners with limited budgets can undertake. Because owners of smaller properties often lack the ability and economies of scale necessary to capture financial value from fire-damaged stands, they often rely on government technical assistance and cost-share programs to achieve successful reforestation projects.

Understanding and properly accounting for noneconomic benefits is important for securing federal funding of reforestation efforts. The USDA Forest Service explicitly defines a broad range of noneconomic goals for reforestation on national forest lands. Federal landowner cost-share programs also consider the noneconomic benefits of successful reforestation such as erosion protection and more tree-based wildlife habitat in determining landowner payments. After applying consistent values to desired noneconomic and economic outcomes, the use of standardized economic analysis tools can help identify projects that will deliver the best outcomes given budget constraints.

On national forest lands, the Forest Service historically financed much of their reforestation by reinvesting a portion of timber revenues into regenerating the forest. Current federal funds for Forest Service reforestation projects now come mainly from its vegetation and watershed management programs and the Reforestation Trust Fund (USDA 2018). The large increases in wildfire damage on Forest Service lands in California have not been matched by increases in successfully reforested areas, resulting in a growing backlog of areas in need of reforestation.

Tax treatment of private reforestation investments

The tax treatment of reforestation investments depends on the purpose of the investment (personal enjoyment, investment, or business); the ownership structure (small family ownership, commercial timber business, partnerships, trusts, or other); and any changes in federal and state tax law. As of 2019, small landowners could deduct up to \$10,000 per year for reforestation costs, while larger expenditures were amortized over 84 months. Larger landowners can deduct some of their reforestation costs if they are closely related in time and purpose to revenue-generating harvest events.

Unexpected costs related to declared disasters such as severe wildfires are treated more favorably. Some cost-share payments from certain defined federal and state programs can be excluded from reported income. Reforestation activities that are undertaken as part of a federally funded conservation activity may not be counted against the overall caps on reforestation costs. Landowners should discuss their plans with

local NRCS staff to understand the potential tax implications. Given the large expenditures required for reforestation and the technical details of specific cases, it is always important to consult timber and forest taxation specialists who are up to date on current policies (Greene et al. 2012; National Timber Tax website 2019; Wang 2019).

Postwildfire loss responses of small landowners

With severe wildfires increasingly common in California, the need for reforestation is growing. These fires often destroy the majority of the forest's timber value and reduce the public benefits that they provide, including diverse wildlife habitats, erosion protection, and carbon sequestration. In addition to financial benefits, successful reforestation projects can provide numerous public and private benefits. Owners of smaller forested properties often place less emphasis on the future financial returns of forestry compared to other benefits from their forests (Ferranto et al. 2011). Management activities that improve wildlife habitat and forest health are the most common activities across family-owned forests of all sizes (Stewart et al. 2012) and accounted for important benefits when planning reforestation projects.

The complexity and high costs of restoration can limit the ability of many small landowners to undertake projects after wildfires if they cannot quickly access technical and financial resources. A recent study of family forest owners whose properties burned in a 2014 wildfire in the central Sierra Nevada provides insights into the goals and challenges for owners of smaller properties who want to reforest their land (Waks et al. 2019). The study noted, "All [landowners] wanted to reforest, but a third would not have without the free reforestation program offered by the local resource conservation district to mitigate climate change through increased carbon sequestration. The rest of the landowners would have tried to do the work themselves or pursued other programs despite complicated logistics and high upfront costs."

Economic analyses of programs designed to assist smaller landowners should also consider the non-timber benefits that accrue to the owners as well as the social benefits of successful reforestation such as the viewshed benefits of healthy forests at sites that otherwise would revert to brush fields in many parts of California. Access to well-funded state and federal cost-share programs will be an increasingly important component of a successful reforestation strategy at a statewide level in California.

State and federal cost-share programs

To help landowners who lack the needed financial and technical resources to undertake reforestation, CAL FIRE and the NRCS both offer cost-share programs for reforestation projects. The full suite of activities covered in this reforestation publication may be eligible for cost-share funding but the two funding agencies have different definitions of treatments and relevant reimbursement rates. Keeping up with the latest requirements and understanding the application processes can be challenging, especially for landowners suffering the many consequences of a high-severity wildfire. Financial assistance programs continually change and are subject to swings in government policy priorities and budgets, so it is necessary to check with the agencies on current guidelines and funding.

Landowners and the professionals working with them should check the CAL FIRE California Forest Improvement Program (CFIP) and NRCS Environmental Quality Incentives Program (EQIP) websites for the most recent program details; and with agency staff to ensure that a reforestation project's funding needs can be supported and timed appropriately. Specific activities have different reimbursement schedules based on a number of factors. The level of cost-share, for example, can be higher for reforestation activities after disasters such as severe wildfire and mortality from pest insects. The federal Farm Service Agency's Emergency Forest Restoration Program uses EQIP's practices and payment rates.

It is important to understand that grants only reimburse the recipient after project expenses, and reimbursements are limited by the applicable cost-share rates and most recent reimbursement schedules. As a matter of standard practice, federal and state programs do not offer payment in advance, but provisions of EQIP allow for contract waivers, which need to be approved in advance on a project-by-project basis. CAL FIRE's CFIP also has the potential for loans that can be made to landowners implementing projects. When selecting which program to pursue, matching the landowner's objectives and needs to the appropriate cost-share program is an important consideration. Forest management plans are also required for each of the cost-share programs.

California Forest Improvement Program

The purpose of this long-standing state grant program is "to encourage private and public investment in, and improved management of, California forestlands and resources." Cost-share assistance of up to 75 percent of project costs is usually available to private and public ownerships containing 20 to 5,000 acres of forestland. A 90 percent rate currently applies to lands substantial-

ly damaged by fire, insects, and disease; all cooperative forest management plans; and lands with less than 500 acres of forest. Consultation with and project supervision by a Registered Professional Forester is required, with some of the costs covered by the grant.

Funded activities include management planning, site preparation (such as mechanical or herbicide treatments), tree seedling purchase and planting, precommercial thinning or release, pruning, forest road repair and upgrading, and other conservation practices. However, paying for seedling restocking requirements after a timber harvest plan is not allowed. The [California Forest Improvement Program](#) website includes current user guides, requirements, cost-share rates, and how to contact a CAL FIRE forest assistance specialist. Available funding has increased over recent decades with more financing, including the Timber Regulation and Forest Restoration Fund and California Climate Investments, but future funding levels are uncertain.

CAL FIRE Forest Health Grant Program

Beginning in 2018, CAL FIRE's Forest Health Grant Program has awarded grants from the Greenhouse Gas Reduction Fund, as allocated by the state legislature for California Climate Investments to implement larger-scale projects that seek to

- proactively restore forest health to reduce greenhouse gases
- protect upper watersheds where the state's water supply originates
- promote the long-term storage of carbon in forest trees and soils
- minimize the loss of forest carbon from large, intense wildfires
- further the goals of the AB32, the [California Global Warming Solutions Act](#) of 2006

In 2018 California committed to spending \$1 billion over 5 years from the Greenhouse Gas Reduction Fund for forest health, fire prevention, and fuel reduction activities. Reforestation projects can be funded, and they are projects with benefits that will continue to grow as the trees grow. Eligible applicants include local, state, and federal agencies including federal land management agencies (excluding conservation easements), state land management agencies, Native American tribes, private forest landowners, resource conservation districts, fire safe councils, land trusts, landowner organizations, conservation groups, and non-profit organizations.

To be eligible for funding under CAL FIRE's Forest Health Grant Program, projects must

- focus on large, landscape-scale forestlands com-

posed of one or more landowners, which may cover multiple jurisdictions (such as subwatersheds, firesheds, or larger management units of 10,000 acres or more)

- generate a net increase of on-site carbon storage over a no-project baseline as calculated by the California Air Resources Board's California Climate Investments Quantification methodology
- be designed to ensure the project benefits are as permanent as possible

Environmental Quality Incentives Program

EQIP is designed to support various reforestation activities through funding pools such as their catastrophic fire recovery, tree mortality, and forest health pools.

Funding is provided for many reforestation practices, including site preparation, seedling planting, and post-planting weed control. EQIP payments made to clients are fixed rates, meaning that regardless of actual cost paid by a client to a contractor to complete work, the payment made by EQIP is fixed. The program pays a fixed rate, usually intended to provide approximately 50 to 75 percent of actual costs, to clients completing reforestation practices. Payment rates to clients can be higher for postwildfire efforts. A forest management plan is required and can be partially financed as part of the NRCS's Conservation Plan assistance.

The goals of EQIP funding include wildfire reduction, forest health improvement, erosion control, and water-quality protection on working lands. The funding priorities are determined by the federal Farm Bill periodically reauthorized by Congress: the 2018 Farm Bill included reforestation and fuel reduction, with no parcel size limitations. The NRCS also provides support through its voluntary Conservation Technical Assistance program, with staff foresters in some county offices and the state office. Registered Professional Foresters can also assist with EQIP applications.

Generalized 2019 reforestation costs for federal and state cost-share programs

Key points from a comparison of federal and state cost estimates include the different ways that they define reimbursable treatments, the wide range between low and high cost-per-acre estimates for all activities, and the lower range of estimated costs for site preparation treatments versus postplanting mechanical and other release treatments (table 2.1).

The forester or landowner submits their cost estimates, but maximum reimbursement rates are fixed by federal and state regulations. Landowners must finance the difference between the actual costs and allowable reimbursements. In general, smaller projects will often have higher costs per acre due to the lack of economies

TABLE 2.1. Comparison of state (CAL FIRE) and federal (NRCS) cost-share programs

Criteria	CAL FIRE California Forest Improvement Program	NRCS Environmental Quality Incentives Program
Ownership size	20 acres, with maximum of 5,000 acres. Forestland is 10% or more cover, including oaks.	No minimum or maximum size. Management can be limited to improving forest health or initiating restoration. Forest management does not require explicit plans for future timber harvests. Must meet the federal definition of nonindustrial forestland.*
Zoning	Must be zoned to allow forest management, via Timber Production Zone or other land-use addendum.	N/A
Maintenance	Projects must be maintained for at least 10 years.	Maintenance of project varies by activity; projects must be maintained for treatment practice lifespan (variable).
Covered activities	May include preparation of management plans, Registered Professional Forester supervision, site preparation, planting, precommercial thinning, pruning, release treatments, and slash disposal.	May include preparation of management plans, brush management, herbaceous weed treatment, prescribed burning, woody residue treatment, fuel breaks, tree/shrub site preparation, tree establishment, forest stand improvement, and forest road and trail erosion control.
Activity size	5 acres minimum for forest management. No minimum on habitat improvement.	NRCS staff may also provide a forest management plan for smaller projects.
Timber Harvest Plan work	Will not cover Timber Harvest Plan stocking requirements.	Does not pay for work to be planned or implemented in a Timber Harvest Plan.
Prequalify	Prereview with CAL FIRE forester.	All projects based on submitting applications.
Management plan requirements	Plan is required, and CAL FIRE will fund. The plan must be done before any work.	Forest management plan is required for all projects. Funding may cover plan cost if requested and receives priority for funding in some cases.
Supervision	Registered Professional Forester supervision required.	No requirement for supervision, but clients are recommended to hire Registered Professional Forester for supervision of field work and use a qualified contractor. A Pest Control Advisor report is required for all projects that involve the use of herbicides.
Funding rates	For live tree/green projects, 75% of expense is funded to maximum in contract. For substantially damaged lands, 90% of cost-share activities are funded over the following 10 years.	Fixed rate paid to clients for completed work, to cover about 50–75% of actual costs; rate can be higher for postwildfire efforts.
Available funds	\$3+ million is available from Timber Regulation and Forest Restoration Fund, with considerable additional funding from California Climate Investments after 2018.	Forestry fund allocates \$5–10 million per year for highest-ranking projects.
Fund timing	First come, first served. Budget year is July through June.	Applications accepted continuously; ranking and funding occur 3–4 times per year.
Payment by activity	Interim payments allowed.	Interim payments allowed.
Proof of payment	Proof of payment to contractors required before payment to landowner.	Practice must be field-certified by NRCS staff and meet requirements and specifications prior to payment.
Adjusted gross income (AGI) cap	N/A	Adjusted gross incomes greater than \$900,000 are not eligible.

*Federal definition of nonindustrial forest land: "Rural land that has existing tree cover or is suitable for growing trees; and is owned by any nonindustrial private individual, group, association, corporation, Indian tribe, or other private legal entity that has definitive decision-making authority over the land."

of scale. Within the site preparation treatments, chemical treatments for controlling competing vegetation are estimated to be more economical than mechanical or hand treatments. Prescribed burning reimbursement rates suggest that such treatments can be economical compared to other methods. In many cases, CAL FIRE permits are required for prescribed fires on private lands, and the agency often will provide some of the necessary fire protection resources.

Table 2.2 summarizes the generalized cost reimbursement range for different practices from the cost-share programs of EQIP and CAL FIRE's California Forest Improvement Program in 2019. For full lists of available treatments and reimbursement rates, visit their respective websites.

Getting additional help

Some owners of smaller parcels may find applying for cost-sharing funds too time-consuming or intimidating

TABLE 2.2. Generalized cost ranges for reforestation cost-share programs in California, 2019

Program	Practice	NRCS EQIP (\$/acre)		CAL FIRE CFIP (\$/acre)	
		Low	High	Low	High
EQIP 490	Tree/shrub site preparation	100	1,000	350	800
EQIP 612	Tree/shrub establishment Without browse protection	300	500	225	550
	With browse protection	500	800	575	900
EQIP 314	Brush management	N/A	N/A	350	800
	Mechanical	200	400	N/A	N/A
	Hand	30	500	N/A	N/A
	Chemical	30	100	N/A	N/A
EQIP 315	Herbaceous weed management	N/A	N/A	250	750
	Mechanical	70	1,000	N/A	N/A
	Hand	200	300	N/A	N/A
	Chemical	30	200	N/A	N/A
EQIP 338	Prescribed burning	10	130	N/A	N/A
CFIP	Precommercial thinning	N/A	N/A	350	700
CFIP	Pruning	N/A	N/A	350	450
CFIP	Mechanical release	N/A	N/A	350	800
CFIP	Other release treatment	N/A	N/A	250	700
CFIP	Follow-up	N/A	N/A	400	1,000

Sources: CAL FIRE California Forest Improvement Program (CFIP) (<https://www.nrcs.usda.gov/programs-initiatives/eqip-environmental-quality-incentives>) and Natural Resources Conservation Service (NCRS) Environmental Quality Incentives Program (EQIP) (<https://www.fire.ca.gov/what-we-do/grants/california-forest-improvement>), accessed 2019.

to undertake by themselves, especially following the trauma of a catastrophic event. Local organizations such as resource conservation districts can create cooperative programs offering reforestation assistance to all small landowners, to reduce financial and technical barriers and allow for more acres to be reforested. After the 2014 King wildfire in the central Sierra, for example, owners of nonindustrial forestland whose properties were burned participated in an innovative program offered by their local resource conservation districts, which contracted with a Registered Professional Forester and crews to carry out the reforestation project.

Estimating potential revenues

A business challenge of reforestation is that potential revenues will not come for decades, and future prices are difficult to predict for both traditional products such as sawlogs and potential new products and services. While timber revenues from mature trees are usually the main source of value, hunting or other recreation-oriented leases may also become more valuable with increasing forest cover and generate future cash flows. In addition, new services such as conservation

easements, habitat mitigation credits, and forest carbon offset credits may also develop into financial value.

Since the potential revenue from these innovative services is somewhat speculative and may involve considerable transaction costs, a conservative estimation method is to initially focus on potential timber revenues and assume that future prices and revenues will be similar to current or recent prices. Potential timber revenues can be estimated from a combination of forest models of biological growth and available information on historic and current price trends. Once a baseline analysis is completed, it is easier to assess scenarios with different prices and products.

Reforestation investments based primarily on future timber revenues benefit from a good understanding of how to estimate future net revenues from timber harvests for the landowner. Net timber revenues will vary significantly by region, tree species, average tree sizes, and harvest method. The California Department of Tax and Fee Administration—which took over some timber tax activities that historically were undertaken by the California Board of Equalization—publishes the green-timber and salvage-timber harvest values based on a sample of timber sales and form the basis

for taxes on all harvests (table 2.3). In California, the stumpage value is calculated as the final product value minus harvest, transportation, and processing costs.

2019 stumpage values

As shown in table 2.3, the California Department of Tax and Fee Administration's green timber stumpage value chart for July to December 2019, larger logs and sales that contain more logs get a slight premium in California. The stumpage value is also reduced for more expensive logging systems, smaller total sales volumes, and lower volumes per acre. In general, regions with many competing sawmills have higher prices than regions with fewer mills. In the event of a future major mortality event such as a wildfire, the salvage value of ponderosa pine logs, for example, is estimated to decrease by more than half, with lesser reductions for other species. The decrease in value of logs salvaged after fires or major mortality from insects is due to both decreased log quality as well as the temporal oversupply of logs compared to the local mill's processing capacity.

Price trends for green tree stumpage values in California, 1977–2019

The most recent prices (by species and by log size) when reforestation projects are planned and implemented are not necessarily the most accurate prediction of future harvest values; as a result, reforestation project planners must make their own estimates of future harvest values for seedlings that will not be harvested for decades. Figure 2.1 shows trends in stumpage values by species in the Shasta County region of California (with redwood prices from Humboldt County) from 1977 to 2019. It is important to note that prices for fire-damaged trees are lower and calculated separately by the California Department of Tax and Fee Administration.

The most noticeable pattern over time is the high variability of prices from year to year as well as between species. Prices climbed rapidly after the 1983 recession and continued to increase until the large reduction in home building following the 2008 recession. Since then, prices have stabilized when compared to previous decades but remain volatile. Douglas-fir, pine, and true fir are the three largest species by

TABLE 2.3. California Department of Tax and Fee Administration green timber harvest values, July–December 2019 schedule

Species	Species code	Volume per log	Timber value area [†]									
			Size code*	1	2	3	4	5	6	7	8	9
Ponderosa pine	PPG	Over 300	1	160	160	60	140	250	220	240	190	140
		150–300	2	120	150	50	120	230	200	200	170	120
		Under 150	3	80	90	30	100	210	180	190	160	110
Hemlock/fir [‡]	FG	N/A [§]	N/A	120	60	N/A	150	240	180	210	140	100
Douglas-fir	DFG	Over 300	1	260	240	60	280	390	220	350	320	N/A
		150–300	2	250	210	50	270	380	210	330	300	N/A
		Under 150	3	240	200	30	260	370	200	310	290	N/A
Incense cedar	ICG	N/A	N/A	100	130	N/A	260	350	320	370	330	160
Redwood	RG	Over 300	1	950	1000	960	N/A	N/A	N/A	N/A	N/A	N/A
		150–300	2	930	880	820	N/A	N/A	N/A	N/A	N/A	N/A
		Under 150	3	830	830	780	N/A	N/A	N/A	N/A	N/A	N/A
Port Orford cedar	PCG	Over 125	1	300	N/A	N/A	300	N/A	N/A	N/A	N/A	N/A
		125 and under	2	200	N/A	N/A	200	N/A	N/A	N/A	N/A	N/A

Source: California Department of Tax and Fee Administration, 2019.

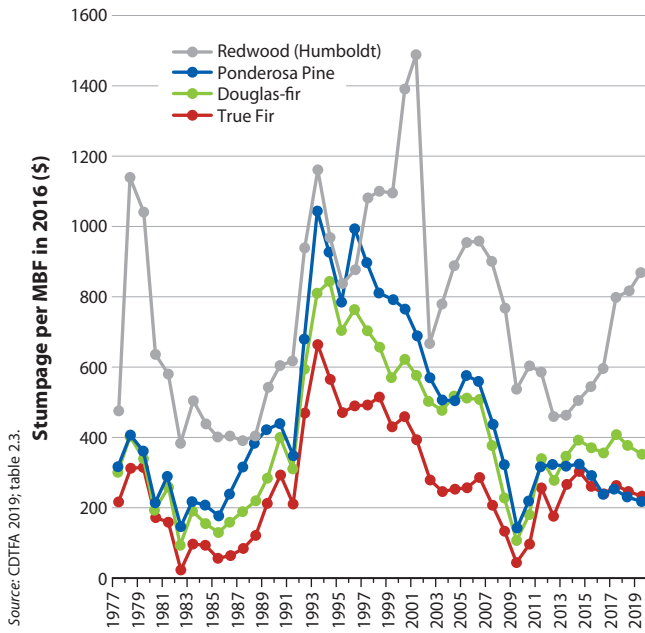
Notes: Table shows harvest values for timber by species, size, and timber value area. The taxpayer makes the adjustments for the timber value area, logging system, small total volume on the harvest operation, and low volume per acre on the harvest operation. More descriptions and clarifications are available on the CDTFA website.

*Size codes capture price premiums for larger logs (board feet per log); a size code 2 log containing 200 board feet per log means that five logs make up 1,000 board feet.

[†]Timber harvest values are in dollars per 1,000 board feet Scribner, the standard unit of harvest measurement in California.

[‡]Hemlock/fir species group includes white fir, red fir, grand fir, and hemlock, and it has no price differentiation based on volume per log.

[§]N/A means that little or none of the species is purchased and milled in that region.



Source: CDTFA 2019; table 2.3.

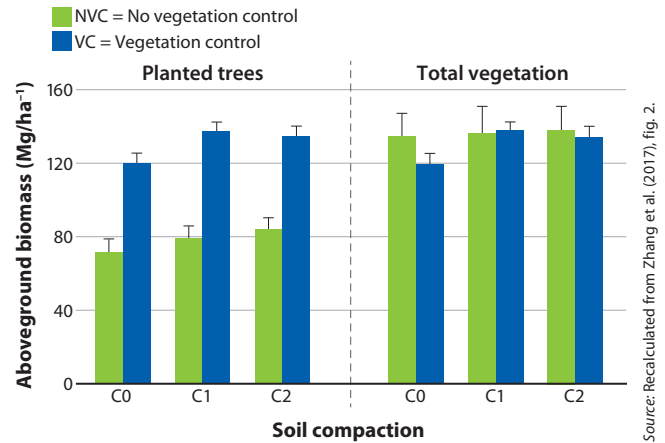
Figure 2.1. Inflation-adjusted stumpage price trends for major species in Shasta County, California.

volume harvested. The most significant trends over the past few decades include a decline in the historically large price premium for pine and the relative increase in value of true fir. Since most trees planted now will not be harvested for 40 years or more, it is difficult to predict future prices accurately. A reasonable economic strategy, beyond planting the highly valuable redwood in its natural region, is to diversify by planting a wide variety of species in forest types that historically had those species, so that the drop in price for one species does not create a total loss of future income for the landowner.

Basic economic analysis tools for reforestation

The physiological rationale for investing more expertise and money in reforestation is that well-spaced, planted trees allow for more valuable tree vegetation to grow on the site, as opposed to a mix of smaller trees, shrubs, and grasses. In the Mediterranean climate common in California's interior forests, small conifer seedlings have a well-documented growth disadvantage compared with shrubs for their first decades, unless competing vegetation is actively and successfully controlled (McDonald and Fiddler 2010).

This pattern was also well-documented across 12 Long Term Soil Productivity network sites in California, as summarized in figure 2.2 (Zhang et al. 2017). After 20 years, the no vegetation control and full vegetation control treatments had essentially identical amounts of biomass in total vegetation, but the



Source: Recalculated from Zhang et al. (2017), fig. 2.

Figure 2.2. Planted conifer tree biomass and total vegetation biomass (Mg/ha) from 20-year-old Long-Term Soil Productivity plots in Northern California. Early control of competing shrubs shifted nearly all biomass to a similar number of larger trees.

full vegetation control treatment reallocated over 50 percent more biomass into the planted conifer trees.

The economics of conifer reforestation projects also must be compared to other long-term investments that private parties or government entities could make. Private and public benefits from a healthy forest stand increase with improved stumpage value of its sawlogs, better recreational opportunities and amenities, and improved grazing opportunities if the understory is grass rather than shrubs. In addition to organizing the different reforestation steps that occur in different years and the timing of various benefits, basic economic analysis tools are often required by private and public funding entities. Forestland investment costs include annual management costs, specialized professional assistance, taxes, and fees, as well as the opportunity cost of capital or the direct costs of loans.

In California, a successful reforestation project typically will not produce significant net revenue for at least 30 to 40 years, and the full value of the trees will not be realized for 50 to 100 years. Over that period of time, owners must also consider the usually uninsurable risk of loss from severe wildfires or large pest outbreaks, major regulatory changes, unpredictable future market prices and conditions, and the actual rate of growth of newly planted forests. For our economic analysis of reforestation, we use a simplified example where increased investment in vegetation control leads to an estimated increase of 50 percent in eventual commercial harvest volume and a premium based on larger average log sizes.

A key for conducting an economic analysis of a major reforestation project is properly accounting for the time value of money. Different alternative investments such as stocks, bonds, or fully liquid cash accounts have different effective interest rates, which

are higher for investments with greater variability and risks of very high or very low returns. It is also important to know if inflation rates are included in prices when considering long-term investments. Economists refer to prices that are corrected for inflation over years as real prices (often quoted as dollars in a specific year, such as 2016 dollars) and nominal prices as values that may include different levels of inflation. It is also important to consider the potential loss of value if a historically forested site is permanently converted to a less valuable shrub-dominated site.

When conducting an economic analysis over a long time period, it is important to bring all the costs and returns to the same point in time (such as in 2016 dollars, which are used in the following examples), so that they can be accurately compared. If an alternative investment to a reforestation project is estimated to deliver a 5 percent real rate of return, that means that \$1.00 today will be worth \$1.05 next year and \$1.00 next year is only worth \$0.95 today. Over time, the effect of an annual interest rate compounds or discounts according to the formulas:

$$\begin{aligned} \text{future value} &= \text{present value} \times (1 + i)^t \\ \text{or} \\ \text{present value} &= \text{future value} / (1 + i)^t \end{aligned}$$

For example, if you invest \$400 in thinning costs today, that thinning would need to increase the future value of the forest stand to \$1,355 in 25 years (t), to achieve a 5 percent rate of return (i; 0.05) over the period. When returns are reinvested, the benefits compound so that the relative advantage of higher rates of return is not linear.

Or, if you expect a precommercial thinning of a reforested stand to increase the diameter at breast height from 16 to 22 inches over the next 35 years (t), you can calculate how much you could invest now that would equal the increased revenue garnered from harvesting the larger trees in 35 years. Assuming that the stumpage value of the larger trees would increase from

\$300 to \$400 per thousand board feet in real terms, the additional harvest volume would be 10 MBF (thousand board feet) per acre. If your benchmark real interest rate is 5 percent per year (i; .05), the break-even amount you can invest today would be \$181 ($\$1,000 / (1 + .05)^{35} = \181) to justify the investment.

FORECON financial analysis tool for forestry investments

The FORECON spreadsheet tool can be downloaded from UC Agriculture and Natural Resource's Forest Research and Outreach website. This simple tool allows users to conduct a basic financial analysis of any reforestation project or forest investment. While the model does not include detailed annual estimates of cash flow or tax implications, it allows the user to quickly assess the overall impact of different activities, such as the cost and revenue assumptions related to user-defined projections of future growth rates of the planted trees. More-sophisticated spreadsheet tools are available and may be necessary to secure external financing, but the FORECON model is presented here to illustrate the basic concepts with realistic scenarios (table 2.4).

Our baseline example is a single acre of a post-harvest reforestation under California's 2019 Forest Practice Rules requirement of planting 200 trees per acre on high site land. We modeled effective vegetation control of competing grasses, forbs, and shrubs to mirror the approximately 50 percent increase in planted tree growth documented in the 20-year data from Zhang et al. (2017). We used recent EQIP and CAL FIRE CFIP reimbursement costs as well as current stumpage prices for small and large logs for revenues. The operation is planned out in year 1, before site preparation is done to control competing vegetation. Planting is done in year 2 with additional weed control conducted in years 4 and 5 to ensure the successful release of seedlings. Finally, a precommercial thinning is conducted 6 years after planting to select the desired number and spacing of trees species that will be

TABLE 2.4. FORECON model for financial analysis of forestry investments (baseline estimates)

Treatment	1st-decade costs	Harvest volume *	\$ Present net worth
1. Ineffective weed control	\$1,069	\$29	\$242
2. Effective weed control (Baseline)	\$1,069	\$41	\$1,288
3a + \$100 additional brush control**	\$1,169	\$41	\$1,095
3b + \$100 additional brush control**(with 75% cost -share)	\$1,169	\$41	\$1,235
4a + \$200 additional brush control**	\$1,269	\$41	\$902
4b + \$200 additional brush control**(with 75% cost -share)	\$1,269	\$41	\$1,183

* Estimate intermediate and final harvest volume

** If needed to achieve effective vegetation control

harvested in future commercial thin and final harvest activities.

Comparing baseline and alternative scenarios

In the baseline scenario we assumed that the site preparation step was effective, only one postplanting weed control was required, and the later precommercial thinning achieved the desired stand of trees that followed the average growth rate expected by forest growth models. Since we cannot accurately predict timber prices in future decades, the purpose of considering a range of alternative scenarios is to provide guidance on the relative value of immediate investments. In table 2.4, we summarize six scenarios to illustrate the potential benefits of different approaches to controlling competing vegetation:

1. Suboptimal scenario with ineffective weed control and no additional brush control, akin to the no-vegetation-control variants in Zhang et al. (2017)
2. Baseline scenario with similar expenditures but where site preparation was sufficient to control herbs, grasses, and shrubs
3. Two scenarios where an additional \$100 per acre is needed for brush control to allow the planted trees to grow to their potential, with and without 75 percent cost-share payments from EQIP or the California Forest Investment Program
4. Two scenarios where an additional \$200 per acre is needed for brush control to allow the planted trees to grow to their potential, with and without 75 percent cost-share payments from EQIP or the California Forest Investment Program

For this example, we assume that effective control of competing vegetation represents the capture of 100 percent of the potential benefits measured in Zhang et al. (2017). Scenarios 3 and 4 illustrate the impact of additional expenditures if even more shrub control is needed on some sites.

The model also makes it simple to evaluate other scenarios such as increased costs to control competing brush, both with and without 75 percent cost-share payments. Without cost-share payments, the additional costs significantly reduce the present net worth of the project since the costs are immediate, but the revenues only occur many decades in the future. If the project proponents apply for and receive 75 percent cost-sharing only for the additional brush removal activities, the long-term value of the reforestation is protected. In addition to assessing the impact of early reforestation costs and the potential role of cost-share payments, the FORECON model can also assess the potential impacts of higher- or lower-than-expected revenues in the future. The change in revenues could be due to

differences in growth rates or future prices. If future revenues are only 75 percent of what current growth models and prices suggest, the financial viability of a project based solely on costs and projected timber revenues would be substantially diminished.

In all scenarios, the landowner invests over \$1,000 per acre in the first decade, even though they would not realize significant revenue for 40 years. If competing vegetation is not successfully controlled, the estimated present net worth for the total project from site preparation to harvest is \$242 per acre (scenario 1). If effective control of competing vegetation can be accomplished with standard site preparation treatments without additional expenditures on brush control, the present net worth increases to \$1,288 per acre. If additional brush control is required to achieve the growth potential documented in Zhang et al. (2017), costs in the first decade increase and present net worth decreases (scenarios 3a and 4a). When additional treatments are necessary to achieve potential forest growth, 75 percent cost-share payments effectively assist landowners in making the significant up-front investments necessary to generate long-term public and private benefits (scenarios 3b and 4b).

This economic analysis illustrates the importance of controlling initial costs and ensuring projected growth rates for a reforestation project to achieve a net positive value. The analysis highlights the financial challenges created by the multidecade gap between initial costs and delayed revenues. Site-preparation and competing vegetation control costs will reduce the present net worth of reforestation to landowners but will still be economically preferable to the much-lower expected growth rates with competing vegetation. If lower-than-predicted harvest volumes or prices substantially reduce future revenues, they can reduce a reforestation project to a break-even or money-losing situation. Without cost-sharing, it is possible that the public benefits accruing from successful reforestation efforts may not materialize, such as if the landowners underinvest in controlling competing vegetation.

A key value of using an economic model is not only to develop an accurate estimate of the financial value of a hypothetical investment, but also to have a decision support tool to better understand the influence of different reforestation activities. The long-term price trends in California, with two crashes and three booms since 1977, make it very difficult to estimate future revenues accurately. What is clear is that cost-effective investments to improve growth and reduce mortality risks from fires, pests, and disease can deliver financial benefits. Not making the correct timely investments can result in forest stands with much of the potential growth going into shrubs and trees that have little or

no commercial value. Investing in effective vegetation control is the key component of successful reforestation in California. In many cases, effective site preparation before the harvest and basic vegetation control during planting will be sufficient. In other cases, such as the scenarios presented here, additional timely investments in brush control may be necessary to fully achieve the potential conifer growth of a site.

Conclusion

While the immediate costs per acre for any reforestation project are substantial, many public and private benefits accrue from successful reforestation projects. Documenting the necessary actions, their costs, and the eventual impact on future forest growth and revenues is critical for convincing landowners and other potential cost-share partners to invest in reforestation. The FORECON economic analysis tool illustrates one way to assess the implications of various initial site-preparation costs, cost-share payments, and assumptions about how future revenues influence the overall economics of a reforestation project. A clear and simple economic analysis can assist forest landowners and managers who have different constraints and goals in planning and executing a successful reforestation project.

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Web addresses

- AB 32, the California Global Warming Solutions Act of 2006 <https://ww2.arb.ca.gov/resources/fact-sheets/ab-32-global-warming-solutions-act-2006>
- CAL FIRE California Forest Improvement Program www.fire.ca.gov/what-we-do/grants/california-forest-improvement
- California Air Resources Board California Climate Investments Quantification methodology <https://ww2.arb.ca.gov/resources/documents/california-climate-investments-quantification-benefits-and-reporting-materials>
- California Climate Investments caclimateinvestments.ca.gov
- Natural Resources Conservation Service Conservation Technical Assistance program nrcs.usda.gov/wps/portal/nrcs/main/national/programs/technical
- Natural Resources Conservation Service Environmental Quality Incentives Program (EQIP) nrcs.usda.gov/wps/portal/nrcs/main/national/programs/financial/eqip
- UC Agriculture and Natural Resources Forest Research and Outreach ucanr.edu/sites/forestry



Chapter 3

Planning a reforestation project

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Successful reforestation in California is a complicated undertaking spread over multiple years. The planning process detailed in this chapter is designed to guide landowners, land managers, and reforestation practitioners through the steps necessary to meet their reforestation project goals. Each step serves a specific purpose essential to the project's success. Failure at one step can limit success or result in complete failure, even if all others are properly implemented. In all situations, it is critical to think through and plan out all the steps while being prepared to adjust the plan for unexpected complications, delays, or setbacks. These basic steps are the same whether you are a small or large landowner or public agency, though slight modifications may be needed depending on the project type and purpose.

For planning purposes, the three basic reforestation project types (and purposes) can be categorized as postharvest, postwildfire, and rehabilitation and restoration. Connecting the many time-critical, sequential reforestation activities that occur over a number of years is also key to eventual success. To represent this process, figure 3.1 is a flow chart of the steps for each project type. Figures A1, A2, and A3, found in this chapter's appendix, shows the timing for each step of the three basic reforestation project types and provides references to the appropriate chapters in this book. These examples are for general reference, as each project will develop its own timeline based on site-specific implementation needs.

Developing and implementing a plan: Essential steps for successful reforestation

Reforestation projects in California are implemented on a diverse range of forestlands, ranging from highly productive timberlands to noncommercial forests with mostly aesthetic and wildlife value, and small private woodlands to large public and private forests. For all landowners, the decision to initiate a reforestation project begins with the desire to accelerate positive changes in the forest that they own or manage. Often this decision is forced by timber harvest or wildfire. Despite the differences in motivation and objectives, the best management practices outlined in this chapter and described in this book will lead to a successful reforestation project.

Select reforestation forester

The administrative and biological steps outlined in figure 3.1 (the flow chart) must be executed in a timely manner. It is advantageous to seek the services of a forester with expertise in reforestation. Large, private ownerships often have a professional reforestation staff or consultants under contract, while small landowners may have an ongoing relationship with a local Registered Professional Forester. Within the private sector, Registered Professional Foresters are licensed by the California Board of Forestry and Fire Protection. Contact the California Department of Forestry and Fire Protection (CAL FIRE) for a list of [Registered Professional Foresters](#) available to offer services in a project's general vicinity. Federal agencies have reforestation specialists, and sometimes contract out for specialized skill sets.

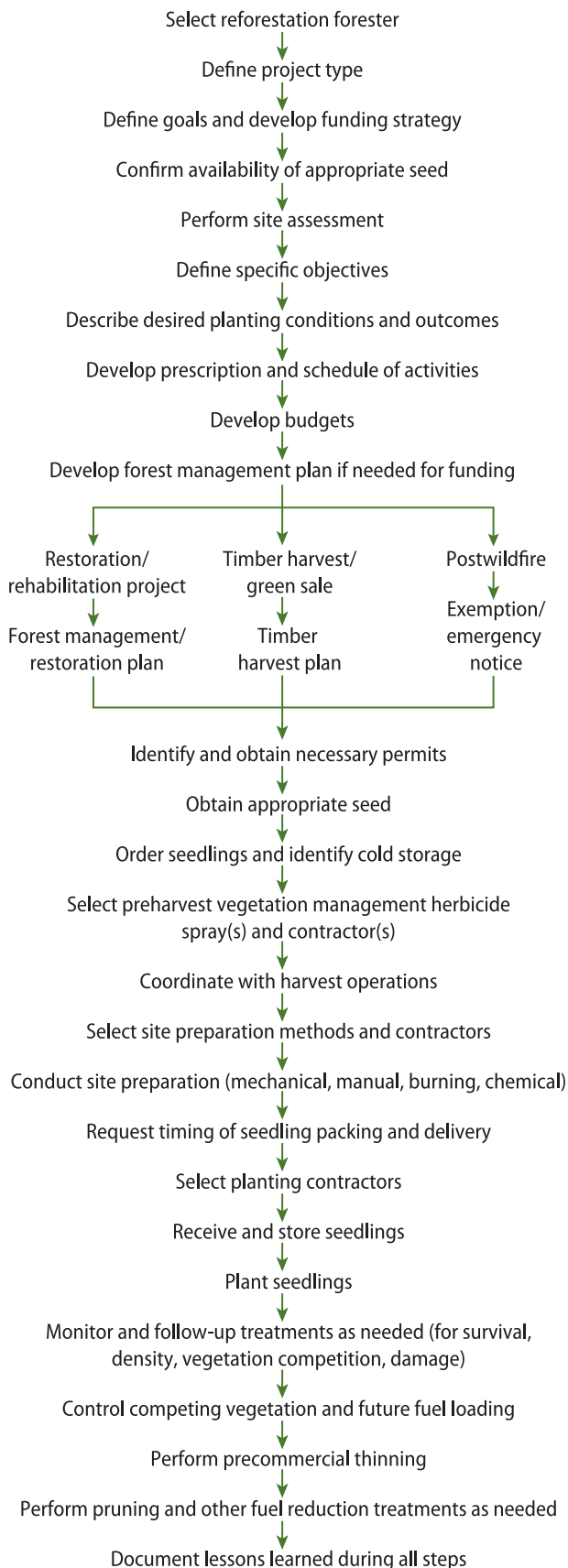


Figure 3.1. Reforestation workflow outlining necessary steps for basic project types.

Landowners should be aware that not all Registered Professional Foresters are experienced in reforestation, due to differences in specialization and previous work experience. A forester experienced in preparing and administering Timber Harvest Plans or salvage logging contracts may not necessarily be experienced in planning and implementing a subsequent reforestation project. The following considerations can help to identify a Registered Professional Forester with expertise in reforestation:

- What reforestation projects have they done and how successful were these projects? Consider visiting some of the project sites.
- Ask for references from other landowners that the Registered Professional Forester has worked with.
- Do they keep up with the most current reforestation practices? Foresters have many excellent opportunities to improve their reforestation skills, such as attending the Forest Vegetation Management Conference and California Forest Pest Council Weed Tour. These conferences also help members network with other reforestation specialists.
- Does the forester have other pertinent licenses, such as those issued by the California Department of Pesticide Regulation? An Agricultural Pest Control Advisor license in the Weeds category allows a forester to make pest control recommendations that are needed for managing competing vegetation. A Qualified Applicators License or Certificate in the Forest Pest category indicates that a forester is knowledgeable in regulations and practices regarding the application of forestry herbicides. Additional information regarding licensing requirements when working with persons or business that are hired to conduct herbicide application may be found in chapter 8 (“Vegetation management”).
- If different Registered Professional Foresters are chosen to manage the harvest and reforestation, can they communicate with each other and coordinate activities as needed? If both harvest and reforestation activities are planned, consider hiring a firm or individual with experience in both.

Define project type

Reforestation projects generally fall into three categories:

1. **Postharvest:** Planting after a green-timber harvest
2. **Postwildfire:** Planting after a wildfire
3. **Rehabilitation/restoration:** Converting a brush field occupying unstocked or understocked forestland back to forest or reclaiming a site from off-site, exotic, or invasive species

While each project type has its own needs and challenges, most will follow the sequence of steps shown in the flow chart (see fig. 3.1). Timing constraints will differ based on the status of competing vegetation and the time needed to order appropriate seedlings.

Define goals and develop funding strategy

After defining the project type, landowners must identify goals for the property. A goal is a broad, general statement of intent that describes a long-term vision, such as producing income, enhancing wildlife habitat, and protecting soil and water resources (Oregon State University Extension 2023). For example, the USDA Forest Service's reforestation goals are to "foster resilient, healthy, and productive forests that sustain ecosystem services, economic values, carbon sequestration, and stable carbon pools" (U.S. Department of Interior and U.S. Department of Agriculture 2023). Goal setting is also essential to identify the relevant funding necessary to implement a project. Specific objectives to reach these goals should be developed after the site assessment phase, when more details are known about the property.

Reforestation is an expensive, long-term investment, as described in chapter 2 ("Investing in reforestation"). Acquiring the funding needed to complete the many steps of a multiyear project can be challenging, particularly for small landowners. Be aware that underinvesting in activities such as vegetation control, seedlings, and planting will result in failure or the need for additional, even more expensive work to salvage the project. An important early first step is to identify and pursue relevant and available financial grant assistance from state and federal cost-share programs. Grant approval can take from several months to more than a year after an application is received. It is important to plan for the reality that the timing of funding may not coincide with climatic or biological windows that dictate the timing of each step.

Large landowners usually finance projects with a portion of net income from the sale of forest products in the project area as well as other private investment funds. To get initial funding, the forester must document the plan and budget needed for a successful reforestation, and the reforestation team typically submits expense requests for inclusion in annual or multiyear budgets. With government agencies such as the Forest Service and CAL FIRE, funding must be allocated from the general fund through spending bills by the U.S. Congress or state legislature.

Federal agencies such as the Forest Service may have several potential funding options for individual reforestation projects. Timber sales, with planned regeneration harvests, commonly use Knutson-Vandenberg

collections. These funds become available after the purchaser pays for the timber and can be used soon after the harvest is complete. However, current reforestation activity is dominated by reforestation after high-severity wildfires, often without salvage harvest of the fire-killed trees. The Reforestation Trust Fund then may become the major funding source and is available for use. Other funds are sometimes available and may be combined with these more common sources to meet the need.

Typically, funding is requested and allocated for annual accomplishments. Largely due to the geographic extent and number of recent high severity fires, combined with the relative absence of salvage harvesting of fire-killed trees and the need to reduce the adverse effects of competing vegetation, the total cost of reforestation is now much higher than any historical average.

Confirm availability of appropriate seed

Without appropriate seed, a reforestation project cannot proceed. The importance of seed origin and quality to long-term reforestation success is described in chapter 5 ("Seeds"). CAL FIRE's California Tree Seed Zones map, shown in chapter 5 (see fig. 5.1), divides the state into 85 unique zones, the result of many years of research into California's complex tree diversity and ecology. Within each zone, conifer seed collections are catalogued by 500-foot elevation bands and subzones less than 50 miles across. Research currently underway on the impact of climatic change on mature trees may result in guideline changes that adjust seed zones and elevations.

Identify the desired species, seed zones, elevation, and number of seedlings for each project before contacting conifer seed suppliers. Potential suppliers include the State Seed Bank at the Lewis A. Moran Reforestation Center in Davis, private seed companies in California and neighboring states, and forest nurseries. The Forest Service and some large private landowners may also make seed available from their seed inventories if they have excess. Large private landowners typically ask potential seed purchasers if they plan to follow all necessary steps for a successful reforestation project before selling their excess seed.

Finding out how much seed is potentially available for the project is a key step. An inadequate supply of seed can necessitate reducing the project size, planting fewer trees per acre (wider spacing), altering the species mix, or delaying the project until a suitable amount of seed can be obtained. Although determining the approximate quantity of seed needed and its availability is necessary prior to proceeding with the next steps, knowing exactly how much seed to order is

determined later in the planning process (see “Obtain appropriate seed” section below).

Landowners can choose to establish their own seed inventory to ensure a supply of seed for future projects, by purchasing seed from one of the sources listed above or collecting and processing cones from their own or neighboring properties (with permission). Additional information on monitoring cones for collection and processing seed for storage is described in chapter 5.

Perform site assessment

Site assessment is the first step in developing a reforestation project’s specific objectives and schedule of activities. The site assessment begins with an in-office assessment of relevant regional information on climate and fire risks and then focuses down to the project site to identify a wide range of project area characteristics so that all project planning is firmly based on the realities of the site. Most planning efforts use geographic information systems (GIS) and spreadsheets to organize, analyze, and map relevant site information and

identify unit boundaries and conditions. Other digital or manual methods may also be used.

Site information may result in dividing the project area into units with similar characteristics for applying treatments. Unitizing the reforestation area into homogenous subunits is particularly important for large project areas. An on-site assessment provides detailed, site-specific information and aids in ground-truthing information derived from other sources. See also chapter 4 (“Site assessment”) for a detailed explanation of this process and chapter 12 (“Reforestation of areas burned by large wildfires”) for an example of unitization.

Define specific objectives

A broad range of environmental and economic objectives may be possible for each previously defined goal. Objectives should be quantifiable (for example, trees per acre by species) in order to measure success and facilitate postproject monitoring. Objectives like aesthetics are not as easy to quantify as others, but it is always valuable to identify metrics for measuring out-

TABLE 3.1. Objectives for reforestation projects and measures of success

Goal	Objectives	Measures of success examples
Sustainable timber	- Manage for a sustainable yield of commercial conifer timber trees. - Manage for broad mix of species for sustainable yield of commercial conifer timber trees.	- Meet postharvest tree stocking needs per acre. - Meet total and per-species stocking needs per acre.
Forest health	- Ensure seedling survival, vigor and growth by controlling competing vegetation. - Maintain tree density and species composition that will create a vigorous and healthy forest, including a diverse understory.	- Allow no competing vegetation within 5 feet of seedling for 1 to 2 years after planting and minimal competing vegetation for next 3 to 5 years. - Plant desired species and remove undesired species to reach specific number of trees per acre within specified number of years. - Precommercial thin to desired species and number by age 10.
Fire protection	Maintain condition of property to minimize wildfire risk and allow for effective fire suppression and postfire recovery.	- Create fuel breaks for fire suppression and maintain roads for access. - Maintain brush and dead woody debris at acceptable levels at specified plantation age(s).
Post-wildfire	Replant all productive forest soils in burned areas with appropriate species.	Achieve specific number of trees per acre per species alive and growing after 2 years.
Wildlife habitat	- Retain oak species to provide acorns for wildlife. - Retain pockets of shrubs and small wood debris for small mammal habitat. - Manage non-conifer vegetation to stay within desired conifer/non-conifer mix.	Retain specific number of oaks per acre during site preparation, preferably large, acorn producing oaks.
Natural diversity	Enhance native plant species by reducing invasive and non-native plant species that can have negative effects on plant diversity and abundance.	Eliminate or control invasive plants to acceptable levels.
Aesthetics	Consider short and long-term effects on viewshed, especially near houses and high use recreational areas.	Develop a low density of large trees per acre in the viewshed.
Erosion Control	Provide for effective ground cover on eroding or potentially erodible sites.	Evaluate site to confirm no visible signs of (sheet, rills, ruts, gullies or mass movement), and no impacts to water quality.
Fuels management	Manage live and dead aboveground biomass to keep fire behavior to manageable levels.	Keep live and dead above ground biomass to less than 10 tons per acre.

comes. Objectives can be short- or long-term in timing and vision. Examples of goals, objectives, and measurable criteria are in table 3.1.

Wildlife, water quality, recreation, and aesthetics

Wildlife should be protected and encouraged to the degree required or desired, while accommodating necessary forest management activities. Treatments needed for successful reforestation also affect the characteristics of the stand; for example, hardwoods such as oaks provide food for many wildlife species as well as valuable habitat elements for cover, denning, and nesting. It is important to identify oaks, snags, large woody debris, and other elements left on-site that will be helpful to meet long-term objectives for wildlife habitat, recreation, aesthetics, and water quality. Depending on the stand's stage of development, habitat elements important for desired wildlife species include:

- Basal area of stems or square feet of cross-sectional stem area per acre (for example, approximately 2 to 10 percent of total basal area or number of stems in a stand)
- Snags, especially large ones, for nesting and denning sites (for example, number of 20-inch snags per acre)
- Coarse woody debris such as large, hollow logs that can be used for denning (for example, one large log greater than 30 inches in diameter and at least 20-feet-long per acre)
- Large-diameter oaks for denning or nesting (for example, one oak greater than 30 inches in diameter every 5 acres)

An example of a long-term objective could be to develop over time a habitat for game species at a forage-to-tree cover ratio of 60 percent to 40 percent. After ensuring seedling survival with treatments to control competing vegetation, this could be accomplished by managing vegetation and tree spacing over time. Another example of a long-term objective could be to develop a mature, mixed-conifer or ponderosa pine stand with 10 percent oak cover. To achieve this objective, the forester would need to leave much less than 10 percent oak cover at planting to account for the significant difference in early growth and site occupancy between newly planted conifer seedlings and resprouting hardwoods with existing, well-established root systems. A rapidly expanding oak canopy cover can significantly diminish conifer growth and site occupancy if it exceeds the manager's initial hardwood target.

Brush and hardwoods are valuable wildlife habitat elements, but they also compete with conifers for valuable resources and are ladder fuels for fire. Another

long-term objective could be to leave a small, specified percentage of the total project area in brush and hardwoods for wildlife habitat.

Tree density

The number of mature trees per acre is the most widely used metric for assessing the success of a reforestation project after the first decade. The initial number of seedlings planted often exceeds the projected number of mature trees, to account for expected mortality and in some circumstances to promote more-vertical tree form and provide early revenue, if there is a market for small-diameter trees. California and other Western states also have tree-per-acre requirements after green-timber harvests on private lands, which can be met with a combination of newly planted seedlings and residual trees.

In 2020, the California Board of Forestry and Fire Protection reduced the minimum trees-per-acre requirement from 300 trees per acre to 200 trees per acre on high sites, and 150 trees per acre to 100 trees per acre on low sites. This rule update brought California's reforestation requirements closer in line with those of other Western states. Planting higher densities of seedlings can result in more total biomass growth, but unless precommercially thinned, the trees will have smaller diameters and take significantly longer to reach the necessary diameter for commercial sale, wildfire resilience, or mature forest habitat objectives. In regions without a strong market for small-diameter trees, forests that are planted at higher densities and not precommercially thinned can stagnate and become prone to insect-caused mortality. Within any area, it is also common to leave some pockets of noncommercial species, snags, designated residual trees, and clumps of understory vegetation for wildlife habitat.

At planting, the number of trees per acre will vary depending on the species planted or whether the reforestation is a green harvest where minimum stocking standards must be met on private lands, voluntary reforestation after wildfire, or part of a restoration effort. The number of trees per acre remaining after precommercial thinning is the most important consideration for the long-term financial and ecological value of a stand. Foresters can aim for an initial planting density that is the desired final density or plant more seedlings based on vigor, species, and spacing characteristics, as well as wildlife habitat elements. As long as competing vegetation is not significant, wider tree spacing will result in faster diameter growth. At wider spacings, each tree has more access to water and other resources and is therefore more resistant to insect attack, disease, drought, and climate change.

Fuels

Choices made during the implementation of a reforestation project can have a major influence on the site's future fire risk. Site preparation and vegetation management methods, the retention of woody material for wildlife habitat, and tree density objectives should all be evaluated for their potential to increase fire risk. A fuel-loading target of less than 10 tons per acre can help to keep fires more manageable. The Rocky Mountain Area Coordination Center website includes photos of [common fuel models](#) for California. This link along with other information is available on the [Fuels and Fire Danger page](#).

Describe desired planting conditions and outcomes

Describing desired conditions applies to two time-frames: 1) the physical and vegetative conditions at time of planting for successful survival and growth of the target seedlings, and 2) a series of postplanting conditions over time, leading to successful future outcomes. Long-term results could be from 10 to 70 years or more.

Determining the desired planting conditions requires a thorough understanding of how planted conifers and competing vegetation will behave on a site. Factors to consider include:

- Soil moisture, air temperature, humidity, wind speed, and frost conditions during establishment
- Shade tolerance of the preferred conifer species
- Species present in the understory
- Responses of potential competing vegetation after harvest, site preparation, or fire; and how competing vegetation responds to treatment
- Species of competing vegetation present or likely to germinate on-site

Regenerated stands include a combination of species that have been planted, resprouted from root stock, and germinated from seed. Decisions must be made about which actions or prescriptions are necessary to achieve both the desired planting conditions and future forest outcomes. Conditions at planting to ensure seedling success vary for different species. For example, ponderosa pine is shade-intolerant, and residual trees that shade pine should be removed. Pine-dominated units are typically more than 1 acre in size. Douglas-fir has intermediate shade tolerance and its young stems are sensitive to heat damage, so large logs, stumps, small debris, and an intact organic layer provide favorable microclimates for their establishment. Douglas-fir and white fir are susceptible to frost mortality, and damage can be reduced by leaving some

overstory trees, utilizing a shelterwood harvest, allowing smaller group openings, or designating some leave trees as protection in frost-prone locations. Larger leave trees will effectively use soil moisture and sunlight and limit the growth of the new seedlings, especially those closest to the leave trees.

Develop prescription and schedule of activities

The prescription process incorporates site assessment, objectives, and desired conditions into a series of treatments designed to achieve the project goals. The timing of these treatments is described in a schedule of activities. See appendix 3.1 for examples of activity schedules (figs. A1, A2, A3), which can be used as outlines for different project types. Depending on the landowner and the need for disclosure, prescriptions can be as brief as these schedules or lengthy documents detailing each step. Each activity on the schedule may also have its own detailed timeline as well as a separate budget.

Develop budgets

Dividing the project area into smaller and more homogenous units, called unitization, helps to facilitate the budgeting process. Providing accurate acreage for each unit in mapping and spreadsheet data allows the forester to accurately estimate the cost of supplies, labor, timing, duration, and other activities. Small landowners can use this information to justify funding when applying for grants, while large landowners and agencies can use it for annual budgeting. If reforestation costs are being paid for with income from annual logging revenues, it is useful to know the timing of future costs so the land manager can retain income in the appropriate years. Landowners who do not budget well for postplanting release treatments, precommercial thinning, or other treatments may not have the resources to invest in future activities that are critical to long-term success. A spreadsheet covering at least 10 years of estimated costs from initial site preparation to precommercial thinning can help to identify budget needs and avoid future funding constraints.

The primary purpose of budgeting is to identify the amount and timing of funding needed throughout the project's scope. Skipping or even delaying a particular activity due to lack of funds can jeopardize the success of the reforestation project, wasting money spent on prior activities and requiring even higher treatment costs in the future. If funding is limited, the budgeting spreadsheet developed for each unit during the site assessment can be used to establish priorities among the units and allocate available funding appropriately. A spreadsheet with all units from the mapping system also helps ensure that a unit is not overlooked. When

the budgeting process is complete, the spreadsheet can aid in prioritizing which units will be treated with available funding. Similar lists developed within an agency can be used to prepare proposals for bidding.

Develop forest management plan if needed for project funding

Written forest management plans help guide reforestation planning on private property or units of public agency land. The plan's geographic scale is usually the landowner's entire forest property, while the time frame for planning and expenditure is at least 5 years, with goals and objectives for much longer. The plan includes site assessment information relevant for long-term forest management. In addition to guiding reforestation planning, a completed forest management plan speeds up the prescription process.

Forest management plans can also facilitate reforestation funding. CAL FIRE requires a forest management plan as a condition of receiving cost-share grants from the California Forest Improvement Program, which can fund 90 percent of the cost for Registered Professional Foresters to prepare project plans following a disaster such as a wildfire. Similarly, the Natural Resources Conservation Service requests that a conservation plan be completed as a condition of its Environmental Quality Incentives Program (EQIP), while the Forest Service requires a plan for funding from its Forest Stewardship Program.

The [California Cooperative Forest Management Plan](#) is a common template used to meet the requirements of agency assistance programs and American Tree Farm Association grants. In addition, CAL FIRE offers a nonindustrial timber management plan option to promote long-term management and planning on forest ownerships of 2,500 acres or less, with landowners agreeing to manage their forests through uneven-aged management and long-term sustained yield (California Public Resources Code §4593). The nonindustrial timber management plan can also be used to qualify for California Forest Improvement Program project funding.

Implement reforestation by project type

The three basic reforestation projects—postharvest (green timber sale), postwildfire, and restoration/rehabilitation (brush-field conversion)—primarily differ in the timing of activities to control competing vegetation, order seedlings, and secure necessary permits. Once seedlings are delivered to the site, the implementation of most projects will follow a similar path, with the timing or methods in some steps modified, added to, or eliminated.

Identify and obtain necessary permits

Federal, state, and local agencies require permits for a number of reforestation project activities. Permitting processes are ever-changing; check with appropriate agencies to determine the latest requirements. Some permits will require a timber harvest plan signed by the landowner, timber owner (typically the landowner), and Registered Professional Forester. The forester typically prepares them in consultation with the landowner and other professionals and agencies and submits them for the landowner.

Green-timber and salvage harvesting permits

Reforestation activities related to green-timber harvest on private land cannot begin until a timber harvest plan that complies with the state Forest Practice Act and California Environmental Quality Act (CEQA) is approved by CAL FIRE. The preparation and approval of this permit can take from 1 to 3 years, depending on the location and issues involved. Site assessment for a Timber Harvest Plan requires numerous surveys, including botanical, fish and wildlife, geological, and archeological. Reforestation activities should be planned well in advance of harvest so that they can be conducted at the appropriate times once the plan is approved.

Salvage harvest permits are not usually required for postwildfire reforestation activities on private and state lands in California. Postwildfire salvage logging operations may be conducted after filing a notice of emergency timber operations (or notice of exemption) with CAL FIRE, which may allow logging to commence within 5 days after CAL FIRE accepts the notice for filing. Harvest operations conducted pursuant to exemption and emergency notices must still comply with all operational requirements of the Forest Practice Rules.

An archeological records check and other assessments may not be required for operations under an exemption, but the landowner and Licensed Timber Operator are still responsible for protecting those sensitive resources. Prior to operations under a notice of emergency, the Registered Professional Forester must conduct an archaeological record check and survey along with other assessments to protect sensitive resources including botanical, fish and wildlife, and geological.

On federal lands, all timber sale operations must comply with federal laws such as the Multiple-Use Sustained-Yield Act, National Environmental Policy Act (NEPA), Endangered Species Act, Clean Water Act, and Clean Air Act. Projects going through the NEPA process can take 2 years or more before approval and longer if appeals and litigation are filed. This

uncertainty can complicate project planning and lead to operational delays.

Water quality and fish and wildlife permits

Water quality permits, or more typically conditional waivers of those permits, along with fish and wildlife permits, may be required for timber harvest activities that potentially affect the beneficial uses of water or threaten fish and wildlife. Examples include Regional Water Quality Control Board waivers of waste discharge permits, California Department of Fish and Wildlife lake and streambed alteration permits (under section 1600 of the California code), and, where needed, surveys for specific plant and wildlife species. Conditional waivers and 1600 permits may be obtained within a month but can take longer. Surveys often are season-dependent and can take a year or more to be scheduled and completed. For example, surveys for the northern spotted owl, which is protected under the state and federal Endangered Species Acts, can take up to 2 years. Such permits and surveys may also be required for salvage logging after a wildfire.

Know what permits or waiver conditions are required and allow plenty of time to get them processed. Permits may also be required by the U.S. Fish and Wildlife Service, National Marine Fisheries Service, U.S. Army Corp of Engineers, or other federal agencies, most often for timber harvest activities that could impact listed species or stream habitats. Some of these permits can take months or years to obtain.

Pesticide application permits

Pesticide application permits are issued and enforced by local county agricultural commissioners under authority of the California Department of Pesticide Regulation and must be obtained before pesticide spray operations begin. An operator identification number and a restricted materials permit for the application of certain herbicides or insecticides is required for reforestation projects (California Department of Pesticide Regulation 2019). The permit identifies sites where applications can be made and lists specific conditions that must be followed during applications. If the permit applicant is not the landowner, the applicant must have written authorization designating them as the landowner's representative, and they must possess a valid Pest Control Advisor license issued by the Department of Pesticide Regulation.

Unless they are working on their own property, applicators must also be licensed as a pest control business, have a qualified applicator licensee on staff in order to apply pesticides for hire, and must annually register with the county agricultural commissioner in each county where work is performed. After

applying any pesticide, the landowner or applicator is responsible for reporting the use to the commissioner online or on approved forms. A written pest control recommendation by a licensed Pest Control Advisor is required when the person making a recommendation on the use of pesticides is not the landowner or an employee of the landowner. For more information on pesticide licensing, permits, and reporting, see chapter 8 ("Vegetation management")

Burn permits and plans

Burning as a site preparation method may require a smoke management plan from the county or regional air quality district, depending on the size of the project, quantity of emissions, and proximity to smoke-sensitive areas. Some districts may also require an air pollution permit, and fees may apply. California's 35 air pollution control districts are responsible for regional air-quality planning, monitoring, and stationary-source and facility permitting; these districts are the California Air Resource Board's primary partners in efforts to comply with the federal Clean Air Act. Due to a declining number of burn days, acquiring approval for smoke management plans that include burning in a reforestation project has become more difficult in recent years.

Private landowners may also need to obtain a project burn permit (LE5) from the agency responsible for fire suppression in the project area (usually CAL FIRE). The LE5 permit is required to burn during fire season, which varies annually and throughout the state as determined by CAL FIRE.

Obtain appropriate seed

Since seed adapted to the project site is not always available, a source for seed should be located prior to the start of project planning. The project prescription should include estimates of the quantity of seedlings needed by seed lot, which is typically grouped by seed zone, elevation, and species. The best way to obtain the proper quantity of seed is to contact the selected seedling nurseries and have them calculate how much seed will be needed based on the forester's plan for the quantity of seedlings per seed lot and each seed lot's attributes, including seeds per pound and germination rate in combination with the nursery's oversow factor and other nursery-specific attributes. How much seed the nursery needs also depends on the quality of seed and how efficiently the nursery uses it (see chapter 6, "Seedlings"). If a reforestation forester knows that a particular seed lot is in short supply, informing the nursery of the situation can result in more efficient seed use.

Order seedlings and identify cold storage

Seedlings should be ordered by the first week of December at the latest (see “Ordering seedlings” section in chapter 6 for more details). If ordered in November or December, 1-year seedlings will be available for planting the following fall (10 to 11 months later), winter (12 to 14 months later), or second spring (14 to 18 months later). Timely seedling orders allow the nursery to optimize seed treatment and sow dates and therefore provide the best quality seedlings. If you haven’t grown a particular species or contracted with a nursery before, be sure to contact them well in advance.

The project prescription identifies the species and seedling stock types (container size or bare-root age) that are best-suited for the project and lists the quantities of each needed. If seed for the project has already been obtained, the nursery needs to know the quantity and quality of that seed to determine how much they will need to grow the requested number of seedlings. If no seed has been obtained, the nursery may be able to secure it (if any is available). The seedling purchaser is responsible for the cost of the seed as well as the seedlings. Chapter 6 (“Seedlings”) offers extensive information on selecting species, seedling stock types, and a forest nursery, and more detail on how to order seedlings. Chapter 9 (“Planting”) has more detail on species and stock types commonly used in various regions of California.

Packing windows for seedlings are getting shorter, making cold storage more critical. This is a particular problem for small landowners and consultants with relatively small and often periodic reforestation projects. Try to line up cold or freezer storage, if applicable, when seedling orders are placed. Often the nursery can provide or arrange for cold or freezer storage. If not, identify an alternative storage location. Do not wait until the seedlings are packed and ready for delivery and then try to find storage as nurseries usually have limited storage capacity. See chapter 9 (“Planting”) for more information on cold storage.

Select preharvest vegetation management herbicide spray(s) and contractor(s)

Preharvest chemical site preparation before a green harvest, if done well, can substantially reduce the need for treatments to release planted trees from competing vegetation after planting, known as release treatments, and related costs. Herbicides to control competing woody and other vegetation may be applied before a site is logged so that the planted seedlings are not damaged. Such treatments are particularly effective for controlling resprouting brush and hardwood species. Depending on the species to be planted and location,

spraying should be done a minimum of 3 months prior to logging and 1 to 2 years before planting.

The need to spray before logging means that timber harvest or sale plans must be completed well in advance. Completing and receiving approvals for plans 2 years before logging is scheduled allows flexibility to conduct vegetation management treatments, even if logging plans change. Road construction or reconstruction that provides access to the project harvest area should be completed prior to this preharvest site preparation treatment to reduce labor costs and allow spray crews and equipment suitable access to harvest units. Find a contractor equipped and experienced in preharvest chemical site preparation. This should occur at least 6 months if not a year before the planned application to give contractors time to schedule the work and secure a labor force. Permits for chemical use may also take time to obtain. For more information, see chapter 8 (“Vegetation management”) and the examples of project timing in appendix 3.1 (see figs. A1, A2, A3).

Coordinate with harvest operations

Green-timber harvest schedules often affect the timing of reforestation treatments, and treatment plans may need to be adapted to account for changes in harvest timing. Harvests are often scheduled to accommodate a mill’s processing capacity or the availability of a logging operator. Being involved with the scheduling process as much as possible will allow for timely reforestation treatments. Harvesting can take place any time of the year depending on the location and weather, but most logging is done from April through November. Some logging occurs on the eastern side of the Cascade or Sierra Nevada mountains on snow or frozen ground from December through February. Logging can occur year-round on the California coast where roads are well-rocked.

Select site preparation methods

Site preparation refers to any measure that prepares an area for the regeneration of a forest stand, and many reforestation practitioners consider it the single most-important step. Vegetation management is a primary controlling factor in any successful reforestation. Chapter 7 (“Site preparation”) describes how to determine the need for site preparation and covers three common non-chemical methods: mechanical, manual, and burning. Chapter 8 (“Vegetation management”) focuses on the chemical (herbicide) methods of forest vegetation management used in the different steps of reforestation. Each method, or more likely an integration of methods, should be evaluated on a unit-specific

basis in terms of comparative cost and effectiveness in meeting project objectives.

Mechanical site preparation

Common reasons for mechanical site preparation include slash removal, vegetation control, reduction of soil compaction, and breaking up hydrophobic soils after a fire. Mechanical site preparation should be done in the summer or fall before planting. In places where chemical preharvest site preparation did not happen, it may be necessary after harvest. In this case chemical and mechanical treatments should be scheduled to allow for maximum efficacy of the chemical treatment while still accomplishing the objectives of any mechanical treatment.

Manual site preparation

Manual labor to prepare a site includes grubbing, applying mulches, and hand-piling. It is much more expensive per acre and tends to be used on sensitive sites such as steep slopes close to sensitive water sources or at the urban-wildland interface, where chemical use might be too controversial.

Burning

The use of burning under prescribed conditions, including pile and broadcast burning, is an option, although its use on private lands has declined significantly in recent years due to smoke management and liability issues.

Chemical site preparation

Postharvest foliar chemical site preparation may be necessary if preharvest chemical site preparation was not done or was not effective on all target weed species. Depending on the vegetation present, units may need to sit fallow for a season to allow woody vegetation to resprout and grow foliage leaf area large enough to absorb sufficient herbicide for effective chemical control. This usually occurs with difficult-to-control species such as snowbrush, tanoak, or golden chinquapin. However, if imazapyr is used, planting should be delayed for an entire year because it is a foliar herbicide with residual soil activity that is harmful to conifer seedlings.

Following pre- or postharvest foliar site preparation treatments, a soil-active residual herbicide application may need to be scheduled for the fall or spring before planting, depending on the elevation, to control competitive grasses and forbs. Depending on the herbicide mix used, this may occur before or as soon as practical after planting.

Select site preparation contractors

Anticipate all labor contracts well in advance of when site preparation work needs to be done. Experienced crews and essential equipment operators are typically booked early. It is wise to get a commitment from contractors several months prior to the project. Seasonal availability varies by the type of site preparation method. The summer season is busy for equipment contractors, so the previous winter is a good time to locate and commit, for example, to a contractor for mechanical site preparation. Spring is generally the busy time for herbicide application contractors. Prescribed fire crews, who have different skills than firefighters, will be needed during the spring and fall burn windows. Plan ahead and be ready when your prescription window opens.

Conduct site preparation (mechanical, manual, burning, chemical)

Site preparation is the most important step for a successful reforestation program. Good control of competing vegetation prior to planting will save land managers a lot of time and money in the long run. It is far more expensive to release established seedlings from competing vegetation after planting than it is to treat it prior to planting during site preparation. Relying solely on release treatments to control competing vegetation limits the land manager's choice of chemicals and forces them to use higher volumes of chemical and significantly more expensive application methods.

It is also important to coordinate the proper sequence and timing of the different site preparation treatments. For example, foliar chemical site preparation applications must be completed prior to mechanical treatments to allow enough time for the chemicals to translocate from the sprayed foliage to the meristems and roots before any mechanical, manual, or prescribed-fire disturbance. Also, planned, mechanical, and prescribed-fire treatments must be completed prior to any soil-active herbicide application for controlling herbaceous vegetation.

Request timing of seedling packing and delivery

Contact the nursery in the fall, at least a month before seedling packing is expected to begin, to discuss its timing for spring planting. Packing requirements for units scheduled for fall or winter planting should be discussed during the summer prior to planting. The approximate date that seedlings are expected to be planted will affect their packing window and the type of cold storage to use. Get requests in early and plan cold storage accordingly. See chapter 6 ("Seedlings") and chapter 9 ("Planting") for more information.

Select planting contractors

Planting contractors can be very busy with existing commitments, so contact them as soon as 6 to 12 months before their services are needed for your project. Government agencies that have lengthy contracting procedures, especially those with complicated bidding processes, may need even longer lead times to ensure that planting contractors will be available for planting. See chapter 9 (“Planting”) for more details.

Receive and store seedlings

Seedlings packed for immediate planting, such as in the fall, will need to be picked up as soon as they are packed and then handled properly and planted within 1 to 2 weeks (see chapter 9, “Planting season” section). Seedlings that will be stored and planted later are packed from November through January. Without proper storage, packed seedlings can develop mold. If storage at the nursery has not been arranged, seedlings should be picked up immediately after they are packed and transported to cold storage. If the travel distance is long and the region is warm, it may be necessary to transport seedlings in a refrigerated truck or van. The type of cold storage required near the planting site depends on the length of time the seedlings will be in storage (see chapter 9, “Cold storage” section).

Plant seedlings

Planting is the culmination of this multistep process. Seedlings must be properly handled with adequate transportation from the cold storage to the field and then by the planters onto the site. Having an experienced planting crew and good planting-quality inspectors helps to ensure success. Doing all the other steps well will not guarantee success if the seedlings are not planted correctly. See chapter 9 for more information about planting and storage.

Monitoring and follow-up treatments as needed

It is essential to follow up any planting project with periodic evaluations of seedling survival and density, vegetative competition, and damage from insects, disease, and animals. Monitoring after planting in a manner and at intervals described in chapter 9’s “Planting follow-up” section allows for timely diagnoses and responses to problems that can otherwise lead to poor performance or project failure. Animal damage is sporadic, making scheduling of labor difficult. If needed, some prevention of animal damage can be done in conjunction with planting if monitoring and diagnoses are timely.

Effective monitoring is based on knowledge of the planting area and habitat that pests thrive in. Facilitating healthy, vigorous tree growth with good

vegetation management and tree spacing significantly reduces the need for direct control of insects, significantly minimizing or eliminating the use of insecticides on most project sites. Early identification of pest species allows for timely treatment. For diseases, particularly root-based fungal rots, knowledge about pathogens in the area is helpful. For animal damage, knowledge of migration patterns or habitat issues can lead to successful preventative programs. Entomologists and pathologists employed by CAL FIRE and the Forest Service’s Forest Health Protection program are available to provide valuable assistance in forest pest identification and management.

If possible, schedule labor for any required treatments well in advance. Aerial applications may be needed for insect infestations that occur over large areas, and lining up aerial contractors can be difficult on short notice. Disease treatments are usually preventative and often occur at harvest. See chapter 9 (“Planting follow-up” section) and chapter 11 (“Damage”) for more information.

Control competing vegetation and future fuel loading

Treatments to control vegetation after planting, known as release treatments, usually occur within 5 years after planting, but can occur later. Target weeds will vary by site, and the appropriate treatments used to control them will depend on the species, stage, and condition of vegetation present. Depending on objectives, release treatments may or may not be necessary. If herbaceous vegetation is present at the time of planting or soon after, a timely release treatment is typically done to assure seedling survival and vigorous first-year growth. Release treatments if needed in later years primarily target woody vegetation to maintain or enhance sapling health and growth and reduce the growth of brushy wildfire fuels. If monitoring after planting indicates the need for follow-up release sprays, plan ahead to secure properly trained and equipped spray crews. Securing a crew that is experienced in protecting seedlings from the herbicide treatment is a must. See chapter 8 (“Vegetation management”) for more details.

Perform precommercial thinning

Precommercial thinning is any activity where the density of trees is modified to facilitate growth of the residual trees into desired sizes over time. Timber stand improvement also refers to treatments that involve pruning, branch removal, or other activities to reduce potential wildfire fuels. Although precommercial timber-stand improvement activities do not generate net revenue, they promote the health and growth of trees and/or reduce the risk of loss from wildfire,

insects, and diseases. When the primary long-term objective is to generate timber revenue or otherwise grow relatively large trees, factors to consider when thinning include the size of tree required for commercial viability and how the treatments will reduce potential wildfire losses.

The timing for completing precommercial thinning varies from site to site. Precommercial thinning typically occurs 5 to 10 years after planting depending on tree growth and site productivity. Thinning should occur when trees are well established but before they get too large and expensive to thin and create an unacceptably hazardous fuel load. Spacing must be wide enough for the trees to grow at an acceptable rate for the next 20 to 30 years until the first commercial thinning. Delaying thinning past the optimum time not only slows the growth rate of crop trees but also increases the level of fuels from thinned trees. Thinning late also increases the cost of thinning projects because larger trees take longer to cut.

When making decisions about when and how much to thin it is important to understand and consider the information in chapter 10, but precommercial thinning ultimately boils down to accepting the number of feet between trees that the forester prescribed and the thinning contractor was hired to achieve. Foresters sometimes have a difficult time watching thinning crews cut down trees that they have planted and cared for, which are growing well. They must overcome a common tendency to focus on the short-term spacing needs of tree sizes at the time of precommercial thinning instead of spacing needs as the trees grow for the next 20 to 30 years. Otherwise, they will want to leave stands too dense. Spacing must be wide enough for trees to grow larger and compete with each other for the next 20 to 30 years and not simply wide enough to manage inter-tree competition for the next 5 to 10 years, when the forester sees much younger, smaller trees at the time of precommercial thinning. It is important to follow through with this crucial step at the right time with proper spacing for the long-term health and productivity of the stand.

For example, a common prescription for productive sites in Northern California starts with planting 200 to 260 seedlings per acre, followed by the precommercial thin to 18-by-18-foot spacing (135 trees per acre) at year 6 or 7 (or perhaps later for lower quality sites). Thinning will happen earlier for very productive sites and a year or two later for drier, less productive sites.

It's important to avoid conducting precommercial thinning between early May and the end of July during the flight of bark beetles in ponderosa pine stands, because the beetles are attracted to freshly cut trees. As

with all other treatments, lining up labor ahead of time is critical.

Deciding which trees to cut and which to retain is a relatively simple task in single-species plantations—the preferred trees are the ones retained at the prescribed spacing. The preferred tree to retain could be the one that is tallest or without defects but thinning to the prescribed spacing is ultimately the most important consideration. Mixed-species plantings are much more complicated due to significant growth differences between species in the first 5 to 10 years after planting. For example, although Douglas-fir and true firs are typically much smaller than ponderosa pine at the age of precommercial thinning, by age 15 to 20 they often catch up and sometimes exceed pine in height. Within the spacing guidelines, species preference should take precedence over relative height in order to retain the desired species mix. Targeting to retain a well-spaced species mix that is naturally adapted to the site should provide protection from insects, diseases, and drought in the decades to come, along with the widest range of market options in the future. See chapter 10 (“Precommercial thinning”) for more information.

Perform pruning and other fuel reduction treatments as needed

A fuel reduction treatment may be considered as a plantation matures or if funds are limited in strategic portions of a plantation, such as within 200 feet of roads and ridgetops. Pruning lower limbs to increase wood quality is no longer a common practice, but it can reduce the probability of surface fires getting up into the branches and facilitate fire suppression efforts under some circumstances. Fuel reduction treatments to manage brush are also important, such as spraying small brush before it grows into the crowns of young plantation trees or becomes hazardous ladder fuels in the understory of an older plantation. If brush has been allowed to grow into ladder fuels in an older plantation, it can be piled and burned or masticated as feasible. However, it is much more cost-effective and safer to treat the brush early before it grows into hazardous wildfire fuel.

Document lessons learned

Learning lessons from the reforestation project should be continuous and not necessarily the final step. It is important to document what worked well, what could have been done better, and what failed—and why. Understanding what happened during a reforestation project may not always be obvious but documenting the steps taken (or not taken) with text and pictures contributes to a better understanding of the project's

success or lack thereof. Over time, documenting lessons learned can substantially improve success rates.

Conclusion

Properly completing the time-critical steps described in this planning chapter addresses the five key principles that should be addressed in a successful reforestation project in California's Mediterranean climate:

1. Plant native species from known, appropriate seed sources that are adapted to the reforestation site.
2. Use quality seedlings that are vigorous enough to grow roots down to permanent soil moisture during the first growing season of establishment and are able to withstand sun, wind, cold, and any other environmental conditions that might be encountered.
3. Prepare the planting site by providing complete control of competing vegetation, access for planters, and management of hazardous fire fuel loads.
4. Properly handle, transport, store, and plant seedlings.
5. Monitor and protect planted seedlings from damage by animal and insect pests, and manage competing vegetation, hazardous fuel loading, and intertree competition.

Positive progress with reforestation over the past several decades has led to many changes in the details of planning projects. However, these common-sense planning recommendations and principles from an Oregon reforestation guide still ring true for California today (Hobbs et al. 1992):

- The region's environment and its well-adapted non-conifer vegetation interact to create often-hostile conditions for the survival and growth of seedlings. Such conditions require the careful and timely execution of well-thought-out plans for reforestation.
- In order to succeed, managers must work to identify long-term objectives.
- Regardless of management objectives, the sustainability of forest productivity must be a primary concern, with a major component of sustainability being reforestation after natural disturbance or harvest. An understanding of ecological principles, management practices, and analysis capabilities pertinent to the reforestation process is relevant to managing lands for all of the listed purposes.
- Managers must make monitoring of reforestation efforts by technically competent people a high priority.
- Actions must be biologically sound, economic sensible, socially acceptable, and operationally feasible.

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Web addresses

CAL FIRE roster of Registered Professional Foresters
caltreesplans.resources.ca.gov/Caltrees/customization/common/rpflicenselist.aspx

Common fuel models for California
gacc.nifc.gov/rmcc/predictive/Fire%20Behavior%20Fuel%20Model%20Descriptions.pdf

National Interagency Fire Center, Fuels and Fire Danger
gacc.nifc.gov/rmcc/fuels_fire_danger.php#

CAL FIRE's California Cooperative Forest Management Plan
fire.ca.gov/what-we-do/grants/california-forest-improvement

Appendix 3.1. Schedule of activities: Examples

The following schedules of activities provide general examples to facilitate the critical thinking necessary to develop and implement complicated biological, operational, and administrative reforestation processes. The left column in figures lists the series of activities necessary for successful execution of the project, which matches activities in the workflow chart (see fig. A1). A description of each of these activities is found in the related sections of this chapter. The second column lists the chapter in this book with detailed information about the topic. The rest of the figure shows when throughout the year activity is likely to occur for the type of project.

Each reforestation project should have its own schedule of activities with a timeline developed for the specific needs of the site. Reforestation includes numerous time-critical steps. Think through your reforestation project and develop a schedule of activities (prescription/plan) that works for your particular situation.

Schedule of activities 1: Postharvest (planting after green timber harvest)

Figure A1 illustrates a project where planting occurs after the harvesting of live trees, such as under even-age forest management, which is often practiced on large industrial ownerships. It can also apply to replanted group selection units that are considered uneven-age management under California regulations. Planting usually occurs in spring in the year or two after harvest if commercial conifer stocking levels are inadequate in the harvest area. However, many harvested sites can also be planted in the fall or winter if conditions are right. See chapter 9 (“Planting season” section) for details.

A post-green-timber harvest reforestation project has the benefit of a longer planning horizon because harvest planning must meet detailed regulatory requirements that result in a timber harvest plan. The schedule indicates this long lead time in the third and fourth columns, with 1 to 3 “minus” years showing the time frame of preharvest activities prior to the reforestation phase. Although many steps are the same as for the other two reforestation project types, post-green-timber harvest reforestation often benefits from preharvest spray treatments, which typically are more difficult to schedule in the other project types.

Schedule of activities 2: Postwildfire

While the need for postwildfire projects is increasingly common, reforestation success can be improved when planning begins immediately after a fire (Zhang et al.

2008) and proper steps, as described in this book, are followed. The planning and implementation timing of salvage activities and reforestation after a wildfire (see fig. A2) is considerably compressed. Quick action with the salvage process can increase income to help offset reforestation costs. Wildfires tend to occur from June through November with later wildfires further compressing planning timelines.

The first activity for a successful and cost-effective response after a wildfire is usually salvage harvest. The objectives are to salvage deadwood, capture as much value as possible before the wood deteriorates, and prepare the site so that residual and newly planted trees reach their growth potential. Salvage harvests are usually performed within a year of a fire, especially for smaller fire-damaged areas. On private land, a notice of emergency operations can be filed with CAL FIRE and logging can start within 5 days of its acceptance. The salvage operation must still comply with all relevant Forest Practice Act requirements, as well as secure and follow the conditions of the required water-quality and fish and wildlife permits. Archaeological record checks and surveys must be done prior to harvest operations.

Large landowners have the advantage of staff who can immediately get started, and most have experience with salvaging after wildfires and know what needs to be done. However, large landowners who do not have manufacturing facilities, along with small landowners, must take the extra step of marketing salvage timber and executing contracts with mills and logging contractors. The decline in the number of sawmills in California in recent decades has made it more difficult and expensive to get logs to market. If other landowners also have fire damage, nearby mills may not have the capacity to process all the trees killed in the region. It is important to start the process of looking for potential log buyers and transporters as soon as possible after a fire loss.

Smaller landowners can be at a disadvantage when planning a salvage harvest after a severe wildfire, especially if they do not have an existing relationship with an experienced forester or a forest management plan in place. Many landowners have lost not only their forestland but also their homes, so finding a place to live and dealing with insurance companies takes priority. Many are in shock, don't know who to trust, and want to wait before making decisions about reforestation, even though quick action will reduce costs and improve success.

Landowners who have the capacity to deal with salvage and reforestation should hire an experienced Registered Professional Forester as soon as possible, preferably one with reforestation experience. After a big fire, foresters and loggers are usually in short

supply. Loggers can quickly become committed to the larger projects of larger landowners. To find trustworthy, professional advice, ask to see the licenses of foresters and loggers and check with CAL FIRE about any violations. Small landowners who don't know the process or who to trust can call CAL FIRE and speak with the forest practices staff about salvage logging or contact a county forestry assistance specialist about California Forest Improvement Program funding for reforestation funding (see chapter 2, "Investing in reforestation," for more information). Be patient: Connecting with agency personnel can be difficult during and immediately after a fire.

Salvage logging and reforestation funding applications should be worked on concurrently. Applications for funding should ideally be filed by October 1 for approval before December 1, so that seedlings can be ordered. If reforestation is delayed for a year, brush and grass may become established, making reforesting more expensive and success more difficult. Federal reforestation projects can take much longer due to National Environmental Policy Act requirements, which can take 1 to 2 years, assuming there are no further delays from lawsuits and appeals. Federal agencies do not have any emergency processes for expediting postfire reforestation. Once salvage logging is complete, the sequence of reforestation activities is similar to other project types.

Schedule of activities 3: Rehabilitation/restoration (brush-field conversions)

Rehabilitation projects involve restoring conifer species to land previously forested but now dominated by other vegetation. The reforestation steps for this brush-

field conversion example vary from the other two schedules primarily regarding site preparation (see fig. A3). It is also key to prevent the return of heavy brush after site preparation with pre- and postplanting vegetation control. Brush-field conversions require less permitting related to harvestable trees than other reforestation project types. The permitting requirements are constantly changing, so landowners and foresters should check prior to any project. Pesticide-use permitting is required for all project types. Brush-field conversions are similar to green-timber harvests in terms of timely (rather than emergency) planning, but they typically have much higher costs for mechanical site preparation. Funding is a big obstacle with conversion projects, regardless of who owns the land. Small landowners may be able to receive funding from federal and state cost-share programs.

Tractor piling followed by burning is a common practice for brush-field conversions. Where feasible the brush is sprayed with foliar herbicides prior to piling to kill the root systems and facilitate piling. Spraying beforehand greatly reduces piling time and costs, limits topsoil disturbance, facilitates the burning of dirt-free piles, and eliminates the resprouting of brush that otherwise would be costly to control after planting. Whether spraying before or after piling, piling and burning is usually followed by herbicide spraying before planting to control vegetation. When herbicides are not applied, manual control of competing vegetation via scalping to bare mineral soil is used in conjunction with planting.

FIGUREA1. Example of schedule of activities for postharvest (planting after green timber harvest)

[illegible]

FIGURE A3. Example of schedule of activities for rehabilitation (brush-field conversion)

[illegible]



Chapter 4

Site assessment

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Site assessment is an essential step to develop plans for successful reforestation. Before conducting the on-site assessment, reforestation practitioners should take time in the office to collect relevant data from local and regional databases and prepare maps utilizing geographic information systems (GIS). This pre-field or office compilation, organization, and preliminary analysis of information will benefit the current project as well as all future projects.

As more-detailed historic, current, and future project information becomes available, practitioners responsible for more than one project should keep the pre-field compilation up-to-date with new resources. The on-site, or field, assessment is key for verifying and adjusting data from the pre-field compilation and capturing operational and logistical characteristics that also contribute to preparing and implementing a successful plan. See the appendices of this chapter for practical examples of on-site assessment forms: a site assessment template (appendix 4.1) and a completed reforestation site assessment and project plan (appendix 4.2).

While on-site, it is important to consider elements of the prescription such as appropriate tree species, planting density, competing vegetation, soil conditions, and any limitations to planting access. The site visit is an opportunity to ground-truth data acquired during the pre-field assessment. If the reforestation project is part of a green harvest, on-site assessments will be needed before and after the harvest. The preharvest visit will assess the existing site conditions, especially brush and other perennials for planning preharvest site preparation treatments, if needed. It can also assess the possibility that logging will help with site preparation and allow the forester to be involved in planning the

harvest. The postharvest visit assesses conditions on the site after all logging activities have ended, allowing for plan adjustments as needed.

Pre-field site assessment

Office research provides important information about the site from local and regional databases and other relevant documents. The maps and data acquired during map development are essential to subsequent steps of the site assessment process. Soil, vegetation type, botanical survey, endangered species, archeological sites, logging history, and climate data is useful to field personnel in preparation for conducting on-site analysis.

Compiling and utilizing existing data to make site-specific maps is a key component of reforestation planning. Virtually all subsequent activities will utilize these maps. Reforestation foresters must be aware of other available informational maps that will aid in reforestation planning and create the necessary site maps. Unless the project is very small, utilizing computer-based geographic information systems (GIS) is essential for operational and regulatory activities.

Geographic information systems (GIS) in reforestation assessment, planning, and implementation

The most critical part of organizing data is determining which data are needed and how they will be used. GIS software is a valuable tool for organizing and presenting all available data. The development and widespread use of various GIS software packages, especially when used in conjunction with spreadsheets, has greatly improved the forester's ability to organize and track information. Spreadsheet data can easily be exported to

TABLE 4.1. Information collected during pre-field and on-site assessments for each unit

Assessment category	Topic	Pre-field	On-site
Location	Ownership	X	
	Legal description	X	
	Property lines and corners	X	X
	Acreage	X	X
	Neighboring properties	X	X
	Road access	X	X
	Easements and utilities	X	X
	Seed zone	X	
Topography	Elevation	X	
	Slope	X	X
Climate	Precipitation	X	
	Temperature/humidity	X	
	Wind	X	
	Frost pockets	X	X
Soils	Soil type/texture	X	X
	Available water storage	X	X
	Organic matter content	X	X
	Soil stability and erosion	X	X
	Soil maps and data	X	X
Vegetation	Site class	X	X
	Natural regeneration		X
	Size and age class		X
	Vegetation species and cover	X	X
	Treatment needs		X
	Conifers prior to harvest/fire		X
	Harvest history	X	X
	Fuel loading		X
	Wildlife habitat elements		X
	Conifer seed zone	X	
Silviculture	Logging method	X	X
	Silvicultural method	X	X
	Site preparation needs		X
	Planting needs		X
Sensitive sites and species	Water quality	X	X
	Aquatic species	X	X
	Endangered species	X	X
	Archeological sites	X	X
Pests, insect, disease	Animal damage		X
	Insects and disease		X
Fire risk	Surrounding stands	X	X
	Residual crown fuels		X
	Ladder tree and shrub fuels		X
	Snag and down wood fuels		X
	Predicted plantation fire risk		X

or imported from GIS software for further analysis to help make management decisions.

Linking pre-field and on-site data for effective decision-making

Table 4.1 summarizes the topics and relevant information that should be collected during the pre-field and on-site phases of the site assessment. In many cases, the on-site assessment can help to verify data collected during the pre-field phase. In some cases, especially those requiring the identification of vegetation, the on-site assessment is critical.

Making and utilizing maps during the pre-field assessment

Compiling and utilizing existing data to make site-specific maps is a key component of reforestation planning. Virtually all subsequent activities will utilize these maps. Reforestation foresters must be aware of other available informational maps that will aid in reforestation planning and create the necessary site maps. Unless the project is very small, utilizing computer-based geographic information systems (GIS) is essential for operational and regulatory activities.

Table 4.1 provides an overview of reforestation topics and whether the data can be collected from the pre-field or office assessment, on-site visits, or both. In most cases, information collected from sources available at the office will be more cost-effective, especially for large operations. The on-site evaluation is often used to verify previously mapped data, but the field assessment should also identify specific locations where specific actions are needed.

Mapping operational units with similar characteristics

A primary goal of effective reforestation planning is to define units with similar physical characteristics that can be treated in the same ways. GIS allows for easy and accurate mapping of the planning units based on the data sources, as well as tracking during implementation and follow-up. Not all GIS data layers are utilized in all reforestation projects; some are more general and relevant to larger scale reforestation programs or for long-term projections.

Planning and operational units are subareas within the project boundaries with similar biological and operational characteristics. These characteristics include soils, aspect, slope, water availability, and site quality. Draft units can be

delineated prior to the field assessment and then verified on-site or created during the site visit by drawing lines or laying units out with global positioning system (GPS) points. Once the units are created and given unique identifiers, relevant site assessment information can be tracked by unit and specific operational or landscape-level prescriptions.

GIS does not just create pretty maps; it serves as a data management tool. Once the data are created either via direct input or GIS calculation, it can easily be exported to a spreadsheet for analysis and organization. Units can be sorted by size, soil type, site class, water-holding capacity, slope, year of planting, or any other factor for which data are available. When added to a spreadsheet, data with unique identifiers can be merged back into the GIS system. The ability to link GIS systems with spreadsheet data has significantly increased the organizational abilities and efficiencies of reforestation planners and implementers over the last 20 to 30 years.

Key regional data sets for baseline maps

Before collecting and integrating on-site data into a GIS, it is valuable to integrate regional site factors that are well documented to affect seedling survival and growth, including locational attributes, climate, soil, vegetation, and fire risk (Lavender et al. 1990; Spittlehouse and Stathers 1990; Stathers et al. 1990).

Some of this information can be drawn from regional data in published maps and databases, while others will require on-site assessment and verification. The many sources of regional data are constantly improving and include the [Geospatial Data Gateway](#), [Web Soil Survey](#), [Region 5 Geospatial Data](#), [Fire and Resource Assessment Program \(CAL FIRE\)](#), and the U.S. Geological Survey. Most counties and cities also have data available. Regional data sets and spatial coverage are often created by interpolating between a relatively small number of field plots, so they may not be accurate at the microsite scale that often determines seedling survival. Successful reforestation must use regionally available information as well as local and microsite information that can only be collected during detailed site visits.

Making a site map

A comprehensive base map is the foundation of the site assessment. It is needed to organize information and divide the site into units with similar treatments. The GIS layers of a useful map may include the following elements:

Contour lines. Contour lines show the site's elevation, slope, aspect, and topography. Traditional survey data is available from the U.S. Geological Survey and

other sources that combine basic data with other information. More-advanced sources of detailed elevation data—including light detection and ranging (LiDAR), radar, and advanced photogrammetry—are constantly improving and increasingly used in forest management in the United States, Canada, and Europe.

Roads. Data on roads to determine access is available from many sources, including:

- counties and state agencies, which supply up-to-date and downloadable GIS-based information
- large companies and agencies with their own databases
- aerial photography and imagery to determine road locations

The locations, condition, and accessibility of all office-mapped roads relevant to the project should be confirmed during site visits.

Water features. Springs, streams, lakes, and watersheds, as well as domestic water sources such as ditches, water intakes, and wells must be mapped in order to adequately protect them from silvicultural treatments and minimize liability. Silvicultural treatments include prescribed fire, mechanical treatments such as tractor piles and mastication and herbicide applications, among other treatments. Leaving buffers along and around water sources protects water quality. Identifying specific sources for water drafting is also important for spray operations and road dust abatement operations, if needed. In addition to state agency resources, the National Hydrography Dataset managed by the U.S. Geological Survey is an excellent source of accurate data on streams, lakes, and watershed boundaries. The Hydrography Dataset has been retired and replaced by the [3DHP](#); the old data is still available but not maintained.

Nearby properties. Property lines, property corners, utility and access easements, and parcel data for determining ownership and ownership patterns may affect road rights-of-way, access to the property and, depending on neighbor concerns, which treatments can be used.

Infrastructure. The presence of infrastructure such as buildings, power lines, water lines, wells, and water intakes and gates can affect management decisions and mitigation measures.

Vegetation typing. The National Agriculture Imagery Program with its [digital orthophotography database](#) provides aerial images of vegetation patterns that are useful for vegetation typing and other data development. GIS contours can be overlaid on the imagery to create an all-in-one contour map with vegetation typing.

Understanding locational attributes

Ownership information for both the reforestation site and neighboring properties can be obtained from county assessor offices, previous timber harvest plans, and other online sources. This information, including maps, can provide the legal description, property lines and corners, neighboring property owners, and access and utility easements across the property. All legal owners of the property must be identified prior to any reforestation activities. Acquiring adjacent ownership information is important to ensure that access permission is obtained before a project gets underway. Rough acreages for the project can be obtained from the initial mapping efforts. California seed zone maps for the project area are available on the CAL FIRE Fire and Resource Assessment Program [website](#) to identify appropriate seed lots for growing conifer seedlings on the reforestation site.

Coverages for locational attributes such as elevation, latitude and longitude, slope, and aspect are included as base maps in most GIS systems. Additional data can be downloaded from the U.S. Geological Survey [GIS Data Download](#) and other entities. More-detailed products using technologies such as new satellites, LiDAR, radar, and advanced photogrammetry are continually being developed. The more-advanced systems provide data at finer scales, which provides valuable microclimate data relevant to planting individual seedlings. The advantages of using more-detailed information should be weighed against the higher costs and limited track record on their long-term efficacy to create the desired stand of mature trees over the next few decades.

Topography

Basic topographical information including elevation, slope, and aspect can be gathered from digital topographic base maps.

Elevation. Elevation ranges must be identified for each management unit. This data—along with vegetation, soil, logistical, and other operational information—can be used to divide the project area into units, which can then be sorted and organized by similar prescriptions, schedules of activities, and cost. Elevation is a critical factor for determining conifer seed and species requirements, planting windows, access issues, vegetation control, and spray timings.

Slope. Slope influences water and air drainage and soil stability. Flats areas may be frost pockets that require planting frost-tolerant conifer species. Slope also influences which management tools are available due to operability constraints on mechanical equipment. Slope can also significantly influence the viability and cost of mechanical or manual treatments.

Aspect. Aspect has a strong influence on a site's microclimate and resulting vegetation complex, which in turn strongly influences vegetation management prescriptions. As a result, aspect is often used to define a project's units. North-facing slopes receive less solar radiation, making them colder and making them experience less evaporation. South-facing slopes are warmer and can often be planted earlier, but also will experience low soil-moisture availability earlier, making vegetation management even more critical. Likewise, aspect affects the choice of conifer species and timing of planting. Sites with different aspects can have very different soil surface temperatures and retain snow for significantly different periods of time. North et al. (2019) suggest that topography, slope, and aspect serve as an appropriate ecological foundation for reforestation decision-making, which may drive changes in reforestation tactics.

Climate data

Climate dictates many of the most important components of a reforestation plan, including species planted, stock size, planting season, and timing of vegetation management treatments. Most climatic information can be obtained before conducting the on-site field assessment. If the landowner does not have locally relevant climate records, current and historical data relevant to reforestation in California can be downloaded from websites such as the [Desert Research Institute](#), Oregon State University's [PRISM Climate Group](#), and UC Berkeley's [Cal-Adapt](#). These entities have developed wall-to-wall map layers based on advanced modeling data from numerous weather stations on temperature, precipitation, wind, solar radiation, fire weather, and vapor pressure deficits. Having better information beforehand about these factors can have significant value for determining which steps will guarantee high seedling survival.

Precipitation. The most important climate factor for reforestation in Mediterranean climates is precipitation. Since available soil water is the greatest limiting factor for seedling survival, initial precipitation levels limit how much water will eventually be available for potential storage in the soil profile and, in turn, seedling growth. In general, reforestation efforts are more successful on sites with high precipitation and more challenging where water is limited. The timing and type of precipitation influences reforestation plans. Areas where precipitation occurs mainly as rain throughout the winter are usually suited to planting between winter and early spring, with spring applications of residual herbicides. In contrast, high elevation sites—where precipitation mainly occurs as snow and can impede access—are more conducive to fall

planting with residual herbicide applications or planting in late spring.

Temperature. Extreme temperature and wind can negatively affect the growth and survival of conifer seedlings (Kolb and Robberecht 1996). High temperatures can cause sunscald that girdles the cambium of tree seedlings, while high winds can result in desiccation and abrasion. Climate data may help forecast these conditions so that the forester can potentially mitigate them via stock type, natural or humanmade sunshades, planting season, or mechanical site-preparation method. Topographic maps are also useful for identifying potential frost pockets, which may be verified in the field.

Climate change. The conifer species planted for reforestation are long-lived (100-plus years), and the climate is changing during this time frame. Tools such as UC Berkeley's Cal-Adapt are designed to help foresters hedge their bets against future climate change by adjusting species and seed zones and incorporating these analyses into pre-field assessments. By factoring in the current and future impacts of climate change, foresters can help facilitate not just seedling survival but also tree adaptability. For example, historic temperature and precipitation data can provide information on the probability of future drought or high temperature conditions, which may warrant even greater attention to controlling water use by managing competing vegetation (Balandier et al. 2005; Zhang et al. 2013) and choosing more drought-tolerant seedlings (Young et al. 2019).

Soils data

Soils are the foundation of the forest ecosystem, and they are critical to its sustainability. Knowing the project site's soil types is essential for determining whether the site can support a conifer forest, understanding its long-term productivity, and identifying potentially limiting factors. The most relevant soils data sets are based on detailed soil survey data from the Natural Resources Conservation Service.

Soil characteristics to consider when developing plans include texture (percentages of sand, silt, and clay), depth to bedrock, rock content, and available water storage, and other relevant factors including organic matter content, nutrient availability, and the potential for mass movement. For example, aspect, soil texture, and available water storage in conjunction with climate data can influence which species to plant. Depth to bedrock or hardpan, nutrient availability, and available water storage combine with climate and aspect to influence productivity. Likewise, rock content and compaction can affect the choice of planting tool, seedling stock type, and cost (see chapter 9 for more

information on planting). Even the color of soil can influence heat reflectance and soil temperatures.

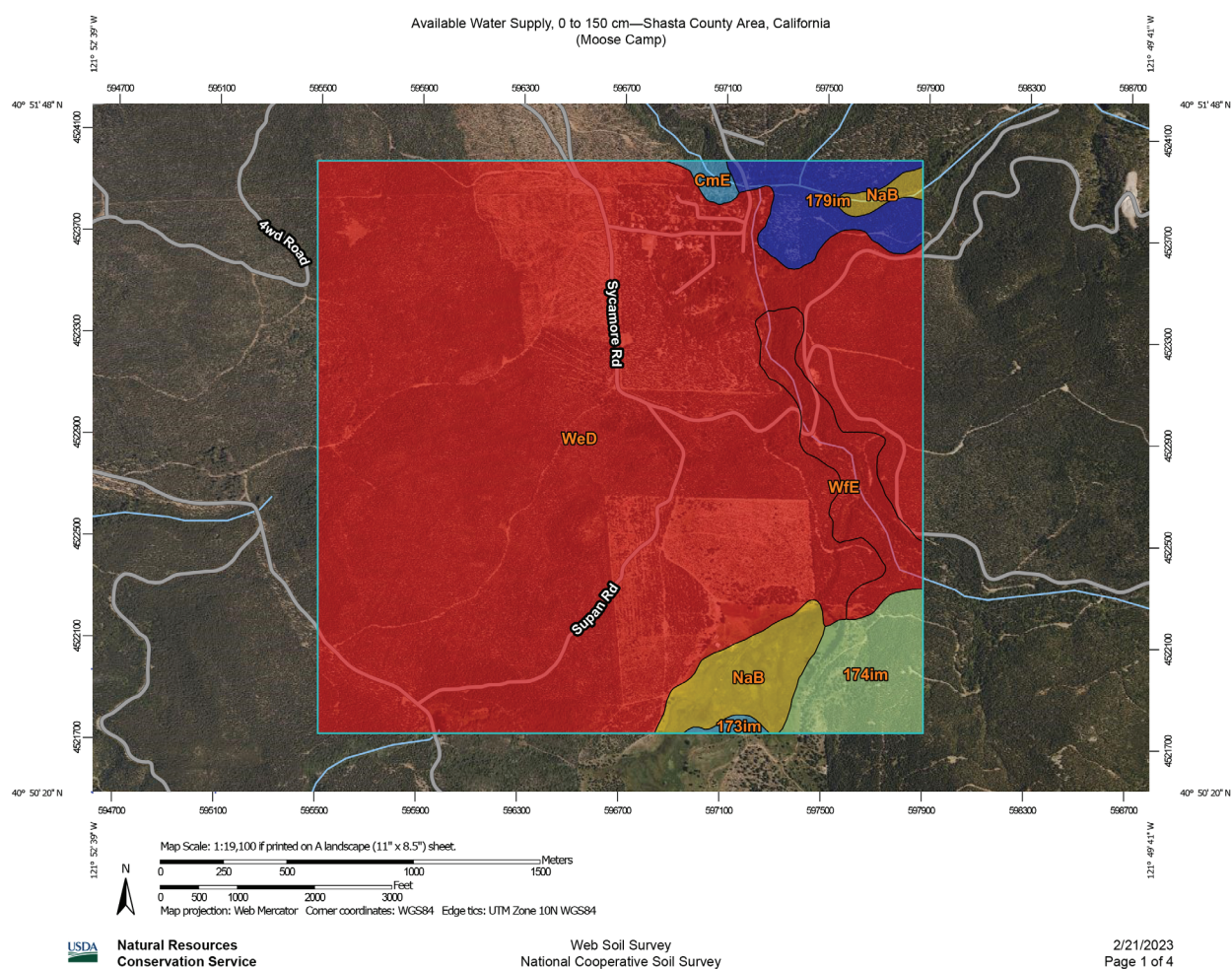
Identifying unstable soils is necessary for developing operational constraints and mitigation measures. Coarser soils with low organic matter are more susceptible to erosion and may need wider equipment and spray buffers. Sandy soil has lower water-holding capacity but is less susceptible to compaction during harvest and mechanical site preparation. Organic matter content can also affect the choice and rate of preemergent herbicides used for vegetation control (Neary et al. 1983) (see chapter 8 for more information on vegetation management).

Soils data is readily available for most forested areas of California from the Natural Resources Conservation Service's [Web Soil Survey](#) and the California Soil Resource Laboratories [Soil Web](#) application, hosted by the University of California, Davis. Since the original data is mapped at a 1-to-20,000 scale, it may not be accurate for smaller mapped units. These databases also include vegetation data on conifer, weed, and brush species associated with each soil type.

A soil-type map of a reforestation project site after the 1992 Fountain Fire illustrates the value of Soil Web Survey data in reforestation decisions planning figure 4.1 (Zhang et al. 2008). Web Soil Survey data for a specific area of interest was used to provide insights into relative reforestation success in the area. After the fire, Douglas-fir seedlings planted in the mid-1990s on Cohasset soils were more likely to survive than on Windy-McCarthy soils. Table 4.2 shows that significantly less water will be available for storage in Windy-McCarthy soils than in Cohasset soils. Lower available water storage indicates less total water availability in the soil profile and greater competition for water among all plants, hence a greater need for vegetation management to ensure the survival and growth of planted seedlings. Low available water storage is also an indication of the potential benefits of planting conifer species such as ponderosa pine, which are better adapted to harsher sites than species such as true fir or Douglas-fir, which need more water.

On-site vegetation

Competing vegetation is the single biggest issue threatening seedling survival and growth, and knowing what vegetation is on-site is critical to developing prescriptions. The types of vegetation on-site vary substantially based on the location and type of project. Reforestation after a timber harvest plan involves native pioneer competing vegetation occurring on units of up to 30 acres surrounded by older forest stands. After a wildfire, when tree mortality ranges from zero to 100 percent, mainly fire-killed understory vegetation will



Source: USDA Natural Resources Conservation Service Web Soil Survey, <https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx>

Figure 4.1. Soil types for a portion of the 1992 Fountain Fire near Moose Camp, CA. Location: 40.851 N, -121.853 W.

TABLE 4.2. Available water storage for several soil types within a reforestation area of the 1992 Fountain Fire*

Map unit symbol	Map unit name	Available water storage rating (em)	Acres in AOI	Percent of AOI
173im	Gaspar-Scarface complex, moist, 15% to 30% slopes	22.73	3.8	0.3
174im	Gaspar-Scarface complex, moist, 30% to 50% slopes	20.72	67.5	5.1
179im	Goulder, gravelly sandy loam, 15% to 30% slopes	25.20	51.3	3.9
CmE	Cohasset stony loam, 10% to 15% slopes, MLRA 22B	22.36	6.4	0.5
NaB	Nanny gravelly sandy loam, none to 8% slopes	13.53	51.4	3.9
WeD	Windy and McCarthy stony sandy loams, none to 30% slopes	10.60	1,072.6	81.8
WfE	Windy and McCarthy very stony sandy loams, 30% to 50% slopes	8.92	58.5	4.5
Total			1,311.5	100.0

*Available water supply at 0 to 150 centimeters soil depth at Moose Camp, Shasta County, California.

Source: USDA Natural Resources Conservation Service Soil Web Survey, <https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx>

resprout or germinate from fire-scarified seed. In projects in need of forest restoration, a mix of shrub and grass species typically occupy sites once covered in trees.

Vegetation mapping

Federal and state agencies offer numerous informational products that map historically present tree species as well as vegetation that may compete with new tree seedlings. These include

- CAL FIRE Forest Vegetation (FVEG) [system](#)
- California Department of Fish and Wildlife vegetation and wildlife [maps for reforestation projects](#)
- Forest Service Region 5 [vegetation map system](#)
- USDA Forest Service Forest Inventory and Analysis [maps](#), based on over 5,000 plots
- U.S. Environmental Protection Agency [ecoregion maps](#)

These products vary based on their information sources and projected uses. Often the most relevant vegetation information is related to the reforestation project's funding and regulatory issues.

Imagery

Ortho-photography (aerial or satellite imagery geometrically corrected to produce an image with the same relative distance measurements across the entire image) and aerial imagery can be used for basic vegetation typing in preparation for on-site assessments. Full-color coverages from the Natural Resources Conservation Service's National [Agricultural Imagery Program](#) and other data sets can be downloaded and integrated directly into the project GIS. These types of imagery provide foresters with an initial estimate of which conifers can grow on-site as well as which woody or herbaceous vegetation may become problematic. The species and type of vegetation present also help the forester to determine the site's quality.

Site history

Understanding a restoration site's disturbance history provides valuable insights into why certain species are present. For example, a past harvest may have removed a dominant overstory of ponderosa pine, leaving an understory of drought-intolerant white fir to dominate the site. This stand may become susceptible to drought and insect attack in the future. If the forester does not know the stand history, they might incorrectly assume that the area is a white fir site and should be replanted with that species, rather than better-adapted pine species.

A document search prior to going out in the field can provide valuable insight into the stand's recent

history. Timber Harvest Plans are public documents that should be available on CAL FIRE's [CalTREES database](#) for any timber harvest since 1973. The Forest Service also maintains timber sale records at the district ranger or supervisor offices of each national forest. CAL FIRE and the Forest Service map California's fire history, which is available on the Fire and Resource Assessment Program [website](#). Landowners are also a valuable source of early harvesting history and fire information that may not be captured in publicly available maps or databases.

Silviculture

Before going out in the field, the forester should know which logging and silvicultural systems have been used on the site and will be used in the future. In many areas historic silvicultural practices have resulted in major changes to vegetation. Historic preferences for higher value species such as pine and dependence on natural, rather than planted, regeneration have resulted in mixed-conifer stands with relatively fewer pines and more white firs in many regions. Single-tree selection silviculture results in more shade-tolerant species reducing the proportion of shade-intolerant species. Even-age or group-selection silviculture allows for the establishment of shade-intolerant species, such as ponderosa pine and sugar pine. Silvicultural choice depends on the goals of the landowner and the individual project.

Considering which mix of species is best-suited for each reforestation site is an important step for a new reforestation project. Silviculture activity planned for immediately prior to the reforestation will affect the unit's condition after logging and influence the necessary requirements for regeneration. Different silvicultural systems—such as clear cutting, shelterwood, or group selection—can influence the amount of artificial regeneration required. The type of logging system used significantly influences the amount of slash generated and hence the potential need for mechanical site preparation.

Sensitive species and sites

Prior to the on-site field assessment, it is important to research any issues regarding sensitive sites or endangered species. Water-quality impacts from excess soil runoff could, for example, present major risks to fish and amphibian species. Foresters should conduct an initial assessment incorporating aerial photography, past Timber Harvest Plans, GIS, and local knowledge to identify any potential water-related issues such as sensitive streams, domestic water sources, ditches, ponds, and lakes.

Protection of sensitive, endangered, and threatened species should be evaluated when planning any forest management project. Identify any species listed under federal or state Endangered Species Acts that may occur in the area. All projects that involve state funding or approval are required to check the California [Natural Diversity Database](#), managed by the California Department of Fish and Wildlife. The database's QuickView tool is free, but there is a fee for complete location data. Most large landowners, agencies, and forestry consultants have subscriptions to this service.

The California Native Plant Society provides a [database](#) of its inventory of rare and endangered plants, with search tools for rare plant locations and their status. The society's rare plant ranking system ranges from presumed extinct to limited-distribution species on a watch list. One particularly helpful search tool is the "9 Quad" search, which provides a list of rare plant species in the nine U.S. Geological Survey quadrangle map areas around a project site. Depending on where the project is located, the actual search may include more than nine quadrants. The idea is to create a list of potential species that may occur on the project area by searching adjacent areas with similar ecological and physical properties. The California Department of Fish and Wildlife has a PDF file online called "Protocols for Surveying and Evaluating Impacts to Special Status Native Plant Populations and Sensitive Natural Communities."

Projects funded or permitted by CAL FIRE—such as timber harvest plans, emergency notices, and California Fire Improvement Program projects—require a records check using the Centers for California History Information System to determine if any known archaeological sites are in the project area. After this information has been received, an archeologist or trained Registered Professional Forester must conduct a field survey of the proposed project area.

Fire risk

Wildfires are an increasingly significant driver of reforestation needs, especially on federal lands (Starrs et al. 2018), and they are an important consideration when planning to manage a stand for the next 50 years or more. When developing strategies to increase the survival of planted trees and reduce fuel loads, review data on the historic impact of wildfires on vegetation in the project area as well as what can be done to increase the probability that planted trees will survive and the role that trees and other vegetation play in creating fuel loads. CAL FIRE's [Fire and Resource Assessment Program](#) provides statewide data on fire risk levels.

Natural regeneration after wildfires in California is not assured, especially when the fire severity was

high (Shive et al. 2018; Welch et al. 2016). Areas with high fire risk are becoming areas that need preplanning for future reforestation needs (Tepley et al. 2017; Thompson et al. 2007; Zald and Dunn 2018). When establishing seedlings, it is important to consider how the future tree density and levels and types of competing vegetation will add to fuel loads and affect future fire behavior. Land managers may want to lower tree densities and patterns of other vegetation to reduce future fire severity and tree mortality (Kobziar et al. 2009; Dodge et al. 2019; Zhang et al. 2019). In areas with high and increasing fire risk, reforestation projects can be designed with stands of different ages to reduce wildfire mortality (Jain et al. 2020), as well as permanent fire breaks with limited tree density and controlled understory vegetation.

On-site field assessment

The main purpose of the onsite field assessment is to verify information obtained from other sources and evaluate critical factors regarding reforestation that cannot be obtained in the pre-field site assessment. Field observations cover a wide range of topics and are the foundation of any reforestation plan (table 4.1). To facilitate the field assessment, we recommend using a site assessment or planning information sheet for each. Examples of a completed site assessment and project plan are in this chapter's appendices along with examples of site assessment and planning templates (appendices 4.1, 4.2).

Site attributes

Topography. When planning for planting and treatment activities, it is important to understand the topography of reforestation units. Field-level evaluations will help to identify steep or unstable slopes that could constrain operations and actions in the future. The primary focus of the site assessment is the area within the boundaries of the reforestation project, but observations about adjacent lands and access roads are also necessary. The reforestation site may need to be divided into smaller, more homogenous units, each of which requires a separate set of observations.

Accurate and reliable acreage assessments are needed for reforestation planning and budgeting. Whenever feasible, use GPS to confirm and mark the closest-known, surveyed corners and identify surveyed property boundaries on the ground. If the project area has poorly defined property boundaries, a licensed surveyor may be needed to conduct a survey. Acreage for project or unit boundaries can be determined after final flagging and GPS mapping.

Surrounding landowners. To prevent misunderstandings or problems later on, identify the owners

of land surrounding the project site and how it is being managed to determine any potential conflicts. Neighbors are often concerned with aesthetics, water quality, equipment noise, and pesticide use, and these concerns will need to be addressed during the planning phase. Communicating with neighbors before a project starts can help to identify and facilitate mitigations. Neighboring properties may also be a source of problems for the reforestation project as well; common issues that may arise include wind-throw (blown down residual trees) from recently logged stands, weed encroachment, and illegal building across property lines.

Access roads. Road systems can affect the cost, management feasibility, and eventual success of reforestation projects. Access to the property via other ownerships may require permission or permits, and locked gates may restrict access. Identify which roads are permanent, seasonal, or temporary on the map. Note the proximity and type of roads closest to each unit, including seasonal dirt roads that are miles from paved county roads. Whether roads are rocky or native-surfaced can affect access early or late in the planting or spraying season, when conditions are wet. Check if any road work needs to be done to facilitate equipment or vehicle access.

Note the aspect and timber cover of roads within the project area. Roads on north faces and those with heavy timber cover may require snow removal in the spring for planting and spraying access, or may be limited to planting in the fall. Be sure to participate in the harvest planning process so that roads remain open and usable for reforestation activities after the harvest is complete.

Easements. Locate all easements, including above- and belowground utilities on or near the project site, which may need to be avoided by heavy equipment during site treatments and planting.

Water usage. Survey for any domestic water uses coming from the property to avoid polluting water during reforestation activities. Water rights held by others on the reforestation site or illegal water use may also need to be addressed.

Climate. Most relevant climate information can be obtained before the field visit. However, frost pockets must be verified in the field since the relevant topographic patterns that create them are often not recognizable from maps. Low, cold, flat areas with poor cold-air drainage are especially susceptible to frost damage, particularly on the east side of the Cascade and Sierra ranges. When planting in frost pockets, choose species that are more tolerant to cold conditions. In most cases, this means avoiding

frost-susceptible species such as Douglas-fir and planting more frost-tolerant species such as pine.

Soils. The soil types identified on soils maps should be verified in the field. Natural Resources Conservation Service maps show soils at a 1:20,000 scale, which may not be accurate enough for small numbers of acres. Don't take for granted that the mapping of soil types is precise enough for a particular unit within the project area. The soil type, texture, and percentage of organic matter will significantly affect the efficacy and mobility of soil-active herbicides.

Soils should also be evaluated for rockiness to determine the optimal planting method and stock type. Available water storage will have a direct impact on the availability of water for seedlings and other competing vegetation. If the forester is unfamiliar with on-site soil types, samples can be taken and sent into a lab to determine their type, texture, and percentages of organic matter. Erodible or unstable areas should be mapped in order to develop mitigation for vegetation management and mechanical site preparation treatments.

Vegetation

Site quality. The on-site assessment complements existing information with more detailed information about the species and condition of competing vegetation as well as the species and condition of advanced tree regeneration (in terms of future growth), natural seeding potential, insects and disease presence, fire history impacts, and other factors. During the site assessment, the forester can verify the relative quality of a site based on the vegetation present and the growth rate of mature conifers. In California, relatively poor sites often have a mixture of brush such as buckbrush, whiteleaf manzanita, chamise, or yerba santa, whereas higher quality sites may be a mixture of tanoak, bigleaf maple, and deerbrush. The presence of black oak indicates a moderate-to-good site capable of growing mixed conifers, but grey pine or Oregon white oak indicates very low site quality.

Natural regeneration. The presence of advanced natural conifer regeneration can affect planting patterns, density, and species choice. Some important questions to evaluate include:

- If there is advanced regeneration, will it be damaged by the logging and is it worth saving?
- Is the advanced regeneration grouped or evenly distributed?
- Does natural regeneration have at least 50 percent live crown? Is the natural regeneration growing sufficiently to release and grow into viable, mature trees?
- Is it infected with a disease such as mistletoe or vul-

nerable to infection by overstory trees not marked for harvest?

- Is it shade-tolerant or shade-intolerant? Will it survive exposure to sun?
- Will the advanced regeneration have a significant negative effect on the growth and health of a new plantation by competing for sunlight or water?

Another factor to evaluate is whether natural regeneration could occur on the site in the future. Generally, small group selection units (groups of trees harvested to create approximately 1- to 3-acre openings for regeneration) will be within the dispersal zone of surrounding trees and may seed-in naturally, at least partially. Natural regeneration is unpredictable, variable, and not guaranteed to be successful or produce the desired mix of conifer species. It is highly recommended to plant group selection openings to get timely stocking of site-adapted species. Larger clearcuts and wildfires are more sporadic in the scale and density of natural reseeding. If a viable cone crop occurred in the logging year, some natural regeneration will likely occur. Silviculture methods such as seed-tree or shelterwood cuts can increase the chances of natural regeneration because seed-bearing trees will be left on-site for a decade or more. The number of trees per acre at planting can be lowered if significant natural regeneration is likely. The species mix to plant can also be adjusted to account for species that are likely versus unlikely to seed-in.

When developing prescriptions during an on-site visit it is important to consider the current stand structure, age classes present, distribution of species and age classes, and age of residual trees; and whether uneven-age stands are worth keeping or brush in the understory might prevent natural regeneration. Is it time to start over? Including the reforestation forester in the silviculture prescription process can help to address these questions in a timely manner that will lead to better outcomes.

Competing vegetation. Detailed information about competing vegetation on the site is essential, particularly the approximate percentage cover by species of hardwood, brush, and herbaceous vegetation. The type and cover of vegetation on a site can indicate site quality as well as determine vegetation management prescriptions, mechanical site preparation needs, potential animal habitat and possible subsequent damage, and necessary herbicide treatments. It is also important to note whether a change in vegetation type could occur after the stand is harvested. Vegetation that has not been visible on the site for many years may reestablish itself from seed in the soil, which can remain viable for several years or decades. Looking at open areas near

the current project or for brush skeletons within the project yields clues regarding the likelihood that vegetation will germinate after logging.

On-site vegetation. The type of vegetation present on a site helps inform the forester about how to treat it. If the understory has large woody brush, piling may be necessary. If the brush height and configuration allows access for hand crews to spray safely, the stand is probably well-suited to preharvest chemical site preparation. This treatment typically eliminates the need for piling as a site preparation treatment after logging, since the logging activity typically crushes the sprayed brush enough to facilitate planting and fuel management objectives. If conifer production is a desired objective, a mature hardwood component in the stand may indicate that an herbicide treatment (such as hack-and-squirt) is required. Regeneration foresters must understand how to deal not only with the vegetation present prior to logging but also with vegetation that may show up afterward, as some seeds and plants respond positively to disturbed conditions. (See chapter 8, “Vegetation management,” for more information.)

Silviculture, logging, and fire history all have significant influences on conifers and other vegetation present on a site. The mix of conifer species currently present may not be the same as the original mix or align with landowner objectives. The site visit and assessment should examine the underlying conditions—and not just existing species—when determining which species can be successfully planted.

Silviculture

Reforestation foresters must anticipate how different silviculture regimes and treatments will affect the desired outcomes of the reforestation project, including how the stand will be logged and any subsequent issues affecting the reforestation. The logging method will have a significant impact on how much additional site preparation is needed. For example, whole-tree logging dramatically reduces slash loads and the subsequent need for piling. In comparison, cable-logged units are usually steeper, leave the most branches and tops on site, are covered in postharvest slash, and have limited road access—all factors that affect the design and specifications of subsequent site preparation and reforestation activities.

The type of silviculture may also have a dramatic effect on stocking levels, spraying methods, mechanical site preparation needs, and disease issues such as mistletoe. The site visit is the time to determine which site preparation methods are necessary: chemical, manual, mechanical, burning, or a combination. The stand structure, logging method, silviculture, and vegetation

complex will all contribute to the decision-making process.

Planting requirements such as specifications for scalping (clearing a small area to bare mineral soil immediately before planting an individual tree), planting methods (for example, hoedad, shovel, auger), and planting stock and density must also be evaluated. The type of silviculture and whether the harvest resulted from a wildfire or green-timber sale may affect the number of trees per acre to plant. Slash loading may also affect stocking levels. Seedling stock type and size also need to be addressed at the site visit. Animal issues, wind or sun exposure, the rockiness of soil, and access will influence planting methods and what size and type of stock is planted.

Wildlife habitat is an important ecological and social aspect of forest environments. This term can refer to vegetation type, seral stage, stand structure, and key elements such as snags or large woody debris. Which habitat elements should be retained or encouraged? Important habitat elements to note at the on-site assessment include the species and size of snags (especially those with evidence of use), large woody debris, and hardwoods. Habitat needs must be balanced with their potential impacts on the land manager's objectives and the young plantation, including but not limited to fuel loading and future fire risks, as well as survival and growth. Excessive fine fuels are a greater fire risk than incidental amounts of large woody debris, which can also provide favorable microsites for planting or habitat for small mammals.

Sensitive areas

The on-site field assessment is critical for confirming and evaluating sensitive resources in need of protection. Hydrologic features such as streams, springs, wetlands, ponds, and lakes should be evaluated to confirm proper field location and flow or status. Consult with the landowner to identify any domestic water sources and determine if buffer zones are required around these features by law or by the landowner. Likewise, determine if water features such as irrigation or domestic ditches, water lines, or wells need protection. Locate and confirm the suitability of water-drafting sources that could be used for herbicide spray operations and road dust abatement, if needed. When on the site, be aware of potentially sensitive species and confirm their presence if possible by searching the Natural Diversity Data Base and California Native Plant Society database. The archeological survey may be conducted during the site assessment as required, if not already completed by an archeologist or trained Registered Professional Forester.

Pests, insects, and disease

Evidence of animal pests, insects, and disease is difficult to collect during the pre-field site assessment but can play an important role in the success or failure of reforestation projects. When in the field, observe and document the subtle signs that might indicate challenges in the future (see chapter 11 for more information). The forester should examine existing vegetation for evidence of insects that can damage seedlings and young trees. Sometimes problems can be anticipated by observing insect activity in adjacent stands. Good vegetation management and conifer stocking control can help to prevent insect problems during plantation establishment. Minimizing competition from other vegetation increases tree vigor and the ability of seedlings to defend against insect attacks.

Identifying potential pest problems may also aid in determining which species to plant. Signs of disease are often present in existing stands prior to harvest and can sometimes be mitigated. For example, in stands where black-stain root disease is present, altering the conifer species is beneficial since the disease is host-specific to either pine or Douglas-fir. Dwarf mistletoe, a parasitic plant that reduces vigor, often leading to death in the host tree by secondary agents, is likely; it is likely to infect understory trees and adjacent stands but is also host-specific. The spread of the diseases can be controlled by altering the species composition to nonhost species and removing infected overstory trees, which in turn helps to promote a healthy forest in the future. Root rots can be particularly difficult to mitigate (see chapter 11, "Damage," for symptoms and treatment strategies of common root rots).

Low site quality can also be an indicator of potential damage from insects, diseases, and animals. Trees on low-quality sites are more prone to attack than those on high-quality sites because the seedlings are under greater stress. Attacks by insects such as pine tip moth, pine reproduction weevil, and pine needle sheathminer are relatively more common on poor sites. In addition, note any obvious existing animal damage to older trees in the vicinity, such as cattle grazing, deer browse, bark removal by bears, and gopher tunnels or gopher-related pockets of mortality (see chapter 11 for a more detailed list). Estimate the cover of dead brush skeletons and slash that can be used as hiding and denning cover for rodents and other animals that may cause damage to conifer seedlings. It is also valuable to note whether the area is in a deer or elk migration or winter range area, as different herbivory patterns can complement competing vegetation control or, alternatively, lead to high seedling mortality (Stokely et al. 2018).

Fire risk

Tree mortality from future fires is a great concern for any reforestation project. Before the harvest or vegetation removal in a restoration project is undertaken, the forester should estimate the current fuel loading and how the harvesting, salvage logging, or brush conversion will affect the remaining fuel load. It is important to assess if there is an opportunity to biomass harvest smaller material to reduce the eventual fuel load. This requires a market, operator and suitable topography. Steep slopes will limit the harvest techniques available and increase the cost to treat fuels. Reforestation activities also have the potential to increase or decrease fuel loads as the stand grows and develops (Knapp and Ritchie 2016; Kobziar et al. 2009). As the stand develops, the amount of both live and dead fuel within the unit increases. To reduce the risk of damage from fire, the reforestation plan should consider actions to reduce fuel load and the continuity of fuels in developing stands.

Conclusion

A thorough site assessment, particularly the field site assessment to validate and improve on the pre-field assessment, is critical in the development of the schedule of activities and prescription for a reforestation project. It should provide information on all the physical and biological characteristics of the reforestation site as well as the operational and logistical characteristics needed to successfully develop and implement the reforestation plan. The final plan will integrate this information with the landowner's objectives and project financing to create an effective prescription and schedule of activities for the project.

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Appendix 4.1.

Unit Planning Information Sheet

Landowner/Property: _____ Date: _____
 Unit: _____ Evaluator: _____
 Acres: _____
 Elevation: _____
 Aspect & Topography (micro climate, temp. extremes) (wind? Frost pockets?): _____
 Soils (Site-Plantability) (bareroot vs plug) (Type & Texture)(Stability): _____
 % Slope (Equipment operability?): _____
 Silviculture method: _____
 Tree species present prior to harvest: _____
 Logging Method: _____
 Logging History: _____
 Fuel Loading (Type, amount & distribution)(Effect on fire hazard vs. plantability): _____
 Wildlife (Endangered Species?) (habitat elements? Winter Range? Summer Range? Local herds? Snags, large woody debris, oaks?): _____
 Plant Species by % (present v. expected climate?): _____
 Plant TPA (Regulatory vs. exp. survival vs.to comm. harvest vs. reduce need for PCT): _____
 Residual Stocking (quality & distribution, seed sources?): _____
 Brush Species Present by % & total cover % (successional trends? Expected response of veg to treatment?): _____
 Animal Damage: Deer browse, gophers, cattle, etc.? _____
 Insect & Disease Problems (root rots, mistletoe, etc.): _____
 Access Issues?(Road network during needed season, snow, gates): _____
Site Prep Needed:
 Spray: Hand or Aerial? _____
 Pre-Harvest and /or Post Harvest? _____
 Foliar or Residual? _____
 Mechanical: Pile/Rip/Mulch? _____
 Burn: Broadcast or Piles? _____
 Planting Timing: Spring? Fall? _____
 Thinning needs: post-harvest? _____
 Neighbors (local concerns?): _____
 Fuel Loading (tons/acre)existing & expected: _____
 Other: _____

 Recommendations: _____

 Harvest Vol/Ac:

	PP	SP	DF	WF	IC
% Species:					
% Small/Large:					

Appendix 4.2.

SITE ASSESSMENT TEMPLATE

_____ (landowner-tree farm name)

BACKGROUND (might need to break the following descriptions into separate units with distinct acreage for each, if each unit would have a separate plan of activities or cost)

Legal: T____N R____W or E Sec_____(sub-section:_____)

Acres: approx._____ (suitable & feasible for reforestation project)

Access: (proximity of road to unit & type of closest accessible road to unit; proximity to main county road or highway etc. e.g. "seasonal dirt road all the way into unit a few miles from paved county road", also is there legal road access or are right of way permits needed and/or watercourse crossing installation(s) needed etc.).

Survey line & corner locations: (if feasible GPS closest known surveyed corner/s which might aid in future mapping)

Easements & Utilities (location of all easements, including above and underground utilities on or near project)

Sensitive areas (e.g. streams, springs, Unstable Areas, Arch. Sites, improvements etc.):

Annual Avg PPT: approx.____" ____ (avg annual ppt + form of ppt e.g. "mostly snow" etc.

Seed Zone:_____

Elev: approx. _____

Slope: _____% – _____%

Aspect(s):_____

Site Class:_____

Appendix 4.3.

REFORESTATION SITE ASSESSMENT & PROJECT PLAN

Landowner/Project Name: Saddle Mountain Project

Legal: NE¼ NE¼ Section xx and S½ SE¼ SE¼ Section xx, TxxN RxxE

Acres: 40 (proposed for reforestation)

Access: County paved and then private rocky road to within ¼ mile of unit and then dirt road to within 300' of unit. Need to confirm or obtain easement/ROW from landowner to the west of NE¼ NE¼ Section xx.

Survey line & corner locations: (if feasible GPS closest known surveyed corner/s which might aid in future mapping): No corners or surveyed lines were readily located during site visit. Since project boundary will be close to property line see pre-condition # 2 in the following project plan.

Easements & Utilities (location of all easements, including above and underground utilities on or near project): The landowner knows of no easements, including utilities within or adjacent to the project area. No utilities were observed on the site visit or aerial photos.

Sensitive areas (e.g. streams, springs, Unstable Areas, Arch. Sites, improvements etc.): None observed on site visit or on topo maps or aerial photos.

Annual Avg PPT: approx. 20" to 25" (in the form of rain and snow)

Seed Zone: 732

Elev: 2,600' to 4,200'

Slope: 10% - 45% (several steep pitches that flatten off to a bench)

Aspect(s): N to NW

Site Class: IV(Dunning)

Soil Type: (NRCS Intermountain Soil Survey) Chirpchat: very deep (60"+), well drained sandy loam soils that formed in volcanic ash and alluvium derived from volcanic rocks; Soils are stony with large boulders scattered throughout the project area, enough good, deep forest soils to plant most of the area to full stocking with commercial conifers.

Vegetation: Dense, decadent brush consisting of deerbrush (*Ceanothus integerrimus*), buckbrush (*Ceanothus cuneatus*), whitethorn (*Ceanothus cordulatus*), Greenleaf manzanita (*Arctostaphylos patula*) and skunkbush (*Rhus trilobata*). Deciduous tree overstory consisting of 15% canopy cover Oregon white oak (*Quercus garryana*) and 5% canopy cover California black oak (*Quercus kelloggii*). There are large conifer stumps left by logging many decades ago in the proposed project area as well as scattered large ponderosa pine trees in brushfields outside the project area but nearby on the same soil type as project area.

General Comments: The proposed project area is surrounded by several hundred acres of similar brush/oak type on Saddle Mountain that has become well established in what historically was a predominantly ponderosa pine/ oak forest prior to logging several decades ago. Disruption of the "natural" fire regime (i.e. instead of frequent light ground fires burning beneath an open overstory of large fire resistant pines, keeping brushy fuels low) has resulted in fires which are less frequent but much hotter, burning decadent brush and relatively small oaks that rapidly re-sprout and grow into a hazardous fuel load. This alteration of the fire regime and vegetation dynamics does not allow for natural ponderosa pine regeneration and/or growth to maturity.

This project would be a good demonstration reforestation project since it would be typical of the hundreds of acres of moderately steep, non-stocked forest land in this vicinity that require management to establish productive native conifer forests again. But prior to contracting for the implementation of the following project plan there are two tasks that would need to be completed:

1. Landowner would need to confirm existence of easement(s) or obtain temporary easement from adjacent landowners (west of project area) to provide general contractor's equipment and crew access to conduct all of the planned operations.
2. RPF would need to obtain survey records and locate all 4 property corners bounding the NE¼ NE¼ Section xx, TxxN RxxE, or the landowner would need to contract with a licensed surveyor to establish those corner and lines if they are not in.

PROJECT PLAN

1. Year 1, Summer: Contract to aerial spray brush and some oaks to kill root systems to facilitate subsequent piling operations and prevent re-sprouting after clearing and planting (this step will facilitate subsequent piling operations as crawler tractors will not have to root out brush and disturb topsoil, but instead just clear enough herbicide-killed brush to facilitate planting operations). Landowner stated that Contractor could use helicopter landing site for loading chemical on Ranch property 1.2 miles NE of the unit.
2. Year 1, Summer/Fall: RPF locate and purchase ponderosa pine (PP) and some Douglas fir (DF) seed (zone 732 elev. 3.5 to 4.0) from CAL FIRE and/or a private timber company and contract w/ Cal Forest Nursery to grow seedlings in Year 2 for outplanting spring of Year 3.
3. Year 2, Summer: Contract to clear & pile, in some areas simply crush, dead brush skeletons with crawler tractor equipped w/ brush rake (do not need complete removal just enough to access ground for planting). Although slopes are steep in some places for tractor piling (up to 45%), having the brush dead for a year will make tractor work for site preparation feasible and not cost prohibitive, with minimal topsoil disturbance.
4. Year 2, Fall: RPF submit Smoke Management plan and obtain necessary permits and burn piles.
5. Year 2, October: Obtain necessary permits & PCA recommendation and contract to broadcast spray 3.5 lbs. Velpar DF per acre on 40 acres.
6. Year 3, January or February (after seedlings lifted and packed at nursery): Transport seedlings from Cal Forest Nursery and place in cold storage.
7. Year 3, March or early April (after snowmelt & soil temperature has reached 42 degrees or higher): Contract to plant 10,000 styro 5 containerized Ponderosa pine and 2,000 styro 6 containerized Douglas fir on 40 acres at 300 trees per acre (12' x 12' spacing)
8. Normally at this elevation and general area we do not net seedlings, but in this case with the surrounding brush habitat for rabbits and the winter deer herd on Saddle Mtn. the site should be closely monitored and if needed install protection netting after planting.
9. Years 4 to 6 (1 to 3 years after planting): Monitor competing vegetation and spray if necessary and funds available from private and/or state cost share sources. Although the pre-harvest foliar spray of current re-sprouting brush on the site, combined with the pre-emergent spray to control new germinate weeds should greatly reduce the number of follow up sprays needed, it is likely an additional follow-up weed control treatment will be needed in Year 4 or Year 5.
10. Years 10 to 13 (7 to 10 years after planting): pre-commercial thin plantation to 135 trees per acre (18' by 18' spacing), favoring any DF that might survive. Even though at PCT age DF will be shorter than PP, within another 10 years DF should equal or exceed PP growth. Also, where present, thin black oak stump sprouts to 2 or 3 stems per clump.



Brushfield in the proposed project area pictured in the foreground.



Large healthy ponderosa pines and sugar pines on a nearby site with the same soil type and precipitation as the proposed project area.



Oregon white oak sprouts that cover approximately 15% of the proposed project area that along with dense brush will prevent natural establishment of shade intolerant conifers that are adapted to this fire prone site with relatively low annual precipitation.



Chapter 5

Seeds

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Successful reforestation is highly influenced by seed origin and seed condition. This chapter summarizes the best practices for planning, collection, processing, and storage of seed collected from trees in natural stands as well as trees in tree improvement programs. It is essential to use genetically diverse, high-quality, local seed and seedling stock that is best adapted to the planting site to ensure long-term success. Conifers are long-lived and must contend with all of the various physical and biological factors and hardships contained within the ecosystems in which they have evolved. Natural selection results in the accumulation of an enormous range of adaptive genes over time. An individual organism's genetic make-up is its genotype. Each tree species responds in its own way to local environmental conditions such as extreme heat or cold, moisture stress, aspect, soil type, and competitive pressures. An organism's phenotype is the combination of observable physical characteristics as determined by its genes from both parents and interaction with the environment. However, it is the maternal parent's phenotype one observes when choosing seed trees for cone harvesting in open-pollinated stand collections.

Superior quality and locally adapted seeds produce vigorous seedlings that establish better; over time they will outcompete surrounding vegetation for moisture, nutrients, and space to occupy the site more rapidly. As noted in the "Tree improvement" section of this chapter, improved seed produced from seed orchards supported by tree improvement associations and cooperatives in California combine the benefits of genetic improvements, strict quality control, and well-tracked genetic and locational information. When improved seeds of the desired species are not available from seed orchards, wild seeds collected and stored in seed banks will be the primary source of seed for reforestation projects.

A successful and timely response for reforestation requires meticulous planning, collection, processing, and storage to ensure that appropriate quantities of seeds of documented origin are available when they are needed. Conifer seed production and quality are highly variable from year to year and should be sufficiently evaluated before collections are initiated. The irregular nature of tree seed crops necessitates storing large quantities of viable seed when it is available for use during potentially long stretches of poor seed production. Low-quality seed crops do not generally warrant the costs and time that will be invested in seed procurement and seedling production, but special consideration may be necessary for specific species or areas of high conservation concern. This chapter describes the many factors that must be considered to ensure that collections are successful and seed quality is maximized.

Our key objective is to review the relationship between seed maturity and seed quality. Many of the concepts presented here have been accumulated from generations of forest resource scientists, geneticists, and conifer seed specialists and are considered common knowledge for the genre. The writers add their collective personal experience with cone and seed planning and collections, seed processing (cleaning and upgrade), and testing and storage to illustrate specific topics. (See sidebar 5.1 for a glossary of terms related to seeds.)

Rapid climate change caused by human activities is changing forested environments. Reliance on long-standing seed transfer guidelines is necessarily being reexamined (Chmura et al. 2011; Erickson et al. 2012). Climate predictions in this century strongly suggest that reforestation practices moving forward should favor tracking both current and modeled future climates in making seed transfer decisions. Broadly

Sidebar 5.1: Glossary

Adaptation: Characteristics that have evolved by natural selection over time which enable an organism to be successful (survive and reproduce) in a given environment

Bract: A modified leaf that extends underneath a seed-bearing scale

Case-hardened: Inability of cone scales to flex, caused by too rapid drying, insects, or disease

Cotyledon: Primary leaf of embryo

Damping-off: Killing of a seedling by microorganisms before emergence from soil or collapse of the hypocotyl and/or radicle immediately after emergence

Dead-filled seed: Seed that is not viable due to complete deterioration of all seed contents. These seeds have specific gravities similar to viable, filled seed and can be difficult to remove during the processing of some species

Dormancy: Physiological state in which a seed is capable of germination but does not

Embryo: Rudimentary plant within a seed

Empty seed: Seed that is hollow, corky, pitchy, or filled with larvae

Fertilization: Fusion of the sperm nucleus with egg cell nucleus and doubling of chromosomes (occurs in early summer for first-year species and spring for second-year species)

Filled seed: A seed containing all tissues essential for germination and considered potentially viable

Frass: Insect excrement found on or within cones; usually indicative of feeding activity/damage

Genetic generalist: Species showing low genetic differentiation across a wide range of environmental gradients

Genetic specialist: Species exhibiting strong genetic differentiation over small geographic and climate scales

Genotype: The genetic makeup of an organism

Hypocotyl: Embryonic stem below the cotyledons and directly above the radicle (primary root)

Imbibition: When seeds that have become swollen and physiologically active due to uptake of water (this moisture must reach the embryo)

Megagametophyte: Storage tissue that provides nutrients to the developing embryo; sometimes referred to as endosperm

Moisture content: For seed, based on the proportion of moisture relative to the fresh weight of the seed, usually presented as a percentage

Morphology: Study of form and structure of an organism, especially its external form (e.g., size, color)

Orthodox: Seeds that can be dried to low moisture content and stored for extended periods without losing viability

Ovule: The structure of a plant that contains the female reproductive cells and develops into a seed

Phenotype: Observable characteristics of an individual resulting from the interaction of its genotype with the environment

Peduncle: The stalk or stem of a cone

Periodicity: Number of years between bountiful crops

Plasticity: the ability of a genotype or population to maintain high fitness across a range of environments by altering its phenotype

Pollen cone: Male reproductive structure that produces pollen grains

Pollination: Transfer of pollen from male cone to female cone (in conifers that are wind-pollinated)

Progeny: Offspring of plants

Purity: Seed lot characteristic describing weight of pure seed in relation to weight of seed plus debris; a purity standard above 98% is necessary for nursery calculations

Radicle: Primary root of the embryo

Recalcitrant: Seeds resistant to drying and storing (must be fresh-collected when available)

Seed: Matured ovule containing an embryo and megagametophyte enclosed by a protective seed coat, which is capable of developing into a plant under favorable conditions

Seed cone: Female reproductive structure, usually with two seeds borne on each scale spirally arranged around a central axis

Seed lot: Quantity of cones or seed having uniformity of species, source, quality, and year of collection

Seed source: Location where seeds were collected, including seed zone and elevation

Seed zone: Geographic area in California designated on the basis of biogeographic regions, climate, and latitude

Self-pollination, selfing: Transfer of pollen from stamen to stigma on the same plant (tree)

Stratification (moist chilling): Pregermination treatment of seeds to overcome dormancy and promote rapid and uniform germination

Tolerance: Permitted deviation from a standard beyond which a germination test must be repeated

Viable: Capable of germinating (e.g., viable seeds are filled but not all filled seeds are viable)

Vigor: Robustness of seed lot; declines with age

adapted seed sources are key to mitigating some of the challenges posed by climate change (Ledig and Kitzmiller 1992; Millar et al. 2007). Tree improvement programs offer forest resource professionals management options that promote adaptation and resilience in rapidly changing environments (see “Tree improvement” section below).

Importance of seed origin

The success of any reforestation effort depends on the origin of the seed and its quality and condition. Seed origin is important because trees are locally adapted to the numerous characteristics of the environment they naturally grow in. However, ongoing changes in forest climate conditions require explicit decisions on matching seedlings to the climatic conditions that trees will face in the coming decades. A key insight coming out of Douglas-fir seed source research across California, Oregon, and Washington has been the need to focus on “climate space” rather than “geographic space,” to include key minimum winter temperature and maximum summer aridity variables rather than simply latitude and longitude (Harrington and St. Clair 2017). In practical terms in California, this means a greater focus on the aspect and elevation where the seeds (or scions used in seed orchards) were collected rather than focusing exclusively on the seed zone number, which often covers large elevation ranges in California. While California does not have as sophisticated a seed transfer system as the one recently developed for British Columbia (O'Neill et al. 2017), ongoing research across the Pacific states is building on forest genetics research to positively respond to new challenges (St. Clair and Howe 2017).

Development of California tree seed zones

Foresters have long recognized that California's climate, topography, and geology are diverse, and that these environmental differences significantly influence the productivity of forest sites and survival of the many tree species found there. This complexity resulted in the establishment of the California tree seed zones (Fowells 1946) with revisions by Roy (1963) and Schubert (1966). In 1970, the Forest Tree Seed Committee (Buck et al. 1970) revised the original zones and restructured the recording system. This version of the California tree seed zone map (fig. 5.1) is still in widespread use today.

The state is divided into six major physiographic and climatic regions and 32 subregions, for a total of 85 separate and unique tree seed zones (see fig. 5.1). Plant associations within each region change as one moves from north to south, west to east, and low elevation to high elevation. In zones where climate and

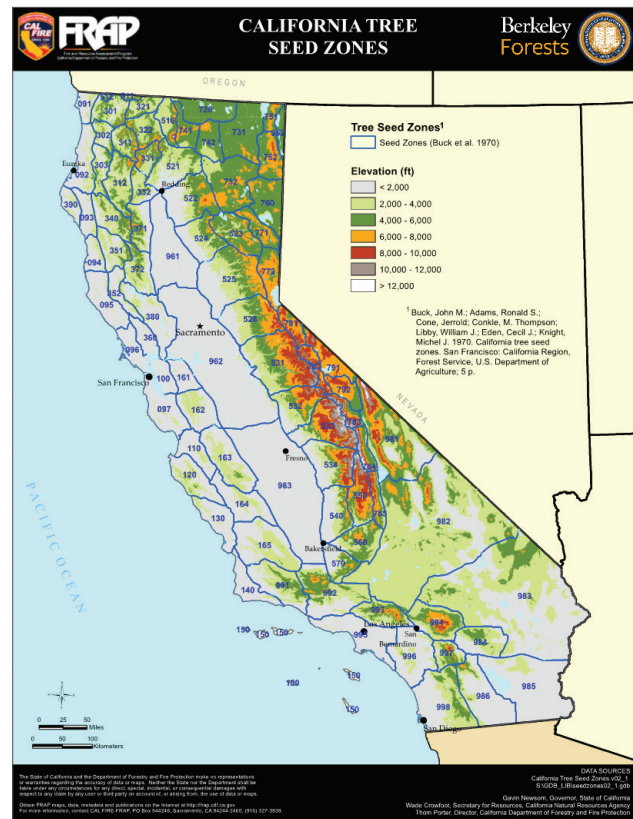


Figure 5.1. California tree seed zone map.

topography are more variable, “local” generally implies the same microenvironment, for example, areas within the same drainage or those having the same aspect or elevation. Within the individual zones, conifer seed collections are catalogued by separate elevation bands with every 500-foot rise in elevation. In addition to recognizing the vast topographic, climatic, and edaphic differences of the landscape, seed zones are meant to inform seed transfer decisions from the seed collection source to a specific planting location with minimal risk of maladaptation. The system of using seed zones and elevation bands to delineate areas of plant adaptation is used in California as well as many other states.

Features of California physiographic and climatic regions

090 Series–North Coast Redwood Belt extends along the coastal fog belt, approximately 5 to 30 miles in width, from California's northern border south to Monterey Bay. The belt lies slightly inland, avoiding direct oceanic influences. Precipitation is plentiful in winter, and summers are moderated by frequent fog. North of Cape Mendocino forest productivity is generally higher and associated conifers include Douglas-fir, grand fir, Sitka spruce, western hemlock, Port-Orford cedar, and western red cedar. West of the redwoods, beach pine forest dominates on shallow, sandy soils.

South of Cape Mendocino is predominantly lower site and redwood mixes with Douglas-fir and remnant patches of Bishop pine and grand fir. The isolated Cape Mendocino area (seed zone 390) is not in the 090 series because it has unique topographic and climatic elements that preclude oceanic effects and cooling fog and, therefore, does not support redwood.

100 series—Central Coast encompasses the coastal ranges from the Sacramento–San Joaquin rivers south to Santa Barbara and includes the Channel Islands. The Pacific Ocean is the chief influence on temperature and moisture that the area receives. While the southern extent of the range for coast redwood and Douglas-fir is found near Big Sur on north-facing slopes and in drainages fed by summer fog, the Central Coast is predominately a mix of disjunct stands of closed-cone pine and cypress groves. The region also contains a series of valleys with elongated ridges that are parallel to but inland from the coast, and the flat San Joaquin Valley borders on the east. The inland region is decidedly warmer and drier than areas west of the Coast Ranges. However, where the mountains intercept Pacific moisture in steep drainages, pockets of ponderosa pine, sugar pine, and Santa Lucia fir can be found. Coulter pine is present at higher elevations with foothill pine and oak woodlands dominating the east-facing foothills and valley floors. The inland southern mountains and valleys are considered semidesert and support an arid plant species mix.

300 series—North Coast Interior extends from the summit of the Siskiyou Mountains south to San Francisco Bay and lies between the coastal fog belt and the Sacramento Valley. The western edge of the region lies in the rain shadow of the Coast Ranges and overall the climate is Mediterranean with winter rains and summer drought. The area supports a wide variety of conifer forest, woodland, and prairie that differs considerably with topography, parent material, precipitation type and amount, and elevation. Indeed, the region has the largest number of subregions. It also includes an isolated zone (390), located on the coast at Cape Mendocino, which is predominately Douglas-fir.

500 series—Western Slope Cascades and Sierra is an extension of the west slope of the Cascade Range in Oregon south through the Sierra Nevada to the Greenhorn Mountains in Kern County. It is bounded by the foothill belt of the Central Valley to the west and the crest of the Cascade and Sierra Nevada ranges to the east. The region supports a rich diversity of conifers, though species occurrence on the landscape is highly dependent on latitude, elevation, and aspect. These gradients define the temperature and precipitation type, depth and duration of snowpack, and length of the growing season. The lowest elevation conifer is

foothill pine, where it intermixes with the oak woodland type. The lower montane, mixed-conifer forest is dominated by a fluctuating mix of white fir, incense cedar, Douglas-fir, and ponderosa and sugar pine, as well as associated hardwoods. It is worth noting that moving south of the Mokelumne River (526/531 border), Douglas-fir begins to decline in occurrence. The upper montane contains the red fir forest type as pure stands or mixed variously with white fir, Jeffrey and western white pine, mountain juniper woodland, and well-defined groves of giant sequoia. Wetter habitats tend to support lodgepole pine. The subalpine type above 8,500 feet consists of a mix of slow-growing and scattered white pine and mountain hemlock associations.

700 series—Modoc Plateau, Eastern Slope

Cascades and Sierra is an extension of the east slope of the Cascade Range in Oregon south through the Sierra Nevada to Walker Pass in Kern County. The Warner Mountains mark the northeastern boundary of the region. The environment is characteristically warm and dry, as it lies within the rain shadow of the southern Cascades and northern Sierra Nevada. The open plains and southern Cascades sport volcanic basalt and porous soils, in comparison to the granitic substrate of the Sierra Nevada. The northern reaches of the southern Cascades consist largely of white fir, Douglas-fir, western juniper, and disjunct groups of ponderosa and Jeffrey pine with a minor incense cedar component. Shasta red fir and Jeffrey pine forest join the mix on the western edge above 5,500 feet. East of the Sierra Nevada (north and south of and including the Lake Tahoe basin), red and white fir and Jeffrey, lodgepole, and white pine dominate in the higher elevations, with western hemlock, while the single-leaf pinyon-juniper woodland is below 5,250 feet. The most common forest vegetation in the southeastern Great Basin is limber pine forest with a lodgepole pine component and the whitebark pine subalpine type in the higher elevations. Trees growing here are adapted to a severe, cold, dry climate.

900 series—Four Separate Areas is a catchall series that includes:

- **950—Great Basin** is a high-elevation desert valley in the far northeastern corner of California east of the Warner Mountain range, extending south from the Oregon border to Lower Alkali Lake.
- **960—Central Valley** is bounded by the northern edge of the Sacramento Valley in the north to the base of the Tehachapi Mountains in the south. Natural vegetation includes grasslands, marsh, prairie, chaparral, and riparian and oak woodland habitats.
- **980—Southern California Desert Region** is in far

southeastern California. It encompasses the Mohave and Sonoran-Colorado deserts. Vegetation in the region is highly diverse but mostly devoid of conifers.

- **990–Southern California Mountains** is an area that comprises most of the natural conifer stands found in Southern California, a high-elevation mix of mostly Jeffrey, sugar, ponderosa, Coulter, and pinyon pine, and white fir, incense cedar, and a variable bigcone Douglas-fir (*P. macrocarpa*) component. A particularly challenging environment inland, the winters are cold but relatively dry. The long, droughty season is especially hot with frequent harsh, drying winds. Shallow soils and low precipitation are limiting factors for the growth and survival of montane forests in the region. Three species of cypress (Sargent, Cuyamaca, and Tecate) occur in the region in small and widely scattered populations. They are naturally fire-adapted but increasingly threatened with postfire establishment failure in the wake of recurring human-caused and climate-driven conflagrations. The subalpine forest above 7,800 feet supports lodgepole, pinyon, and limber pine and western juniper where temperatures remain low, and snow persists well into summer.

Labeling seed zones and elevation bands

The numbering system for the tree seed zones uses a three-digit designation (for example, XYZ). Two digits follow the decimal and identify the 500-foot elevation band (for example, XYZ.00). For example, 500 feet equals 0.05 and 4,000 feet equals 0.40.

X = Major geographic areas having similar topographic, climatic, and edaphic environments

Y = Divisions within the major regions representing localized topographic, climatic, and edaphic environments

Z = Zone number

If Z is a number 1 through 9, then it is an arbitrary division of a subregion to keep seed zones about 50 miles in latitude. If Z is 0, this is a unique zone, and the zone is considered a subregion.

For example, 340.15–3YZ represents the 300 series, or North Coast Interior physiographic and climatic region. 34Z represents one of the 17 subregions in the 300 series, and 340 is a unique zone and, therefore, a subregion itself because there are no other 34Z zones. The 0.15 indicates an elevation between 1,001 and 1,500 feet.

As another example, 526.45–5YZ represents the 500 series, or West Slope Cascades/Sierra physiographic and climatic region. 52Z represents one of the seven subregions in the 500 series. 526 is a zone, an arbitrary unit of the 52Z subregion, in this case the most southern zone in the 52Z subregion. The 0.45 signifies an elevation between 4,001 and 4,500 feet.

Seed transfer guidelines

The seed transfer guidelines in use since 1970 (Schubert and Adams 1971), served forestry professionals well for nearly 40 years, but they assumed long-term environmental and climatic stability (Buck et al. 1970). Climate cycles have historically changed over millennia, century, and decadal time frames, and species have adapted by shifting ranges and adjusting, over considerable time, through genetic change (Rosenthal and Millar 2003). Science indicates that global climate change is currently accelerating more rapidly than in the past due to human influences. Such rapid changes demanded a review of the existing paradigms. The USDA Forest Service (2011) implemented new research-based seed movement guidelines in 2011, which may help to promote resiliency in a changing environment (Millar 2013; St. Clair 2013). Key elements of the new guidelines include:

- Use source identified seed only; accurate and detailed seed collection records are key.
- Deploy forest reproduction materials, within a seed zone, upslope from source origin a minimum of one elevation band (500 feet) to 1,000 feet upslope.
- Disallow the deployment of forest reproductive materials downslope from the source origin.
- Use the closest available seed. Seed from an immediately adjacent seed zone (*from south to north only*) within the same physiographic and climatic subregion (same XY) is compatible if environmental conditions are similar.
- Professional judgment of seed movement adaptation and survivability can be uncertain, but not unreasonable, if the source origin is within 100 miles (be advised, photoperiod changes more quickly at higher latitudes). (See sidebar 5.2 for information about the seed lot selection tool.)
- When moving seed any significant distance from its source origin, take into account whether the species is a generalist or a specialist in adaptive traits.
- Increase the use of improved genotypes from tree improvement programs, which are generally more broadly adapted and pest-resistant and can be moved farther in both distance and elevation.
- Add a more diverse species mix and broader genetic

base of a given species to account for climate uncertainties over the life of a stand.

- Use a *mixture* of seed sources, which may be better adapted to the temperature and moisture extremes predicted in the next few decades.

Aitken and Bemmels (2015) suggested that the potential maladaptation of trees to climate change could be addressed by choosing seeds from other regions with climates that match predicted future conditions. They further suggest that a strategy of obtaining seed from multiple sources will increase diversity and provide a buffer against future climate uncertainty.

The discussion about climate change and forest adaptation is in flux. Climate-driven changes necessitate that trees and forests adapt to new climatic conditions and environments. Forest resource professionals must remain flexible when making deliberate seed transfer decisions. Genetic diversity is key—broad mixtures of species and sources that may be better adapted to future conditions may offer resilience in shifting environments.

Climate change mapping tools that support decisions on moving plant material across environmental gradients are becoming more readily available. These mapping applications are designed to assist with matching alternative seed sources with planting sites using specific climate variables. The main objectives

are to determine which seed lots will work in a given planting site and where on the landscape a given seed lot is best-suited for survival.

Future climate projections

Future climate scenarios are inexact, but they largely forecast a rise in temperature and changes in the amount and distribution of precipitation across California (Fire and Resource Assessment Program 2018). Mean annual temperature is expected to increase in all ecological regions, but the magnitude of temperature rise will vary by region with lower increases near coastal environments and greater increases inland. While climate models and forecasts differ, a moderate range of increased warming from +2.5°C to 4.6°C in Northern California is projected between 2000 and 2100 (Barr et al. 2010). These projected increases are creating uncertainty about long-term forest tree adaptations and responses to novel climates. There is widespread agreement that climate threats in California will include accelerated heat and drought (though some regions are projected to be warmer and wetter), increased fire frequency and intensity, and increases in ancillary stressors such as insects, disease, and interspecies competition. As temperatures rise, more precipitation is expected to fall as rain rather than snow, resulting in diminished water reserves in the Sierra Nevada. Less snowpack and earlier snowmelt will result in increased flood events during winter and spring causing more soil erosion and less water availability for forest plants during the lengthy dry period (Fire and Resource Assessment Program 2018).

Greater climatic variability and uncertainty is expected to have serious implications for future tree health and cone production. It may be necessary to collect from a greater number of parent trees over a wider area than current standards require in order to capture as much variability as possible. The climate gradients that define an environment as compatible for a given population of trees are changing. Climate warming will impact winter minimum temperatures, summer maximum temperatures, and the number of frost-free days. The impacts on bud-set and bud-flush are anticipated but will likely vary based on the biology of the species. As the rate of climate impacts increases, many trees may not adapt to the changed conditions fast enough and be vulnerable to failure (Fire and Resource Assessment Program 2018). Tree communities located at lower elevations or the southern, drier margins of a species range will likely show signs of decline first. In general, range expansion is expected at the leading edge (northern latitudes and higher elevations), with contraction in species ranges

Sidebar 5.2: Seed lot selection tool

The [seed lot selection tool](#) is a web-based mapping tool that was designed through a collaborative effort by the USDA Forest Service, Oregon State University, and Conservation Biology Institute. The goal of the tool is to help resource managers match seed lots (seed collections from a known origin) with appropriate planting sites based on models of current as well as predicted climate change projected across the landscape. This approach assumes that plants are adapted to the climate where they are currently found. Other important physiographic and edaphic factors such as aspect, slope, and competitive environment are not considered. Inputs allow users to select transfer limits, climate scenarios, and a set of climate variables. While the results from this tool are subject to the uncertainties and limitations of such predictions, users can explore and compare the output derived from different variables to gain an understanding of how climate variation is distributed across a geographic area.

occurring at the trailing edge (southern margins and lower elevational limits).

In California, one current challenge is to prioritize collections of existing foothill and other low-elevation seed sources as a hedge against the loss of this habitat type. In addition to potential genetic maladaptation to future conditions, foothill plant communities with limited moisture and high fire risk are especially vulnerable to the loss of species abundance and distribution due to a variety of human-caused factors. These include urban encroachment, fragmentation, overgrazing, past logging and mining, conversion to agriculture, and increased fire and insect activity. Furthermore, these low-elevation conifers are currently found in relatively hot and dry environments, and they may have adaptations that will be valuable for planting out in a range of landscapes with future similar environments.

Biology

In conifers, cone and seed production involves four principal stages: the formation of reproductive buds, the development of male and female strobili (pollen and seed cones), pollination and fertilization, and seed maturation (Eis and Craigdallie 1981).

Cone and seed development

Bud initiation occurs each spring, but development into vegetative or reproductive structures depends on a variety of factors including environmental conditions, biological processes, and position on the branch. Bud differentiation takes place throughout the first growing season and is generally apparent by fall of the first year. The general appearance of the bud and position on the branch or part of the crown are indicative of bud type. Female (seed) cones are generally wider at the base, longer than male and vegetative buds, and are in terminal or subterminal position. Male (pollen) cones are generally laterally positioned and often found on the undersides of lower branches in the crown. Under favorable weather conditions (dry, sunny weather in spring) and high nutrient status, a higher percentage of buds will become reproductive and fewer are likely to abort or become latent. The difference between an abundant cone crop and a poor one is more likely the result of the number of buds aborted rather than the number of buds produced in a given year.

Impediments to formation and development of reproductive buds

Impediments to developing and forming reproductive buds may include unfavorable weather, timing of frost, and poor tree nutrition. While flowering can increase

in trees under moisture stress, persistent drought conditions lead to decreased shoot growth, reduced crown development, and increased bud failure. Good nutrient status and greater light intensity favor good seed crops; therefore, irrigation and fertilizer applications in seed orchards or seed production areas can promote successful bud development. Additionally, thinning treatments in orchards and seed production areas increase light intensity and reduce competition for moisture and nutrients for desirable leave (seed) trees.

In late fall reproductive buds slow their metabolic activity, becoming nearly dormant, but still undergo internal changes through winter. They resume active growth and burst the following spring when pollination (and for some species, fertilization) takes place—in the cone development year. The male pollen cones elongate rapidly and swell, then split open as they dry and release pollen grains into the wind (fig. 5.2). Nearly simultaneously the female seed cones elongate, causing the immature bracts to spread apart slightly and allowing the airborne pollen grains to enter. Upon capture by a receptive female cone, the pollen grains drift down the scales toward the ovules at the base of each scale and the female cone scales and bracts close again (fig. 5.3). In most species—with the exception



Figure 5.2. Male pollen cones of ponderosa pine.



Figure 5.3. Female cone of ponderosa pine.

Photo: Chris Evans, University of Illinois.

Photo: USDA Forest Service - Forest Health Protection Intermountain Region - Ogden, UT.

Photo: Mary Ellen Harte.



Figure 5.4. Spent cone and pendant first-year cone of Douglas-fir.

of true firs, which remain upright in the uppermost branches of the crown—the seed cones become pendant, and pollination is complete (fig. 5.4).

Because conifers are wind-pollinated, factors affecting success in this time period are mostly weather driven. Therefore, conditions of frost, drought, excessive wind, lack of wind, and excessive rainfall all have a strong influence on pollination success or failure. Losses can occur after pollination as well if temperatures become extremely low, causing cones to abort. In instances when pollen flight is low or mixing, self-pollination becomes a factor that can contribute to embryo degeneration or low vigor. Additionally, pollen viability, which can vary from 1 day to 2 to 3 weeks depending on species and female cone receptivity may differ in timing, duration, or both in some years, further effecting pollination success. With all of the variables involved at this early stage of cone development, it is difficult to predict in advance whether the end result will be a collectable crop of a given species in any given year.

Within the female cone, the pollen grains germinate and each will produce a long tube, with one pollen tube penetrating a single ovule. After a series of cell divisions, fertilization occurs when a single sperm cell fuses with an egg cell. The time period for this process varies greatly by species and is generally 2 or 3 years. For 2-year species fertilization closely follows pollination, usually within weeks, and cones develop through summer and mature in late summer or fall. For 3-year species the female ovule continues to grow

slowly through the next winter while development of the pollen tube stops in mid- to late summer; fertilization occurs the following spring and cones mature in the fall of the 2nd year after pollination (approximately 15 to 16 months later). The cypresses comprise a third category and are mature after the embryo emerges from a dormant phase and resumes maturation in the year after fertilization, for a total reproductive cycle of approximately 3 1/2 years.

Postfertilization growth includes enlargement of the female cone and differentiation and maturation of the embryo within the female gametophyte (megagametophyte) or food reserve. The embryo has all of the necessary structures and genetic information to grow into a miniature plant: a radicle (primary root), hypocotyl (stem), and cotyledons (first leaves). The seed coat protects the inner structures and may be thin, soft, and papery as in true firs and incense cedar, or thin to thick and woody as in pines, Douglas-fir, and juniper. In some species with especially hard seed coats, such as several species of pine and cypress, the seed coat may also restrict water uptake, gas exchange, and emergence of the radicle, thereby requiring treatment before germination can occur.

True firs, incense cedar, western red cedar, and hemlocks have resin pockets, or vesicles, in their seed coats, which may protect the embryo from excessive drying and play a role in seed dormancy. Seeds with resin vesicles must be handled carefully as these structures are easily damaged, which may result in poor quality or death of the seed. The megametophyte surrounds the embryo and provides the nourishment necessary for initial growth of the embryo. Most conifer seed is winged, which facilitates movement from the tree during dispersal. Some wings are affixed lightly and are easily removed as with most pines, while others are an integral part of the seed coat, as in true fir, Douglas-fir, and incense cedar. Moisture reduction is the final stage of maturation before the tree naturally sheds seed. This drying allows the seed to enter a quiescent period necessary for the synthesis of many enzyme systems including those required for seed dormancy and desiccation tolerance.

Impediments to cone and seed development

Many factors can prevent seeds and cones from developing properly, including insects, pathogens, mammals and birds, and human impact.

Insects

Insects that feed on cones and seeds of forest trees can have a significant impact on reforestation planning (Furniss and Carolin 1977; Wood et al. 2003).

Included are various species of cone beetles, cone

worms, moths, maggots, chalcids, and true bugs (Sutherland et al. 1987). For most conifers, cone and seed production is highly variable from year to year, producing moderate-to-heavy crops only periodically, interspersed by several years of low-to-scarce seed production. This periodicity varies among conifer species, so the size of insect populations can fluctuate wildly based on food supply from year to year. When back-to-back crops are good, insect populations may increase and the second crop can be severely damaged. Likewise, if a poor crop follows an abundant one, insect populations will decrease or disappear and the subsequent crop may be insect-free.

Even minor insect activity may severely damage developing cones and seeds. Early damage may be caused by defoliators that eat buds and foliage at the earliest stages of development (fig. 5.5). The spruce budworm (*Choristoneura* spp.) can decrease the quantity of pollen buds available and girdle female buds at the base, causing them to abort. Cone beetles (*Conophthorus* spp.) kill developing cones by boring into the stalk; the conelets become brown and case-hardened and cease development. Later damage occurs in developing cones by cone worm and cone moth larvae. These larvae hatch from eggs deposited onto the scale during pollen reception or from larvae that bore through the cone scale or axis causing a pitch response, and consume the seed contents (fig. 5.6).



Photo: Bugwood.org, John Moser.

Figure 5.5. *Dioryctria* spp. feeding on buds of ponderosa pine.



Photo: USDA Forest Service.

Figure 5.6. Pitch response on Douglas-fir from *Barbara* spp.

The Western conifer seed bug (*Leptoglossus occidentalis*) feeds on conelets as nymphs and causes later damage to developing cones when adults pierce the cone scale and extract seed tissues with their sucking mouth parts, causing the contents to collapse (fig. 5.7). Cone scale and cone gall midge activity deforms cones; this damage fuses the developing seed to the scale leading to extraction difficulties. Seed worms and chalcids may cause extensive damage to cone interiors but often go undetected because the cone may continue to develop normally. These losses are usually discovered only after samples are collected for quality and maturity assessments later in the summer (Ruth 1980).

Management strategies to control insect populations in native forest ecosystems are generally uneconomical but they may be feasible in seed orchards or seed production areas. Maintaining healthy trees and employing sound sanitation practices is key. Dead and injured branches should be pruned and destroyed. Stressors, such as soil compaction from equipment and competition from weedy vegetation, must be reduced as much as possible. It is important to keep the orchard free of overwintering pests by removing and destroying unharvested and spent cones on the ground that could usher damaging insect and disease pathogens into the following season (Cram and Fraedrich 2009).

Pathogens

Several important pathogens can adversely affect the cones and seeds of conifers in California.

Sirococcus blight. Sirococcus blight is caused by fungal spores that are ever-present and can spread to new shoots and cones in the spring. Infected seeds often have shrunken and discolored contents and the seedborne inoculum results in a diseased seedling

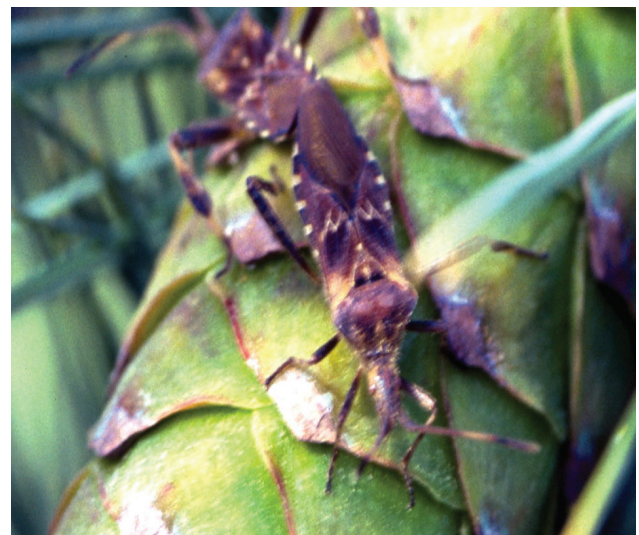


Photo: Sandy Kegley, USDA Forest Service.

Figure 5.7. Western conifer seed bug (*Leptoglossus occidentalis*) on white pine.

when exposed to favorable conditions for growth and spread during germination. *Sirococcus* spp. fungi become established in seed lots when older cones are included in the harvest and can contribute to seed deterioration and subsequent losses in nursery operations. Improved cultural practices over the years such as strict avoidance of squirrel caches, spent cones, and ground collections all have contributed to a significant reduction in the collection of cones and seed diseased with *Sirococcus* blight.

Western gall rust. Western gall rust (*Endocronartium harknessii*) is a disease that causes branch and stem galls on California pines. These galls can cause severe damage to cone-bearing branches and result in cone and scale distortions in knobcone, lodgepole, Coulter, bishop, and Monterey pine, where the cone base and peduncle (stalk or stem of the cone) come into contact with the stem.

Pitch canker. Pitch canker (*Fusarium circinatum*) is an introduced disease that is present in the coastal areas of California less than 75 miles inland from San Diego County in the south to southern Mendocino County in the north. Pitch canker is a highly virulent disease common to knobcone, bishop, and Monterey pine but is also found on other pine species. Because infections can include both reproductive and vegetative stages, the collection of cones and seeds of these species must remain local to avoid introductions of the disease into other areas of the state.

Other seedborne pathogens. Some seedborne pathogens such as *Aspergillus*, *Fusarium*, *Mucor*, and *Penicillium* may simply be indicators of poor seed quality rather than the cause of deterioration. These agents may colonize seeds as a result of adverse environmental conditions such as high temperatures or moisture conditions, or physical damage due to improper handling during collection, transport, storage, or extraction and cleaning processes. These fungi can infect seeds internally, destroying the embryo and megagametophyte, or externally on the seed coat, affecting seed germination via damping-off or root rot in the nursery. Disease development is also strongly affected by the degree of cone and seed maturation attained before cones are collected. Seed viability and storage capacity decline when cones are not allowed to properly mature on the tree.

Sudden oak death. Sudden oak death (*Phytophthora ramorum*) is a disease that has killed countless oaks and other forest species since the mid-1990s. It also causes Ramorum blight, a twig and foliar disease in many other plant species, including coast redwood and Douglas-fir. *P. ramorum* thrives in cool, moist environments and in California is currently limited to coastal evergreen and tanoak/redwood forests. It

is a federally quarantined pest resulting in regulated or restricted movement of host material out of the zone of infestation to uninfected areas of the state or out of the country. Inoculum is not present on the cones or seeds of the conifer host species. Consequently, collections of coast redwood were successful in 2008 in Santa Cruz County and 2009 in Mendocino County, albeit with strict sanitation precautions in place. The redwood cones were removed from the top half of the crown; clipped in place on-site at the base of each cone to remove all green material, needles, and twigs; and transported in sterile cone sacks to the processing facility.

Mammals and birds

Activities by mammals and birds may also cause loss of cones and seeds. By far the greatest losses are attributed to squirrels and chipmunks, which collect and cache large quantities of ripe and unripe cones of pine, true fir, and Douglas-fir for winter retrieval. A squirrel cache is a damp and decayed environment with a high level of diseased seed and debris. In addition, the cones and seeds that comprise them are from unknown parent trees, making these caches totally undesirable for collection purposes. Squirrel feeding can destroy 50 to 90 percent of a cone crop in some years. For high-value trees, removing the lower branches, installing metal banding around the stem, and increasing tree spacing to avoid crown-to-crown migration are known to significantly reduce damage by these agents.

Mammals may also cause minor damage by feeding on cambial tissues, destroying buds and flowers—ponderosa pine is a favorite. Many bird species also feed on and cache developing and mature conifer seeds. While caching plays an essential role in seed dispersal and tree establishment, damage can be serious for collections when birds feed in flocks. Larger birds such as the Lewis's woodpecker, Steller's jay, and Clark's nutcracker mine through cones, which may leave large, damaged areas that cause significant seed loss and difficulties with extraction.

Humans

Harvesting cones too early will interrupt the maturation process and prevent seeds from developing properly. Green cones and seeds have very high moisture content and will dry too rapidly if picked too soon. Research has shown that drying on the tree is necessary for the seed to enter the stage required for desiccation tolerance and germination, when rehydration occurs (Bewley and Black 1994). When the connection to the parent tree is broken too early, the internal tissues will not have completed the normal accumulation of storage food reserves. Other impediments caused by

human activity may be direct or indirect, but all can create an unhealthy environment for growing trees. These include increased emissions and air pollution from urban areas, compaction of soils from overuse, and the myriad impacts realized as a result of climate change.

Cone-bearing age

Conifers are slow-growing, long-lived trees, and the length of their juvenile period is extremely varied in the temperate zone. The majority of species may begin flower production at 8 to 20 years of age but likely produce only one sex or exhibit only intermittent flowering. It is generally many more years before conifers will reach cone-bearing age (when significant quantities of viable cones and good quality seed are produced) and become prolific producers later still. A dominant Douglas-fir, for example, may produce cones at 20 to 25 years of age, but trees 80 to 100 years and older generally have many more viable cones per tree. Cone production tends to occur earlier on high-quality sites. In most conifers the correlation between tree size, crown position, vigor, and cone production is strong. Good cone production is generally best among dominant, young-to-mature, vigorous trees with wide crown widths and pointed tops. These trees receive more sunlight from all sides. Cone production then tends to drop off as trees become overmature; this is true of ponderosa pine, sugar pine, and true fir. However, one study of the differences in cone production among different age classes of giant sequoia found that the oldest age cohort (individuals 1,000 to 3,000 years of age and older) consistently produced greater quantities of viable cones when compared to adjacent individuals comprising a second-growth cohort (approximately 170 years old).

Comprehensive cone collecting and seed banking programs

Most native trees used for reforestation are grown from seed. Sufficient quantities of high-quality, site-specific seed are therefore needed to restore and sustain plant communities that are increasingly threatened by catastrophic fire, insect and disease outbreaks, human impacts, fragmentation, invasive species, and the effects of climate change. In support of sustainable, healthy forests, the California Public Resources Code (sec. 4681–4695) and Board of Forestry policy direct the Department of Forestry and Fire Protection (CAL FIRE) to provide an adequate, reliable, and continuous supply of site-adapted seed of the widest possible diversity and highest quality to promote responsible reforestation and protect the genetic integrity of

California's forested landscapes. To that end, a comprehensive Forest Tree Seed Bank is maintained to provide the facilities for processing and storing seed from a maximum number of species and adaptive seed zones. CAL FIRE maintains a full collection from all lands and provides quality seed storage for private owners who collect seed from their lands for future use. In addition, private seed banks store seed for some of their clients according to the same categorization protocols. Finally, the USDA Forest Service maintains its own seed bank.

Cone and seed production are highly variable from year to year. For that reason, developing cone crops must be sufficiently evaluated before collection can be considered. Good seed crops are the exception, so a high degree of advanced planning and cooperation among all stakeholders (USDA Forest Service, state and local agencies, forest companies, and private landowners) is necessary to have the requisite reserves of each species from different seed zones and elevation bands in a seed bank for the years between bountiful, high-quality seed crops.

Vigorous, site-adapted seedlings are produced from good-quality local seed. Successful seed production requires extensive knowledge of seed development, handling, cleaning, upgrade, testing, and storage procedures (Leadum 1990; Lippitt 1994). The individual responsible for seed bank operations must have highly specialized knowledge of numerous species including their ranges, adaptations, genetic variability, age to maturity, cone crop periodicity, seed structure and physiology, maturity indices, dormancy mechanisms, expected seed yield, storage capacity, and more. This information is used to determine the seed needs list: the quantity of cones needed to satisfy long-term seed requirements, seed quality standards, crop monitoring systems, and the identification of seed collection areas (table 5.1). Planning in any given year will be based on this knowledge and budget constraints, collection procedures, the need for source certification, and the timing and pace of cone and seed ripening in that collection year. Understanding and monitoring these processes is essential to planning a successful cone collection.

Step 1: Determine long-term seed needs

The first step in the development of any cone and seed collection program is to determine, for each species, the amount of seed required to meet the reforestation and emergency needs over a given planning period. The number of years in a planning period will vary with each species' periodicity and seed storage life expectancy but is usually a minimum of 10 years pro-

TABLE 5.1. Seed lot data used to determine seed needs*

Species	Cones/bushel (average no.)	Clean seed per bushel of cone (average lbs.)	Germination rate (%)	Seed per pound (average no.)	Correction factor [†]	Plug seedlings per pound of seed (average no.)
Jeffrey pine	35–50	1.2	85	3,700	0.72	2,664
Ponderosa pine	90–100	1.0	85	9,200	0.76	6,992
Sugar pine	12–18	1.4	80	1,900	0.72	1,368
Coulter pine	10–12	0.9	85	1,360	0.72	979
Incense cedar	1,000s	0.7	65	13,600	0.54	7,344
White fir	170–200	1.1	70	10,200	0.54	5,508
Red fir	50–65	0.9	70	4,700	0.54	2,538
Douglas-fir (coastal)	900–1000	0.5	85	33,400	0.70	23,380
Douglas-fir (Sierra)	700–900	0.75	85	27,400	0.70	19,180
Bigcone Douglas-fir	300–400	0.75	80	4,300	0.70	3,010
Coast redwood (Northern Calif.)	1,000s	0.75	60	92,700	0.42	38,934
Coast redwood (Southern Calif.)	1,000s	0.75	60	86,900	0.42	36,498

*Estimates based on seed lot data from seed processed and grown at CAL FIRE Lewis A. Moran Reforestation Center, 1980–2014.

[†]Nursery correction factors are usually lower for bare-root production due to its greater environmental variabilities. Container production is generally a more efficient use of good-quality seed. Shown correction factors are for container production at Lewis A. Moran Reforestation Center.

duction plus an emergency reserve for unforeseen events. An adequate emergency reserve is another 50 percent or more above the 10-year production estimate. A simplified calculation is:

$$\text{Planning period need} - \text{number of trees} \\ \text{potentially available from seeds in storage} = \\ \text{seed collection need}$$

The estimate of seed needed for each species is based on

- Expected yield (pounds of clean seed per bushel cones)
- Number of seeds per pound
- Germination percentage
- Ratio of seedlings to viable seeds

Cone crop periodicity

Periodicity is the number of years between collectable cone crops. Nature produces a medium-to-heavy cone crop over a wide area only intermittently, usually once in 3 to 10 years, or even much longer (table 5.2). Cone production differs by species, regional location within a species, between individuals in a stand, and between stands. Good cone crops may occur more frequently on a local basis while some locations regularly fail to produce viable cones. Indeed, failures may occur sporadically across a landscape even in abundant crop years.

Furthermore, seed yield, quality, and storability vary considerably by species, making procurement of an adequate supply an important and complicated consideration. The goal is to collect the maximum amount of high-quality seed in good years and store them for the years in between. For example, coastal Douglas-fir trees may have conspicuous cones every 3 to 5 years, but these are often a combination of insect-riddled and low-filled seed cones. An abundant Douglas-fir cone crop with good-quality seed in these areas has occurred only three times since the mid-20th century: 1968, 1982, and 1997. In another example, ponderosa pine generally produces a plentiful cone crop at 3- to 10-year intervals in much of its range, but in the inland coastal area (300 series of zones) ponderosa pine has produced only very light to light crops approximately once every 10 to 12 years, and a good crop has failed to occur since the mid-1990s. Cone survey records dating from 1958 to present document generally poor overall crop ratings statewide but show considerable local variation.

Step 2: Conduct annual cone crop survey

The annual cone crop survey assesses the potential for collections in each of the specific physiographic and climatic regions of California. The purpose of the cone crop survey is to forecast the likelihood of successful cone production in the current year; compare one stand or potential collection area with another; and

TABLE 5.2. Conifer reproduction and periodicity of important California reforestation species

Species	Elevation range (meters)	Maximum height (meters)	Onset of cone bearing age (years)	Reproduction range (years)	Time between significant crops [†] (years)
White fir* (<i>Abies concolor</i>)	1,000–3,000	55	40	40–400	3–9
Red fir* (<i>A. magnifica</i>)	1,400–2,700	60	35–45	35–600	3–6
Incense cedar* (<i>Calocedrus decurrens</i>)	50–2,960	50	20	20–500	3–6
Coulter pine (<i>Pinus coulteri</i>)	300–2,000	25	10–20	10–100	Serotinous
Jeffrey pine* (<i>P. jeffreyi</i>)	500–2,900	60	10–20	10–500	2–8
Sugar pine* (<i>P. lambertiana</i>)	150–3,000	65	40–80	40–600	3–5
Ponderosa pine* (<i>P. ponderosa</i>)	150–2,700	50+	15–20	15–600	4–10
Douglas-fir* (<i>Pseudotsuga menziesii</i>)	700–1,800	75–90	20–25	20–500	5–15
Coast redwood* (<i>Sequoia sempervirens</i>)	10–975	84–120	15	15–2,200	12–20
Giant sequoia (<i>Sequoiadendron giganteum</i>)	1,400–2,600	76	20	20–3,000	Serotinous
More narrowly distributed California conifers					
Pacific silver fir (<i>A. amabilis</i>)	1,700–2,100	70	20–30	20–500	2–6
Grand fir (<i>A. grandis</i>)	0–50	60	30	30–300	3–5
Subalpine fir (<i>A. lasiocarpa</i>)	1,700–2,200	30	50	50–200	3–5
Port-Orford cedar (<i>Chamaecyparis lawsoniana</i>)	800–1,400	60	5–10	5–600	4–5
Whitebark pine (<i>P. albicaulis</i>)	2,220–3,660	20	20–30	20–700	3–8 [‡]
Knobcone pine (<i>P. attenuate</i>)	180–2,000	15	10	10–90	Serotinous
Foxtail pine (<i>P. balfouriana</i>)	2,100–3,700	22	20	20–1,500	5–6
Lodgepole pine (<i>P. contorta</i> var. <i>murrayana</i>)	1,500–3,400	30	15–20	15–600	2–4
Limber pine (<i>P. flexilis</i>)	2,200–3,350	18	20–40	20–1,000	3–6 [‡]
Bristlecone pine (<i>P. longaeva</i>)	2,600–3,600	15	50	50–4,000	2–4 [‡]
Western white pine (<i>P. monticola</i>)	1,370–3,170	60	20	20–400	3–7
Bishop pine (<i>P. muricata</i>)	0–400	25	10	10–200	2–3
Monterey pine (<i>P. radiata</i>)	0–300	35	10	10–100	Serotinous
Foothill pine (<i>P. sabiniana</i>)	300–2,100	25	25	25–200	2–4
Torrey pine (<i>P. torreyana</i>)	0–175	18	12–18	12–150	Serotinous
Singleleaf piñon pine (<i>P. monophylla</i>)	1,000–2,900	12	35	35–800	5–7
Brewer spruce (<i>Picea breweriana</i>)	1,150–2,700	30–50	20–30	20–900	2–3
Sitka spruce (<i>P. sitchensis</i>)	0–20	70	25–40	25–800	3–4
Bigcone Douglas-fir (<i>Pseudotsuga macrocarpa</i>)	275–2,400	30	20	20–600	7–10
Western hemlock (<i>Tsuga heterophylla</i>)	10–400	60	20–30	20–500	5–8
Mountain hemlock (<i>Tsuga mertensiana</i>)	1,900–2,700	30	20–30	20–250	3–5

*In the temperate zone the length of the juvenile period is extremely varied. Reliable and abundant production of viable seed tends to occur at a later age, often after 30 to 80 years.

[†]Periodicity: The authors' 60+ years collective experience has been that significant collectable (economical and operational-sized) crops occur at irregular intervals that often exceed the parameters listed. The periodicity of collectable crops can often be longer at the lower, drier end of the elevation range.

[‡]Source: Patricia Maloney, UC Davis Department of Plant Pathology, personal communication.

collect cone production information for long-term periodicity records. The decision to collect cones in a given year will be based on a systematic crop monitoring process that begins with visual observations of tree crowns in early summer and continues with assessments of the cones and seeds as they begin to mature. The cone crop rating is a numeric method for expressing the size of the *potential* crop and is based on two factors: 1) the number of well-distributed trees bearing cones in a mature stand, and 2) the relative number of cones in the acceptable portion of the crown on those individual trees. CAL FIRE uses the rating system described on the cone crop survey form (fig. 5.8). A rating of (3) heavy is generally considered collectable when seed quality is determined to be acceptable as well.

Few versus many cones

Of particular importance is understanding the different cone production characteristics among the species being assessed, including the variance in number of cones considered abundant and their distribution throughout the crown (Eremko et al. 1989). A cone crop rating of “few” or “many” is highly subjective and largely dependent on the experience of the surveyor. For example, 80 to 100 cones on a sugar pine or red fir tree would be classed as “many” while the same number on a Douglas-fir would scarcely be noticed.

CALIFORNIA DEPT OF FORESTRY & FIRE PROTECTION L.A. MORAN REFORESTATION CENTER CONE CROP SURVEY FORM																				
Date: _____			Rating By: _____																	
Seed Zone: _____			Elevation: _____																	
T: _____	R: _____	Sec: _____	Lat: _____		Long: _____															
Stand Observed From: within stand _____ road _____																				
Motor Log: _____ _____ _____																				
Comments on Stand Condition: (form, density, access, safety for collection) _____ _____ _____																				
RATING (Check number that applies)																				
Species	PP	JP	SP	DF	CRW	WF	RF	IC	Other											
1. Light																				
2. Medium																				
3. Heavy																				
The cone crop rating is based on ocular estimates of cone quantities on dominant and co-dominant trees, 12 inches d.b.h. or greater. Five classes are used as follows: <table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th>Rating</th> <th>Criteria</th> </tr> </thead> <tbody> <tr> <td>1. Light</td> <td>Few cones on more than ¼ of the seed trees.</td> </tr> <tr> <td>2. Medium</td> <td>Many cones on ¼ to ½ of the seed trees.</td> </tr> <tr> <td>3. Heavy</td> <td>Many cones on more than ½ of the seed trees.</td> </tr> <tr> <td> </td> <td> </td> </tr> </tbody> </table>											Rating	Criteria	1. Light	Few cones on more than ¼ of the seed trees.	2. Medium	Many cones on ¼ to ½ of the seed trees.	3. Heavy	Many cones on more than ½ of the seed trees.		
Rating	Criteria																			
1. Light	Few cones on more than ¼ of the seed trees.																			
2. Medium	Many cones on ¼ to ½ of the seed trees.																			
3. Heavy	Many cones on more than ½ of the seed trees.																			

Figure 5.8. Example of cone crop survey form.

Likewise, several thousand cones may constitute “many” on a Douglas-fir, but the same quantity would be rated as “few” on a mature incense cedar.

In developing judgment of “few” and “many,” attention is confined to the portion of the tree crown expected to bear acceptable cones for that species. In the white pines (sugar and western white) and true firs, cone production is often limited to the top four to five branch whorls. In abundant crop years, cones of

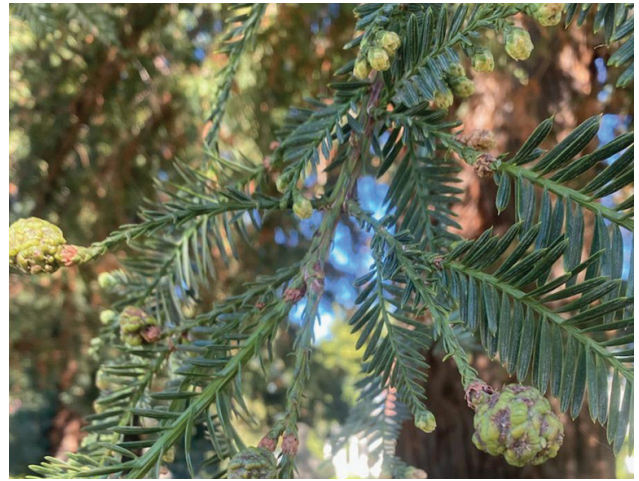


Photo: Tori Norville.

Figure 5.9. Coast redwood cones.



Photos: (A) Susan McDougall; (B) CAL FIRE.

Figure 5.10. Douglas-fir cones: (A) one and (B) many.



Photo: Don Owen.

Figure 5.11. White fir cones.



Photo: Craig Ostergaard, Sierra Pacific Industries.

Figure 5.12. Sugar pinecones.

Photo: Dave Powell, USDA Forest Service.

Figure 5.13. Ponderosa pine cones.

Photo: Canadian Forestry Service, 1989.

Figure 5.14. Subalpine fir with few cones (left in photo) and many cones (right in photo).

ponderosa pine will occur in clusters of three to five or more on the previous year's growth in the upper half of the crown. Abundant small cones on coast redwood or incense cedar will alter the appearance of the tree as the branches literally droop under the weight of a heavy crop (figs. 5.9–5.14). For those species with cones found throughout the crown, the highest quality seed cones will be in the top half of the crown on vigorous branches exposed to the sun; seed cones in the lower crown are more likely to be self-pollinated.

Additionally, isolated trees (individuals located more than 300 feet from any other of the same species) should be avoided in rating assessments and collections; they are likely self-fed, or self-pollinated, and therefore not good genetic material.

The cone crop surveys are completed in early summer when cones are readily visible, usually in June through July depending on geographic region, elevation, and climate conditions of the cone year. The surveys are done on a stand basis within each designated seed zone and across elevation bands within a seed zone. Surveyors observe current-year cones on well-distributed, dominant (and rarely codominant) seed trees. A seed tree is defined as one of cone-bearing age, minimum diameter at breast height greater than 12 inches (often larger depending upon species), with good phenotype, fast growth rate, high vigor, disease-free, straight stem, and small branch size. Well-distributed means seed trees are 100 to 300 feet apart and stands are separated by approximately 600 feet, the required large separation for wind-pollinated plants.

Surveyors must avoid two common errors when conducting surveys:

- Do not include spent cones (those that have already shed seed).
- Do not sample only roadside trees as they receive more light from all directions and will frequently have a heavier crop (generally not representative of the stand).

Visibility is improved if surveyors keep the sun behind them when viewing cone crops, especially species with small cone size such as Douglas-fir and coast redwood. The survey objective is to collect data from as many sites as possible to ensure a representative cross-section of cone production over a wide area. Surveyors are encouraged to evaluate 20 to 30 or more well-distributed inspection sites from low to high elevation per seed zone. Positive species identification is crucial. Sometimes identification is simple and straightforward because of the uniqueness of a species. Douglas-fir is one example: these cones are highly recognizable due to the characteristic three-pronged bracts that overlap each scale. Other species, such as ponderosa and Jeffrey pine, are similar in appearance and have overlapping ranges. Evaluators must look at all species characteristics to eliminate misidentification of similar-looking trees. In such cases, it is helpful to dissect a few cones and inspect seed structures as well.

Crop rating

Evaluators use a crop rating designated for each species present in the sample area and a separate survey form for each site. Based on the results of the cone-

crop estimates, potential collection areas can be selected for further evaluation. To be considered for collection, each stand must have sufficient area and number of acceptable cone-bearing trees to meet collection standards and be cost-effective. The cone crop survey form should also include details about the stand's location and condition. It is important to be specific about location; a good motor log, in addition to global positioning system (GPS) coordinates, is key to relocating a stand for further evaluation if necessary. When surveying for cone crops and choosing potential collection areas, the surveyor should also consider and catalog useful site characteristics including local topography and degree of slope, species composition and density, stand age and structure elements, overall stand health, and property ownership, if known.

If an area is selected for collection, its microclimate features (including aspect, slope, drainage elements, soil type and moisture holding capacity) should be recorded as well. Nearby bodies of water create microclimates that moderate the local area. South-facing slopes will be warmer and drier than those with a northern aspect. Low-lying and shady areas will experience lower overnight temperatures and allow snow and frost to linger. Soils may be rocky or compacted, both of which will affect drainage. It is important to consider all elements of the site when making seedling deployment decisions and include them in the cone collection report.

Step 3: Select cone harvest trees

Characteristics such as growth rate and form, multiple branching, and pest resistance are highly heritable and vary widely between individuals. Trees with a desirable phenotype may be genetically superior to neighboring trees with less desirable traits and often produce more viable seed. Forest tree selection for cone collection involves choosing parent trees that possess the following desirable characteristics:

- fast growth rate
- full, compact crown indicative of high vigor
- straight stem and minimal taper
- small branch size with horizontal or slightly upward angle
- high needle retention
- strong resistance to attack by insects and disease pathogens
- free of obvious defect such as forking or spiral grain

These genetic differences are important because they are passed on to progeny. Stands containing poorly formed and otherwise inferior trees should be avoided.

Genetic variation is necessary for populations to evolve and undergo adaptive changes in response to changing environmental conditions. The most likely place to collect seed with genetic combinations that are best-suited for long-term survival on a given site is on or near the site itself. Decades of research has demonstrated that the use of nonlocal genotypes can result in immediate or delayed mortality, poor vigor, and reduced fertility (Guinon 1992). In addition, nonlocal seed can introduce inferior or maladapted genotypes into the ecosystem. Failures from improper seed source may not become apparent for many years because of the slow-growing nature of trees.

Broad or narrow genetic base

The ability to adapt to different environmental conditions varies considerably among California tree species. Genetic generalists are species with more adaptive traits and perform well in a broad range of environments. Incense cedar and western white pine are examples of species that can tolerate a wide range of elevational and climatic gradients and may be better able to adapt to a variety of environmental stresses. Ponderosa pine is one of the most widely distributed conifers in California and is characteristically present in the mixed-conifer type from approximately 500 feet near coastal and foothill environments to more than 9,000 feet on the west slope of the Sierra Nevada. Ponderosa pine succeeds in a variety of soils, exposures, and environments and is considered intermediate in adaptive traits. In broad terms, generalists and intermediates have more genetic diversity and can move farther in both seed zone and elevation than other species.

Douglas-fir is known as a genetic or climatic specialist in adaptive traits. Specialists show strong genetic variances over small geographic and climate ranges. Douglas-fir has an extensive latitudinal range in the Pacific Northwest and is broadly distributed in California, but movement out of its local range typically causes a decline in productivity or even death. The coastal and Sierran populations within California are morphologically and ecologically dissimilar and are not recommended as interchangeable. Measurable genetic differences can be found in Douglas-fir populations separated by just 656 feet (200 meters) of elevational change and in response to temperature extremes, number of frost days, and drought stress (Rehfeldt et al. 2014). Bigcone Douglas-fir is another specialist; it is restricted to fragments of Southern California's forested regions in canyons, canyon bottoms, and mostly northern and eastern slopes. Its endemic status in California and limited range of favorable environmental conditions of temperature, soil, and precipitation mark bigcone Douglas-fir as potentially maladapted to future

projected environmental conditions. Adverse effects due to climate change are expected to have a greater impact on specialists and other marginal populations such as regional endemics, those at the trailing edge of their ranges, and high-elevation alpine species, making them more vulnerable to extirpation if conditions change too rapidly.

Inbreeding

Within a stand, it is highly likely that many individuals are related. Conifers are wind-pollinated and therefore require a larger separation between seed trees than other plants to promote cross-pollination; 200 to 300 feet apart is recommended. Selfing and close-relative mating can have significant negative impacts on seed crops and tree populations produced from open-pollinated seed. Inbreeding results in loss of seed yield, lower germination rates, poor storability, poor seedling vigor, and higher mortality rates (table 5.3).

It is essential to choose collection candidates with care. The best approach to avoid inbreeding and decreased vigor of progeny is to collect from a number of widely spaced trees in a stand and collect an equal number of cones from each and from a number of different stands within the same elevation band of a seed zone. A stand is considered different when separated from an adjacent collection area by a minimum of 600 feet. With seed from many stands, collections are more likely to include individuals adapted to local variations such as cold and drought hardiness, vegetative bud phenology, disease resistance, and soil conditions. In addition, collection priority for operational size collections should be given to stands and individuals at the center of the range, which are generally more broadly adapted and can be moved farther than material at the margins of a species range.

Location-to-location variation exists even among individuals and stands in the same elevation band. This is especially important on harsh sites or in regions that experience severe climate events. When considering a good match for deployment, the environmental, or climatic, parity between seed source and planting site is more important than geographic distance. Notably, collections from fragmented or threatened populations,

or individuals at the trailing edge of the range where frequency is lower (areas typically excluded for bulk collections), should be considered a priority for future gene conservation. These types of very specific collections should remain separate from operational-sized collections.

Selecting collection trees in natural stands provides an opportunity to improve the overall health of the forest. While collection candidates are compared with adjacent trees for phenotypic characteristics, tree health or lack thereof is also critical to the success of collection efforts. Parent trees must show resistance to disease, a strongly inherited trait. Trees with mistle-toe or other disease may have a heavy crop, but it is important to avoid collecting from these individuals or stands containing diseased trees. Removal of diseased trees and general thinning is recommended to promote healthier and more resilient stands while also stimulating larger cone crops by reducing competition for light, nutrients, and growing space.

Harvesting summary

When selecting harvest trees for general seed collections the following standards should be considered:

- Collect only from trees with the desirable phenotype in stands with a high proportion of desirable trees—pollen from trees with poor form can affect the quality of progeny.
- Do not harvest cones in areas that had a poor pollen crop (identified by the number of trees in the vicinity with abundant spent male cones present or on the ground).
- Collect only in years of moderate-to-heavy cone and seed production throughout most of the seed zone. (Moderate means the majority of dominants and approximately 50% of the codominants are producing cones.)
- Maximize diversity by maximizing the number of unrelated individuals represented.
- Avoid seed cones from trees with seed counts below 50 percent filled that are not otherwise attributable to damaging agents such as frost or insects.
- Avoid collecting cones in the lower third of the live crown, as the probability of self-pollination increases below midcrown.
- Avoid isolated trees and small isolated stands, which are usually inadequately pollinated.
- Avoid stands or areas that have been selectively logged.

The goal is to collect seed lots that represent the maximum number of unrelated female parents. A *minimum* of 33 to 50 individuals is required for a

TABLE 5.3. Inbreeding in *Pinaceae*

Trait	Loss due to inbreeding
Yield	–50%
Seed germination percentage	–12%
Height growth	–12%
Mortality	+1.3 times

Source: Franklin 1970.

100-bushel lot, ideally two bushels maximum per tree. Each stand collected from should be separated by at least 600 feet.

Some individuals in a population will typically produce more seed than others. Do not skew bulk collections by collecting more cones from loaded trees. An equal amount from each is necessary to maintain equal representation of donor genes.

Step 4: Collect cones

The objective of any cone harvest is to collect the assigned quantity of high-quality cones during the appropriate window of opportunity in a safe and cost-efficient manner. Important factors to consider include

- target species availability
- crop size
- collection timing
- collection site certification
- cone handling and transportation
- cost

Collections are inherently more efficient and successful when crops are bountiful and filled-seed numbers are high. Yearly variation in cone production, collection timing, and seed quality can be high, so early determination of quality or lack thereof can prevent expensive failures.

Seed maturity

Even with an abundant cone crop it is important to examine cones and seeds for quality and progress toward maturity. *Seed maturity is vitally important!* The relationship between seed maturity and germination capacity and yield is well established. Seed maturity has been defined as the stage at which seeds are capable of germination and successful storage (Edwards 1981). Seeds collected too early may germinate but they will be of low vigor and may perish in storage.

Mature seeds have greater vigor and establishment potential, higher yield, and increased storage capability. Seed maturity is generally associated with dispersal. The best time to collect cones is when they begin to open on the tree, but that is rarely practical with operational-sized collections. Instead, collectors must know how far in advance cones may be harvested without compromising seed quality. This may be a matter of days or up to 3 weeks in advance of natural seed-shed, depending on the species being collected and anticipated weather conditions. For an accurate assessment, it is necessary to cut a sample of cones longitudinally and slice the extracted seed. (Specific gravity tests in the field were long used to estimate collection start dates, but cone and seed cutting tests have become the

preferred method because of increased reliability and ease of use in the field.)

Evaluating the cone crop involves closely observing common indicators of ripeness including cone color and condition; seat coat and wing color and condition; evidence of insect or fungal damage; and internal tissue color, texture, and condition. These physical and physiological indices are reasonably dependable but can be subjective with differences varying widely among species, between cones on the same tree, between individuals in a stand, and among populations across the landscape. The reliability of these assessments is dependent on the observer's experience.

Major ripeness indicators

As cones ripen, a gradual but obvious reduction in moisture content occurs; they will feel lighter. This moisture loss is accompanied by changes in cone color and texture. Cone color varies by species but, in general, cone exteriors change from a vegetative green to some shade of yellow-green or golden to brown. As cones ripen, there will be a slight flexing of the scale margins. Every effort should be made to collect when cones and seeds are fully mature (table 5.4). After-ripening, a method infrequently used to improve cone and seed maturity when collections are premature, may also be possible for particularly valuable collections (for example, Douglas-fir, sugar pine, or true fir) under strictly controlled conditions of cool temperature (10°C), relative humidity, and sufficiently rapid air movement.

A representative sample is a must in order to accurately estimate the quantity of sound seed available and the degree of maturity attained; two to three cones from the top half of the crown from several unrelated trees in a stand is ideal. The sample cones are cut lengthwise through the center core, and the exposed seeds are counted on one cut face. The seed minimum (average) per cut face varies by species but, in general, if 50 percent or more of the cut seed is empty or damaged then a collection is not considered worthwhile (fig. 5.15). The percentage of desirable seeds required increases to 75 percent for pines (fig. 5.16). The seeds at the tip and base end of the cone are not considered in this count because, for most species, these areas likely contain a high percentage of undeveloped seeds.

Conifer seeds have three main components: the seed coat, embryo, and megagametophyte. Seed coat morphology among trees of different species is quite variable in color, shape, size, texture, and the presence or absence of seed wings and resin vesicles. Even seeds from different trees of the same species will show great variability in seed color, shape, and size. As they mature

- Seeds become easier to separate from the scale.

TABLE 5.4. Major ripeness indicators for selected California conifers

Species	Minimum sound seeds per cut face*	Cone color and condition†	Seed coat and wing color and condition	Embryo and megagametophyte color, texture, and condition	Favorable collection period (wide geo-elevational variability)‡
White fir (<i>Abies concolor</i>)	50%	Greenish-yellow to golden, may have grayish or purplish tinge at ends; cone scales become slightly pliable	Cream or tan color and soft; contains more resin vesicles than red fir, loosely attached to scale; wing is golden-brown with magenta or golden margins and slightly translucent (if coats and wings still all purplish, it's too early); wings feel papery	Embryo occupies 90–100% of cavity, yellow in color, cotyledons well-developed; megagametophyte whitish, fleshy, and firm though may appear somewhat oily	True fir cones disintegrate fairly quickly upon maturation, so must be collected slightly prematurely; late August through October
Red fir (<i>A. magnifica</i>)	50%	Greenish-brown to russet brown with reddish or grayish tinge; cone scales change from rigid to pliable before scales dehisce	Coat reddish-brown and thicker than white fir, loosely attached to scale; Shasta red fir have visible bracts on scale exterior; wing reddish-brown with magenta margin and papery	Embryo occupies 90–100% of cavity, yellow in color (radicle end encased by root cap); megagametophyte fleshy and firm, somewhat oily in appearance	September through October
Incense cedar (<i>Calocedrus decurrens</i>)	2	Yellowish-green to golden-tinged with shades of brown; cone tip flexes slightly	Thin, papery coat ripens to light tan color; two persistent wings must remain intact (to avert damage to embryo)	Embryo bright yellow (may have pinkish radicle end), 90% extended; megagametophyte appears firm and oily	Mid-August to October perishable; be alert to overheating
Jeffrey pine (<i>P. jeffreyi</i>)	10	Greenish-purple to yellowish-brown or dark purple to lighter purplish-brown; scales begin to flex	Coat pale brown color, hardened, smooth evenly brown on top, coarser on scale side; wing light tan to brown and brittle, adheres to coat	Embryo creamy white and 90% length of cavity; megagametophyte whitish color, opaque, firm, nutlike	Early September through October
Sugar pine (<i>P. lambertiana</i>)	12–15	Yellow-green to light brown; cone scales become less rigid and begin to flex	Coat is dark brown (preripe color is orange and mottled orange-brown); wing dark brown, thin, papery	Embryo 90% length of cavity, yellow color; megagametophyte creamy white, opaque, firm, not milky	Mid-August through October
Ponderosa pine (<i>P. ponderosa</i> , var. <i>ponderosa</i>)	8–10	Pale yellow-green to light brown-green to lustrous yellow-brown; scales begin to flex	Pale brown to gray-brown and usually mottled on scale side, hardened; wing golden to tan, brittle, adheres to coat	Embryo 90% length, pale yellow color; megagametophyte whitish color, opaque, firm, nutlike	Early August through September
Douglas-fir (<i>Pseudotsuga menziesii</i> , var. <i>menziesii</i>)	5–6	Pale yellowish-green to golden-brown color, three-lobed bracts turn golden-brown first (but may also brown prematurely due to insect activity)	Golden- to dark-brown, shiny and darker on one side, hardened; wing light-brown to tan, easily detaches from scale; coastal seeds longer with pointed tips; interior generally rounder tips and more triangular-shaped	Embryo occupies 90–100% of cavity, pale yellow color; megagametophyte whitish color, full, opaque, firm	Earliest ripening cone at lowest elevations late July–August; most seeds released by October
Coast redwood (<i>Sequoia sempervirens</i>)	3–4	Greenish-yellow to golden-brown; cone scales separate slightly	Reddish-golden to red-brown (should not be green tinged); wing slightly lighter color and part of coat	Embryo and megagametophyte barely indistinguishable without magnification, but whitish color and firm	Early October to November

*For pine, Douglas-fir, and redwood, place cone on hard surface and cut lengthwise from stem to tip through center axis, exposing cut seeds; count number of filled seeds on one half only. For true fir, cut cone lengthwise from stem to tip and parallel to the core but offset by ~ ¼ to ½ inch; seed count is measured as percentage of exposed seeds that are sound. For incense cedar, cut cone through the bottom third widthwise and observe from one to four seeds per cone (rarely up to six).

†Determining maturity by exterior cone color can be subjective. Color varies by individual, population, site, and weather.

‡Physical characteristics vary with location and elevation. Maturity may differ by more than 1 month between low- and high-elevation sites. Seed dispersal is greatly influenced by local weather patterns. If unusually warm or drying winds, seeds of most conifers will disperse in days.

Photo: Bill Morrison, Soper-Wheeler Company.



Figure 5.15. Coast redwood with more than 75% filled.

Photos: CAL FIRE Lewis A. Moran Reforestation Center.

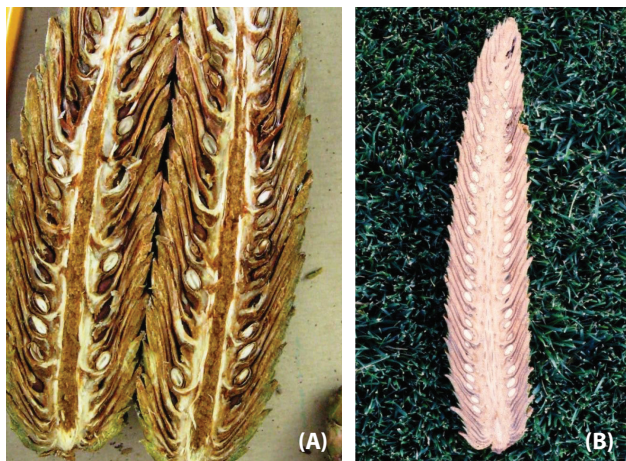


Figure 5.16. Sugar pine with poor filled-seed count (A) and more than 75% filled (B).

- Seed coat will begin to harden.
- Seed coat color changes from pale green, orange, magenta, or tan-gold to golden, dark, and/or mottled brown.
- Seed wing will darken, begin to dry, and separate more easily from the scale; approach a golden to golden-brown to medium-brown or tan to reddish; and feel somewhat brittle, similar to parchment paper when exposed to air.

Seed cutting tests: Embryos and megagametophytes

The seed cutting test is a seed anatomy test. It reveals the proportion of filled (presumably viable) seed and degree of maturity. A sample of seeds is bisected on the longest axis and thinnest dimension to visually examine the embryo condition and length. The cut must be precisely through the center because an improper cut will not show true embryo elongation. The number of seeds sampled varies by the precision required and whether it is a field test (10 to 20 seeds) or postharvest examination in the seed lab (100 seeds per lot).

As it matures, the embryo loses moisture and differentiates from the megagametophyte, turns creamy to

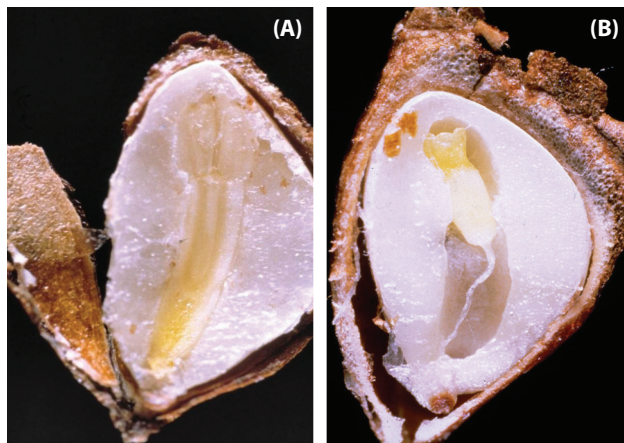


Figure 5.17. Douglas-fir seed with mature appearance and embryo fully extended (A) and embryo less than 50% and suspensor (part connecting embryo to surrounding tissue) still clearly visible (B).

Photos: British Columbia Ministry of Forests, 1989.

pale yellow in color, and elongates to fill the embryonic cavity. Embryos nearing acceptable maturity will fill approximately 90 percent of this cavity (fig. 5.17A). The cotyledons develop fully and become visible at the rounded (chalazal) end, and the hypocotyl and radicle extend toward the pointed (micropylar) end of the seed when fully elongated. A thin suspensor connecting the radicle to the micropylar end may still be visible if the embryo is underdeveloped (fig. 5.17B). The color, texture, and general appearance of the megagametophyte varies with the moisture content of the tissue as well. When immature, the megagametophyte appears gelatinous or milky (fig. 5.18). As it matures the color and texture changes; moisture is lost and the megagametophyte becomes opaque, firm, and nutlike as it differentiates from the embryo. If cut while still immature, the megagametophyte will shrink away from the seed coat if it is left exposed to sunlight or air. In true fir and incense cedar the megagametophyte normally appears somewhat oily because of the many resin



Figure 5.18. Immature bigcone Douglas-fir seed with pale seed coat color and quite moist megagametophyte.

Photo: Arnaldo Ferreira, USDA Forest Service, 2014.

vesicles within the seed coat. Damaged megagametophyte tissue will appear grey or yellowish in color and may have a rubbery or chalky texture.

Evidence of insects

The presence of insects in cones is often externally apparent by one or all of the following: premature browning or flexing as a whole or in patches, small holes caused by boring, excessive pitch exudation, the presence of frass, and areas of disfigurement (figs. 5.19, 5.20). Insect damage will result in lower seed counts and a decrease in the number of seeds that can be extracted from the damaged cones.

Immature or insect-damaged cones

Many problems may be encountered with immature and insect-damaged cones and seeds. Immature seeds are harder to extract and process because the cones tend to dry too rapidly once they are separated from the tree and the scales will case-harden in a partially flexed position. This traps the seeds inside the cone and reduces yield. Immature seeds have reduced germinative capacity and are slower to germinate. Germinants of immature seeds are less robust and produce seedlings with decreased vigor. Immature seeds

are more susceptible to fungal attack and diseases, and they tend to have more abnormalities, which leads to eventual death of the seedling. When seeds are collected too soon they are less viable and will decline in storage at a much faster rate than seeds that are fully mature when collected.

Insect-damaged cones are harder to extract and process because they are often contaminated with frass and pitch exudation, which fuses the seeds and scales, preventing the seeds from falling freely during extraction (fig. 5.21). In addition, insect activity often causes deformation of cones; the affected areas do not flex, and the seeds are trapped (fig. 5.22). In these situations, seed yield will decline significantly. During upgrade, seeds with an insect larvae inside may be more difficult to separate from filled seeds because they often have the same specific gravity and result in a seed lot with fewer germinable seeds. Damaged cone fragments, seeds, frass, and insects contaminate the seed lot and the equipment being used and make cleaning the seeds far more challenging. These seed lots must often be consigned to the end of the processing cycle, after the healthier lots are completed, because of the extra time and effort that they require.

Collection timing is critical

Cones and seeds must be physiologically mature at the time of collection or seed viability and vigor will be

Photo: Ward B. Strong, British Columbia Ministry of Forests, British Columbia, Canada.



Figure 5.19. Douglas-fir cone with Douglas-fir cone gall midge (*Contarinia oregonensis*) galls.

Photo: USDA Forest Service, Ogden, UT; Bugwood.org.



Figure 5.20. Ponderosa pine damaged by *Dioryctria* spp. Cone scales are patchy in color with frass grains at the stem end.



Figure 5.21. Excessive debris and pitch in this seed lot of sugar pine (*P. lambertiana*) makes processing and seed upgrade difficult.

Photo: CAL FIRE Lewis A. Moran Reforestation Center.



Figure 5.22. Douglas-fir cone heavily burrowed by western spruce budworm (*Choristoneura occidentalis*).

Photo: Canadian Forestry Service, July 1980.

unacceptable. In California, the majority of forest tree seeds reach physiological maturity in late summer and early fall, about 1 to 2 weeks before natural seedfall. The actual timing of collection and length of the harvest period in a given season will depend on the species, area of the state, site elevation, and local weather conditions. Moisture, temperature, and altitude play an important role in local ripening. For example, a warm, dry summer or sudden drying wind can cause early cone opening and seed release. Conversely, a late spring, cool summer, or wet fall can delay cone-ripening and lengthen the collection period. For the most part, cones ripen first at lower elevations and on west- and south-facing slopes and later at higher elevations and on eastern and northern exposures (Schubert and Adams 1971). Not all cones in a stand or on a single tree ripen at exactly the same time, so it is best to wait until the majority are ripe than to begin too soon. However, collecting too late may be detrimental because seeds may be lost to premature shedding, predation by animals or insects, or deterioration (Bonner and Karrfalt 2008).

Species with serotinous cones are an exception to the fall maturity and 1- to 2-plus week collection window (see sidebar 5.3 for the definition of serotiny). The collection period for Coulter, Torrey, foothill, and knobcone pine may instead be several months after fall maturity because resins prevent the scales from opening immediately after ripening. Collection of these species may be conveniently scheduled after other time-sensitive collections are complete.

Giant sequoia, though not truly serotinous, is another interesting exception to the fall collection pattern. Giant sequoia cones are persistent; they remain in the crown for many years past peak maturity and intermittently release seed. Mature older cones (more than 6 years old, and yellowish-green with a brown stem/

peduncle) may be collected at any time of the year but may have approximately 10 percent fewer viable seeds depending on the age and condition of the cone. Very old cones (grey, usually lichen-covered) commonly contain few viable seeds, having intermittently flexed their scales and released seeds during warm, dry periods over many years.

Giant sequoia cones become physiologically and morphologically mature 13 months after fertilization, and these cones open readily upon detachment and drying. However, second-year cones (immature, just-fertilized females) may attain nearly full size by the fall of the same year as fertilization (September to October) and have often been mistaken for mature cones (fig. 5.23). In one study on the University of California Whitaker's Forest, adjacent to Kings Canyon National Park, researchers looked at differences in seed yield and germination capacity between cones of different ages, (fig. 5.24) to identify the ideal collectable cone (personal communication, Ken Somers, Center for Forestry, University of California, Berkeley, 2017).

Collectors must be alert to sometimes-subtle color differences between second-year cones and those that are fully mature when fall-collecting giant sequoia to

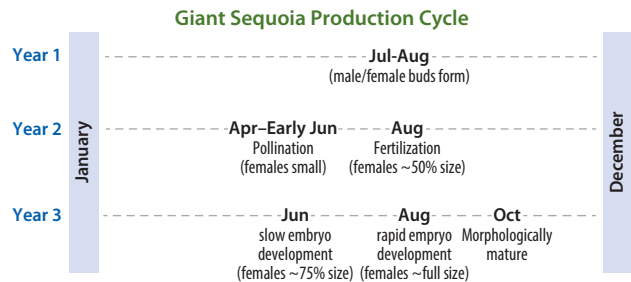


Figure 5.23. Giant sequoia production cycle shows which females are morphologically mature when considering candidates for collection.



Figure 5.24. Giant sequoia with just pollinated female conelets (top in photo) in June 2015 (A); and the same now-fertilized female cones (top in photo) in June 2016 (B). They must continue development before attaining full embryo maturity in September through October 2016.

Sidebar 5.3: Serotiny

Serotiny is an ecological adaptation in conifers that prevents immediate seed dispersal upon maturation. The cones remain closed on the parent tree for a year or more after the seeds have matured. In some species of pine and cypress, serotiny is more severe and seed release usually occurs in response to an environmental trigger such as fire or after treatment artificially in a cone kiln at a processing facility. Cones that exhibit this type of serotiny include knobcone, Monterey, Bishop, and Coulter pine from the Central Coast (seed zones in the 100 series), as well as cypress.

avoid collecting unripe cones. Making this distinction is easiest in late spring or early summer (late May through June) when color and size differences between mature and immature cones are more conspicuous. Early findings show that seeds from fall-ripened, delay-collected cones consistently show higher germinative capacity and increased seed yield when compared to fall-collected giant sequoia, which may include unripe cones.

Cone and seed losses

Cones and seeds may fail postdevelopment for a variety of reasons. In a cutting test, the two most easily recognized causes for seed germination failure are lack of a properly mature embryo and the complete deterioration of all seed contents (Kolotelo 1997). Empty seeds are common among many conifers because they may still develop a seed coat and megagametophyte without fertilization. For example, without a fertilized embryo the megagametophyte of an *Abies* seed will eventually deteriorate, leaving a seed coat that is woody and difficult to cut during sampling. Conversely, an unfertilized pine seed does not develop a megagametophyte, therefore it will have a lower specific gravity and be easily detected by crushing during assessment, or later removed by air separation during seed upgrade.

Conifer seeds with partially or completely deteriorated contents (dead-filled seed) may have been attacked by pathogenic fungi or damaged by insects. Several species of fungi are known to damage conifer seed and seedlings. Particularly harmful are those belonging to the genus *Fusarium*, which causes pre- and postemergence damping-off. The affected embryo and megagametophyte may still be visible but with obvious discoloration, appear as a solid mass, or be missing entirely. These dead-filled seeds often have the same specific gravity as healthy, filled seeds and are harder to separate during processing.

Seeds with resin vesicles (including true fir and incense cedar) may be damaged by overheating and rough handling at any stage postharvest. Damage to resin vesicles will result in decreased germination or death of the seed. Seeds with damaged resin vesicles may emit a foul odor and have a tacky feel and discolored seed coat. It is important to keep freshly harvested cones out of direct sunlight and limit movement and potential damage to sensitive seeds during collection handling and transport. Do not stack the cone sacks in piles or throw them onto or off the truck while loading or unloading.

Cone and seed insects are the most significant cause of seed losses after the cone development stage, especially in years when seed production is light. Cone

worms, midges, seed chalcids, and maggots may easily destroy half to nearly all of a seed crop in some years. *Dioryctria*, a cone worm that bores through cones and seeds feeding indiscriminately throughout the season, is an especially damaging insect affecting the majority of high-value tree species. Cone worm caterpillars continue to cause damage in cones awaiting processing until they pupate later in the fall. If populations are especially high, it may be necessary to expedite seed extraction from affected seed lots and get the seed into coolers to slow further damage. *Megastigmus*, a seed chalcid, is another harmful insect that attacks Douglas-fir, true fir, and pine species. A single larva consumes the entire contents within each affected seed and remains undetected inside until a cutting test or X-ray radiograph reveals its presence.

The feeding or tunneling activities of some insect species can cause extensive seed yield losses by causing distortion to the cones or fusing seeds to the scales, making seed extraction efforts difficult to impossible (table 5.5). The tendency of natural stands to produce large crops in some years and none for several years (periodicity) has led to biological strategies in which insect populations survive low cone production years by greatly reducing their numbers and then reemerge in large numbers when cone production resumes, often destroying the entire cone crop (Kolotelo et al. 2001).

Collection methods

Several different methods can be used to access tree crowns for ripened cones on selected trees. While each method listed in this section has advantages and disadvantages, the safety of the climber and the tree must be considered first and foremost. In California, collections in wild stands are usually done by trained individuals who free-climb selected standing trees, gaining access to sturdy branches in the lower crown via rigging ropes or occasionally using special ladders. Entry into the lower crown of taller trees may be accomplished by firing a throwline up to 120 feet with a sling (such as the Big Shot) or up to 200 feet with a crossbow to the first supporting branch and, using appropriate rigging, ascending to the top of the crown (fig. 5.25). The climber then ties onto the bole for support and accesses cones at the ends of branches with pole pruners or special hook devices designed to pull the ends of the branch within easy reach for clipping.

Climbing spurs, while used infrequently, should not be used on especially valuable trees or species with stems that could be easily damaged, such as five-needle pines and white fir. Free-climbing is practical in open-grown stands with trees up to 100 feet tall. Branches must be well spaced and large enough to support the climber. Tools are hoisted up after the climber is safely

TABLE 5.5. Significant cone and seed insects

Insect	Host conifer						Larva color	Type and extent of damage
	Douglas fir	White fir/Red fir	Ponderosa pine	Jeffrey pine	Sugar pine	Incense cedar		
Cone beetle (<i>Conophthorus</i>)	—	—	X	X	X	—	White, C-shape, light brown head	Bores into cone at stalk or base, killing cone; may see pitch globules here. Cones underdeveloped or brown and shriveled. Moderately common in some years. Cones are not collectable.
Cone moth (<i>Barbara</i> , <i>Eucosma</i>)	X	X	X	X	X	—	White with dark head	Burrows within cone. Cones pitchy, brown, deformed. May see pitch and frass on cone exterior. Can see damage by midsummer, with extensive destruction of seed and scales. One larva can destroy 60% of seed in a cone, and damage may be half of crop or more.
Cone worm (<i>Dioryctria</i>)	X	X	X	X	—	—	Amber brown to dark red-brown	Bores through cone scales and seeds, feeding indiscriminately. May see round holes and coarse frass. Cone scales may not flex in area of damage, and cones maybe be badly distorted. May destroy most of a poor crop and more than half of good crop.
Cone scale midge (<i>Contarinia</i> , <i>Asynapta</i>)	X	X	—	—	—	—	Small, bright-orange to red	Deforms cone and fuses seed to scale, forming swollen galls. Reduces extraction of seed from cones.
Seed chalcids (<i>Megastigmus</i>)	X	X	X	X	—	—	Small, white, curved, footless	No external evidence of damage. One larva develops per seed and consumes all seed contents. Larva remains in seed, or round exit hole may be seen where adult emerged. Damage is complete by harvest. Major pest on Douglas-fir and ponderosa pine.
Seed moth (<i>Cydia</i> , <i>Laspeyresia</i>)	—	X	X	X	—	—	White with black head	Consumes seed by moving from one seed to another leaving each filled with frass, then bores into axis. Usually no external evidence of damage. Once in axis, no further seed damage expected. May destroy one-third of crop or more.
Seed cone maggot (<i>Earomyia</i> , <i>Hylemya</i>)	—	X	—	—	—	—	White with black mouth hooks	Consumes seed and moves into axis. No external evidence of activity but will see holes on seed coat. Larvae exit in late summer, and damage is over by harvest. Abundant in true firs.
Incense cedar tip moth (<i>Argyresthia</i>)	—	—	—	—	—	X	Small, green with red dorsal bands	Mines cones and seed. May destroy almost entire crop.
Western spruce budworm (<i>Choristoneura</i>)	X	X	—	—	—	—	Brownish head, body; blackish head capsule	Feeds on male and female flowers and bores into developing cones. May cause significant decline in seed production.
Western conifer seed bug (<i>Leptoglossus</i>)	X	—	X	X	X	X	Adult insect with orange and black bands on abdomen	Pierces seed scale and sucks out immature seed content, collapsing megagametophyte and rendering it gray-brown; or may leave hard seed coat intact but tissue inside becomes withered, off-color, spongy.

secured in the tree crown. It is best to start at the top of the crown where the crop is normally heaviest and work down to the lowest acceptable collecting portion of the tree, usually midcrown. Cones are bagged in the tree and lowered to the ground, or branch ends with cones attached may be clipped and dropped onto tarps when vegetation or other means of providing a cushioned landing is available. Sugar pine and true fir cones are known to suffer serious impact damage (shattering) when dropped to the ground, therefore should always be bagged in the tree and lowered to the

ground (personal communication, L. Lippitt, T. Griffis, Lewis A. Moran Reforestation Center, 1986).

In orchard and plantation applications where tree spacing and terrain allows, truck-mounted ladders or hydraulic lifts are suitable to access tree crowns up to the designated height determined by the machinery. Impediments to this method are its high cost, availability and efficiency of the equipment, tree crown height limitations, and the enhanced organization of crew required on the ground.

Photo: Ken Somers, Center for Forestry, University of California, Berkeley.



Figure 5.25. Climber ascending a giant sequoia.

Helicopter collections using an aerial cone rake may be practical in coastal areas, especially on steep terrain and other limited-access areas where large cone crops are concentrated in the top whorls of narrow, conical crowns. This method has been successful for coast redwood collections in California. Helicopter collections can be more economical when a large quantity of high-quality cones are available, but they are generally high cost, require highly trained pilots, are often hampered by unfavorable weather conditions, and pose a greater risk of damage to the trees.

Collecting from felled trees during active harvesting operations can make access to cones easier, but this method has many disadvantages. Timing is critical. If falling occurs before the cones are properly mature, ripening will cease and the cones and seeds will dry out; if collected too late, the cones may open and seed may be lost. There is also a high risk of fungal contamination to cones through ground contact, a greater percentage of cone and seed lost due to impact damage and incomplete recovery, and high potential for injury to workers.

Seed lot identification

The importance of maintaining accurate seed lot identification cannot be overstated. The goal of conscientious labeling and record keeping is to provide the most comprehensive seed collection and site specifications to forest managers, so they have the tools needed to make sound deployment decisions. The collection supervisor (Registered Professional Forester or silviculturist certified by the Forest Service's National Advanced Silviculture Program) approving the cone collection must record the species; location information, including latitude, longitude, and county of origin; date of collection; number of bushels collected; and genetic base; as well as a complete profile of the collection site on a cone collection report.

Report of cone collection (A)

Completing the FM44 form

1. Preprinted lot number: Identifies the source of cones, seed extracted from them and resulting planting stock
2. Species name
3. Seed zone as defined by California Seed Zone map
4. Elevation in 500-foot bands, as follows:
0–500 feet = 0.05; 501–1,000 feet = 0.10;
1,501–2,000 feet = 0.20; 2,001–4,500 feet = 0.45, and so on.
5. Legal description: T, R, section, and county of collection
6. Aspect and site class
7. Indicate number of trees collected from to track genetic base
8. Date(s) collected
9. Number of bushels (should equal number of sacks; 1 bushel = 8 gallons per sack)
10. Rebate info, if applicable (name, address, phone/email)
11. Remarks: notes on local collection area, stand form, composition, etc.
12. Certifying Forester signature and Registered Professional Forester number

CAL FIRE (B)
COLLECTION TAG

Company	
Species	
Lot Number	
Seed Zone	Elevation
T _____ R _____ Sec. _____	
Date	

Use waterproof ink.
Two tags per sack: one inside, one outside

Figure 5.26. Samples of agency collection documentation forms: FM-44 (A) and collection tag (B).

The FM-44 form used by CAL FIRE is one example of a standard form for tracking seed lot archives. The seed lot data is recorded on this form during a mandatory site visit to verify details of the collection. The FM-44 is a permanent record that includes a progressive numbering system identifying a given seed lot from collection through to nursery production (fig. 5.26). During collections, the seed lot number is written on each collection tag along with the species; seed zone and elevation; latitude/longitude and/or township, range, and section(s); and the date(s) of collection. (Note that for decades, township, range, and sections were universally required to record location information, but in recent years GPS coordinates have become standard. Computer programs easily convert one format to the other.) Two seed lot tags are mandatory per sack—one inside and one attached on the outside with a tie at the top; the inside tag is insurance against losing the seed lot's identity should the outside tag become detached. To avoid seed lot confusion, it is important to specify all information requested on the tags legibly with a permanent marker or waterproof ink to prevent fading or damage during inclement weather.

Interim handling and storage

Cones and seeds are highly perishable. Correct field handling at this stage has long-term effects on seed viability, seed longevity, and seedling vigor. *Adequate ventilation and free airflow are the most important storage criteria.* Even mature cones contain water; they expand as

they dry and generate heat. Heat encourages mold and the webbing formed by mold results in direct damage to the seeds and hinders seed extraction efforts. Mold on the seed surface can compromise germination and subsequent storage life. Collections of true fir and incense cedar are especially prone to such damage because of their characteristically high moisture content at maturity.

Collection sacks should be constructed with strong mesh fabric, or burlap sacks may be used if not too heavy or woven too loosely. They must allow free air-flow but disallow seed loss through the open weave. One bushel of cones per 2-bushel sack is ideal, filling only to the halfway mark and fastening at the top to allow ample room for cone expansion. Overfilled sacks damage seed; cones are more prone to mold or compression-hardened scales when they remain wet longer due to overcrowding. Debris in cone sacks such as needles, twigs, bark, and unacceptable cones should be avoided. Such debris is known to cause abrasion, bruising, and tissue damage to seeds and result in decreased seed viability and reduced yield. Inclusion of spent cones may cause contamination of the seed lot with fungal spores.

In the field, interim cone storage racks and portable fans allow for unrestricted air movement. If racks are unavailable, a building with open sides may provide good cross ventilation. The sacks must lie free from each other *in the shade*, turned at regular intervals (daily if not on racks, or every other day otherwise) to facilitate even curing and avoid case-hardening, and *never* left in piles on the ground. Avoid heating by direct sunlight and additional moisture from rain. Wet cones should be spread out to surface-dry and resacked as soon as possible into dry sacks. Cone sacks should not be covered with plastic while stored on an interim basis or during transport. To minimize damage to cones and seeds from overheating, the cones should be transported to the processing facility as soon as possible and must not be left in a truck overnight. For best results, cone delivery within 24 hours of collecting is highly recommended. Open-sided trucks or trailers with netting to stabilize the load and refrigerated vans are the best options. Closed vans without refrigeration should never be used to transport cones and seeds! The field supervisor should verify that each cone sack is properly tagged, provide an inventory by seed lot, and notify the extractor of the estimated time of arrival to expedite unloading of cones.

Step 5: Process cones and seeds

Cone and seed processing begins with the arrival of cones at the extractory and ends when the upgraded

seed lots are entered into long-term storage. When cones arrive at the processing facility the cone and seed lot inventory and identification tags are verified and corrected, if required. Any cone sacks that may have been damaged in the field or during transport are identified and replaced to prevent loss of seed. A random and representative sample is withdrawn for a pre-conditioning assessment using the cutting test procedure described earlier. Adequate sampling is a must, and a sampling of cones from 10 percent of the sacks is standard. For example, a 100-bushel cone lot necessitates a minimum of several cones from each of ten individual, randomly selected sacks. This assessment will address the current condition of the cone lot: maturity level, insect and disease activity, potential yield, and need for proper cone curing. It will also provide the basis for prioritizing processing timing and define the subsequent cone and seed handling activities necessary for a successful outcome.

For most species, cone and seed processing involves several standard steps: drying (air dry, then kiln), extraction (cone tumbling), precleaning, dewinging, seed processing and upgrade (with screens, pneumatic separator, or gravity table), final cleaning, and seed drying, if necessary (fig. 5.27).

Cone curing

Once delivered to the extractory, the cone sacks are spread out on steel mesh racks and stored under an open-sided structure out of the direct sun and rain but exposed to good airflow from all directions (fig. 5.28). The sacks are turned every other day to promote gradual moisture loss and uniform curing and to prevent

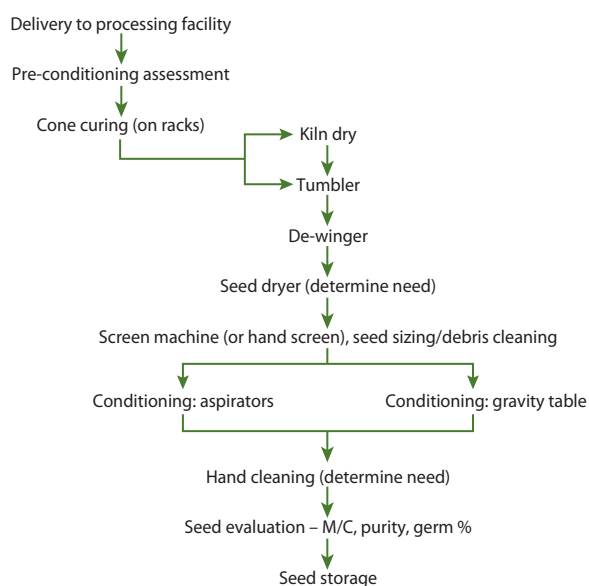


Figure 5.27. Typical cone and seed processing flowchart (sequence may vary).



Photo: CAL FIRE Lewis A. Moran Reforestation Center.

Figure 5.28. Cones air-drying on racks in a cone shed.

overheating and fungal growth. The mesh sacks permit visual monitoring of cone curing progress. As cone drying continues and the cone scales open and release their seeds, the frequency of sack turning may be reduced over time to one or two times per week. The length of cone storage (curing) varies by species and initial cone condition but is typically 2 to 4 weeks.

Kiln drying

Kiln drying refers to the cone drying process in which temperature, airflow, and in some facilities, relative humidity, are carefully controlled. Kilning causes the cone scales to flex and open, allowing the seeds to be extracted. The temperature and duration of kilning may vary by species and cone condition but is generally effective between 32 to 37°C and 14 to 18 hours duration. It is important that cones be properly air-dried before kilning to avoid a condition called case-hardening, when the outer layers of the cone dry more quickly than the moist interior. In case-hardened cones, the scales freeze in a partially open position and trap the seeds inside, causing significant-to-complete loss of seed yield.

The two main types of kilns are batch and rotary. The batch kiln involves placing a thin layer of cones into trays fitted with a screened bottom, stacking the trays four to six high, and capping the top box. The trays are placed onto plenums in the kiln, which allows for heated air to course through the stacks of trays evenly at moderate velocity. The operational-sized kiln at the Lewis A. Moran Reforestation Center in Davis is capable of drying up to 300 bushels of cones from multiple seed lots at one time (fig. 5.29). A rotary kiln combines drying and tumbling in the same phase and releases the extracted seeds from the drum to exit the heated and dry environment (fig. 5.30). The rotation speed and duration can be adjusted but this kiln type is restricted to processing a single seed lot at a time.



Photo: Dawson Hall, CAL FIRE.

Figure 5.29. Batch kiln with kiln boxes loaded onto plenums for cone drying at Lewis A. Moran Reforestation Center in Davis.



Photo: CAL FIRE Lewis A. Moran Reforestation Center.

Figure 5.30. Rotary kiln with conveyor and cone tumbler at USDA Forest Service in Placerville.

Processing variations

Processing methods also vary by cone type. Species with serotinous cones, for example, generally require a hot water treatment and high-temperature kilning to break a resin seal that prevents the scales from opening readily. One effective treatment is a 60-second dip in boiling water followed by 18 to 20 hours of kiln drying at 50°C. Alternatively, serotinous cone collections may be delayed until early spring when the cones still retain significant moisture from the recent wet season. These cones will generally open with kilning alone, without the cumbersome and time-consuming hot water treatment.

Another processing variation involves species that have soft and fragile seed coats. These types of seeds are prone to serious damage, especially to the resin vesicles in their seed coats. True fir and incense cedar are especially sensitive to heat and easily damaged in a kiln. They may also sustain mechanical injury during dewinging and screening, all of which makes them particularly challenging in the extractory. When true fir cones have been allowed to dry naturally on racks, little or no additional drying may be needed because

the cones disintegrate rather than flex to open and the seeds generally separate from the axis and scales readily. If kilning is necessary, the cones are spread out sparingly in the drying trays, the temperature should be ambient (may not exceed 30 to 32°C), and kilning should be of short duration. Subsequent tumbling is usually cursory to separate the scales from the winged seeds or help break apart any cones that did not dehisce during drying.

Incense cedar is best dried naturally in mesh sacks arranged flat on racks in a shady, well-aerated area. The sacks may be turned periodically for even curing but in a lifting and rolling motion, very carefully, to avoid piercing the seed coat and resin vesicles with needles or other sharp debris that may be present. Extraction is handled in small batches in a screened drum, which separates the trident-shaped cones from the seeds. Alternatively, incense cedar cones may be separated from the seeds using hand-screens.

Tumbling

Following batch-type kilning, the cones are transferred to a tumbler for extraction. The tumbler drum is fitted with a mesh screen that is sized to allow the seeds to fall through to a container below, while the drum rotates and spent cones are disposed of through an opening at the end of the rotation. The length of the tumbling phase is vital to seed lot yield and quality; removal of all viable seeds is essential, but the process must stop short of damaging seeds through excessive tumbling or introducing excessive debris from broken cones and scales into the seed lot. After a seed lot is passed through the kiln and tumbler, the seeds may be temporarily collected in rigid plastic boxes or fiber drums and stored in a cooled environment (3 to 5°C) to facilitate easy handling of seeds during subsequent processing steps. The cool temperatures also are effective in slowing down insect activity in a seed lot, when insects are present.

Screening

After seeds are separated from the cones, seed lots that contain considerable debris may be passed through a screen machine with airflow over a series of slotted, round-holed, or mesh screens to preclean the lot before further processing. Screen size and shape is varied to suit the species of seed being cleaned and the debris being removed. This process, called scalping, is effective at removing cone scales, needles, pitch, small rocks, and other inert matter that could injure the seed (fig. 5.31). Incense cedar is *not* screened using this process to avoid unnecessary damage.

Screening may also be done with a variety of hand-screens similarly fitted with different-sized openings



Photo: Dawson Hall, CAL FIRE.

Figure 5.31.
Screen machine.

that allow target material to pass through. Note that a custom determination of screen size and shape is needed for each seed lot, even if the species is the same, since the sizes of seed and debris may differ. Precleaning the seed lot increases the efficiency of the processing steps that follow. Incense cedar is commonly screened using hand-screens.

Dewinging

Dewinging is the process that removes the seed wing from its attachment to the seed coat. Seeds of most species may be dewinged by one of several methods. By far the majority of species are dewinged using a rotary drum specially designed to control rotation speed and angle and apply moisture if needed (fig. 5.32). Species that are dewinged with a wet process



Photo: Dawson Hall, CAL FIRE.

Figure 5.32. Custom seed dewinger.

include some pines and spruces, which have seed wings that are weakly attached to the seed coat via the integument (the coat of an ovule that develops into the seed coat). To remove these wings, a short spray of water mist is intermittently applied while the seeds are rotating in the drum, causing the seed wing to expand at this connection and cleanly detach from the seed coat.

In a slightly different scenario the seed wings of true fir and Douglas-fir, which are an integral part of the seed coat, must be broken off by mechanical friction. Dewinging of these species with a dry process is done with no added moisture. The paddles within the rotating drum allow the seeds to gently roll over one another, breaking the wings, though somewhat imperfectly and frequently incompletely. If the seed moisture content is high, then drying the seed lot to below 15 percent of fresh weight may result in a more brittle seed wing and more complete dewinging.

For both wet and dry dewinging methods, the seed wings then may be gently blown off in the dewinger with an air hose set on low or separated later with a pneumatic separator. It is important to use an oil-free compressor when blowing. Alternatively, removing the seed wings of small-sized seed lots (hard-coated seeds only) may be done by gently rubbing seeds between one's hands. For all methods discussed here, it is important to avoid prolonged dewinging to minimize seed injury through bruising or abrasion. Seeds with resin vesicles such as *Abies* spp. are particularly susceptible to damage. Dewinging should be carefully monitored and be as brief as practical.

Several species in California are *not* routinely dewinged. With incense cedar seed, for example, the embryo is reversed with the radicle emerging from the seed wing end (fig. 5.33). This anatomical anomaly makes significant damage to the seed unavoidable when attempting to remove the wing. Lastly, several genera including *Sequoia*, *Sequoiadendron*, and *Cupressus* have very small seed wings that are tegumentary extensions of the seed coat and no attempt

Photo: Dorus Van Goidsenhoven, CAL FIRE



Figure 5.33. Incense cedar seed with radicle emerging from wing end.

is made to remove them. The damage to these seeds would be severe.

Seed upgrade

Seeds are processed to upgrade the seed lot, for reasons that include reducing bulk and weight, increasing seed lot purity, increasing germinative capacity by removing empty and damaged seeds, improving seed storage life, and making seedling production easier and more economical. Seed upgrade removes empty, immature, and nonviable seeds, plus any fine debris that may still contaminate the seed lot. Two main types of mechanical separators are commonly used: the pneumatic separator (also known as an aspirator or air separator) and the gravity table.

Pneumatic separator. The *pneumatic separator* utilizes an adjustable air column fitted with a vacuum or blower to separate seeds based on differences in weight. A vibratory feeder is used to deliver seed into the air column (fig. 5.34). Air velocity can also be manipulated to capitalize on the differences between the target seeds and the debris being sorted. An X-ray radiograph or cut test is used to calibrate the airflow settings and determine if the separation is acceptable; each seed lot requires its own unique settings. The goal is to separate the heavier seeds, which are presumed to



Photo: Ricky Satomi, UCCE

Figure 5.34. Wall-mounted pneumatic separator (vacuum version).

be filled and viable, from lighter fractions, which may contain partially filled, empty, or otherwise undesirable seed and debris.

While it may be tempting to use a stronger airflow setting to remove a greater quantity of empty or partially filled seed or debris, care must be taken not to use too strong an airflow if it also removes a significant number of small, filled seed with similar weight to larger but empty seed. Inadvertent removal of the smaller, filled seed component would effectively reduce the genetic base one has worked so hard to achieve. If necessary, it is possible to rerun the seed in a discharge bin with an adjusted airflow setting when it contains a combination of filled and undesirable seed. Seed lots are often run through an air separator more than once with progressively finer-tuned settings to achieve the desired end product.

Vibratory feeder. The vibratory feeder speed can influence upgrade results as well. Excessive speed may result in too much seed in the air column at one time, preventing the light seed from being drawn up into a discharge fraction. A slower vibratory feeder speed may permit a better separation but may take much longer and tie up the separator. A proper balance between processing efficiency and accuracy is desired. Pneumatic separators are available in various designs and sizes (fig. 5.35).

Gravity table. The gravity table utilizes an inclined deck that moves in two directions: up and down, and

backward and forward. The deck is covered with a mesh cloth that allows an air current below the deck to move the seeds based on specific gravity (fig. 5.36). When seeds are lighter they are lifted off the deck slightly and moved toward the lower end of the deck. If seeds are heavier and in contact with the deck, they move toward the upper end of the deck and can be collected in different fractions based on the placement of dividers that are manipulated by the operator based on seed weight. The seed lot is separated into heavy, light, and lighter fractions and collected in separate bins. An X-ray radiograph or cut test is used to calibrate the airflow and settings related to the deck tilt and position of the dividers. Each seed lot requires its own custom setting. It is common to run a seed lot more than once with adjustments to these settings. A gravity separation can be an effective option for species that are more vulnerable to damage such as true fir, but the equipment requires a highly experienced operator to manage the many variables of the different settings for a successful outcome.

Incense cedar seed poses a challenge to seed processors at every stage. Mechanical separation tends to be harsh on its delicate seed coats. A series of hand-screens with slotted openings may be used to dispose of debris and the flat (empty) seeds, but care must be taken to avoid rubbing the seeds against the screen and damaging the seed coat and resin vesicles. The intact seed wing also makes air separation challenging because of the natural lift of the wing by the air column, but it can be done. Incense cedar seed is easier to work with when chilled at 2 to 4°C prior to separation. Using a slow speed on the vibratory feeder and a low vacuum setting for a light separation, the air



Photo: Dawson Hall, CAL FIRE.

Figure 5.35. Four-chamber forced-air separator (free-standing).



Photo: Dawson Hall, CAL FIRE.

Figure 5.36. Air gravity table.

column will pull light and empty seed up and out of the column with minimal effect on the wings of heavier (filled) seeds. The process is purposefully slow but suitable for smaller seed lot sizes (20 bushels or less) with minimal damage.

Hand-cleaning. The final stage of processing and cleaning a seed lot is hand-cleaning. It is important to maintain a strict purity standard of 98 percent or higher of pure seed per unit weight for a variety of reasons. Purity percentage is one of the essential parameters when determining quantity of seed needed for nursery sowing. The removal of impurities reduces bulk and the amount of storage space needed, and fewer impurities reduces the potential for injury to seeds in storage. After final cleaning, the seed lot is mixed thoroughly for homogeneity before testing and extended cold storage.

In each stage of cone and seed processing and upgrade, care must be taken not to overprocess. Seeds that do not possess a hard protective seed coat are particularly susceptible to damage from heat, bruising, breakage, and abrasion. In practice, seeds should not be handled when conditions are too warm or if the seeds feel sticky.

Cross-lot contamination

The most important consideration during each of the cone and seed processing steps is to avoid contamination between seed lots. A thorough cleaning of all equipment and tools used is essential and may involve any or all of the following: vacuuming, brushing, sweeping, blowing, electrostatic cleaner, depitching, steam cleaning, and sterilization.

Step 6: Assess seed lots

Analytical tests are performed on seed lots to determine

- moisture content
- seed purity and seeds per pound
- percentage filled (by X-ray)
- germination percentage

The most significant aspects of good seed testing are proper sampling and uniform testing procedures. Guidelines for these tests and sampling procedures are found in the Association of Official Seed Analysts (AOSA) and the International Seed Testing Association (ISTA) rules. These tests provide the basis for evaluating seed lots and determining the number of seeds needed for sowing in the nursery. Additionally, knowledge of the quality of the seed lots and the number of potential seedlings available in storage for reforestation is crucial to future collection planning efforts.

Sampling

Sampling, first and foremost, must be random and truly representative of the entire seed lot to be of value. Drawing the sample may be done with a seed probe (or trier) or by inserting an open hand into the seed lot to a sampling point and withdrawing the closed hand. With one to five containers, a primary sample must be taken from each and mixed thoroughly. For more than five containers, five of them plus 10 percent of the remaining containers is required. This blend of primary samples constitutes the composite sample from which a smaller working sample is taken (approximately 2,500 seeds). Sampling and seed testing are routinely conducted on-site at seed processing facilities in California rather than shipped to a separate seed lab for testing. When drawing a working sample, seed lot moisture content should be in the safe storage range of 5 to 9 percent.

Moisture content

Measurement of seed moisture content is vital in preparing seeds for long-term storage. Moisture content is the most important factor in viability retention. Correct low moisture content and low storage temperature assures that metabolic rates are minimal and fungal and insect activity ceases. If seed moisture content exceeds the standard 5 to 9 percent threshold for storage, the seed lot must be dried down by kiln drying for larger lots, small-lot seed dryer, or solar drying.

Seed moisture content may be measured by one of several methods including the oven-dry method or a rapid method using an electronic moisture meter. The oven-dry method is a destructive test but is the most accurate. In the oven-dry method, duplicate samples of 5 grams each per seed lot (3 grams each for redwood and giant sequoia) are dried in a forced-draft oven (for even, accurate drying) at 100°C for 17 to 18 hours. At the end of drying, the samples are covered with a close-fitting lid and cooled to room temperature (30 to 45 minutes) then reweighed. A scale that is accurate to three decimal places should be used for all measurements. The moisture content is expressed as the difference between the fresh weight and dry weight of the seeds, as a percentage of the fresh weight:

$$\text{Moisture content} = \frac{(\text{fresh weight} - \text{dry weight})}{(\text{fresh weight})} \times 100$$

If the difference between the two samples exceeds 0.3 percent, ISTA rules require that the procedure be repeated.

An electronic moisture meter (for example, Dole 400 grain moisture tester) is a quick test that is generally accurate to within ± 1 percent of the oven-dry

value. It is nondestructive and commonly used for small seed lots or a quick moisture check during processing. Logical timing during seed processing when a moisture check may be appropriate includes after wet dewinging or during an air separation run in which an effective separation falls short of expectation. Moisture values using a Dole meter are generally more accurate when the seed is at room temperature. A disadvantage of the Dole meter is that it requires calibrated values for each species that must be determined in advance. Calibrations have been done for bishop, Coulter, Jeffrey, Monterey, ponderosa, and sugar pine; coast redwood and giant sequoia; grand, white, and red fir; Douglas-fir; and incense cedar. Moisture content directly influences seed weight, so the seed lot should be in the 5 to 9 percent moisture range before further tests are done.

Seed purity and seeds per pound

Calculating the total number of seeds within a seed lot requires both the seed purity percentage and seeds per pound. The seed purity test determines the proportion of pure seed by calculating the weight of pure seed relative to the weight of the entire seed lot, including impurities such as needles and pitch. Using the working sample, 1,000 seeds are counted out in groups of 100 and maintained in separate piles. Debris and other crop seed encountered as the sample is counted are separated and maintained in another pile. If cracked, broken, or otherwise damaged seed is encountered, it is counted as crop seed if it comprises more than one-half the size of the seed. Damaged seeds in the bulk lot will reduce the germination percentage and must be included in the purity and seed count determinations. The piles are weighed separately, and combined to calculate the purity percentage:

$$\text{Purity percentage} = \frac{\text{Pure seed (grams)}}{(\text{Pure seed [grams]} + \text{other crop weed [grams]} + \text{debris [grams]})} \times 100$$

The purity percentage standard for tree seed at the Lewis A. Moran Reforestation Center is greater than or equal to 98 percent. If impurities or overall debris comprise over 2 percent of the seed lot, further cleaning is required.

Seeds per pound is measured using the working sample of 1,000 seeds (without impurities):

$$\text{Average seeds per pound} = (1,000 \text{ seeds/weight of 1,000 seeds [grams]}) \times (453.6 \text{ grams/1 pound})$$

Combining the purity test with seeds per pound allows a seed lot owner to calculate the total number of seeds in a seed lot:

$$\begin{aligned} \text{Total number of seeds in seed lot} = \\ \text{Weight of seed lot (pounds)} \times \text{Seeds} \\ \text{per pound} \times \text{Purity percentage} \end{aligned}$$

The purity percentage and seeds per pound calculations are important factors for determining nursery sowing requirements. However, to estimate the number of useable seedlings that can be grown from a seed lot additional information is needed, including a current germination test and sowing practices at the chosen nursery. (See chapter 6 Seeds for further information.)

Percentage filled (by X-ray)

Since the mid-1980s, the use of high-resolution X-ray images has become an increasingly important tool for initial evaluations and in the processing, upgrade, and analysis of conifer tree seed. (Bruggink 2012) As opposed to cutting tests, radiographic images are non-destructive and provide valuable information on the interior morphology of the seed and presence of insect larvae, abnormalities, or disease. The X-ray cabinet component utilizes low-energy (soft) X-rays only and is deemed safe when personnel are properly trained and use appropriate precautions. The risk of damage to seeds by X-ray is considered minimal to none. Digital systems are available that can enlarge the image of the seed to allow more definition and apply coloration to tissues based on density. Long-term storage and the transfer of digital images has become convenient and routine. Preliminary and periodic X-ray images are

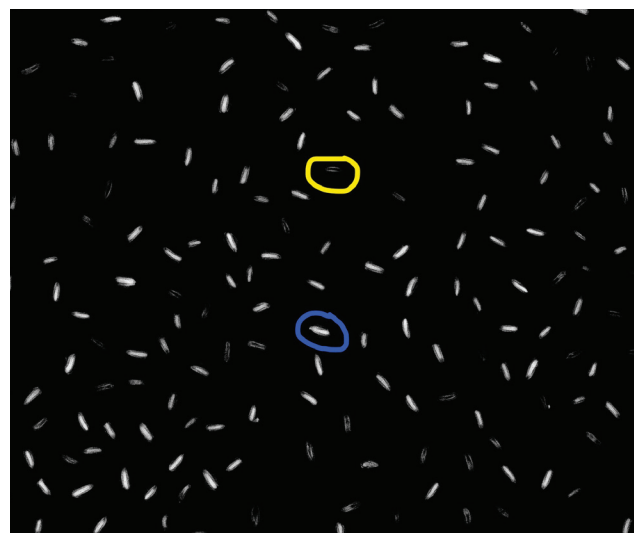


Figure 5.37. Giant sequoia filled seed (blue circle) and empties (yellow circle).

Photo: CAL FIRE Lewis A. Moran.

Photo: CAL FIRE Lewis A. Moran.

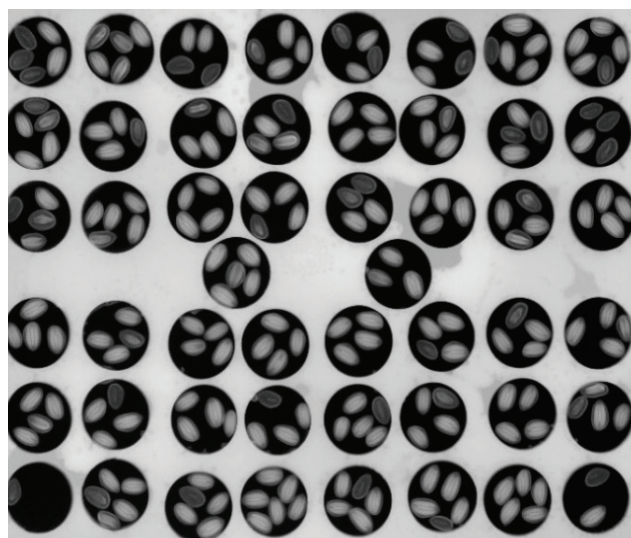


Figure 5.38. Sugar pine seeds trayed for upgrade by X-ray. The empty and damaged seeds are removed using forceps.

used to determine appropriate settings for seed processing equipment and also to confirm separation progress during upgrade (fig. 5.37). Small seed lots, or especially valuable or delicate seeds that may be damaged using mechanical separation methods, may be sorted using celled acrylic trays that enable the hand-selection of higher quality seed. Sugar pine seed lots that are resistant to blister rust and seed lots of endangered species have been processed using trays and hand-selection (fig. 5.38).

The pure seed component of purity and seed-per-pound analysis allows the seed technician a quantifiable means to estimate the germinability of the final seed lot via X-ray image and compare it to the laboratory germination result. Initially the interpretation of X-rays may be subjective, but over time the seed technologist acquires the aptitude to reliably correlate an X-ray image versus a germination test result. Admittedly, such correlations are better for some species such as redwood and less reliable for others, such as white or red fir.

Germination percentage

The laboratory germination test determines the quantity of seedlings that may be produced from a seed lot under optimal, controlled conditions. Germination capacity is the chief standard used to define seed lot quality; this is the percentage of seeds that germinate normally during a specified period, usually 28 days. The germination value is a measure of vigor, or speed of germination. An official germination test consists of 400 seeds (four replicates of 100 seeds each) selected at random from the pure seed component of the purity and seed-per-pound analyses. A second 400-seed test is reserved for a germination retest after 1 year in long-

term storage and is enclosed within the storage container that holds the bulk seed lot until needed. Subsequent germination tests are conducted at 3- to 5-year intervals to ensure that recent and reliable test data is available for nursery growing.

Not every seed that germinates is included in the germination count, but rather those that are defined as normal according to the AOSA standard guidelines. A normal seedling is one that possesses the essential structures to indicate its ability to produce a normal plant under favorable conditions. The most common abnormalities identified in a germination test include a breached embryo, in which the cotyledons emerge before the radicle, stunting of tissues such as the hypocotyl or the radicle, or rapid internal fungal growth (fig. 5.39).

Germination percentage (nearest whole number; do not round up) is calculated by the following:

$$\text{Germination percentage} = \frac{\text{Number of normal seedlings}}{\text{Number of seeds sown}} \times 100$$

The four replicates are compared. If they are within the accepted range of tolerance established by the rules, the average of the replicate values is the germination result for the seed lot. If the replicate values are not within the established tolerance, the germination test must be repeated.

Standardized germination tests are designed to provide ideal conditions for maximum values with minimum variation and achieve results that are reproducible. The pretreatment regimes that have been adopted as the recommended procedure for each species are the result of research and comparative tests over time that produced the highest germination results with the least variation.



Figure 5.39. Coulter pine seed germinants (day 7). Normal development of hypocotyl and radicle (top), stunted tissues (bottom left) and fungal growth (bottom right).

TABLE 5.6. Recommended seed germination protocols for California conifers

Species	Imbibition (hours)	Stratification* (weeks)	Germination light-dark [†] temperature (°C)	Test duration (days)
White fir, grand fir	24	6	25–15	28
Douglas-fir, coast redwood, Monterey cypress	24	6	30–20	28
Red fir, Shasta red fir	24	10	25–15	28
Incense cedar, bigcone Douglas-fir, Sitka spruce, Tecate cypress	24	8	30–20	28
Giant sequoia [‡]	48	6	30–20	28
Lodgepole pine	24	4	30–20	28
Ponderosa pine (low to high elevation)	24	(4–8)	30–20	28
Ponderosa pine (orchard)	24	8	30–20	28
Pinyon pine, Santa Cruz cypress	24	12	30–20	28
Jeffrey pine, knobcone pine	48	6	30–20	28
Coulter pine	48	10	30–20	28
Torrey pine, western white pine	48	12	30–20	28
Sugar pine [‡]	48	13–16	30–20	28–35
Foothill pine	48	16	30–20	28

*Cold stratification is most effective between 2°C and 4°C.

[†]8 hours at higher temperature with illumination and 16 hours at lower temperature in dark.

[‡]Special protocol: running water rinse.

Standard testing protocols for several conifers in California are listed in table 5.6.

Seed dormancy

Seed dormancy is a condition of viable seed that prevents it from germinating even when exposed to suitable environmental conditions. Dormancy is the mechanism in conifer seeds that eliminates the risk of immediate germination after natural seedfall in autumn when conditions are generally unfavorable for growth and survival. Most California conifer seeds have the type of dormancy known as morphological (or physiological). This type of dormancy is believed to be a consequence of immaturity within the internal seed tissues. In nature, the cool, moist conditions of winter allow the seed to absorb moisture and advance the after-ripening processes, allowing germination the following spring. These conditions are mimicked in the seed lab and forest nurseries by soaking the seeds in water followed by moist chilling in a refrigerated chamber at the appropriate temperature and duration, as determined by experience for each species (see table 5.6).

This process is called stratification or moist pre-chilling (the terms are used interchangeably here). In some pines, such as Coulter and foothill, the seed-coat thickness may act as a barrier to moisture and oxygen

exchange and can delay swelling and imbibition of the embryo. This type of seed-coat dormancy is overcome simply by a longer soak in room temperature water (48+ hours). The longer water treatment tends to soften the seed coat and allows for imbibition, which is then followed by an extended period of stratification.

Preparing seeds for laboratory germination

The degree of dormancy and optimal length of stratification varies greatly between species and also among families of the same species, though differences among the latter can generally be attributed to the geographic origin and latitude or elevation of the seed source. Moisture availability is the primary factor controlling germination. The optimal moisture content for seeds to overcome dormancy during stratification is between 30 and 35 percent. This moisture level is achieved by soaking or rinsing the seeds for the specified period, changing the water daily if the period is more than 24 hours. For species requiring a running water rinse or bath, this is effectively done with mesh sacks in nonrecirculating water and aerated with a bubbler from a small pump. The running water rinse is an effective strategy to remove fungal inoculum from seed coats, namely *Fusarium* spp. from sugar pine seeds and *Botrytis* spp. from giant sequoia seeds.

After soaking, seeds are drained thoroughly and allowed to surface-dry on blotter paper, then placed into a dry ziplock-type bag for the duration of the moist prechill period at 1 to 2°C. No fruit should be stored in the refrigerator used for the prechill, since ripening fruit gives off ethylene gas that is detrimental to germination. For proper aeration, the bags should have sufficient airspace above the seeds and be turned at least weekly for the duration. After stratification an appropriate number of seeds are counted out and placed in closed, transparent boxes on a sterile, moist substrate where the roots may grow and be examined without damage. The closed boxes help to maintain the high seed moisture content, but the substrate should not be so wet that it restricts aeration nor be allowed to dry out and cause seed desiccation. The seed analyst, when placing seeds onto the substrate, must leave space between each to reduce the potential for the transfer of seedborne pathogens.

The temperature and light conditions within the laboratory germination testing cabinet or chamber are carefully controlled. The temperature in the germination cabinet primarily affects the rate of germination and is set to alternate with lows at night (16-hour dark cycle) and highs during daylight (8-hour light cycle). The alternating light effects are thought to benefit germination in conifer seeds but are strongly related to and difficult to separate from temperature effects.

For germination capacity the germinants are counted every 7th day for the duration of the test. Any abnormalities or decayed seeds are recorded as well. If a number of seeds are firm and ungerminated at the end of the test, it may be extended an additional week to allow for more complete germination. The delay may indicate that the seed lot requires more prechilling, which should be noted in the record. For germination vigor testing, or germination value, the counts are more frequent, usually three times per week.

Note that rapid tests such as tetrazolium and excised embryo are not discussed here. See references for details on the different types, methods, and limitations of rapid tests (Bonner and Karrfalt 2008).

Variations among species

Germination rates vary among conifer species in California, and these variations appear, in part, to be related to seed morphology. The woody seeds of pine and Douglas-fir tend to germinate more readily and at higher rates, once impediments to dormancy are overcome, than seeds with softer seed coats. However, some species of pine with deeper dormancy requiring a longer stratification period are known to have lower and sometimes erratic germination, such as western

white pine and foothill pine. The soft seed coats of true fir and incense cedar, and the resin vesicles within them, are easily damaged by heat, poor handling, or equipment used during processing. These species tend to have more nonviable seeds in a seed lot not only because of this delicate nature, but also because of the tendency of seed processing staff to avert undue damage from excessive processing, which results in more unfilled seeds in the lot. True fir seeds also tend to have a higher rate of defects such as reversed embryos and radicle irregularities.

Coast redwood and giant sequoia naturally tend to produce a high percentage of cones with empty or tannin-filled seed, often exceeding 70 percent. The seeds are extremely small and lightweight, offering little difference in seed weight (or specific gravity) between the viable and tannin-filled seeds. This tendency poses a significant challenge for a successful separation outcome between the filled and unfilled seed fractions. Continued attempts to upgrade will at first increase the filled seed percentage but will eventually cause a loss of viable seed as well.

The overarching goals of the CAL FIRE forest-tree seed bank in California is to promote resiliency in a changing environment and maintain a sizeable inventory of site-adapted seed of the broadest diversity and highest quality for reforestation, emergency restoration, gene conservation, and climate change mitigation. To that end, minimum germination standards have been established for general population seed lots below which the seed may be culled and scheduled for replacement (table 5.7). Exceptions are made for improved genotypes, other special accessions, and seed from zones with infrequent production (low periodicity). High-quality seeds are essential for producing vigorous seedlings for outplanting and must be readily available for nursery production when they are needed.

TABLE 5.7. Minimum germination standards

Species	Germination rate (minimum %)	Goal* (% filled)
Coulter pine, Jeffrey pine, ponderosa pine, knobcone pine, bishop pine, Douglas-fir, bigcone Douglas-fir	80–85%	95%
Sugar pine, Torrey pine, foothill pine, western white pine	75–80%	95%
Incense cedar, white fir, red fir	60–75%	80%
Coast redwood, giant sequoia	40–50%	70%

*Post-upgrade seed lot goal (X-ray percentage).

With a changing climate and the resulting uncertainties, cone crops may be less frequent and more sporadic with perhaps even fewer filled seed and lower quality seed. In the future, this may mitigate against culling seed that has decreased to minimum germination standards until sufficient replacement seed of better quality has been obtained. However, if lower quality seed is retained it will have decreased storability, decreased germination capacity and vigor, and decreased seedling production value.

Seed laboratory germination results and the nursery

The nursery seed user must relate the seed lab results they are provided with to seed lot performance in their operation under local conditions. Oversowing results in waste of valuable seed, disease problems brought on by high seedling densities, and labor-intensive activities such as thinning. Undersowing wastes time, growing components, growing space, and water, and results in fewer seedlings than contracted for. Both situations are unacceptable. Standardized seed-testing procedures and dependable germination results from the seed lab have led to more reliable methods of calculating sowing rates and schedules in nursery operations.

Germination capacity—the germination result most often supplied by the seed lab—doesn't always provide all of the necessary details for success in the nursery. The lab germination test is designed to be a maximum under ideal, controlled conditions and may need to be adjusted downward based on nursery conditions. Nursery sowing, where germination environments are almost always more variable and less favorable than in the laboratory, may require a longer (or shorter) prechill. In addition, the criteria for gauging germination between the two are different. In the lab, a seed is considered germinated when the radicle is four times the length of the seed and all seed components appear healthy. This stage generally occurs between the 7th and 14th days in a 28-day germination test. In contrast, the nursery judges germination at a point further along in the seedlings' development when the cotyledons have emerged from the seed coat. Abnormalities or failures occurring at this later stage often are not considered in the laboratory evaluation. Another factor to consider is seed age and length of time in long-term storage. As seeds age, they begin to show signs of deterioration. Seed vigor declines more rapidly than viability. Therefore, a vigor test (germination value) may provide valuable insight into how best to care for the seed lot in the field. Seeds of low vigor often germinate better with a shorter prechill, and normal prechill of such lots may decrease germination (Bonner et al. 1994).

Other cultural factors in the nursery such as pruning and sanitation practices may affect survival and

cull as well and must be accounted and prepared for. The nursery seed user must establish a survival factor unique to their nursery operation through a series of trials, experiments, and history plots which, over time, establishes the survival statistics that become the basis for calibrating the differences between the laboratory and nursery practices.

Lessons learned: Testing and trials

Seed germination tests and nursery operation outcomes provide numerous opportunities to conduct in-house trials that examine the efficacy of different treatments on seeds of many species. For example, past imbibition trials largely determined the amount of water uptake necessary for metabolic processes to begin without raising moisture levels too high and contributing to anaerobic conditions. The result was a significant reduction in soak times for a variety of pines including Coulter, foothill, and knobcone, and was accompanied by higher germination values and minimal losses to fungal disease. Another trial that looked at improving the germination of true fir through longer stratification periods resulted in refined germination outcomes for white fir based on seed condition and the elevation of its source. Similar improvements in germination values for white fir seed were realized by exploring different temperature regimes in the germination chamber (alternate and constant) for a variety of species; this trial resulted in the adoption of lower temperature parameters (25 to 15°C) for *Abies*.

Other in-house studies looked at sterilization treatments to reduce seed surface pathogens on a variety of species when seed germination was low. Sterilants frequently used on hard-coated seeds have included varying solutions of sodium hypochlorite (2.5% household bleach) and hydrogen peroxide, given that seeds are undamaged and rinsed thoroughly after treatment. The effect of surface sterilization with bleach on select conifers was mostly mixed but found to be harmful in many instances. However, a solution of 3 percent hydrogen peroxide reduced the levels of fungal inoculum in ponderosa pine when seed quality was low, and the procedure has been adopted when the seed source is of high value or scarce. A running-water rinse in a nonrecirculating water bath to remove fungal spores is considered safest for soft-coated seeds and has effectively improved germination in species susceptible to damping-off fungi such as *Botrytis* and *Fusarium* spp. In all, the most successful outcomes of these treatments and trials and others have led to adoption as the standard practices, and they have contributed to better results in the seed lab and more successful outcomes in nursery operations.

Nurseries have also found that extending stratification periods beyond those in the testing standards may result in improved germination vigor for high-quality seed lots with no reduction in germinative capacity (personal communication, Tom Jopson, 2017).

Step 7: Store seed long-term

The objectives of long-term seed storage are to have a viable seed supply when it is needed for regeneration and to delay deterioration, or at least decrease its rate until the seeds are needed or can be replaced by the next good seed crop. Tree seed storage has been an important topic of research for many years, and effective storage methods have been established for certain classes of seeds. For seeds of species that can be stored, proper storage conditions are critical to maintaining seed viability over an extended period. The two most important factors affecting success in long-term storage are seed moisture content and storage temperature.

Orthodox or recalcitrant

Conifers and other woody plants are generally classified as orthodox or suborthodox (intermediate) in their seed storage behavior. Orthodox species are tolerant of desiccation (below 10% of fresh weight) and may be stored for long periods (usually 20 to 25 years or more) without loss of viability. This type of seed tends to have a hard or woody seed coat that provides good protection from damaging agents. A hard seed coat also restricts moisture uptake and gas exchange that could contribute to seed deterioration. The best seed moisture range for successful storage is between 5 and 9 percent. *Pinus*, *Picea*, *Pseudotsuga*, and *Tsuga* are among species in California described as orthodox in storage behavior.

Suborthodox species also tolerate desiccation and subfreezing temperatures but storage is limited to shorter periods (usually less than 15 years). This type of seed tends to have a thin, permeable seed coat, a higher lipid content (rather than starch), and resin vesicles. These characteristics make them more susceptible to damage and therefore harder to store. Seeds of *Abies*, *Calocedrus*, *Sequoia*, and *Sequoiadendron* may be described as suborthodox in storage behavior though some still consider them orthodox. Incense cedar seed is particularly sensitive to damaging agents and must be handled with extra care. Successful storage of incense cedar seeds is typically less than 10 years.

Seeds of woody species that are classified as recalcitrant in storage behavior tend to be fleshy and will not tolerate drying below rather high moisture levels without losing viability. The seed moisture content must remain at 30 percent or higher and requires storage temperatures above freezing. These conditions allow

for the continuation of metabolic activity but also promote rapid fungal growth. This type of seed is best collected fresh in years when it is available and sown directly. Species known to be temperate-recalcitrant include *Quercus*, *Umbellularia*, *Arbutus*, and *Aesculus*.

Cryogenic storage in liquid nitrogen may extend storage life, but it is not a practical method for bulk seed lots or in these applications and is not detailed here.

Seed longevity in storage

Seed longevity is affected by

- seed maturity at the time of collection
- seed quality
- seed morphology
- genetics
- prestorage handling and treatment
- conditions of storage

Seed maturity indices and the timing of collections are very important when considering long-term storage potential. Fully ripened seeds retain viability longer, are less susceptible to handling damage, and have longer storage capability. Immature seeds tend to dry out rapidly, damaging vital tissues. They are also more likely to have low vigor and be more susceptible to disease.

The life expectancy of seed varies greatly among different species of conifers. These differences are, in large part, related to seed morphology. A hard seed coat protects the embryo from mechanical injury and minimizes metabolic rates in storage by excluding moisture and oxygen when the seed is properly dried. For example, hundreds of pine and Douglas-fir seed lots have been stored in the CAL FIRE forest-tree seed bank in Davis at subfreezing temperatures for more than 35 years with minimal reduction in viability over this period. In contrast, seeds with soft, permeable seed coats are more likely to suffer bruising of sensitive tissues or be subject to moisture uptake, both of which contribute to seed damage and storage difficulties. In germination trials over several years, many *Abies* seed lots from a variety of seed zone and elevation sources retained high viability status for a minimum of 15 years (in-house records, Lewis A. Moran Reforestation Center, unpublished, 1998). However, *Abies* seed of lower quality generally presented a greater decline in germination over a shorter period of time.

Environmental stress during cone and seed development and maturation, such as drought or nutrient deficiencies in the maternal parent, may limit shoot growth thus adversely affecting seed quality and storage potential.

Genetics also plays a role in seed quality; some trees are reliably better cone producers than others. It is believed that individual tree fecundity is an inherited trait, likewise, influenced by the maternal parent (see “Genetic quality of seeds and propagules” section below).

Prestorage handling that damages seeds leads to reduced seed viability in general and particularly after any length of storage. Problematic handling practices to watch out for include

- impact damage during collection
- physiological overheating of cones or seeds at high moisture content during transport or kilning
- excessive tumbling, screening, or dewinging that may cause bruising or breakage
- failure of coolers during interim storage

An undetected crack or other opening in a seed coat may allow the invasion of harmful pathogens and result in the loss of viability in the short and long term.

Proper storage conditions

Seed moisture content is the most significant factor in the storage environment. Conifer seeds are dried to below 10 percent moisture content (fresh weight basis) for long-term storage. Optimal moisture content is between 5 and 9 percent; moisture levels of 4 percent or lower may lead to overdrying during storage and deterioration, especially for seeds of suborthodox species (table 5.8).

To avoid moisture uptake, proper storage in airtight and moisture-proof containers is essential. Properly sealed containers not only deter fluctuations in seed moisture content but also circumvent the need for costly humidity controls in the freezer unit. Fiberboard drums with plastic liners are effective for storage, as are heavyweight polyethylene bags (6 to 8 mil is recommended) positioned inside a lidded, standard-sized cardboard or plastic storage box. While a wall thickness of 6 millimeters or greater is an effective moisture

barrier, a single bag may be pierced or torn whereas two double-bagged 4-millimeter bags are less likely to be compromised. This extra precaution provides better maintenance of seed moisture content over long periods and minimizes the effect of a freezer malfunction. If stored seeds are exposed to ambient conditions, either through distribution or sampling activities, they may gain or lose moisture to the atmosphere depending on the humidity level. Seeds stored for long periods should be retested for moisture content at infrequent intervals to be certain seed moisture levels are maintained in the acceptable range.

Conifer seeds retain viability for longer periods when storage temperatures are very low. Seed metabolic rates are minimized at low temperatures well below freezing; temperatures above -10°C may allow resumption of respiration. The standard temperature recommendation for successful storage of orthodox seeds is -18°C , assuming seed moisture content is in the acceptable range of 5 to 9 percent.

The reliability of the storage unit and equipment used is of paramount importance. The storage unit must have a reliable and dedicated power source plus safety alarms and a backup generator in the event of malfunction or power failure. Placement of the storage unit inside a building will increase security and help to deter vandalism (fig. 5.40). Temperature controls and freezer management should be handled by knowledgeable and authorized personnel only (fig. 5.41). Any controls on the outside of the building should be appropriately enclosed to prevent manipulation by unauthorized persons (fig. 5.42).

The sealed storage boxes are lightweight and unbreakable, and they maximize use of shelf space. Each box has a capacity of 15 to 25 pounds of seed depending on the species being stored, and fiber drums

TABLE 5.8. Moisture content thresholds and potential effects on stored seeds

Moisture	Effects
> 30%	Germination begins
18–20%	Overheating from respiration
10–18%	Seed fungi become active
> 9%	Insect activity occurs
5–9%	Best range for sealed storage
< 5%	Desiccation damage (possible in some species)

Source: Bronner et al. 1994.



Figure 5.40. Enclosed walk-in freezer at the Lewis A. Moran Reforestation Center in Davis.

Photo: Ricky Satomi, UCCE.

Photo: Ricky Satomi, UCCE.



Figure 5.41. Freezer temperature control panel.

Photo: Ricky Satomi, UCCE.



Figure 5.42. Secured condenser units for walk-in freezer are protected from the elements.

can store 35 to 50 pounds each. Shelf systems must be sturdy and designed with seismic safety in mind.

All labeling must be clear and detailed; legible tags are located on the inside and outside of each bag with duplicate labeling affixed to the outside of the container. Avoid stacking containers vertically to minimize the risk of crushing seed in the lowermost layers. Avoid repeated opening and resealing of containers to minimize moisture fluctuations. The storage location of an individual seed lot is recorded on its corresponding seed lot history form and in an electronic database.

Step 8: Manage inventory

It is essential to maintain meticulous records and compile a seed lot database to ensure the integrity of stored seed and associated source information. This is the

data on which future collection planning and seed deployment decisions will be based. Specifics of the cone collection should be recorded on the official report of collection (FM 44) and conscientious labeling practiced throughout the collection, processing, and storage phases. Critical seed quality information about individual seed lots may be assembled from the initial cone and seed assessment notes, extractory notes, preliminary and final X-rays, and observations made during the germination testing process, all of which are contained in the permanent record.

A seed lot history (tracking) form is initiated upon delivery to the seed lab. This permanent record contains the source information from the report of collection and follows the seed lot through analysis, germination testing, repeat testing (when appropriate), storage, inventory, and distribution (fig. 5.43). If two or more seed lots are combined for any reason, all due diligence is necessary to make appropriate notations on records of each lot for tracking purposes. It is important to mix the combined seed lots thoroughly to maintain homogeneity.

Germination retest schedule

Ideally operational seed lots are retested every 3 to 5 years to confirm germination percentage or identify potential losses in seed quality or vigor over time. Seed quality must be monitored at regular intervals because so much variation in quality exists between species and among individual seed lots and the particulars in which they were collected, processed, and stored. An effective retest schedule is easily maintained by consulting the germination record in the master database. If germination loss has occurred, even under proper freezer storage conditions, the cause can generally be attributed to immature seed, poor seed quality, or deterioration due to harmful pathogens or advanced age.

When initial seed quality is high, seeds tend to store for extended periods and retain high-quality status for much longer than seeds with low initial quality. This is especially true for incense cedar seeds. Incense cedar falls into the suborthodox category for seed storage behavior and typically declines more rapidly than hard-coated seeds. However, if initial germination is high (more than 75%), loss is held to 10 to 20 percent or less over 5 to 7 years and is still acceptable for the species. Alternatively, if the initial germination percentage is below 55 percent, then germination decline is generally much greater (20 to 40%) and occurs over a shorter period, usually 3 years or less.

Replacement considerations

A germination retest may eventually indicate a drop in vigor whether germination capacity remains constant

SEED LOT HISTORY

SPECIES CODE PIPO		ZONE.ELEVATION 524.40		LOT NUMBER 6076			SOURCE T. 23N R. 4E		LAT: SEC. 25, 26		LONG: CO. BUTTE		CONE YEAR 1994	
NO. BU CONES 50		LBS. CLEAN SEED 52.7		LBS. C.S/B.C 1.05		INITIAL ASSESSMENT Good_X Fair__ Poor__ %Filled_84%				PURITY% 99.9%	SEED/LB. 9800		MOISTURE % 7.8%	
X-RAY % FILLED 96%				REBATE % _____			STORAGE LOCATION 2-B-3-2							
GERMINATION RECORD				REBATE TO: none										
DATE	PRE-TREATMENT	1 st Week	2 nd Week	3 rd Week	4 th Week	Final %	INVENTORY DISTRIBUTION				DATE	AMT USED	BALANCE	
3/95	24 hr., no chill	0	3	12	146	40%	m/c, purity, s/lb., x-ray, 2 germs				1/17/95		52.76	
3/95	24 hr., 6 wk. chill	10	318	63	0	97%	Magalia sow spring '95				1/17/95	4.2	48.5	
8/96	24 hr., 6 wk. chill	9	326	54	0	97%	Davis sow '96				1//96	1.2	47.3	
3/01	same	15	302	71	1	97%	Magalia sow '97				1/15/97	4.5	42.8	
6/06	same	3	315	64	3	96%	Davis sow '98				12/30/97	1.2	41.6	
8/11	24 hr., 6 wk. chill	5	293	61	19	94%	Magalia sow '01, germ sample				1/13/01	4.0	37.6	
4/14	24 hr., 6 wk. chill	5	289	62	24	95%	Davis sow '02				1/3/02	1.1	36.5	
							Seed order # 02-17s				12/15/02	2.5	34	
							Magalia sow '04				1/15/04	3.0	31	
							Germ sample				5/3/06	0.1	30.9	
							Magalia sow '08				1/12/08	2.6	28.3	
							Seed order # 08-03s				11/29/08	1.4	26.9	
							Germ sample				6/29/11	0.1	26.8	
							Seed order # 14-32s, germ sample				2/28/14	2.1	24.7	

Figure 5.43. Sample seed lot history form.

or has similarly declined. The speed of peak germination in a test may slow over time when compared to a previous result and is often the first expression of a decline in vigor. Vigor will decline in advance of viability. When both vigor and viability have waned and a subsequent test confirms the loss at 15 to 20 percent below the initial germination result for that seed lot, it is common practice to consider replacing the seed lot. As previously discussed, minimum germination standards vary by species and collection region. If a seed lot declines to the minimum germination standard or lower for that species and its source is the northern or central Sierra where good cone crops are generally more frequent, the expectation is high that an opportunity to replace the failing seed lot will likely occur within the next local periodicity cycle. If the seed source is coastal, inland-coastal, or in Southern California, where cone crops tend to be more erratic or lower quality, replacement may not be possible even if the germination is substandard. Without firm guidelines, the seed manager must thoroughly familiarize themselves with the intricacies involved in sound seed replacement factors and strategies for many different species. Species such as pine and Douglas-fir may store for decades, but other species including redwood, true fir, and incense cedar may require more frequent monitoring and collections to update the supply more often.

One must plan for sufficient inventory of viable seed to meet the projected need for a given planning period and for the myriad environmental challenges

facing forest restoration professionals today, including adapting to a changing climate, unforeseen events of uncontrolled fires, and massive die-offs from elevated insect populations. The principal goals are to plan for the sometimes long intervals between good seed crops and increase the odds for successful reforestation by obtaining the best seeds and storing them under optimal conditions to retain the highest viability.

Good reasons to be as efficient as possible in this endeavor include

- short supply of seeds
- higher costs associated with collections (especially improved seed)
- perceived increase in periodicity (number of years between bountiful cone crops)
- increase in climate unknowns and unforeseen catastrophic events

Tree improvement

The science and practice of forest genetics in California involves the selection of superior tree candidates (an outstanding tree with no visible undesirable characteristics that produces more cubic feet of volume per year than immediate even-aged neighbors), the establishment of clone banks, progeny test sites and seed production orchards, and the limited use of vegetative propagules. Tree improvement programs are designed not only to achieve sustained levels of improved volume growth and yield but also enhance the quality and

broad adaptability of tree populations (Kitzmilller 1976). After a robust expansion in tree improvement activities through the 1980s, state and federally funded tree improvement programs began to rapidly decline in the early 1990s. This decline was primarily due to severe budget cuts plus the advent of shifting public views about harvesting on public lands and a greater emphasis on protecting old-growth forests and habitat for endangered species. Opportunities for deploying improved stock were greatly reduced (Wheeler et al. 2015). At this writing, state and federal participation still exists through tree improvement cooperatives, but funding support remains low. For these agencies, the majority of forest-tree seed collections are focused largely on collecting and utilizing local seed from the full range of commercially managed conifer species.

In the private sector, however, interest in faster growing, more-productive forests continued and steered the desire to create forests of improved stock. This was accomplished mainly through the establishment of cooperatives, which allow for sharing the considerable costs and benefits of such programs. Tree improvement associations in Northern California have active programs in the most productive subregions for four species: ponderosa pine and white fir in the Sierra, Douglas-fir in northern forests, and sugar pine throughout the state for resistance to white pine blister rust (*Cronartium ribicola*). It is estimated that greater than 60 percent of reforestation plantings on private industrial forestlands in California are derived from such seed collections.

Genetic quality of seeds and propagules

Genetic considerations should play a part in all forest regeneration efforts, whether they are natural or artificial, or low or high management intensity. Stock selection for reforestation begins with a careful evaluation of the intended genetic constitution of the new forest. With the exception of vegetation propagules used for some coastal redwoods, the genetic considerations for most reforestation in California is addressed by collecting and utilizing quality seed from the region where the new seedlings will be planted. The high level of environmental site variability combined with the numerous commercial species that coexist on most sites has led to a much greater dependence on collecting seeds from local trees rather than regionwide tree improvement programs. Most organizations managing forests are also involved in tree improvement programs for their key species of interest. These tree improvement programs follow a recurrent selection strategy where promising individuals are selected, bred, and

tested over multiple generations (Kitzmilller 1990; Matheson and Lindgren 1985; Wright 1976; Zobel and Talbert 1984; White et al. 2007). Offspring of the best individuals are deployed to the forest. Reforestation strategies can range from natural regeneration relying on sprouting or seedfall from residual stands to clonal propagation and deployment of elite varieties.

Natural stands

Regeneration from natural stands and plantations represents the least-intensive approach to managing the genetic composition of the new forest. Foresters relying on regeneration from natural stands through seed collection, seedfall, or sprouting from residual trees would not rely on a tree improvement program for the species of interest. The genetic composition of the new forest would be determined by the genetic legacy available on the land.

When relying on seed collection or regeneration from natural stands, the forester has considerable latitude and the obligation to control the genetic composition of the new forest to accomplish long-term reforestation goals. Traditional seed tree and shelterwood harvesting systems are intended to provide managers with the opportunity to leave phenotypically desirable trees on the site as parents of the next generation. In California, appropriate seed collection and management depends to a large degree on the collection of viable seeds by private industry, CAL FIRE, and the USDA Forest Service. Restoration of disturbed ecosystems—a consequence of wildfire, insect infestation or storm damage, for instance—can also be achieved by regeneration from the residual stand. In this situation, foresters should carefully evaluate the potential of the residual forest to provide the necessary levels of genetic quality and diversity to achieve a desirable outcome. Restoration of disturbed ecosystems may also require supplementing the genetic legacy of the site with stock from other sources deemed to be adapted to the site.

Seed production areas

Seed production areas are established by converting high-quality natural stands, plantations, or genetic evaluation tests to stands intensively managed for seed production (White et al. 2007). For species or seed zones without a tree improvement program, natural stands or plantations can be converted to seed production areas with a well-planned and meticulous thinning operation. Prior to thinning, a careful marking operation should be done, attempting to leave only the fastest-growing, well-formed, and disease-free trees. Plantations should not be converted to seed production areas without verifying that the seed source of the

planted trees is documented and preferably of local or near-local origin.

Converting genetic evaluation tests to seed production areas has the potential to generate higher levels of genetic gain and diversity than the conversion of natural stands or plantations to seed production areas. Genetic evaluation plantations, such as progeny tests, have usually been intensively measured for the desirable traits intended to be selected for by tree improvement programs. Analyses of these data may be used to guide thinning and roguing of the test plantation to convert it into a seed production area. In most cases, leave trees should have performed at least above the mean of the test population or some other quantitative benchmark.

Open-pollinated seed orchards

Most tree improvement programs rely on open-pollinated seed orchards as their seed production populations (Zobel and McElwee 1964; Faulkner 1975; Simpson and Smith 1988). Seed orchards have several advantages as seed production populations. They can be located and managed specifically for seed production. Location is one of the most important factors in their success. Location should be carefully considered prior to establishing a new seed orchard. Many organizations have established seed orchards in administratively convenient locations, often near job sites on land that happens to be available, and have regretted this decision in the long run. Seed orchards should be located on land that is fertile and amenable to operability by farm machinery and aerial lifts; in climatically favorable zones for seed production, preferably isolated from wild stands or plantations of the same species; and where management practices such as fertilization, irrigation, pest control, flower stimulation, and crown management can be implemented to enhance seed production.

The genetic quality of seed-orchard seed is often neglected by managers in their drive to achieve high productivity. Seed orchards containing parents with high breeding values have the potential to produce high-quality seed. This potential is realized when several biological assumptions essential for achieving genetic efficiency in seed orchards are met (Woessner and Franklin 1973):

- isolation from nonorchard pollen sources
- balanced production of female and male flowers among the parents
- flowering synchronization
- random mating with equal compatibility for all crosses
- minimal self-fertilization

A seed orchard meeting all of these assumptions is said to be panmictic. But panmixia is rarely achieved. A manager striving to produce seed crops that reflect the potential genetic gain of the seed orchard population must identify deviations from these assumptions and correct or compensate for them (Hodge and White 1993).

Family forestry

Erosion of genetic gain from open-pollinated seed orchards can be offset or overcome by managing the seed orchard to produce propagules with a defined family structure. Open-pollinated seed orchards are seldom panmictic, often deviating considerably from the seed orchard assumptions listed above. Although panmixia may promote a higher level of genetic diversity from the seed orchard crop, managers may decide to sacrifice some diversity for increased genetic gain by favoring families known to perform best for the traits of interest (Lindgren and Matheson 1986; Lindgren and El-Kassaby 1989; Kang et al. 2001).

Open-pollinated families. Parents in the seed orchard known to be especially desirable for a trait or traits of interest are identified, and seed is collected and processed from these parents. Depending on the variation among seed orchard parents and the selection intensity of the parents chosen for seed collection, considerable genetic gain can be realized in the planted forest using this simple and inexpensive management practice. Many variations of this strategy are possible. For instance, seed can be collected from a subset of top-quality “blue ribbon” seed orchard parents and mixed. The principle disadvantage of open-pollinated family deployment is that the pollen parent is uncontrolled (Adams and Tosh 1998). Many unknown pollen parents are represented in each open-pollinated family, often originating from lower quality parents located within the seed orchard or from contaminants from outside wild stands or plantations.

Full-sib families. In a full-sib family, both the maternal and paternal parents are known. Producing and planting full-sib families has the potential to dramatically increase realized genetic gain in the new forest (Adams and Tosh 1998). In most forest tree species that are wind-pollinated, full-sib seed lots are produced by controlled pollination. Unreceptive female flowers are isolated with pollination bags and pollen is injected into the bag when the isolated flowers become receptive. The pollination bags are removed when the flowers are past receptivity and the developing seeds are allowed to mature.

Controlled pollination, done in the breeding population, is a laborious and expensive process because the purity of crosses generated for genetic testing is of

paramount concern. In the seed orchard, large quantities of full-sib seed can be produced by controlled mass pollination. Controlled mass pollination employs the techniques of traditional controlled pollination scaled up to a production process (Carson 1986; Bramlett et al. 1993; Bridgwater et al. 1998). Large quantities of pollen are collected, processed, and stored for immediate use or for use in subsequent pollination seasons. Inexpensive paper pollination bags are rapidly installed and pollination is accomplished using automated systems.

Controlled mass pollination can be done cost effectively on a large scale because it is not necessary to achieve absolute purity in the full-sib seed lots destined for outplanting. Full-sib seed lots of, for example, 80 percent purity are acceptable for outplanting. Full-sib families generated by controlled mass pollination are usually deployed to the field as single-family blocks, giving the silviculturist greater control over the stand. Family block plantings can be observed and managed as an entity throughout the rotation (Adams and Tosh 1998). Organizations committed to establishing a fine-grained pattern of genetic diversity across the landscape can mix a number of full-sib families for outplanting. An intimate mixture of individuals from comparable families can probably achieve levels of realized genetic gain on a par with single-family block plantings.

An organization practicing family forestry must commit itself to a durable system of record keeping that documents the genetic composition of the stand, and to complete harvesting of single- or mixed-family blocks at the end of the rotation. Seed collection from, or regeneration cuts (i.e., seed tree and shelterwood systems) applied to family blocks should not be attempted. The seed parents resulting from this would be related, and the subsequent stand established from this residual population would suffer the deleterious effects resulting from inbreeding depression in the progeny that establish the new forest.

Varietal forestry

Cloning of highly desirable individual genotypes is the ultimate means of capturing all of the gains generated in a tree improvement program (Ahuja and Libby 1993a, 1993b). The principal weakness of relying on seed as the delivery vehicle for genetic gain is the genetic recombination process that occurs after pollination and fertilization. Recombination tends to break up or disassociate combinations of genes that work together in an additive or synergistic fashion to produce a desirable trait or combination of traits. Cloning, theoretically, offers the forester the ability to capture that one-in-a-million individual identified during the

testing phase of the breeding program and bulk it up ad infinitum. In most forest tree species, however, cloning is technically very challenging. Deployment of varieties across the landscape also presents many challenging social and biological considerations related to genetic diversity that the responsible forest manager must address. In forest trees, varieties are typically generated by vegetative propagation via the rooting of cuttings and tissue culture techniques of organogenesis and somatic embryogenesis.

Rooted cuttings. Cloning by the rooting of cuttings is a well-established process that has been practiced by horticulturists for centuries. For some species, such as those in the genus *Populus*, it is relatively easy to accomplish. In many conifer species, however, rooting of cuttings is technically demanding, inefficient, and costly. Few forest tree species lend themselves well to the mass production of varieties from rooted cuttings. An important consideration in vegetative propagation in general and rooted cuttings in particular is maintaining juvenility in the stock plants. The ability to root falls off rapidly as the stock plant matures. Rooted cuttings derived from more-mature stock plants may also grow slower and exhibit form traits more typical of mature plants.

The most common means of maintaining juvenility in stock plants is to cut them back or hedge them yearly and serially repropagate stock plants as they become decadent. Maintaining juvenility, or at least slowing maturation, is essential. Restoring mature individuals to a juvenile state does not appear to be feasible with current technology. Organizations contemplating the mass production of varieties by rooted cuttings should employ an experienced horticulturist and must invest in the greenhouse and nursery technology required for success.

Organogenesis. Organogenesis is the tissue culture process of differentiating plant organs such as stems, leaves, and roots from undifferentiated cells and tissues (Ahuja and Libby 1993a, 1993b). This tissue culture technique, applied to forest trees, is technically demanding, requiring laboratory personnel and facilities to execute the tissue culture phases of the process. Organogenesis has been accomplished in numerous tree species, but only a few organizations have devoted the resources necessary for establishing a mass-production operation. First, the process requires inducing shoot production and proliferation from callus tissue. These shoots are then harvested and induced to form roots. The timing and application of specific media formulations in a highly controlled, sterile environment are critical to success. Somaclonal variation—genetic changes induced by the tissue culture process—are a problem with organogenesis and must be carefully

screened for. Mass production of varieties via organogenesis has limited potential in forest trees. It may be most useful in some hardwood species and as an avenue to facilitate genetic transformation approaches used by molecular geneticists.

Somatic embryogenesis. Somatic embryogenesis is a promising tissue culture technology for cloning conifers by which somatic cells—usually immature, just-fertilized embryonic tissue—are induced to proliferate and then differentiate somatic embryos in a tissue culture system (Ahuja and Libby 1993a, 1993b). Like organogenesis, it is technically demanding and requires considerable expertise and facilities to accomplish. Unlike organogenesis, somatic embryogenesis produces intact embryonic plantlets ready to germinate and grow. This makes it amenable to artificial seed technology. The starting material for somatic embryogenesis is usually generated by controlled pollination, generating elite full-sib crosses. Somatic embryogenesis has, so far, proven to be highly genotype-specific in that the efficiency of the process varies widely depending on the female and male parents comprising the cross, the individuals within a cross and, often, the direction (female-to-male) that the cross was made. Because somatic embryogenesis is a tissue culture process, it also has the potential to integrate with genetic transformation technologies.

Varieties can be mass-produced by combining rooted cutting and tissue culture approaches. Tissue culture techniques can be used to establish lines, or clones, and the moderate number of propagules generated from the tissue culture process are then used to establish cutting orchards from which rooted cuttings can be mass-produced. This capitalizes on the ability to cryopreserve tissue culture lines, thus indefinitely preserving and halting maturation in the donor line, and it takes advantage of rooted cutting technology to bulk up and mass-produce cuttings in a less technically demanding greenhouse or nursery environment.

Conclusions

High-quality seed is essential to long-term reforestation success. Problems with seed quality can potentially plague a reforestation project for the entire life of the stand. This chapter summarizes best practices for seed need planning, cone collection and processing, seed processing (cleaning and upgrade), and testing and storage. The many concepts and practices presented here have been accumulated from generations of forest resource scientists, geneticists, conifer seed specialists, and authors' personal experience and, if carefully applied, provide seed that will produce vigorous seedlings.

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Web addresses

- Seed lot selection tool
seedlotselectiontool.org/sst



Chapter 6

Seedlings

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Tree seedlings for reforestation projects in California need to survive and grow well without the additional care of irrigation and fertilization applied to trees planted for landscaping. For this reason, as well as the need to keep per-seedling costs low, reforestation seedlings are grown in nurseries specialized for the task. Reforestation nurseries offer a range of species and growing regimes because site, climate, and seedling conditions can affect seedling performance. Foresters can improve seedling success by choosing a target seedling with characteristics that match the site where it will be planted (Dumroese et. al. 2016.)

This chapter details how these factors affect the three major considerations that influence the selection of target seedlings: species and seed source, stock type, and nursery. The goal is to obtain seedlings that live and grow vigorously when they are planted on a reforestation site. This chapter describes how to evaluate nurseries but does not detail seedling growing practices; for a detailed discussion on how seedlings are grown, see *The Container Tree Nursery Manual* (Landis et al. 1994).

Choosing species and seed source

When planning a reforestation project, the choice of which species to plant within the project area will have long-term effects on the productivity of the site and options available to landowners and future generations of foresters who will manage the forest.

Historical species composition

A guiding factor for any decision regarding which species to plant is the original species composition of the predisturbance forest (before logging or fire), reflecting those species that performed well over the preceding decades. Although a general indication of which species are adapted to a given site can be determined from

previous species on the site or those immediately adjacent, decades of fire suppression and logging may have significantly altered the original species composition. For example, a recent history of low fire occurrence will favor species that grow fast but have high mortality rates from fires. Historical market preferences for certain species with higher harvested market value can also have major influences on the current mix of species by reducing the natural seed supply from trees harvested for their high historic timber market value. Besides past management activities and fire incidence, a review of long-term site conditions can help with determining the species composition that is naturally adapted to the site.

Another consideration is species composition by age class for the overall land ownership. If a landowner manages primarily with uneven-aged silviculture, then the only opportunity to establish new age classes of relatively shade-intolerant Douglas-fir and ponderosa pine is by planting in conditions where the seedlings are not under heavy shade from overstory trees. If the forest lacks young trees of these desirable species, shade-intolerant species should be considered when planting opportunities arise, provided they are adapted to the site. New age classes of shade-tolerant species such as white fir and incense cedar often do not need to be planted as they often will reproduce and grow naturally when planting opportunities arise.

Site conditions

Aspect, elevation, and soil type also influence species choice. Reforestation units may have several different aspects, which will require different distributions of species. When replanting a mixture of species, planting the hardiest species at a higher rate on south-facing slopes or rocky soils will improve establishment success. On most California sites, ponderosa pine is the

hadiest and least shade-tolerant species. On north-facing slopes, relatively more shade-tolerant species such as Douglas-fir or true fir species such as red or white fir may be more successful. On harsh, north-facing slopes, if there is no evidence of ponderosa pine in the original forest species mix, it is likely not well-suited to the site and should not be planted. Species that are highly sensitive to hot temperatures and sunscald should be planted in the most favorable microsites, using natural features that provide seedlings with protection from harsh conditions. For example, the north-east side of stumps, rocks, or large woody debris are microsites that will shade seedlings in the afternoon.

Elevation is another important consideration when assessing a site for the proper species mix. In general, ponderosa pine dominates interior, low-elevation sites, and the mix of other species increases with elevation. Mid-elevation sites in California's interior tend to have higher percentages of incense cedar, Douglas-fir, and sugar pine, while species that are adapted to heavy snow loads, such as red fir and white fir, predominate in high-elevation sites. In high (from 5,500 to 6,500 feet) and eastside sites in the Sierra, Jeffrey pine, ponderosa pine, and sugar pine may be appropriate if seed adapted to high elevations is available.

Climatic conditions

Precipitation and temperature are also important considerations when choosing the appropriate species for a site. For example, in areas with low annual rainfall and coarse soils, hardy species such as ponderosa pine or Jeffrey pine are a better fit than Douglas-fir or true fir. Because the ability to survive months of limited water availability is not consistent across species, the seasonal distribution of precipitation on a site is more important than its total annual precipitation. In coastal areas, the range of coast redwood is determined by rainfall patterns and elevation. In general, the species mix transitions from redwood to Douglas-fir with increased elevation and distance from the ocean, as redwoods are less likely to survive without coastal fog and summer rain.

Sites with large, diurnal temperature fluctuations, such as basins with warm spring days and overnight frost inversions, may require well-adapted species to avoid premature budbreak and the dieback of new growth. White fir and Douglas-fir are difficult to establish in areas with frequent inversion frost events after growth has initiated in the spring. It is important to assess the topography to identify possible locations where cold air drainage and temperature inversions could result in seedling mortality.

When selecting the appropriate species for a site, it is important to consider all site conditions in order to

identify the most appropriate mixture of species. For example, a 2,500-foot elevation site with sandy soils and predominately south-facing slopes is a good candidate for ponderosa pine, but another site at the same elevation with north-facing slopes and loamy soils will be best-suited for a mixture of species.

Natural range

The natural range of the species should influence the choice of species to plant in a reforestation project. If the planting site is near the edge of a species' range, the percentage of that species in the mix should be decreased. For example, in areas where the eastern range of Douglas-fir meets eastside pine types (as annual rainfall diminishes and high-desert types predominate), it is prudent to plant Douglas-fir on favorable aspects and avoid planting them in flat areas prone to spring frost, where ponderosa pine naturally do best.

When choosing species, it is important to understand the stand's succession history (Hessburg et al. 2005), such as whether its dominant species grew in the shelter of a nurse crop. Higher elevation sites dominated by white fir or red fir may have originally been brush fields created by old burns, which served as a nurse crop to protect the young firs from frost and sunscald. Reforesting this type of site with red fir and white fir may be difficult if seedlings are planted in full sunlight conditions. Rather, it would be best to plant species such as ponderosa pine, which is more tolerant of the severe conditions, as a nurse crop for the fir, even though it will not be a major component of the final stand. Likewise, a Douglas-fir stand that resulted from growing in the understory of oak may need to be regrown with a mix of species for Douglas-fir to thrive again on the same site. Finally, sites with a long history of selectively harvesting taller or more valuable trees may have changed significantly from the initial shade-intolerant pine to more shade-tolerant species such as white fir.

Forest health

The future forest's long-term health can be profoundly affected by the choice of species planted. In general, it is best to avoid planting a high percentage of species in areas known to have diseases that cause mortality to that species. Creating a monoculture in areas that historically had a mix of species could result in failure from pests. Species diversity is the only way to ensure that a single pathogen or insect outbreak does not compromise the stand's health or result in the reforestation project's failure.

High rates of species-specific diseases such as black stain or Annosus root rot will dictate planting different

species in those areas (Hessburg et al. 1995). *Annosus* root rot has two distinct biological species with different host preferences. The “P” group attacks pine, cedar, and juniper while the “S” group attacks fir, hemlock, and giant sequoia. It is important to know which type of *Annosus* is present and plant seedlings that are not affected by that group of pathogens (see chapter 11, “Damage,” for more information).

The choice of specific seed lots within a species can also influence the likelihood of planting success. Planted sugar pine seedlings, for example, should be from parent trees that are resistant to blister rust, if such seed is available. Similarly, in areas where ponderosa pine is known to have high levels of damage from gouty pitch midge, some or all of the seedlings should be from resistant parent trees or alternate species that aren’t attacked by pitch midge.

Seed source

The source of seed used for a reforestation project will have a lasting effect on the quality of the future forest. A properly sourced seed lot can have a dramatic impact on the stand’s future growth, the quality of the resulting forest products, and the stand’s ability to resist insect and disease problems. The two basic types of seed available for reforestation projects are improved seed from seed orchards and seed that is collected from wild stands.

When selecting seed for a sowing order, a clear first choice is to source improved seed produced by tree improvement associations, groups of landowners that share genetic resources for the purpose of producing superior seed. Improved seed is distributed to association members but may also be available to the general public via the Lewis A. Moran Reforestation Center’s state seed bank, commercial forest seed sellers, or association members. The choice of which improved lot to use depends on several factors. First, the forester may have to choose between using the oldest appropriate seed versus the best available seed, the one with the highest germination percentage that was produced after final rogueing (systematic removal of individuals with undesirable traits such as poor form, inferior genetics, or disease) in the seed orchard. This choice may be driven by the user’s seed bank management policies. A second criteria is the weighted elevational average of the seed collected in any given year. Each year, seed is collected from different trees in the orchard, which influences the average elevation of the resulting seed lot.

Wild-collected seed has many more variables than seed produced in cultivated orchards. Careful selection of trees with superior phenotypes, following the basic collection standards detailed in chapter 5, is a

key factor in acquiring a seed lot that produces quality seedlings. In many cases, the quality of the seed lot depends on the forester’s experience in choosing which trees to harvest cones from.

When considering lots for sowing orders at the nursery, the most basic requirement is matching the seed zone and collection elevation to the reforestation site. The seed lot must also have a sufficient quantity of seed with a high enough germination percentage for the nursery to produce the requested number of seedlings. If many lots are available to choose from, then more factors can be considered to better match the seedling to the site. Collection data should show the number of trees harvested, number of bushels per tree allowed to be harvested, and extent of the area harvested. If the seed lot is produced from a few trees growing in close proximity, the seed will have low genetic variability and would not be expected to perform well on a wide range of sites. The genetic variability of seed differs somewhat by species. Douglas-fir, for example, is more of a genetic specialist, with greater sensitivity to elevation or movement out of its local range. As a result, choosing seed lots from the general area to be reforested is important with Douglas-fir. Orchard collections of Douglas-fir may not be as adaptable as local collected seed for areas on the edge of its range or different climatic regions. In those circumstances, it is advisable to favor local seed lots over orchard lots or to mix orchard seedlings with locally sourced seedlings.

Collection data may include information on disease and insect resistance. For example, the forester may note in the cone collection data sheet that ponderosa pine trees with evidence of gouty pitch midge and western gall rust damage were avoided.

The age of the collection is also important in some species. White fir, red fir, and incense cedar have a relatively short storage life, which may influence the choice of seed lots. Even if older seed germinates, the seedlings produced may fail to perform both in the nursery and after planting. Seed does not perform well if the cone harvest occurs before they are fully ripe. Low germination rates and poor seedling growth must be considered or even expected when sowing seed lots that are less than fully ripe. Frequent collection to upgrade the quality of stored seed is advisable.

Working with the nursery is helpful when using the same seed lots over the course of many years. All seed lots have unique performance characteristics, especially those that are wild-collected and open-pollinated. Germination rates will decline in some seed lots over time, which the nursery will note. These lots should be avoided at sowing time unless no better alternative is available.

Choosing stock type

Stock type refers to the production method used—typically container or bare-root—to produce seedlings and the range of choices within each of these methods. Almost all seedlings currently planted in California are container seedlings. The key to making a successful stock type decision is relating choices to the physiological and morphological conditions that indicate seedling quality.

Seedling physiology

A successful reforestation seedling must be able to survive initial planting conditions and then rapidly grow roots and shoots when site conditions are favorable. This expectation means that each seedling must be in a proper physiological state when it leaves the nursery or storage facility.

Physiological characteristics that contribute to the overall quality of seedlings are (Haase 2008)

- root growth potential
- dormancy
- cold hardiness
- plant moisture stress
- nutrient status
- chlorophyll fluorescence

Unlike morphological characteristics such as height, stem diameter, and root-to-shoot ratio, most physiological attributes are difficult to measure and require laboratory equipment.

Root growth potential

Root growth potential is perhaps the most commonly used test to evaluate the physiological condition of forest seedlings. Planting tests are simple, nonquantitative measures of root growth potential, which do not require specialized laboratory equipment and are easily accomplished by nurseries and reforestation specialists. Seedlings are planted in a field plot or growing media in an easily accessible location, then these seedlings are dug up later to observe the root growth. Nurseries can use this test to evaluate the health of seedlings at the time of lifting and packing, or when they are removed from storage and shipped. If the seedlings are stored at the nursery, they can be evaluated when they are removed from storage and shipped. Field foresters can plant seedlings in a field plot to compare the performance of multiple seed lots and species, different stock types, and seedlings sourced from different nurseries. Drawbacks of the planting test are that the results are usually not quantified, except if survival is an issue, and are typically not available until after seedlings have been outplanted.

A more rigorous, quantifiable test for root growth potential is conducted by planting a random sample of seedlings into a laboratory environment that is favorable for rapid root growth and systematically evaluating root growth after 3 to 4 weeks. The minimum sample size should be at least 25 to 30 seedlings, and it is best if 60 randomly collected seedlings are tested. The sample collection time depends on the purpose of the testing. If the nursery is evaluating the seedlings' ability to produce roots, then the sample should be taken during packing. If the forester is interested in outplanting performance, taking the sample just before planting will quantify the effects of lifting, transportation, and handling. The seedling samples should be truly random, taken from different areas of the packing boxes and throughout the stored lot.

Root growth potential can indicate the health of seedlings, but it may not be a comprehensive indicator of seedling performance after outplanting because it is conducted under ideal conditions rather than those typically found on reforestation sites (Simpson and Ritchie 1997).

Dormancy

Dormancy is a period of inactivity of buds or other plant organs that may be imposed by unfavorable environmental conditions or the result of the seedlings' physiological conditions (Cleary et al. 1978). Common observable indicators that seedlings are becoming dormant include the development of terminal and lateral buds with mature bud scales (in species that form bud scales), stiffening of stems as they become woodier, thickening and darkening of foliage, and slowing of root growth. Evaluating dormancy is critically important for determining the best time to pack and store seedlings, a period often referred to as the lifting window. Seedlings packed when not fully dormant do not store well and will not perform well when outplanted. Evaluating dormancy is particularly important for the late fall and winter planting decisions described below.

In container nurseries, some species may transition to dormancy in response to natural conditions. However, in most cases seedling dormancy is induced by increasing moisture and nutrient stress, exposing seedlings to cold ambient temperatures, and/or artificially shortening the day length (photoperiod). Nursery dormancy induction protocols typically include combinations of reduced fertilization (particularly nitrogen), increased moisture stress between irrigations to the point of wilting or near wilting, and exposure to ambient conditions. After the onset of dormancy is apparent, stress levels are reduced until the seedlings become fully dormant.

Dormancy may be induced in many seedling species by artificially shortening the day length using blackout equipment in the greenhouse. This reduction in photoperiod may be accompanied by a short-term reduction in nutrient levels, although high levels of nutrient and moisture stress are not necessary. Seedlings produced using this method are often shorter with larger stem diameter and higher tissue nutrient levels and root-to-shoot ratios. Field performance of Douglas-fir planted on high-stress sites in California has particularly benefited from the proper application of blackout technology during seedling production.

In nurseries located in areas with cold winters, seedlings are typically in a state of deep dormancy from mid-November or early December through mid-February. Following a chilling period with temperatures below 45°F, the dormancy is released and the seedlings resume growth when environmental conditions are favorable. Quantitative testing for identifying the end of dormancy is usually done with a budbreak test, which involves planting randomly selected samples in a greenhouse under favorable growing conditions. Visual indicators that dormancy has ended include root growth initiation and terminal bud swelling.

Dormancy is important when considering plant timing in the fall because the seedlings must be metabolically active and capable of active root growth. Seedlings planted in late October or November where soils are cold are unlikely to support root growth and are at risk of mortality if they are not covered with snow during the winter. For spring planting, the deep dormancy period will be over when the seedlings are planted and they will be ready to grow when conditions become favorable.

Cold hardiness

Cold hardiness is the level of a plant's resistance to damage from cold temperature (Rose and Haase 2006). An indicator of the seedling's physiological state, it is commonly used to assess forest seedling quality. It is important to remember that seedling cold hardiness is not the same as dormancy (Haase 2011a). Seedlings begin to develop cold hardiness in fall as they become dormant, but they usually don't achieve maximum hardiness until midwinter, well after full dormancy. They often remain cold-hardy even as dormancy levels begin to drop. Absolute hardiness varies greatly among species and ecotypes and is highly influenced by the climate of seed origin and nursery growing conditions.

Seedlings can be tested for hardiness before packing or during or after storage. One commonly used cold hardiness test is the whole-plant freeze test, in which the entire plant is exposed to freezing temperatures

and then evaluated for its response (Linden 2002). Another is the freeze-induced electrolyte leakage test, which is used to test foliar and root samples (Landis et al. 2010). These tests are mainly used by nursery managers to establish lifting windows or determine whether frost protection measures are necessary.

Plant moisture stress, nutrient status, and chlorophyll fluorescence

Plant moisture stress, nutrient status, and chlorophyll fluorescence levels are other physiological conditions that may influence seedling quality. Plant moisture stress can be measured in the field using portable pressure chambers, and seedlings with very high readings are unlikely to do well if outplanted. Nutrient status can be easily assessed by labs that specialize in tissue analysis. Seedlings with appropriate tissue levels of mineral nutrients, particularly tissue nitrogen, will perform better than those where nutrients are either too high or too low. Measurements of chlorophyll fluorescence indicate seedling quality (Ritchie 2006). The recent development of portable equipment to measure chlorophyll fluorescence has made this test more accessible to foresters and nurseries. The *Container Tree Nursery Manual* (volume 7) is an excellent source of detailed information on these topics (Landis et al. 2010).

Seedling morphology

The most common measurements of seedling morphology are height, caliper, root system quality (fibrosity and mass) (Haase 2011b), and the ratio of shoot-to-root mass. Caliper is the seedling diameter measured just above the root collar and is often expressed in millimeters. The root-to-shoot ratio is the root weight divided by shoot weight or the root volume divided by shoot volume (Rose and Haase 2006).

These measurements, particularly height and stem caliper, are the most common measure of seedling quality used by nursery operators and reforestation specialists. Reforestation seedlings grown in the 1970s and early 1980s were mostly bare root and the influence of morphology on seedling survival and performance was well studied (Cleary et al. 1978). Survival is best predicted by caliper, while shoot growth tends to be related to initial seedling height. With bare-root stock, when stem diameter increases above 5 millimeters, other morphological indicators become less important (Mexal and Landis 1990). In addition, bare-root seedlings with larger root volumes at the time of outplanting have greater subsequent growth and survival than those with smaller root volumes (Rose and Haase 1997).

Container seedling morphology is influenced by cell volume and growing density. In general, larger cells produce seedlings with larger root volumes, and lower densities produce seedlings with larger stem diameters and increased lateral branching. The quality attributes of container stock are similar to those of bare-root stock, but container nurseries are better able to control height and diameter growth with blackout technology and other cultural practices.

Reforestation specialists should specify the type of stock morphology desired at outplanting so that nursery staff can adjust cultural practices to produce the desired results. For example, to minimize transpiration stress during the critical first year of seedling establishment, reforestation foresters in interior California typically order seedlings with relatively shorter shoots and larger root systems.

Stock types

Three basic types of conifer nursery stock are available for reforestation projects in California: container, bare-root, and plug+1 seedlings, which are grown for a year in the nursery and a year in the ground. The choice of stock type is influenced primarily by the biological limitations of the planting site and the reforestation forester's economic resources and preferences. In the Sierra-Cascade region, soil moisture is the primary limiting factor during the growing season but other factors also influence the choice of stock type, including low humidity, extreme temperature regimes, and herbivory. Storage capacity may influence the choice of stock type, because large container stock or plug+1 transplants are packed at lower numbers of seedlings per container than small container stock or 1-0 bare-root seedlings.

Container stock

Container (or containerized) seedlings are the predominant stock type used for reforestation in California. Container seedlings are grown in potting media in small, usually multiple-celled containers with at least part of the production cycle carried out in greenhouses (fig. 6.1). Container seedlings are often referred to as plug seedlings because the root system and the media it was grown in remain intact. As such, it retains the shape and size of the cell in which it was grown throughout the packing, storage, transportation, and planting process. When soil conditions are favorable, the intact root system of a properly grown plug seedling will grow rapidly and become established on the site quickly, often within 2 to 4 weeks of planting. This potential for rapid establishment, and the resulting rapid shoot growth, is the key benefit of using plug seedlings in reforestation.

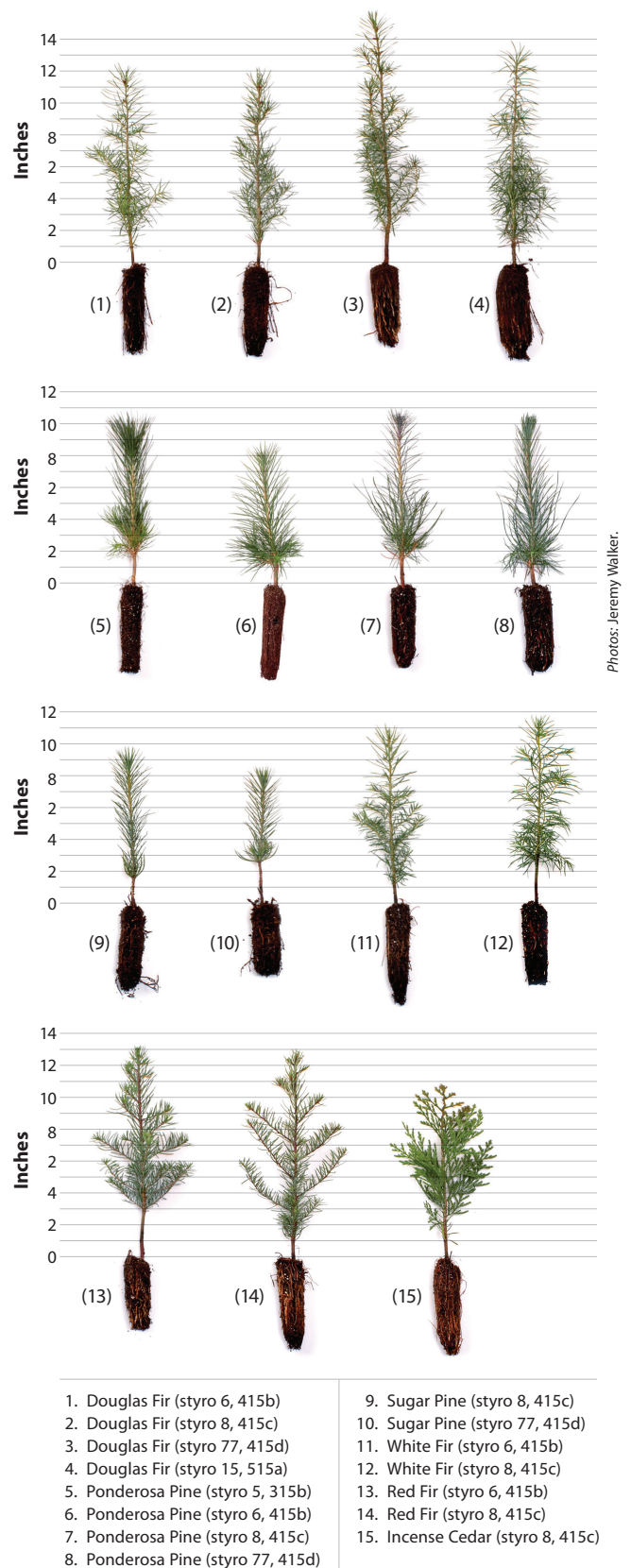


Figure 6.1. Container seedling sizes.

Use of plug seedlings for large-scale reforestation projects in western North America began in the 1970s with the development of a variety of multicelled containers made from an assortment of plastic materials (Cleary et al. 1978; Tinus and McDonald 1979). By the late 1980s and early 1990s, nursery technology had improved such that reforestation foresters in interior California's hot, dry summer climate started using significant amounts of plug seedlings in their reforestation programs. As the technology matured, growers focused on using a few standard container formats (Landis et al. 1990; Rose and Haase 2006).

Container size

In the western United States and Canada, molded Styrofoam blocks and other container types are available in a wide range of cell volumes, depths, and densities (fig. 6.2). The minimum size of deliverable seedlings varies by container size and species (see table 6.1 for examples). Experience has shown that if seedlings grow rapidly after planting, initial seedling size is inconsequential within a few years. The container size chosen by the forester is based on the desired specifications, cost, storage limitations, and site conditions such as water availability and the potential for animal browsing.

The preferred container for each species varies from nursery to nursery. Species that produce a substantial number of lateral branches as first-year seedlings need more growing space than those that remain single-stemmed. Douglas-fir and white fir tend to grow lateral branches in containers, while sugar pine and Engelmann spruce do not branch much during the first year of growth.

The location and conditions at the planting site may also influence container choice. For instance, smaller seedlings are easier to transport and plant if site access

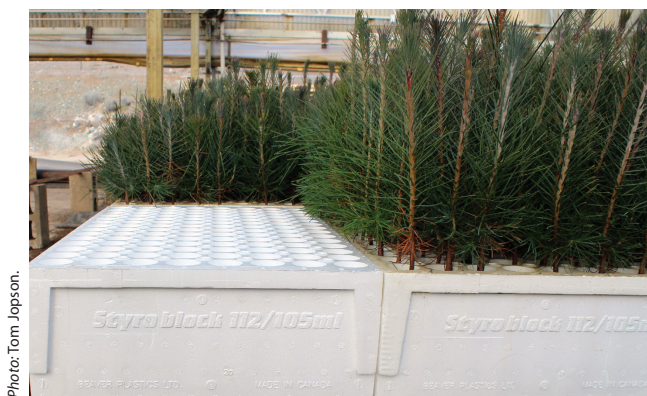


Photo: Tom Jopson.

Figure 6.2. Styroblock is manufactured in different densities and cell sizes. This Styroblock 112/105 with 1-year-old ponderosa pine seedlings has 112 cells in a standard-size block (14-by-24-inches) with a cell volume of 105 milliliters (about 6 cubic inches).

TABLE 6.1. Comparative seedling target sizes by container size and species

Species	Container size	Minimum height (cm)	Minimum caliper (mm)
Douglas-fir	2	6	1.5
	5	12	2.3
	6	12	2.5
	8	12	3.0
	10D	12	2.7
	10	12	3.0
	15	12	3.2
Incense cedar	20	12	3.5
	8	10	2.8
Jeffrey pine	10D	12	3.7
	5	8	2.5
	6	8	2.7
	8	8	3.0
	10D	8	2.7
Lodgepole pine	10	8	3.0
	5	8	2.3
	6	8	2.5
	8	8	2.7
	10D	10	2.7
Ponderosa pine	10	10	3.0
	2	8	1.7
	5	10	2.5
	6	10	2.7
	8	10	2.8
Red fir	10D	10	2.8
	10	10	3.0
	15	10	3.5
	2	6	1.5
	5	8	2.0
Sugar pine	6	8	2.3
	8	8	2.5
	10, 10D	10	3.0
	15	12	3.2
	20	15	3.5
Western white pine	5	8	2.0
	6	8	2.2
	8	8	2.4
	10D	10	2.4
White fir	5	6	2.0
	6	6	2.3
	8	8	2.5
	2	6	1.5
	5	8	2.0
	6	8	2.3
	8	8	2.5
	10D	10	2.7
	10	10	2.8
	15	12	3.0

Source: Prepared by CalForest Nurseries, Etna, CA.

is difficult, particularly if large numbers of seedlings are required or the soil is rocky.

Seedlings from larger containers tend to be more browse-resistant because they are taller and have a larger woody stem and more buds. However, if heavy browse pressure is likely on the site, mechanical browse protection may be necessary after planting (see chapter 9, “Planting”). The extra height of seedlings grown in larger containers is also beneficial on sites where moisture is not limiting and seedlings must outgrow competing vegetation.

Bare-root stock

Bare-root seedlings are produced by sowing seeds directly into the soil in prepared nursery beds. After one or two growing seasons, during which the grower uses cultural practices to enhance the roots and shoots, the seedlings are dug (lifted) from the soil, graded, and packed for storage or shipment. Common types of bare-root stock are described as 1-0, 2-0, and 1-1. The first number represents the number of seasons the seedling grows in a nursery seedbed and the second number is the number of seasons it is grown in a transplant bed. Seedlings are transplanted to enable the culling of poorly developing stock and planting into lower densities.

Each bare-root stock type has distinct features that affect its suitability for planting on various sites. One-year-old bare-root stock (1-0) has a small shoot-and-root system. Two-year-old bare-root stock (2-0 and 1-1) has a higher root-to-shoot ratio, greater stem diameter and height, and a better developed and fibrous root system than 1-0 stock.

When compared to container stock, bare-root stock is generally slower to grow roots after outplanting, may require more careful handling, is sometimes more difficult to plant, and offers less production flexibility. However, bare-root stock usually costs less and may ultimately perform as well as container stock depending on site conditions. Weather can affect bare-root seedling production, resulting in limited lifting and packing windows during years when there is excessive precipitation in late fall and early winter, the optimum time for lifting and long-term storage.

Proper handling of bare-root stock is more critical than with containerized stock because of the potential for desiccation and physical damage to exposed roots. If the fine root hairs are subjected to dry air during the handling and planting process, then seedling survival can be diminished. The initiation of root growth in packed seedlings during storage is also a potential problem because the new growth is susceptible to damage in the cold storage facility. Freezing bare-root stock is advisable if long-term storage before planting

is planned. Bare-root seedling roots must be placed vertically in the ground without any sweep or “J” roots in the soil (see chapter 9, “Planting”).

The overall growth potential for bare-root seedlings is good, and this stock type can yield excellent results if rigorous standards for storage, handling, and planting are adhered to. Better success with bare-root planting has been achieved with ponderosa pine compared to true firs and Douglas-fir. Bare-root seedlings may also be less expensive, especially if larger seedlings are needed, although planting costs may be higher.

Plug-1 stock

Plug-1 (P-1) stock is produced by growing seedlings in a small container for one growing season and then transplanting them into a bare-root nursery bed for the second growing season. P-1 seedlings typically have large tops and stem diameters as well as large, fibrous root systems. The limited benefits of planting large seedlings on sites with low soil-moisture availability means that P-1 seedlings are not often planted in California. In some cases, however, where animal browse is excessive or competing vegetation cannot be controlled, P-1 seedlings may be a good choice. Competition for light, not soil moisture, should be the limiting factor on these sites, which usually limits the use of the P-1 seedlings to the humid, coastal areas of Northern California.

Choosing a nursery

Highly successful reforestation programs require a solid, positive relationship between the nursery and forester. This relationship includes not only seedling production but also the timing, handling, storage, and shipping factors that contribute to the program's success (Haase 2014).

Evaluating and working with nurseries

The most important consideration when choosing a nursery is their ability to produce the target seedling for the planned reforestation sites. Successful seedlings must be able to rapidly grow roots into the surrounding soil after planting. This means that when the seedlings leave the nursery their root systems must be physiologically ready to grow, they must contain sufficient nutrients to support rapid growth, and their shoots must be able to survive conditions present on the site at the time of planting, including light, heat, wind, and humidity. In practice, it can be difficult to evaluate seedlings for these characteristics prior to outplanting. The most reliable indicator of a nursery's ability to produce successful planting stock is past performance of its outplanted trees over a period of years.

Other factors when choosing a nursery are easier to evaluate. These may include

- the ability to provide a sowing, packing, and shipping schedule that works for your reforestation program
- storage capability
- efficiency of seed use (quantity of seed required to produce a given quantity of seedlings)
- capacity to produce sufficient quantities of seedlings
- ability to meet contracted volumes with target specifications
- consistency in quality from year to year
- flexibility to respond to changing conditions
- ability to ship seedlings in the desired planting window
- price

Another consideration is the convenience of having all seedlings grown at a single facility versus the potential risk reduction from growing seedlings at more than one location. Price per seedling should be a secondary factor when considering the eventual return on investment when planting quality seedlings that perform well and avoid the need to replant and subsequent delay in stand development.

Cultural practices

Nursery growers take advantage of location, facilities, and practices to manipulate the characteristics of seedlings and, in rare cases, clonally produced planting stock. Substantial variations may occur between facilities and practices as nurseries tune their production programs to conditions at particular locations.

Location

Container nurseries usually use greenhouses to modify ambient conditions for all or part of the year, but extremes of heat and cold, as well as ambient light and humidity, can still affect seedlings. Location can strongly influence the conditioning (hardening) of seedlings to prepare them for outplanting. Most seedlings in California need foliage that can withstand full sun and low humidity at planting, therefore nursery locations that have similar conditions during the growing season may give the growers more options for conditioning.

Location is particularly important for bare-root nurseries, where field production is subject to ambient conditions year-round. Bare-root nurseries must also be located in areas where the quality of agricultural soil is good.

Facilities

Growing facilities must be able to provide appropriate environmental conditions for each of the three main phases of crop development:

- Optimal moisture, temperature, and humidity during the **germination and early growth phase**
- Sufficient exposure to ambient temperatures, humidity, and light consistent with species requirements for good growth during the **rapid growth phase**
- Protection from extreme cold during the **hardening phase**

Nurseries use irrigation, fertilization, heating, integrated pest management, ventilation and, for certain species, photoperiod extension lighting to optimize growing conditions at each phase of crop development (fig. 6.3) (Landis et al. 1990, 1992, 1994). To provide maximum exposure to ambient conditions, conifer seedling production greenhouses typically have full roll-up walls, removable or retractable roofs, and/or transportable benches that allow movement of the crop in and out of the greenhouses as needed (fig. 6.4). The ability to expose the crop to ambient conditions can help with timely dormancy induction. Some greenhouses may also include blackout equipment that



Figure 6.3. Seedling nurseries use mechanical technology such as irrigation pumps and fertilizer injectors to optimize seedling success.

Photo: Tom Jopson.



Figure 6.4. A double-layer, polyethylene, gutter-connected greenhouse designed to grow tree seedlings in California. Note the roll-up walls and the black-cloth system for dormancy induction using a shortened photoperiod, with lights to extend the photoperiod.

permit the grower to induce dormancy by artificially exposing seedlings to shortened day lengths. In certain locations, greenhouses serve to protect the crop from potential lethal low temperatures when the crop is dormant, as well as during the vulnerable germination and early growth phase.

Growing practices

Even though a quality seedling is likely to have the same basic set of characteristics regardless of nursery, the practices employed to grow that seedling can vary widely because of differences in location and facilities. Therefore, a successful growing program should anticipate crop needs based on past experience at the location, monitor crop parameters at appropriate intervals,

and then respond to any deviations from the desired condition.

Table 6.2 describes the important elements for an annual seedling crop schedule. Each activity may occur over a wide range of calendar dates depending on the location, species grown, target characteristics, and shipping window. Table 6.3 shows parameters of a growing crop that should be monitored by the nursery.

Seed availability

The availability of quality seed appropriate for a given site is often the most critical limiting factor for reforestation projects. Seed shortages can be particularly problematic for nonindustrial forest landowners, who usually have not collected seed from their properties. The efficiency of seed use—the seedling yield for a given amount of seed—by nurseries is strongly influenced by the quality of the seed available. Seed quality is usually assessed as the germination percentage under a specified pretreatment and germination regime for the species. Germination potential is influenced by species, collection year, cone handling, and seed processing. But even with the same seed lots, the efficiency of seed use can vary considerably among nurseries, depending on factors such as seed treatment practices, sowing strategy, capability of sowing equipment, and the sensitivity of nursery managers to the need for efficient seed use.

Presowing seed treatment practices, including seed sanitation, soaking methods, length of stratification (cold moist) treatments, and conditions during the stratification treatment can also influence seed use

TABLE 6.2. Schedule of nursery activities for seedlings

Activity	Time	Comments
Seed receipt and stratification	November to May	Presow seed treatments (usually cold-moist stratification) may require 0 to 120 days, depending on species.
Sowing and germination	January to June	Sow dates vary depending on species, stock type, and customer planting dates. Relatively high temperatures encourage rapid and uniform germination.
Rapid growth	March to August	The time period for rapid growth depends on growth rate of the species, stock size, and timing of hardening off. High rates of irrigation, fertilization, and photoperiod enhancement promote rapid growth in some species.
Hardening off, dormancy induction	July to September	Depending on species, customer ship dates, and sow date, practices may include nutrient and moisture stress, exposure to ambient conditions, and/or artificial reduction of photoperiod.
Packing for immediate planting	September to February	Seedlings may be packed as early as late August if they can be planted immediately. Seedlings may be shipped for planting through the winter to mild climate areas along the coast and in Southern California.
Packing for storage	November to February	Packing for storage begins after seedlings are fully dormant and must be complete before they break dormancy in early spring.
Shipping	September to June	Seedlings are shipped to customers for immediate planting from September through February, storage from November through February, refrigerated storage from December through April, and freezer storage from March through June.

TABLE 6.3. Seedling crop monitoring at the nursery

Parameter	Interval	Purpose
Block weight	1 to 3 days	Determine when to irrigate; other methods may also be used
Media electrical conductivity	Each irrigation	Prevent buildup of excess salts
Media pH	Each irrigation	Maintain media pH at appropriate level
Shoot tissue analysis	2 to 6 times per year	Verify nutrient content of seedlings, particularly as they approach the end of the growing season; especially useful when developing a crop's nutrient regime
Shoot height and caliper	1 to 4 weeks	Keep crop on track to meet minimum and maximum specifications
Insect traps	As needed	Respond to pests in different locations
Disease monitoring	Ongoing	Monitor by greenhouse staff for disease as seasonally appropriate

Photo: Tom Jopson.

**Figure 6.5.** A stratification cooler for conifer seed, with seed lots clearly identified in individual trays. Seed requires oxygen when in stratification. Large lots are divided into multiple trays so that the seed is in thin layers and can breathe.

efficiency (fig. 6.5), and many benefits result from these practices (table 6.4).

Sowing strategy, including seeds per cell for containers or seeds per bed foot for bare root, as well as oversow requirements, also influence the efficiency of seed use. For example, a nursery may choose to sow multiple seeds per container cell. This strategy improves the chances that each cell has a germinated seedling, but more cells will have two or more seedlings that need to be thinned out and discarded. The result is more efficient use of growing space in the nursery but less efficient use of seed because many good seedlings are discarded. If the nursery chooses to sow fewer seeds per cell, it must increase the number of cells sown to

TABLE 6.4. Importance of seed treatment practices

Seed treatment practice	Benefits for seed use efficiency
Sanitation treatments before or after soak	Reduce seedborne diseases
Rinse and aeration during soak	Reduce seedborne diseases and maintenance of seed health
Monitor seed moisture content during stratification	Maintain seed health, reduction of molds
Length of stratification (soaking dry seed to 30% to 35% moisture content then store at 34°F to 36°F for a period of time until it is sown)	For many species, longer stratification (up to 120 days) results in faster, more uniform germination at cooler temperatures



Photo: Tom Jopson.

Figure 6.6. A high-speed vacuum seeder sows Styroblocs in a forest nursery. To guide the sowing process, a display above the seeder shows information about the seed lot used.

make up for the increased number of empty cells; this alternative strategy results in greater efficiency of seed use because fewer seedlings are discarded. Sowing strategies may, in part, be dictated by the nursery's sowing equipment (fig. 6.6). If the forester knows that seed is in short supply, informing nursery operators of the situation can lead to better efficiency, although perhaps with some price adjustment.

Packing

When seedlings are ready, the nursery extracts them from containers or lifts them from the soil (bare root) and prepares them to be shipped for planting or cold or freezer storage. Seedlings are packed in boxes or bags for transportation and/or storage.

Packing container seedlings

Nurseries remove seedlings from the containers with the root plug intact. For most species, the plug is nearly the same depth as the original container. For some

species, particularly the true firs (*Abies*), the plug may form only in the bottom portion of the container because no lateral roots grow in the upper part. Field experience has demonstrated that these seedlings will still perform well after outplanting if they meet other specifications.

Seedling extraction (fig. 6.7) may be by machine or hand, depending on the rooting density of the species and equipment available at the nursery. After extraction, seedlings that don't meet specifications are culled. A predetermined quantity of seedlings is placed in a plastic bag or bundled together by tightly wrapping the plugs with plastic. The bagging or bundling protects the root systems from drying and provides some physical protection for the seedlings during handling and storage.

The bags or bundles are then placed in a packing box or crate with the seedlings either upright or on their sides. Boxes of seedlings going into storage are lined with a plastic bag that fully encloses the bagged seedling, to reduce moisture loss. Lining is usually not needed for seedlings that are planted directly. A lining can be detrimental to seedlings packed for fall planting because it reduces ventilation and increases heat build-up in the box or bag.

The corrugated packing boxes used by nurseries vary considerably in size and type. The box chosen influences the effectiveness of seedling handling and storage. Factors to consider include:

- **Unwaxed cardboard.** Boxes made with unwaxed cardboard will not withstand much moisture. Good liner bags and complete protection from external moisture during storage and transportation are essential. This type of box cannot be stacked very high without racking.
- **Waxed cardboard.** Boxes made with fully waxed (cascaded) cardboard will maintain their strength even when subjected to rain and moisture. These boxes are also much stronger than unwaxed boxes,

particularly if they are made with high-strength cardboard. Such boxes can be reliably stacked quite high without failure if they are properly secured to a pallet.

- **Weight.** The size of the box affects the number of seedlings in the box, and most importantly, its weight. In general, boxes over 50 pounds are more difficult to handle and transport in the field.
- **Height.** Boxes should be large enough to allow the tallest seedlings to fit with little or no bending of the shoots.
- **Arrangement.** The required size and shape of the boxes is dictated in part by how the seedlings are arranged. Seedlings placed upright in the box will generally take more space than seedlings lying flat.

Nurseries should place labels on both the outside and inside of the box (fig. 6.8). Outside labels can be lost during transportation and storage, particularly with waxed cartons. The label should at minimum display the customer's name, seed lot identification familiar to the receiving forester, and quantity of seedlings in the box.

Boxed seedlings are often placed on wood pallets (that is, palletized) at the nurseries (fig. 6.9). This procedure can greatly reduce handling for users who have a forklift available. If pallets are used, they must be of adequate size to fully support the seedling boxes. Boxes may also be handled individually and stacked for transport and storage. (Chapter 9 contains more details about seedling shipping, handling, and storage.)

Packing bare-root seedlings

From the time they are lifted to the time they are bagged, bare-root seedling roots must not be allowed to dry. After lifting, seedlings that don't meet specifications are culled and shippable seedlings are counted



Photo: Tom Jopson.

Figure 6.7. A containerized seedling extraction, grading, and packing line.

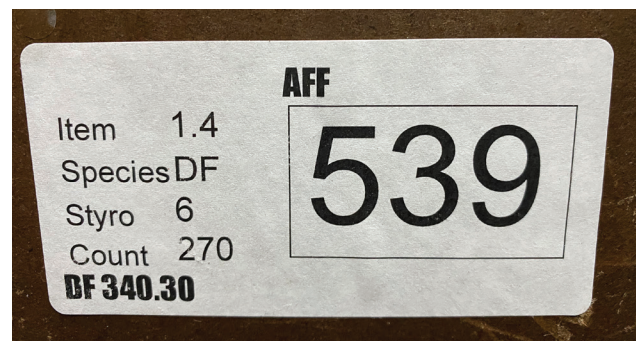


Photo: Tom Jopson.

Figure 6.8. This box label has important information about the seedlings, including species (Douglas-fir), container size (styro-6), number of seedlings in this box (270), purchaser seed lot ID (DF 340.30, which means it was collected in California seed zone 340 at an elevation of about 3,000 feet), nursery lot (#539), and organization that contracted for the seedlings (American Forest Foundation).



Photo: Tom Jopson.

Figure 6.9. Pallets of packed seedlings await transport to cold storage. The spacers between the boxes indicate that these will be stored frozen at 28°F. The spacers help seedlings freeze faster and allow uniform thawing without removal from the pallets.

into bundles, which may be packed in durable, plastic-lined, paper seedling bags manufactured for this purpose. The bags come in a variety of sizes, including those large enough for large bare-root transplants. Seedlings may also be packed in waxed boxes with plastic liners that sometimes contain moist packing material such as sawdust. The bags or boxes are sealed to prevent moisture loss and labeled as specified previously. Seedlings stored in bags typically need support racking for storage or long distance transportation. Boxes may be stacked or placed on racks depending on their weight and rigidity.

Ordering seedlings

Seedling orders for reforestation projects are best undertaken after a detailed plan and schedule of activities is developed (see chapter 3, “Planning a reforestation project”). Because no planting project can occur without appropriate seed, one of the first steps is to ensure that seed is available for the project. Planning activities such as the site assessment, defining specific objectives, and development of a prescription and

schedule of activities will develop the information necessary to place a seedling order with a forest nursery. Following the the sample schedule of activities allows sufficient lead time for seedlings to be custom-grown in a forest nursery for each project.

A riskier approach is to attempt to buy appropriate seedlings just before they are to be planted, from nurseries that have grown them on a speculative basis for walk-in sales. Because of the large number of seed zones and species in California and the state's large variation in climates and altitudes, finding seedlings of the desired stock type and grown from appropriate seed is nearly impossible. Seed is often in short supply, so no one wants to waste it on seedlings that don't sell. Sometimes useable seedlings can be found in nurseries or excess seedlings can be obtained from nearby large landowners or public agencies, but it is strongly recommended to order seedlings to be grown for each specific site in advance. Advanced ordering, usually called contract production, is the process that is discussed here.

The typical nursery seedling order is for a quantity of seedlings, usually in the thousands, of a particular stock type and species to be grown from appropriate seed and delivered during a particular timeframe. Additional considerations include when to place the order, whether an adequate amount of seed is available to produce the desired quantity of seedlings, and how payment will be structured.

The needed quantity of seedlings is determined by the planting area's acreage and density (trees per acre). The choice of stock type determines whether the seedling order will be placed with a container or bare-root nursery. Container nurseries need to know the stock type's container size, while bare-root nurseries need to know the stock type's years in production and whether they are transplants. The nursery may have a preferred stock type for the desired species.

Nurseries should be contacted well in advance to determine when to place orders. Each nursery has a different order window, which may vary by species. When ordering, the nursery needs information about the seed, including species, seed zone and elevation, seeds per pound, purity, and germination percentage. This information is used to calculate how much seed is needed. Large forest landowners and public agencies typically have the seed they want to grow. Landowners without seed should identify sources for appropriate seed during the planning process, which sometimes will be the nursery. When the order is placed, the nursery should be made aware of the anticipated delivery time frame and whether the seedlings will be planted immediately after they are packed for delivery or placed into storage.

The contract between the seedling purchaser and nursery typically includes all the conditions detailed above plus seedling size specifications (usually minimum height and stem caliper) and payment terms. Payment terms vary between nurseries, but advance payment of 25 to 40 percent based on quantity is typically required at the time of ordering, with additional payments as the crop matures. The final payment is due at the time of delivery, based on the quantity of seedlings actually delivered. Most lots will have small variations in quantity, either over or under the ordered amount. Purchasers are usually not required to buy excess seedlings if any are produced, but most do.

Seedling storage, shipping, and handling

Careful handling and storage of seedlings after lifting is crucial for ensuring the best possible outcome for seedling survival and growth. Care should be taken to avoid common stressors such as elevated storage temperatures, rough handling, and desiccation (Landis et al. 2010).

Cold storage

Cold storage of packed seedlings is a common practice in California and throughout western North America (Camm et al. 1994). Cold storage of seedlings requires constant temperatures of 33°F to 36°F inside boxes or bags to maintain optimum seedling quality (fig. 6.10). The temperature inside storage boxes is usually somewhat higher than the air temperature in the cooler facility due to seedling respiration and the insulating qualities of the media and storage boxes. Therefore, cooler air temperature should be 32°F to 34°F and good air circulation around the storage boxes is essential. Monitoring should include both the air tempera-

ture in the cooler and the internal temperature of the storage boxes.

Temperatures above 36°F in the box will result in reduced seedling vigor due to the loss of stored carbohydrates to increased respiration. Additionally, seedlings may break dormancy and initiate root and/or shoot growth in the box or bag if temperatures are too high. Warmer storage box temperatures also favor the development of postharvest gray mold (*Botrytis*) that will rapidly deteriorate seedling quality. During transport to the planting site, seedlings must be protected as much as possible from the same potential stressors of heat, rough handling, and desiccation. Refrigerated boxes on pickups or trailers are excellent ways to transport seedlings to the field, but not absolutely necessary. Judicious use of tree tarps and placing seedlings in the shade will help prevent heat buildup in storage containers.

Freezer storage

Freezing seedlings for long-term storage is a good method to ensure that the seedlings remain in stasis and prevent development of *Botrytis* when longer storage durations are needed (for example, for high-elevation sites that are snowed in until late spring). Freezer storage is best at temperatures from 25°F to 30°F and in boxes with polyethylene liners to prevent seedling desiccation. Seedlings can be stored for 6 to 8 months in freezers.

Good air circulation through the pallets is important so that all seedlings freeze in a short time period. This can be accomplished with spacers between boxes on pallets and by maintaining space between pallets for air circulation. Spacers also facilitate uniform thawing when seedlings are removed from storage.

The speed at which frozen plants are thawed is an operational variable that has been studied across tree nurseries in western North America. In British Columbia, Camm et al. (1995) studied the physiological effects of thawing regimes on container spruce seedlings and found no significant differences between rapid thaw (1 to 2 days at 60°F) and slow thawing (17 days at 41°F). In a similar study, the Nursery Technology Cooperative at Oregon State University found no significant differences between slow and rapid thawing periods or for stock that was rapidly thawed and then held in cold storage (Rose and Haase 1997).

Accelerated development of *Botrytis* can occur with both thawing methods compared to seedlings that were never frozen. Outplanting seedlings as rapidly after thawing as possible is strongly recommended. With rapid thawing, the timing should ideally correspond with a period of favorable planting weather. If slow



Photo: Tom Jopson.

Figure 6.10. Boxed container seedlings in cold storage.

thawing is underway and the weather turns unfavorable for planting, refreezing the seedlings is not recommended if they have been thawing for more than a week. Rapid thawing also requires a moderate, relatively controlled temperature that may not be available at high altitudes when daytime temperatures remain below 60°F and dip below freezing at night.

When thawed tree seedlings are delivered to the field, thawing should be uniform throughout the containers. Partially frozen seedlings or bundles of seedlings should not be torn apart in the field as root damage is likely to occur.

Shipping and handling

All seedlings and especially bare-root seedlings are intolerant of poor storage conditions, rough handling, and desiccation during delivery to the field. The effects of handling stress in outplanted seedlings may not be evident until weeks after planting. Root damage can occur during shipping, handling, and planting. Handlers and planters should not drop boxes or throw bags of seedlings, and seedlings must never be subjected to dry or windy conditions. Unfortunately, it is common on planting sites to observe tree boxes being thrown out of the backs of trucks and seedling boxes exposed to direct sunlight. Both of these practices negatively influence seedlings and must be avoided.

Bare-root seedlings are easily damaged when the roots are exposed to dry conditions. Caution must be exercised when removing seedlings from packing bags or boxes and placing them into planter's bags. Dipping seedling roots in water can also help to minimize desiccation damage. Exposure to dry conditions for just a few minutes can cause significant reductions in survival (see chapter 9, "Planting").

Conclusion

Seedlings are perhaps the most visible part of any reforestation project. This can make it easy to think that they are more important than other aspects of a project, such as site preparation, vegetation control, and planting. The truth is that all of these factors must work in harmony for a project to succeed.

Choices made when selecting and growing seedlings will have both short- and long-term effects. Choices made for seed source and species will affect the project for the lifetime of the stand. Choices made for stock type, production practices, and seedling packing and storage will affect more short-term aspects, such as survival and early growth. Fortunately for reforestation practitioners, progress over the past 40 years in seed availability and seedling production and handling practices has resulted in seedlings becoming a reliable part of reforestation.

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Chapter 7

Site preparation

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“Site preparation is the single most important step in the reforestation process.”

— Professor Michael Newton,
Oregon State University

Site preparation refers to any measures taken to prepare a site for regeneration of a forest stand following harvest or wildfire, or reforestation of a brush field or other site in need. In order to achieve optimal growth rates of the forest stand and the best growing environment possible, seedlings need ample contact with bare mineral soil, adequate sunlight, sufficient levels of organic material to conserve soil moisture, and reduced vegetative competition. Other objectives include reducing fuels to limit the future risk of fire, while leaving enough organic debris to control erosion; maintaining enough structure in the form of large woody debris, snags, hardwoods, and other elements to provide for wildlife habitat; and leaving some residual trees to maintain visual aesthetics. Balancing the primary objectives of the landowner with the broader, and sometimes contradictory, expectations of neighbors and the general public is a challenge.

Factors influencing site preparation needs

Determining the need for site preparation involves many factors, some of which may be limiting, including constraints on seedling survival and mitigation of, for example, hydrophobic soils (Hobbs et al. 1992). It is also important not to create new limiting factors in the process of preparing the site. These factors revolve around creating the ecological conditions necessary to enable the survival of planted trees and the desired

level of natural regeneration. The primary methods for site preparation include mechanical, chemical, burning, and manual, with the best outcomes usually resulting from an integrated combination. Logging—including whole tree logging, biomass harvesting, and sending unmarketable material to cogeneration power plants—can also assist with site preparation.

Slash loads and fuels loading

Historically the objective of site preparation was to clear logging debris by piling it with a brush rake and sometimes broadcast burning to make the site suitable for planting. To expose mineral soil for planting, some landowners use ripping, also known as subsoiling, and crushing to reduce the depth of slash. Heavy loads of logging debris or slash can be difficult to plant through, and they add to the fuel load if a fire occurs. It can be difficult to determine how much slash must be removed from a site to allow for adequate planting access, optimum growth, and minimized fire risk.

For many landowners in California’s fire-prone interior, leaving a minimal amount of slash is necessary to help facilitate the plantation’s survival to maturity. Other landowners with less money available to invest in site preparation or for whom achieving optimal stand growth rates is less important may use less-intensive treatments. Thompson et al. (2007) found that the risk of losing a plantation to wildfire decreases as its age and tree size increase and the basal area of the stand decreases. Weatherspoon and Skinner (1995) found that removing excess fuels via site preparation activities is the most effective method for reducing the risk of a future fire, and Peterson et al. (2007) reported that reduced basal area and surface fuels increase the chances of seedling survival. By maintaining low fuel levels and controlling vegetation, landowners can

increase growth rates and improve the resilience of their reforested area.

Slash levels for fuel models are generally classified as

- **Light:** total fuel loads of less than 11.5 tons per acre and fuel bed depth of up to 1 foot
- **Medium:** total fuel loads of 11.5 to 34.5 tons per acre and fuel depth of 1 to 2.3 feet
- **Heavy:** total fuel loads over 34.5 tons per acre and fuel depths greater than 2.3 feet

Levels of slash loading affect a fire's rate of spread and potential flame length. Medium and heavy fuel models commonly present in clearcut or heavily thinned stands of mixed conifer or mixed conifer and hardwood. Medium and heavy slash loads should be considered a high priority for site preparation treatments that reduce the depth of slash and aid in the rapid decomposition of residues. In postwildfire situations where high-intensity fire has removed a high percentage of small material, the retention of remaining organic material should be a priority.

Vegetative competition

After removing, slash to make sites physically plantable, vegetative competition is the next most-important limiting factor to successful reforestation. In a Mediterranean climate, the lack of available water is the most critical factor affecting the survival of planted seedlings. Competition for available soil water can come from native species or invasive weeds. After disturbances such as logging or fire, conditions are ideal for pioneer species (grasses and forbs) to establish or recover and then dominate a site.

To successfully regenerate a site, vegetation must be controlled for the first 2 years (the year of planting and the following year) so that most of the available water can be used by the planted conifer seedlings. Keeping vegetative cover below 30 percent of ground cover for 5 years is best for optimal growth. Site preparation only reduces the extent and water use of competing vegetation temporarily. Pioneer species are adaptable, and likely to rapidly revegetate through early successional grass and forbs. The soil seed bank and resprouting ability of many brush and hardwood species assures their long-term presence. Good site preparation generally reduces the amount and expense of follow-up release treatments that will be needed to achieve the desired rate of conifer tree growth.

Soil type

Soils are the foundation of the forest and its long-term productivity. Forest soils warrant our respect and attention to conserving them. The texture of soil influences what types of site preparation to use. Soils can range

from fine-textured heavy clays to very coarse, sandy soils. In general, soils in California forests are loams to sandy loams due to the geology being primarily volcanic, sedimentary, and igneous. Fine-textured soils (clays) can be susceptible to compaction if operated on under wet conditions. Coarse soils are more erosive than fine-textured soils. Decomposed granite, for example, is very erosive. Picking a logging system that minimizes soil disturbance while leaving the site clean enough to plant is preferable to a logging system that requires additional mechanical or burning site preparation, which can remove much of the organic matter that helps to control erosion. On erosive soils, an integrated approach with proper logging and good chemical vegetation management usually achieves the best environmental outcomes by limiting soil erosion and downstream impacts.

Findings from the Long Term Soil Productivity experimental sites in California emphasize the importance of organic material and highlight the relationship between soil compaction and the subsequent growth of conifer seedlings (Zhang et al. 2017). The 20-year study examined the effect of residual organic material and soil compaction from timber harvest activities on conifer growth across nine factorial treatments (three levels of organic matter removal by three levels of soil compaction):

Organic material removal:

- **OM0.** This treatment removed only tree boles and residual crown was lopped and scattered. Forest floor organics were retained.
- **OM1.** This treatment removed all aboveground living vegetation. Forest floor organics were retained.
- **OM2.** This treatment manually removed all surface organic matter to expose bare soil. No organic matter was retained.

Soil Compaction:

- **C0.** This treatment resulted in no soil compaction.
- **C1.** This treatment resulted in compaction to intermediate bulk density.
- **C2.** This treatment resulted in high bulk density.

Contrary to the common wisdom in forestry, none of the treatments to organic material had little effect on the subsequent growth of planted conifers. Despite indications at several sites that nitrogen availability was reduced in the forest-floor removal treatment (compact-to-severe bulk density), it did not limit growth at 20 years. Intermediate and severe compaction had insignificant effects on seedling growth and in some cases (primarily on coarse-textured soils) had a positive effect, due to the soil's increased water holding capacity.

Compaction did not negatively affect seedling growth at any of the sites; and while rates of seedling survival varied at some sites, compaction was not associated with seedling mortality.

The results of Zhang et al. (2017) were similar to a 10-year study of North American reforestation sites (Ponder et al. 2012), which found that:

- Removing organic matter had no consistent impacts on 10-year planted tree or total aboveground biomass.
- Soil compaction generally increased planted tree biomass on predominantly coarser-textured soils, particularly in the absence of forest-floor removal.
- Vegetation control increased 10-year planted tree biomass and in many cases, foliar nitrogen concentrations, with positive responses usually occurring consistently across organic matter removal and compaction treatments.

These results are contrary to an international meta-analysis by Achat et al. (2015), which found that losses in soil fertility from removing organic material had negative consequences for subsequent forest ecosystems, with tree growth reduced by 3 to 7 percent in the short- to medium-term (up to 33 years after harvest) in the most intensive harvests (such as when branches with foliage are removed from the site).

Ponder et al. (2012) suggested that possible factors contributing to the lack of impact on seedling growth attributed to the removal of organic material and soil compaction in the Long Term Soil Productivity studies included:

1. Most study sites were on deep, relatively productive soils where nutrient limitations were less likely because of the greater quantities and proportions of organic material left on-site.
2. Substantial quantities of fine and coarse woody material were left on-site in the less-productive jack pine and black spruce sites due to the operational nature of the full-tree removal treatments, which leave many needles and small twigs while removing debris larger than 2 inches.
3. Soil microorganisms played a potentially confounding but variable role in enhancing tree nutrition by utilizing otherwise inaccessible and/or mineral nutrient reserves.

Most managed timberlands in California, including the Long Term Soil Productivity sites, had loamy and sandy loam-to-sandy soils, which are tolerant of some compaction. In sandy soils, compaction provided some benefits including increased water-holding capacity. Many of these same soils are deep, providing a large reservoir of nutrients. However, while California soils tend

to be manageable, evidence from older multirotational studies (Achat et al. 2015) indicates that in reforestation it is wise to adopt best management practices, such as:

- not operating when soils are wet, especially on clay soils
- leaving as much foliage as possible on-site, especially on sensitive soils (shallow, highly acidic, highly weathered, coarse textured)
- not removing the top layer of soil, or A horizon, during operations

Keep the results of these studies in mind when determining the most appropriate method of site preparation, or if site preparation is even necessary. The ultimate goal of any site preparation activity is to create a positive environment for planting seedlings. Planting sites well is important for the initial establishment of seedlings and their long-term growth. Site preparation activities that remove slash or mitigate compacted soils are less predictably successful, but to optimize soil health it is wise to be cautious and avoid compaction at harvest and retain as much organic material as possible.

Topography

The slope of a site can influence the options available for its preparation. Steep ground has fewer options than gentle slopes, and the options for site preparation on steep ground are generally more expensive and limited to whole tree logging or broadcast burning. Whole tree logging usually leaves a significant slash load along roads that needs to be burned, but broadcast burning is increasingly limited by smoke management concerns and the liability and cost associated with escaped fire. Sites can be prepared manually, but at considerable expense. For mechanical methods, tractors are generally limited to slopes of less than 35 percent. Excavator-mounted equipment with self-leveling cabs can work on slopes of up to about 45 percent, depending on the soil. The spyder (a modified excavator that can “walk” on hydraulic legs in front and wheels below) can be used on slopes of up to around 65 percent. The increasing trend of leaving slash loads on steep slopes—in part due to declining markets for small materials and increased liability concerns—adds to fuel loads and increases the risk of wildfire.

Hydrophobic soils

Hydrophobic soils, which can result from high intensity wildfire, particularly on coarse textured soils, and contribute to significant soil erosion after a wildfire. Further disturbing coarse-textured soils after a wildfire is discouraged due to the increased risk of erosion. A 4-year study of erosion in sites with different combina-

tions of postfire logging and contour subsoiling treatments suggested that on moderately sloped sites affected by high-severity forest fires, salvage logging—particularly when implemented immediately after the fire—can substantially reduce erosion (James and Krumland 2018). It is also crucial that tractors follow contours when subsoiling to avoid concentrating water in new ditches, which can turn into gullies.

Compaction

Subsoiling (drawing ripper shanks through the soil with a tractor) is the primary method for mitigating the compaction caused by mechanical activities such as logging or piling, particularly in clay soils. Subsoiling to mitigate past or present compaction adds another mechanical disturbance to vegetation, while making planting easier and less expensive.

Animals

Vertebrate pests such as pocket gophers, deer, and elk can do significant damage to planted seedlings, as can mountain beavers, rabbits, wood rats, and voles. Short-term protection and control methods such as netting, bud caps, repellants, and baiting may be necessary, but manipulation of animal habitat is usually the long-term solution. It is important to make sure not to create habitat during site preparation that encourages pests.

Disease

When diseases are present or in the vicinity the best time to deal with them is during harvesting and site preparation. Root rot in stumps can transfer to young seedlings of susceptible species. Chapter 10 (“Precommercial thinning”) provides guidance on how to deal with root rot and other diseases. Mistletoe is another example that is best dealt with during harvest and site preparation; removing mistletoe-infected trees within spreading distance of seedlings is the easiest solution.

Temperature

High temperatures can be problematic for seedling survival, especially Douglas-fir. Southerly facing slopes are always hotter and should be reforested carefully. Burned surfaces and organic material also generate hotter surface temperatures than bare mineral soil (Haig et al. 1941). With Douglas-fir it is also important to leave coarse woody debris on the ground whenever possible, to provide microsites for planting that offer dead shade (from sources that do not compete with seedlings for water and nutrients) and shelter from afternoon sun. When planting in harsh sites, it is even more important to plant seedlings with small tops, good caliper, and high root-to-shoot ratios so that they have a better chance of survival.

Low temperatures that create frost can also be problematic for seedling survival, especially with Douglas-fir and the true firs. Planting seedlings at higher elevations, particularly on easterly, flat locations, can also threaten their survival. Clearing brush can improve airflow, and site preparation activities that block airflow should be avoided. Douglas-fir should be planted on slopes where possible, avoiding low-lying flat areas on the east side. Areas with known frost pockets can be planted with ponderosa or lodgepole pine to ensure seedling survival.

Costs

Costs can significantly influence the types of site preparation chosen. The time value of money often incentivizes landowners to spend as little as possible upfront on site preparation due to the length of time (often decades) that costs must be carried. At the same time, good site preparation can significantly increase tree growth and considerably reduce follow-up release costs, while the lack of site preparation or poor site preparation can result in a completely failed plantation and the need for a costly replanting (see chapter 2, “Investing in reforestation,” for more information).

Safety

Worker safety concerns vary based on the type of site preparation. Worker’s compensation claims are most often filed for work with chainsaws, and worker injuries occur most frequently during burning activities, followed by equipment operations. The safest reforestation activity for workers is applying herbicides (Newton and Dost 1984). With current worker protection safety standards, herbicide exposure to humans and mammals during reforestation activities is minimal. In order to limit exposure to nontarget plants, fish, and animals, hand-applying herbicides along buffer zones on streams can help to mitigate public exposure to herbicides in recreational areas.

Snags are increasingly left on-site for wildlife habitat. When leaving snags, keep the safety of heavy-equipment operators and the public in mind. The quantity, quality, and location of snags retained should be well planned to minimize safety hazards. Snags should not be left within a tree length of roads, which are often used as fire lines; snags can cast sparks over fire lines and speed the spread of wildfires. Snags should also not be left along ridgetops to help prevent the spread of wildfire from embers carried in the wind. For operator safety, remove snags that are public safety or fire risks as soon as possible after a wildfire, while snags that are still sound and can be safely cut. As snags age, they are increasingly prone to falling. Research conducted on Blacks Mountain Experimental

Forest after the Cone Fire in 2002—with a species composition of primarily ponderosa pine, white fir, and incense cedar—found that 80 percent of snags fell within 10 years (Ritchie and Knapp 2014).

Methods of vegetation control

Selecting the most effective methods for controlling unwanted vegetation is a keystone to the success of a reforestation project. We introduce the following methods that can be used in site preparation; detailed information on application of these methods are found in other chapters of this book.

Mechanical vegetation control

Many forms of mechanical site preparation and equipment can be used to make sites plantable. Mechanical site preparation methods include logging, piling, subsoiling, mulching, V-blading, terracing, mastication, and chipping. The more complex objective of balancing fuel-loading, erosion control, wildlife habitat, aesthetics, economics, and other goals can be difficult. Ease of planting and ensuring a favorable environment for tree seedlings should be the underlying goal of mechanical site preparation.

Logging

Disturbance from logging is one of the most cost-effective methods for basic site preparation. The process of transporting harvested material to the landing can remove excess organic material from the site and provide a level of scarification, site disturbances that help to identify good planting sites. The construction of skid trails provides additional scarification. Site preparation with logging may not be evenly distributed across the harvested area or achieve desired results.

Whole tree logging involves taking the whole tree to the landing, which can help with slash disposal and reduce the need for tractor piling. Whole tree logging also allows for the disposal of treetops left on the landing and the chipping of small materials that would otherwise be waste. Removing this submerchantable material can reduce or eliminate the need for additional site preparation. Once at the landing, leaving submerchantable material on-site for at least a month after shearing allows more drying time, which facilitates chipping and optimizes the material weight during transportation to the cogeneration facility. Likewise, more foliage and nutrients remain on-site because drier foliage is more likely to fall off during the skidding process. Removing as much submerchantable material as possible can reduce or eliminate the need for additional site preparation. When markets are strong for biomass and cogeneration power, whole tree logging is

a popular method for harvesting commercial and submerchantable materials.

Because of limited biomass markets and diminishing forestry infrastructure, landowners have been adopting a variation on whole tree logging. After merchantable timber is processed at the landing, the skidding equipment grapples the unmerchantable tops and limbs from the processing operation and packs it back into the harvest unit, evenly spreading out the material. Repetitive turns from the unit to the landing and back allow for additional dispersal and breakdown of the slash (fig. 7.1).

In-woods processing is another alternative that landowners are implementing. In this operation, a feller buncher (hot saw) cuts all of the submerchantable material (3 to 10 inches in diameter at breast height) along with merchantable timber (typically up to 23 inches in diameter at the stump) in a harvest unit. A log processor in the harvest unit processes the logs to remove the limbs and sever the tops of merchantable trees from the boles, leaving the material more evenly distributed throughout the unit (fig. 7.2). Then the skidding equipment grapples and skids a full payload of the processed logs to the landing. The logs can be



Figure 7.1. Unit with landing slash returned.



Figure 7.2. Logs processed “in woods.”

decked or immediately loaded without generating any material at the landing. The action of the log processor moving through the unit along with repetitive turns from the skidding equipment allow for additional dispersal and breakdown of the slash.

Piling

Piling involves gathering the slash generated from logging activities with a brush rake mounted on a cat or excavator and placing it in piles or windrows for burning (fig. 7.3). For the conversion of brush fields, a common practice is to root out brush, place it in windrows, allow it to dry, and roll it into a pile. This helps to remove soil held by the roots. Keeping soil out of the pile is important because the A horizon contains nutrients that help with the initial establishment and growth of seedlings. When the A horizon is completely removed, the plantation may grow poorly for many years or fail to properly establish. Also, when soil is incorporated into burn piles, piled material is more likely to burn incompletely and the mixture of soil and combustible biomass can lead piles to smolder and perhaps reignite when conditions are drier in the spring. When nutrient-rich soil in the piles smolders at a high heat for a long time, nutrients from organic matter are volatilized and lost.

Piling can also be done by hand, but it is cost-prohibitive in most cases. Slope can be a limiting factor for mechanical site preparation as most equipment can't be used on slopes greater than 35 percent. In areas of high fire risk or that are subject to dry, windy conditions, site preparation methods that do not require burning may be a good alternative.

Subsoiling

Subsoiling, or tilling, is the practice of using a tractor to pull a single or double set of shanks with winged subsoilers through the soil. Rock-ripper shanks do not fracture as much ground as winged shanks. Wings on shanks should be placed at a slight angle from horizon-



Photo: Mark Gray.

Figure 7.3. Cat with brush rake piling logging slash.



Photo: Mark Gray.

Figure 7.4. D8 Caterpillar with winged subsoiler shanks.

tal (less than 3 degrees). The objective is to lift and fracture the soil, but not to plow it (fig. 7.4).

Subsoiling to mitigate the compaction of primarily clay and clay loam soils should target a minimum depth of 18 inches, because most compaction caused by mechanical equipment occurs in the soil's top 18 inches. Because this method of site preparation causes a linear gully effect, it is extremely important that the feature is made on the contour. If the feature is not on the contour, a concentrated flow of surface water could occur, increasing the potential for erosion. Subsoiling can be used in conjunction with other site preparation methods or done as a single treatment.

As discussed previously, subsoiling has been used extensively in reforestation programs as mitigation for compacted soils. While the rationale for tilling may not be supported by scientific evidence in most California soils, other benefits can be achieved with the practice. Tilling after fire and salvage operations can have a beneficial effect on infiltration rates, as it breaks up the hydrophobic layers that frequently develop in burned sites, particularly with coarse-textured soils. Tilling of coarse-textured soils other than to mitigate hydrophobic soils is not advisable because it reduces the soil's water-holding capacity. Tilling also breaks up slash and incorporates it into the soil, speeding up the breakdown of combustible material on the site and perhaps allowing organic matter (humus) to develop in the soil.

Mastication

Mastication has been used extensively to reduce fuel loads at the wildland-urban interface, as an effective way to clear brush along fire breaks and reduce overall fire risk. More recently it has been used to reduce fuel loads in harvested units and provide a beneficial mulch layer to the soil. Mastication involves crushing or grinding vegetation on-site with a specialized head mounted on a piece of heavy equipment, which can range from small Bobcat machines to large excavators.

This method of vegetation control is expensive, but burning afterward is not necessary. Organic mulch that is left on-site may also increase the soil's water holding capacity (Hudson 1994). Mastication is also a good way to prepare the site when vegetation is very large and hinders reforestation efforts. Mastication (figs. 7.5 and 7.6) will not kill most vegetation, and resprouting will most likely occur. It is best used in combination with herbicides for effective control.

Mastication is increasingly used for site preparation to avoid the potential liability of burning, most often in treatments where large brush is present. Due to the risk of starting a fire by hitting rocks and creating sparks, many mastication operators prefer to avoid work during the hot, dry summer months or to work in areas that are less risky (rocky). Some mastication equipment has mounted foam units to immediately put out fires that may start.

Chipping

Chipping submerchantable or unmerchantable material prior to harvesting reduces the overall impact of too much biomass on the harvest unit. This method involves cutting unmerchantable trees of all sizes for use as woody biomass. Typically, the biomass is cut and bunched with a feller buncher and then skidded to the landing, where it is chipped into a van for shipping to a cogeneration facility. This can be done during preharvest as seen during clearcuts, or as a postharvest treatment.

Postharvest chipping includes cutting the remaining unmerchantable material left standing after harvest and skidding it to the landing, where it is chipped along with the top piles. Postharvest logging debris can also be skidded to the landing for chipping, further reducing the amount of organic material left in the harvested unit. The removal of biomass does not increase the

site's growth potential, but it does facilitate the ease of planting and reduces fuel loads.

Biomass thinning can serve as a stand-alone site preparation treatment or in conjunction with other mechanical activities, such as subsoiling and/or chemical treatments. Biomass chipping usually eliminates the need for piling and leaves more organic material on-site to act as mulch, which is particularly beneficial to Douglas-fir. More organic debris on-site also reduces the risk of erosion.

Many small landowners may think that chipping is done with a small hand-chipper, and they do not understand what biomass chipping is. It is important to recognize the difference between commercial biomass chipping for power cogeneration, for example, and small chipping to create defensible space around a structure.

V-blading

Tractors mounted with a V-blade can effectively mitigate high slash loads or make way for planting sites in brush-field conversions. The V-blade casts the brush to the side, exposing bare mineral soil that is ready to plant. In brush-field conversions, brush is best killed with an aerial application of herbicide at least a year in advance of V-blading, as large green brush can be difficult to root out. A single ripper shank can be pulled behind the tractor if subsoiling is desired. This method of site preparation is limited to level terrain, and it is difficult, if not impossible, to do where many tree stumps are present (fig. 7.7).

Spot cultivation

Spot cultivators, such as with VH mulchers, utilize a spinning head with angled blades that not only crushes vegetation in a circular area about 4 feet in diameter, but also mitigates compaction and creates planting



Photo: Mark Gray.

Figure 7.5. Before mastication.



Photo: Mark Gray.

Figure 7.6. After mastication.



Photo: Mark Gray.

Figure 7.7. V-blade clearing landing slash for planting.

spots for seedlings by tilling the soil (fig. 7.8). Spot cultivators crush and grind vegetation to create fairly small planting spots, so another form of vegetation control is usually necessary for it to be successful. Spot cultivation has been used in California with some success, but it is expensive and can cost between \$150 and \$400 per acre depending on the number of planting spots created, the density and size of brush, and the site's slope and rockiness. The planting spots created are depressions in the soil that have been vigorously disturbed. Vegetation is usually slow to come back in the holes themselves, but encroachment from the edges can be rapid.

Spyder

The spyder is a specialized form of mechanical site preparation equipment that is designed to pile slash on steep slopes (fig. 7.9). This equipment can operate on slopes over 65 percent at costs that increase as slopes get steeper. To keep costs under control when using the spyder, sites should only be made plantable and not overly clean. If burning piles, be careful on steep slopes that have not been cleaned (with too much slash on the unit after piling) as they can easily turn into a broadcast burn. When burning these units with high fuel loads that are evenly distributed, putting in a fire line is highly recommended to prevent ignitions from turning into broadcast burns.

Terracing

In areas where the terrain is steep, planting sites were historically created using terracing to clear brush and occasionally logging debris. Terracing involves using a tractor with a straight or angled blade to dig into the hillside and side-cast organic material and soil downhill, creating nearly level surfaces. The terraces must be slightly out-sloped and on the contour to facilitate proper drainage and minimize potential erosion. When



Photo: Mark Gray.

Figure 7.8. VH mulcher mounted on an excavator.

Photo: Mark Gray.

Figure 7.9. Spyder site preparation machine.

the topsoil is displaced and mixed, the flat terrace surface's subsoil can become less hospitable and long-term productivity may be diminished. For these reasons, and because creating terraces can be extremely expensive, this once-common site preparation method is rarely used now in California.

Mounding

Mounding with a VH mulcher or excavator is used in areas with high water tables to create well-drained planting spots. This practice, which is common in Canada but rare in California, is used primarily in areas around meadows or flats with high water tables.

Other site preparation methods

Many other equipment types or systems can be used to accomplish site preparation objectives. Old equipment can be modified and new equipment is being developed all the time, providing operators with new options. Some innovative examples include the tree planting excavators used in Canada to create mounds and plant trees at the same time and farm tractors mounted with large, heavy-duty rototillers.

Manual vegetation control

Manual vegetation control involves cutting, grubbing, pulling, and using other methods to physically remove vegetation by hand, usually on sensitive sites such as steep slopes; those that are highly visible from busy highways, parks, and towns; and at the urban-wildland interface.

Vegetation controlled manually is usually only effective for a short time and the costs can be very high (Knowe 1992). As a result, manual controls are commonly used in combination with other methods of vegetation control. It can be particularly useful on sites where chemical treatments are not feasible, such as those close to residential areas or with multiple water courses and associated buffer zones; and in remote areas with limited access for application equipment, where grubbing crews can hike in. Manual treatments are also frequently used by the USDA Forest Service in its reforestation activities, in part due to complex regulatory requirements for chemical treatments.

Grubbing

Grubbing, using hoes or other hand tools to remove weeds near planted seedlings, can be used as an alternative to herbicides, most often as a release treatment but also for site preparation. Researchers with the Forest Service Pacific Southwest Research Station have conducted studies in Northern California since the 1970s focused on woody competition and its effects on tree survival and growth. In a comparison of grubbing techniques and herbicide treatments, McDonald and Oliver (1983) found that seedling and sapling growth was significantly reduced when more than 20 to 30 percent of cover was woody shrubs. Subsequent studies found that the minimum effective grubbing radius was 5 feet, and smaller radii did not give conifer seedlings enough time to develop the deep and extensive root systems necessary to secure adequate soil moisture for growth (Fiddler and McDonald 1984). In addition, these studies found that the first year is critical for managing vegetative competition and the first 3 years are important, as seedlings must be free to vigorously expand their root systems in an ever-increasing volume of soil.

Tesch and Hobbs (1989) found that in the near absence of competing vegetation, Douglas-fir roots expanded greatly in biomass and volume of soil occupied but scarcely developed if the roots of competing species were present. However, McDonald and Fiddler (1990) found that grubbing radii less than 4 feet around ponderosa pine seedlings did not appear to be biologically effective and was expensive compared with herbicide treatments. Compared with other studies, they found that applying treatments earlier—before

vegetative competition damaged the seedlings—resulted in statistically significant differences among treatments, suggesting that treating competing vegetation as early as possible achieves better results. The two most-intensive treatments in this study—applying the herbicide hexazinone and increasing the radii to 6 feet—were most effective. The best treatment is one that not only effectively controls competing vegetation, but also does so when conifer seedlings are becoming established.

A clear conclusion from these studies is that the minimum cleared radius for effective grubbing treatments is 5 feet. At smaller distances, the roots of the adjacent vegetation were able to access enough water and nutrients from the cleared area to impede seedling growth. Treating entire plot areas, either by grubbing or with herbicides, resulted in the best survival and growth.

From a cost perspective, grubbing treatments are significantly more expensive than herbicides, depending on site and soil conditions. McDonald and Fiddler (1990) found that effective grubbing to 6-foot radii had labor costs of \$578 per acre versus total costs of \$152 per acre (\$38 per acre for labor and \$113 for chemicals) with hexazinone. McDonald et al. (1996) showed that grubbing to a 4-foot radius for 3 years cost \$420 per acre versus \$102 per acre (\$27 per acre for labor) with hexazinone. In McDonald and Fiddler (1995), grubbing an entire plot twice cost \$1,696 per acre, compared to \$27 per acre for labor to spray with hexazinone.

Mulching

Mulching for site preparation to regenerate conifers has been tested and applied commercially with many different types of sheets—including paper, polypropylene fiber mats, plastics, and other materials—with varied results. The rationale for applying mulch in sheets is to control competing vegetation and allow more moisture for seedlings.

Studies have shown that mulch mats should be 10-by-10-feet to significantly enhance the growth of conifer seedlings (Fiddler and McDonald 1984). Large mats should be made of a permeable material that allows moisture through to the soil below. These types of mulches can be expensive to purchase and install, and they are generally less effective for controlling weeds than herbicides or manual weeding. Gophers and voles that find the mulch material a good place to take up residence can damage seedlings. In high-value areas such as campgrounds or park settings, herbicides may not be an option and these sheet types of mulches may be a viable alternative.

Hand-piling

Piling up organic debris manually and burning it, called hand-piling, is often used to dispose of slash and fuels in difficult areas such as along roads and around structures, particularly at the urban-wildland interface. Small piles (up to 4-by-4-by-4 feet) provide defensible space, allowing for rapid burning and better control near structures. They can be used in landscapes where it is not cost-effective to bring in equipment, such as on steep slopes. Hand-piling and burning is expensive and risky due to liability concerns, and it is generally an option only for high-value, sensitive areas.

Biological control

Biological control utilizes naturally occurring organisms or substances to control vegetation; successful examples include the control of tansy ragwort (*Senecio jacobaea*) with cinnabar moth and St. John's wort (*Hypericum perforatum*) with Klamath weed beetle. Pathogenic fungi are also under investigation to control certain types of vegetation, but the results have not been as successful. Because they are limited to specific pests and their geographic ranges or elevations, biological controls do not provide broad-spectrum control of vegetation. In most cases, biological controls will be a small part of a larger vegetation management program (Newton and Dost 1984).

Burning

Historically fire has been one of the most common treatments in forestry to reduce postlogging slash and residual vegetation on-site. However, in recent years the use of burning has declined due to increasing constraints such as air-quality and smoke management regulations, general liability concerns, and the reduced number of burn days available.

When burning is used in combination with herbicides, vegetation control can improve substantially (Powell et al. 1982). Burning without the use of herbicides can actually release fire-adapted species such as deerbrush, snowbrush, and blueblossom (*Ceanothus spp.*), as well as knobcone pine (*Pinus attenuata*) (Newton and Dost 1984; Weatherspoon 1987).

Burning for vegetation management has been shown to increase conifer survival and growth, especially in combination with herbicides. Taylor et al. (1991) compared hand-piling, broadcast burning and spraying, and burning alone, and all treatments with and without disking. Two years after treatment, the spray plus burning treatment had greater fuels consumption compared with burning alone, and better vegetation control and seedling growth than either burning alone or hand-piling.

Fire behavior and prescriptions

The disadvantages of using fire for vegetation management include the possibility of escape and associated liability if the fire burns onto an adjacent property and causes damage. Gross negligence is the standard for liability in California. Fire can be used with low risk of escape when foresters thoroughly understand fire behavior, carefully monitor local weather, and follow a prescription that confines burning to occur during proper weather conditions. Fuel moisture inside and outside of treatment units should be monitored before the burn with 10-hour fuel sticks. Relative humidity, temperature, and wind speed should be monitored during burning. Patrolling in forests in the days afterward, before the fire is fully extinguished, is especially important since strong winds can cause fires to escape. The forester in charge must also have the experience and ability to call off a potentially high-risk burn when conditions are not right.

Broadcast burning

Broadcast burning is a primary method to reduce fuel loads on steep slopes, make them plantable, and facilitate follow-up planting and spraying. (fig. 7.10). A significant advantage of using fire is its adaptability to steep slopes where bringing in heavy equipment is not feasible. Fire makes the work of hand crews easier during subsequent planting, spraying, and thinning, thereby reducing costs (Newton and Dost 1984).

Once the prescription is complete it is important to prepare the unit for burning. A key step is creating an adequate fire line to contain unexpected fire behavior. Often this is best done by the logger while they are on-site with the proper equipment rather than trying to move equipment in to build the fire line. Sometimes slashing or chemical applications are used to kill brush in the burn area; these treatments allow brush to dry faster than adjacent fuels. When adjacent ground is wetter, the drier treatment area will burn more readily,



Figure 7.10. Broadcast burning.

Photo: Mark Gray

preventing fire spotting and escapes. Another practice to reduce the risk of escapes is “black lining” the top of the unit before lighting the rest. By burning a strip off the top of the unit and letting it cool down, the fire line will effectively be widened.

Access to equipment, especially water tenders and fire trucks, is essential for safe burning and to prevent fire from escaping. Getting personnel and equipment to a spot fire in a timely manner facilitates its control. In preparation for burning, it is important that loggers not block off roads or water bar them (create berms to divert water) so extensively that a water truck cannot access the unit.

Adequate personnel and equipment must be available to accomplish ignition and any subsequent containment. A helicopter can be used to limit the number of personnel needed for ignition, although the risk of generating too much fire too fast or a fire escape is greater. The benefit of using helicopters is avoiding risks to workers associated with lighting the fire by hand, including falling, dehydration, and being struck by rollers (large logs and rocks that roll downhill as the fire progresses). Additional logistics are involved, but if several burn units are located in the same general area landowners can take advantage of narrow and infrequent burn windows by burning at the same time.

Burning piles

Types of piles that are burned include hand piles, tractor piles, windrows, and landing piles, each with its own pros and cons. Liability is an increasing concern and limitation with all burning methods. Like broadcast burning, piles must be monitored after burning to make sure the fire is out and to mop up as necessary, particularly if high winds are forecast. When preparing burn piles, it is wise to cover them partially if not completely with waterproof covers, especially with small hand piles and landing piles. This facilitates the burning of piles during wetter, safer conditions by creating a dry portion in the pile to assist with ignition.

It can be tempting to wait for very wet conditions to burn, but usually it is better to burn a little earlier (but after adequate precipitation) to get more complete fuels consumption. Poor consumption can lead to holdover piles that may smolder for months, rekindling in the spring. Large landowners are more likely to accept marginal fuels consumption, while small landowners normally expect cleaner sites upon completion. When burning large units with large piles, is advisable to contain the piles with a fire line prior to burning to help avoid escapes (fig. 7.11).

Hand piles have the advantage of being smaller, burning down more rapidly, and going out faster. But if too many are lit and they are not out before a major



Photo: Mark Gray.

Figure 7.11. Top and landing pile burn.

wind event, they can still cause problems. Tractor piles are large and can burn for days, weeks, or months depending on how much dirt ends up in the piles; dirt can bury large fuels and cause them to smolder for a long time. When piling brush, it may be difficult to avoid getting dirt in the pile, especially with species such as chinquapin that have extensive root systems. The best way to reduce dirt in the pile is to uproot brush throughout the unit, then go back and finish the piles. This allows the brush and soil time to dry, which enables some dirt and finer foliage to fall off as material is moved into the completed piles. With less dirt in piles and more nutrient-rich vegetation on-site, some organic material also remains for erosion control. We recommend avoiding the temptation to burn piles before they are adequately cured.

A technique being used for logging slash in conjunction with whole tree logging is to shear the material with hot saws and then skid sheared bundles into larger concentrated piles at a landing or to scattered piles in a unit. Compared with pushing submerchantable material into piles with a brush rake, the advantages of this method include fewer piles to burn, cleaner piles with less dirt in them, and faster burning. Excavator-type loaders from logging are used to stack sheared materials into larger and fewer piles. Individual sheared bundles usually do not burn well, so it is better to combine the bundles to improve burn conditions and consumption levels.

With whole tree logging, the landing piles can end up being very large if no markets for biomass are available. To provide for a safe burn it is critical not to push the piles up against green residual trees that are being saved. Since these piles can generate tremendous amounts of heat, a wide fire line around the pile is essential to contain them and prevent radiant heat. It is most efficient to build the fire lines when the appropriate logging equipment is on-site. Working with the logging administrators—foresters in charge of logging

operations—is critical to ensure that appropriate and economical fire lines are constructed.

Large landing piles generated from chipping residue can be particularly problematic. These piles may contain a lot of small organic debris and soil without enough air space, resulting in poor burn consumption. If these large piles are built with a landing Cat tractor instead of a grapple loader they may contain a lot of dirt, which reduces the degree of burn consumption. Large landing piles take a long time to burn and need to be monitored in the spring to make sure they are out.

An alternative is to skid this residue material back out and scatter it in the harvest unit as it is being generated. This residue is often nutrient-rich and good for the long-term productivity of the soil. It's important to not spread it too thickly so it can be planted through and spread to areas beyond the landing.

Prescribed burns can expose workers to a variety of toxic byproducts such as methanol, acetic and formic acid, dioxin, terpene, tar, xylene, and benzene (Newton and Dost 1984). In addition, workers may be exposed to rolling debris from the fire that they may not see coming due to the smoke. Rollers can be dangerous during holding (patrolling fire lines and putting out any spot fires) and mop-up operations. Tripping and falling can result from walking through thick slash with a drip torch, and dehydration is a concern under hot and strenuous fire conditions.

Cutting, clearing, and walking fire lines on steep slopes can also be dangerous for workers. However, Kauffman (1992) demonstrated that the incidence of worker injury and worker's compensation claims during postburning activities such as planting, backpack spraying, and thinning was less on units that had been broadcast-burned compared to units with heavy slash and brush loads.

Chemical vegetation management

Chemicals such as herbicides, desiccants, or growth regulators can be used to control competing vegetation by treating it prior to tree planting, or before or after harvest using application methods such as broadcast, direct, hand, or aerial (see chapter 8, "Vegetation management," for more information). Herbicides are generally the most effective and efficient method of vegetation control, and they have been the focus of decades of technological improvement as well as state and federal regulations to ensure a high level of safety and the mitigation of specific concerns (Newton and Dost 1984). Herbicides are used in the vast majority of programs to control unwanted vegetation, so we will focus primarily on them here.

Preharvest site preparation

Since the herbicide imazapyr was registered in California in 1997, treating sites prior to harvesting trees has become common. Imazapyr is particularly effective with hard-to-control woody species. Due to conifer tolerance issues, more chemicals are available for site preparation than for release treatments. Treatment costs for site preparation are lower than for releases, when seedlings must be protected. The need for follow-up release treatments is also reduced, which is an additional cost savings. An added benefit of reduced release expenses is the overall reduction in chemical use. The two primary methods of preharvest site preparation are foliar applications to control brush species, and hack-and-squirt applications for hard-to-control hardwood species such as tanoak on the California coast.

Logistical planning and coordination with logging operations is important when utilizing chemical vegetation management. Timber Harvest Plans must be completed at least a year before logging commences to allow sufficient time for preharvest chemical treatments to take effect, and for the reentry interval to pass so that loggers and other workers can freely work on the site without running into post-herbicide-treatment requirements. Herbicide treatments should be done at least 2 months and ideally at least 1 year, or through one winter, before logging. Some fallers—workers who cut timber—will not work in stands that have been treated too long before cutting, because limbs can break off of dead and brittle trees, creating dangerous conditions.

Postharvest site preparation

Postharvest chemical site-preparation sprays were common prior to the registration of imazapyr in California, and they are still widely used after wildfires. A problem with postharvest treatments is that the vegetation is frequently damaged during the logging process and goes into shock, making the application less effective. With hard-to-control woody species it may be advantageous to wait and control them after their crowns recover, as foliar herbicides are most efficacious on actively growing plants. With resprouts it may be necessary to hold off on spraying for 2 or 3 years until regrowth occurs in the aboveground leafy area (to match the belowground root system), which allows better chances of control. If using imazapyr to control hard-to-kill woody species postharvest, wait at least 1 year—depending on soil types and precipitation—to prevent seedlings from taking up imazapyr in their roots. Ponderosa pine seedlings are particularly susceptible to this type of damage.

Regardless of when woody species are treated (pre- or postharvest), grass and herbaceous species still must be treated. In the first year after planting, the grass and forb community poses the greatest risk to the survival of seedlings. Treatments for herbaceous weed control include broadcast treatments prior to planting and directed sprays afterward. Broadcast treatments of hexazinone, oxyfluorfen plus penoxulam, or other soil-active herbicides can prevent the emergence of competing herbaceous species, and they are currently the best alternatives available. If no preplant application is made and grasses emerge after planting, a directed spray may be necessary for the tree seedlings to survive. See chapter 8, “Vegetation management,” for more information on chemical site preparation.

Brush-field conversion

Converting brush fields that result from old burn scars is a unique challenge when preparing sites for planting. A combination of treatments will be necessary if large amounts of living brush are present on the site. Brush removal can be done mechanically by rooting out green brush with a Cat tractor equipped with a brush rake. The most common way to achieve this is to push the brush into windrows and allow it to dry for a few weeks. After drying the brush should be moved in a way that releases soil held by the roots, then the clean brush can be piled for burning.

Another way to convert brush fields is to spray the brush with herbicides well before the anticipated planting date. Herbicide applications may need to be done with a helicopter or fixed-wing aircraft because the brush impedes ground access. Fixed-wing applications are best-suited for flatter terrain and herbicide options are more limited than with helicopter applications. Once the brush is dead and brittle, numerous mechanical options are available to prepare sites for planting, including crushing/tilling, mastication, V-blading, or broadcast burning (fig. 7.12).

Other cultural treatments

Cultural treatments include any management practice that has a direct or indirect effect on vegetation control. In addition to practices already covered in this chapter, cultural treatments can take on many forms to directly affect competition vegetation from activities such as grazing, or indirectly such as through seedling development programs. Cattle grazing can reduce grass competition, while goats browse primarily on brush and forbs. However, goats will browse conifer species and care must be taken to limit damage from overgrazing. Seedling development programs have included seedling nutrition and stock type selection to enable



Photo: Mark Gray.

Figure 7.12. Sprayed brush crushed and planted in dozer tracks.



Photo: Mark Gray.

Figure 7.13. Well-prepped unit with retention islands and cedar seed trees.

seedlings to outcompete competing vegetation. All methods of cultural treatments are just one component of an integrated vegetation-management program.

Conclusion

Good site preparation is critical for establishing a successful plantation. Evaluating the site (see chapter 3, “Planning a reforestation project,” and chapter 4, “Site assessment”) is imperative to identify potential limiting factors on-site and develop a prescription that creates the conditions planted seedlings need to survive. To achieve the best results, use a combination of site preparation methods based on site conditions. Effective and economical site preparation integrates science and experience to anticipate problems and mitigate them in a timely manner. Prevention is more effective and economical than doing additional treatments after problems develop. Years of experience have shown that the best money spent in reforestation is for good site preparation (fig 7.13).

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Chapter 8

Vegetation management

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This chapter focuses on the use of chemicals to control competing vegetation before and after conifer seedlings are planted. Mechanical, fire, and managed intensive grazing can be used in combination with chemical methods but are not a substitute for chemical vegetation management on their own. Nonchemical methods are typically more expensive per acre and often do not achieve the same level of competing vegetation control as with chemicals.

Competition

In California's Mediterranean climate, competing vegetation is the most critical factor influencing the success or failure of new forest establishment (Powers and Reynolds 1999). Competing vegetation can and will deprive newly established conifer seedlings of valuable light, nutrients, and, most importantly, water (White and Newton 1989). In California, where summer temperatures can exceed 100°F, relative humidity can be in the single digits, and long periods without rainfall are common; competing vegetation in excess of just 25 percent cover may be enough to influence the growth and survival of first-year seedlings (Oliver 1984).

Pioneer brush species and hardwoods grow inherently faster than conifer seedlings and can quickly overtop planted trees, depriving them of valuable light needed for photosynthesis (McDonald and Abbott 1997). Herbaceous vegetation in the form of grasses and forbs has adapted to capitalize on early available soil moisture for growth and can quickly deplete the amount of water available for seedlings (White et al. 1990). Any vegetation other than planted conifers utilize light, nutrients, and water that new seedlings require to establish successfully.

Benefits of vegetation control

The impacts of competing vegetation on conifer seedlings are well documented. Tappeiner and Radosevich (1982) demonstrated that survival of ponderosa pine (*Pinus ponderosa*) may be dramatically increased by controlling bear clover (*Chamaebatia foliolosa*). Ponderosa pine survival ranged from 6 to 12 percent in areas where bear clover was not controlled compared to 80 to 100 percent where it was removed. The same study also predicted wood volume losses of 75 percent by age 50 if bear clover was not controlled. Fisk (1984) estimated volume losses of up to 70 percent in mixed-conifer forests where bear clover was not controlled. Oester et al. (1995) showed that survival increased from 18 to 63 percent and stem volume increased from 39 to 819 cubic centimeters in ponderosa pine 5 years after planting with a single application of hexazinone compared to untreated controls in northeastern Oregon. White and Newton (1989) found that ponderosa pine growth was substantially reduced when competing with manzanita occupying as little as 20 to 30 percent of ground cover. Powers and Reynolds (1999) showed a three-fold gain in stem volume 8 years after treatment when comparing herbicide treatments to untreated controls in the Garden of Eden study. Ponderosa pine growth was reduced by 80 to 90 percent 3 years after planting when greenleaf manzanita (*Arctostaphylos patula*) cover reached 50 percent (Radosevich 1984).

Controlling competing vegetation is most important early in the life of a new forest. McDonald and Fiddler (2001) showed that delaying release treatments until 4 years after planting and then treating each year for the next 3 years did not significantly increase growth over the untreated controls, and small trees that received release treatments during the first 3 years after planting were statistically larger.

Fuel loading and fire risk

A secondary reason to manage competing vegetation is to maintain a relatively fire-resistant landscape. When woody brush goes unchecked, it can quickly outgrow planted conifers. Usually, one or two species will dominate a site and suppress others, while heavy fuel loads accumulate and plant biodiversity is reduced (DiTomaso et al. 1997). Radosevich (1984) showed that on a good site, greenleaf manzanita biomass grew to almost 60 times that of ponderosa pine seedlings 1 year after planting, and the density of greenleaf manzanita was 123,500 seedlings per acre. In a 10-year study, manzanita plant numbers decreased, but manzanita foliar cover increased by 21 times while height increased 7 times (McDonald and Fiddler 2001). The average investment by private landowners to establish new forests is around \$500 per acre, so managing vegetation to reduce fire risk is critical. Fire-proofing a stand is impossible, but by managing the density and size of vegetation the fire intensity may be lowered to allow the stand to survive.

Environmental considerations

Herbaceous and woody vegetation have positive benefits and are an important but minor component of most reforestation projects in California. They provide habitat and food for wildlife, protect water quality, increase soil stability, and improve the aesthetics of the landscape. It is important for land managers to realize that effectively treating vegetation to establish a new forest produces a short-term effect on the landscape. Vegetation rebounds quickly, and by not letting one or two species dominate a site, plant biodiversity and species richness increase in the long-term (DiTomaso et al. 1997). How vegetation is managed depends on the landowner's objectives. Goals for wildlife, water quality, soils, and aesthetics can be easily integrated into a management plan. Recognizing where, when, and how special vegetation management considerations will be addressed is critical to sound and responsible reforestation planning.

The chemical control of competing vegetation is tightly regulated in California and commercial application is limited to licensed professionals who must follow current regulations.

Choosing a vegetation control method

Failure to choose the right method of vegetation control can have enormous financial and biological ramifications. The inherent cost of treatment and potential costs of unsuccessful reforestation should provide the incentive to choose a vegetation control method wisely and get it right the first time.

Foresters must fully understand the objectives of vegetation control and treatment for the site before starting. When the primary goal is conifer production, site preparation treatments are usually much more intensive than when managing wildlife or recreation. Land management objectives and constraints dictate which methods are suitable and which are not. Land managers must have a clear understanding of the desired outcome in order to evaluate the effectiveness of their work.

Budget is also an important consideration. The greatest savings can be achieved by doing things right the first time, and vegetation treatments are inherently expensive. Some treatments cost much more than others and may be less effective. It is important to consider both present and future treatment costs. Will the treatments be mechanical, chemical, or manual, and are repeat treatments going to be necessary?

Another question involves the duration of desired control. Certain herbicide prescriptions can provide control over a number of years, while manual and mechanical treatments generally provide short-term control, with some exceptions. Large whiteleaf manzanita (*Arctostaphylos viscida*), for example, does not sprout much when disturbed. If it is too large to treat chemically, mechanically piling or masticating may provide satisfactory control.

Surroundings are another important consideration when deciding on a treatment option. Are sensitive areas nearby that would preclude the forester from using one type of treatment over another? The presence of sensitive water courses or wells, property lines, neighbors, or endangered species can all influence the decision on which type of treatment to use. Conifer species tolerance to herbicides may also dictate using another control method if for example, a particular crop species is intolerant to available herbicides.

Worker safety also influences the selection of a method. Slope, rockiness, temperature, and access are safety issues that may favor one type of treatment over another. Newton and Dost (1984) showed through medical records that the risk of worker physical injury was magnitudes greater with manual removal treatments when compared to hand-applied chemical applications.

A wealth of knowledge is available to landowners regarding all types of vegetation control, depending on the resource professional. Foresters who work for private industry, consulting foresters, Pest Control Advisors, licensed applicators, and university personnel choose chemical vegetation management more than state or federal employees, who tend to rely on nonchemical vegetation control and have a vast amount of experience with alternative,

nonchemical treatments. The County Agricultural Commissioners' offices and California Department of Pesticide Regulation can provide valuable information. Consulting with vegetation management professionals will save the landowner valuable time and money as well as ensure a successful application that achieves their desired objectives.

Vegetation control methods

The selection of vegetation control methods is the key-stone to the success of a reforestation project. The methods introduced here are described in greater detail later in this chapter as well as in other chapters of this manual.

Chemical

Chemical vegetation control involves the use of herbicides, desiccants, or growth regulators to control unwanted vegetation. The overwhelming majority of chemical vegetation management is done with herbicides, which are generally the most effective and efficient.

Mechanical

Mechanical vegetation control—such as piling, ripping, and mulching—utilizes equipment to manipulate existing vegetation on a site. With subsequent weed germination or resprouting, mechanical vegetation control alone does not provide long-term control (Fiddler and McDonald 1997). As a result, mechanical vegetation control is usually done in combination with other methods, such as chemical applications. Mechanical treatments are especially appropriate where large brush or trees are present that cannot be treated by other methods or where soil amelioration may be desired.

Manual

Manual vegetation control involves cutting, grubbing, pulling, and other methods of physically removing vegetation by hand. These methods are usually effective for a short duration and application costs can be high (Knowe 1992); as a result, they are commonly used in combination with other methods. Manual control of vegetation is particularly useful in areas where chemical applications are not feasible, such as those in close proximity to residential areas or with sensitivity to herbicide applications due to multiple water courses and associated buffer zones. Another use for manual control is in remote areas with limited access by application equipment, where grubbing crews can provide a release treatment by hiking into the site. Manual treatments are frequently used by the USDA Forest Service in their reforestation activities, at least in part due to

the complex regulatory authorization process required for chemical treatments.

Biological

Biological control uses naturally occurring organisms or substances to control vegetation. Successful examples include control of tansy ragwort (*Senecio jacobaea*) using the cinnabar moth (Fuller 2002) and of St. John's wort (*Hypericum perforatum*) with the Klamath weed beetle (Holloway 1964). Pathogenic fungi have been investigated to control certain types of vegetation, but the results have not been as successful (Wall 1996; Wall and Shamoun 1990). Biological control methods are usually limited to specific pests, which does not make them applicable for broad-spectrum vegetation control or certain geographic ranges or elevations. In most cases, biological controls will be a small part of a larger management program (Newton and Dost 1984; Isaacson and Brooks 1999).

Other cultural

Cultural treatments are management practices that have a direct or indirect effect on vegetation control. These include land management activities such as burning or grazing, which can affect competing vegetation itself, and seedling development programs such as seedling nutrition or the selection of stock type to enable seedlings to outcompete vegetation. There is virtually an endless stream of concepts and ideas that can be incorporated into management programs to minimize management inputs. Like other methods, cultural treatments are one part of an integrated approach to vegetation management.

Nonchemical weed control methods

In this section, we discuss various types of nonchemical weed control methods. It is important to remember that while these are not substitutes for chemical weed control on their own, they are an important part of an integrated vegetation management system.

Mechanical

Mechanical operations in forestry are not only for weed management. They may have multiple objectives, including mitigating compaction, improving water absorption, facilitating planting, removing slash, thinning, or managing vegetation. Mechanical treatments are not usually used alone but are one part of a larger program (McHenry et al. 1982).

We briefly discuss the benefits of vegetation removal here; for more information, see chapter 7, "Site Preparation." Mechanical vegetation removal can be an important part of a reforestation program and usually

has significant impacts on the cost, quality, and accessibility of future treatments.

Biomass removal

Removal of unwanted vegetation may start before logging operations are even complete. When markets allow, chipping to remove biomass is one of the most important mechanical treatments foresters can do. The ability to chip and remove unwanted material in the woods has several advantages. Because unwanted material is chipped and hauled off-site, fuel loading is drastically reduced and the need for costly piling, and potentially slashing, after logging is limited or unnecessary. Accessibility for planters, spray crews, and other reforestation efforts is also improved. While chipping treatments won't provide long-term control of competing vegetation, they do bring it down to manageable levels. Entering the reforestation site for chemical, hand, or mechanical treatments will also be much easier and more cost-effective in the future.

Piling

Depending on the slash load and quantity of large, woody brush or submerchantable conifers following logging operations, reforestation units may need piling to improve access, remove residual vegetation, and facilitate planting operations. Weed control by piling is completed primarily via the removal of large brush. In many cases, large plants such as manzanita can be entirely pulled or pushed from the ground, root systems and all. In other cases where the brush is too small or flimsy to be removed entirely, another method will be needed for control. If sprayed with herbicides prior to harvesting, most brush is dead by the time piling occurs and it can be easily crushed or piled. This spraying also reduces the amount of time needed to dry piles prior to burning.

Bulldozers, which are the primary method used for piling, should be equipped with brush rakes to minimize the amount of soil disturbance. Piling with an excavator is another mechanical option with additional benefits. Due to the reach of the boom, the excavator's tracks cover much less of the ground compared to a bulldozer, reducing potential compaction. Large brush and woody sprouts can be pulled from the ground with the boom's grapple, minimizing movement of topsoil. Furthermore, excavators can reach steeper slopes with grades of up to 40 percent.

With bulldozer piling, costs usually range between \$150 and \$250 per acre for logging units, but using excavators can add another \$50 to \$100 per acre. Piling costs are usually higher in old brush fields due to the density and size of the brush. Piling for site preparation has declined in popularity, and more

alternatives are now available to avoid the cost and disruption. These include chemical pretreatment and planting through the resulting slash, which creates microsites for conifer seedlings. In addition, poor piling practices can impact site quality through excessive soil disturbance. Finally, the liability when burning piles or windrows created by this method is a risk many landowners are now unwilling to accept.

Subsoiling

Site preparation treatments with subsoiling utilize a bulldozer fitted with a brush rake and a series of steel shanks fitted with slightly angled wings on each side. The shank and wings are designed to rip, lift, and drop the soil to mitigate compaction. A secondary result of the treatment is that it disturbs any remaining vegetation it comes into contact with.

The Long Term Soil Productivity Study is one of the largest and longest (since 1989) environmental studies in the history of the United States, with many sites over a wide range of conditions and soil types across the country and 12 sites in California (Page-Dumroese et al. 2021). The study looked at several factors affecting conifer survival and growth, including compaction, vegetation management, and soil organic matter. Treatments consisted of light, moderate, and heavy compaction; with or without vegetation; and organic matter removed or present.

Regarding subsoiling, some interesting results occurred at the Challenge, Calif., site. At the end of the fourth growing season, the average volume of ponderosa pine was greatest in compacted plots and least in the lightly compacted treatments that were subsoiled in two directions. This result seems counterintuitive, but it occurred because of competing vegetation. Vegetative cover averaged 56 percent in the compacted plots and 91 percent in the subsoiled plots. Less weed cover translates into increased moisture availability. When the effect of vegetation was removed, the subsoiled plots were clearly superior to the compacted ones (Powers 1997). Potter (1984) also showed that when units with bear clover present were ripped, rhizomes were broken up and spread across the unit, resulting in even greater infestations. This result seems to rely heavily on the type of vegetation present. Others have shown positive growth responses to subsoiling with ponderosa pine (Froehlich and Robbins 1983; Helms et al. 1986).

Mastication

Mastication involves crushing or grinding vegetation on-site with a specialized head mounted on heavy equipment. This method of vegetation control is

expensive, but it negates the need for follow-up piling. Organic mulch left on-site may also increase water holding capacity of the soil (Hudson 1994).

Mastication is a good method for sites where vegetation is large enough to hinder reforestation efforts, and it can sometimes be used instead of broadcast burning. Masticating vegetation will not kill sprouting species, and as a result, it is best used in combination with herbicides for effective control.

Recently, dense stands of 60-year-old tanoak (*Lithocarpus densiflorus*) regrowth in the Sierra were operationally treated using this method. Trees were severed and laid on the ground with a feller buncher and then masticated. This created a relatively thick layer of shredded organic matter that could be picked through for planting spots, albeit with some difficulty. While this operation was expensive, ranging from \$400 to \$500 per acre, it created an opportunity to recapture hardwood-dominated, high-site timberland that otherwise would have required high-risk burning and heavy equipment for clearing. However, mastication may result in heightened fuel loading during a plantation's early years, and the presence of sprouting species may make site preparation sprays a necessary part of the prescription.

The VH Mulcher is a masticating site preparation tool that was widely used in the past, but its availability is now relatively limited. This machine utilizes a high-torque spinning head with angled blades that grind down into the soil. In doing so, it not only masticates vegetation in a circular area about 4 feet in diameter but also alleviates surface compaction and creates planting spots for seedlings. Masticating with a VH Mulcher is expensive and can cost between \$250 and \$400 per acre depending on the number of planting spots created, density and size of brush, slope, and rockiness. This method generally does not preclude the need for herbicide treatment of the surrounding terrain, as encroachment from the edges can happen quickly. Care should be taken in fine soil textures as the vigorously disturbed planting spots may initially have a high percentage of macropores that can impact root growth.

Using masticating heads on a maneuverable boom can reduce residual damage to conifer plantations. Where large brush is present in established plantations, mastication can be used as an effective release tool by reducing brush competition at the same time as pre-commercial thinning of existing conifers to desired levels. Release treatments such as these usually occur in older plantations, where brush has been allowed to dominate and is too large for manual treatment.

Fiddler and McDonald (1997) compared different mechanical release treatments in a 12-year-old

ponderosa pine plantation (with an untreated control), removing vegetation with a Hydro-Ax shear only and with the shear followed by an application of 2,4-D to sprouting vegetation the year after mastication. After 11 years, the Hydro-Ax plus herbicide treatment had significantly larger crowns, diameter, and height than either the Hydro-Ax alone or untreated controls. The only difference between the Hydro-Ax only treatment and the untreated controls was crown volume.

A study by Fiddler et al. (2000) showed similar results on a 16-year-old ponderosa pine plantation using a Trac-Mac shear instead of a Hydro-Ax. The treatments consisted of an untreated control, Trac-Mac cut-only, and Trac-Mac cut-only plus an herbicide treatment with 2,4-D 2 years after cutting. Eleven years after treatment the Trac-Mac-only treatments had no significant differences in crown volume, diameter, or height compared to the untreated controls, whereas the Trac-Mac plus 2,4-D treatment had significantly larger crowns than the untreated control or the Trac-Mac only treatment. Somewhat larger diameters and heights resulted from the Trac-Mac plus 2,4-D treatment, and while not significant, the authors pointed out that growth rates diverged over time between the treatments.

All mechanical mastication methods are expensive and should be reserved for situations where other options are limited or specific objectives have been identified, such as the reduction of herbicide use or elimination of burning. The costs necessary to reclaim a site using mechanical methods—when needed for release—emphasize the importance of adequate vegetative control in the first place.

Manual

Manual release treatments include hand-grubbing, cutting, mulch mats, shade cards, and nonchemical controls. An advantage of manual weed control methods is that they have fewer environmental constraints and are more socially acceptable. Additionally, manual treatments can be highly selective and incorporated into precommercial thinning programs. The disadvantages of manual treatments include that they require a large skilled crew, often result in more worker injuries, and are less effective than chemical methods (Newton and Dost 1984). The biggest disadvantage is high cost and short duration of control (Knowe 1992).

Hand-grubbing

Hand-grubbing—the manual removal of live vegetation through the use of hoes, shovels, or other implements—is perhaps the most popular method of manual weed control. It is usually done after seedlings have been planted. To maximize effectiveness, treatments

should occur after the majority of vegetation has emerged in the late spring to early summer. To be effective, all root systems within the grubbed area should be removed.

Several studies have evaluated the effectiveness of hand-grubbing. McDonald and Fiddler (1990) compared several sizes and intensities of hand-grubbing treatments to a single application of hexazinone (Velpar L). Treatments included 2- and 4-foot scalps applied at age 1, half of which were expanded to 4- and 6-foot scalps at age 4. Four years after treatment, trees treated with the single application of hexazinone were significantly larger in caliper and height for all treatments, except the 4-foot scalp that was expanded to 6 feet. No grubbing treatments had significantly larger calipers or heights than the untreated controls, other than the 6-foot radius scalp.

Labor costs were high, however, with the 6-foot-radius scalp treatment: \$1,466 per acre in 2020 dollars compared to \$96.40 per acre for the single hexazinone treatment. With annually repeated grubbing treatments for the first 3 years after planting, McDonald and Fiddler (2007) showed increases in ponderosa pine caliper and leaf area compared to untreated controls, but at a cost of \$4,794 per acre (assuming labor rates of \$28 per hour).

While expensive, hand-grubbing can help to promote seedling survival, provided the scalps are large enough and treatments are repeated when competing vegetation returns. In the absence of chemical vegetation control methods, hand-grubbing is better than doing nothing.

Cutting

Another manual method for releasing conifer seedlings is cutting brush or hardwoods with a chainsaw or handsaw. However, sawing without chemical follow-up is a short-term treatment. McDonald et al. (1989), showed that tanoak cut with a chainsaw was overtopping Douglas-fir (*Pseudotsuga menziesii*) seedlings 4 years after treatment. By 9 years after treatment, Douglas-fir height was not significantly different from the untreated controls, with only small gains in diameter.

D'Anjou (1990) found that when woody brush and hardwoods were cut, they reached 50 percent of their pretreatment height by the end of the first growing season. This study also showed that no brush mortality occurred as a result of cutting and treatment timing had little effect. When compared to herbicide treatments, cutting provided significantly poorer control than glyphosate. Similar results were found by Simard and Heineman (1996), who showed that cutting had no effect on Douglas-fir caliper or height 9 years after

treatment, but treatments with glyphosate significantly increased diameter. The same study on a different site showed significantly larger diameters on lodgepole pine for the cutting and glyphosate treatment compared to untreated controls, 9 years after treatment.

Whitehead and Harper (1998) compared four vegetation control treatments for release of Engelmann spruce, including glyphosate, 2,4-D, manual cutting, and an untreated control. After 10 years, the glyphosate treatments were the most effective in reducing brush cover and height, and they significantly reduced the height-to-diameter ratio and competition index. All other treatments failed to meet Canada's minimum stocking standards at the completion of the study.

Others found mixed results on conifer growth. Pendl and D'Anjou (1990) found no growth response from grand fir, but height growth in Douglas-fir was significantly increased 5 years after cutting. Some research suggests that cutting woody brush and hardwoods is better later in the season, when carbohydrate reserves are low (Pendl and D'Anjou 1990). Increasing the frequency of cutting and cutting to the lowest stump heights possible may also reduce sprouting (Harrington and Tesch 1992) and cutting is more effective when followed up with herbicides to reduce sprouting (Wagner and Rogozynski 1994). McDonald and Tucker (1989) concluded that cutting treatments are too expensive for the short-term reduction in cover that they provide.

Mulch mats

Mulch mats can be made out of paper, plastic, polyester, asphalt, or other durable materials, and they range in size up to 10 feet in diameter. The purpose of placing mulch mats around tree seedlings is to deprive competing vegetation of light, heat the soil enough to prevent germination, and retain valuable soil moisture for tree seedlings (Haywood 1999). Mulch mats can be an effective method of control under some circumstances, but they are expensive, difficult to install, require maintenance to maintain their position around seedlings, are problematic with sprouting species, and often don't degrade in a reasonable amount of time (McDonald and Fiddler 1992).

McDonald and Fiddler (1992) also found that polyester mulch mats reduced the amount of vegetation around tree seedlings but didn't significantly increase Douglas-fir diameter or height over controls; the mats didn't allow water to penetrate, creating desertlike conditions for seedlings. As a result, the type of material used is extremely important, and subsequent studies found that porous plastic was the best available material that didn't constrict tree growth, reduce water penetration, or degrade too fast, and was easy to install

(Craig and McHenry 1988; McDonald and Fiddler 1992).

The growth responses of conifer to the use of mulch mats are mixed. McDonald et al. (1994) compared polyester and paper mulch mats to annual hand-grubbing treatments repeated for 5 years. Five years after treatment, the polyester mats and hand-grubbing treatments yielded significantly larger diameter and heights compared to untreated controls for ponderosa pine seedlings. However, the cost of the mulch mats was \$2,072 per acre.

Harper et al. (2005) found that mulch mats reduced the amount of herbaceous vegetation in the first 3 years, but they failed to significantly increase survival, diameter, or height for Douglas-fir seedlings compared to untreated controls; this result is opposite of what was found with either glyphosate or hexazinone treatments. Haywood (2000) found that both mulch and hexazinone treatments resulted in taller loblolly pine seedlings and caused them to grow out of the grass stage faster than untreated controls. Other studies by Haywood (1999) had mixed results regarding growth of loblolly pine.

Mulch mats have potential, but they are expensive and require considerable labor to install. McDonald and Fiddler (1992) reported that the cost of large mulch mats can be as high as \$9.90 per seedling, severely limiting the number of seedlings that can be treated effectively. Land managers that choose mulch mats may want to focus on treating only a certain number of crop trees to keep costs down.

Manual vegetation-control treatments will always have a limited use in forest management. However, the results are usually short-lived when used alone, and they are best used in combination with chemical treatments for longer-lasting control. If chemical methods are not available, repeated manual treatments will be necessary and costs will be high.

Biological

Biological control of vegetation includes the use of insects, pathogenic fungi, and allelopathic organisms. Little is known about the latter two methods, but some gains have been achieved with the use of insects on species such as Klamath weed (St. John's wort), tansy ragwort, and to a lesser degree, Mediterranean sage (Isaacson and Brookes 1999; Fuller 2002). New biological agents are currently being tested to control alligator weed, Cape ivy, Dalmatian toadflax, gorse, musk thistle, Russian knapweed, Russian thistle, Scotch broom, tamarisk, and yellow starthistle. Of these, the hairy weevil, which was introduced to California to control yellow starthistle, is showing the most promise, but yellow starthistle populations remain high.

In general, biological control agents are host-specific. From a forester's standpoint, controlling one weed out of a thousand does little to reduce competition. Getting populations of insects established is another limiting factor. In many cases predators reduce populations of beneficial insects to insignificant levels. Some insects only produce one generation per year, making establishment difficult (Pitcairn 1999). Using biological control agents is generally out of the forester's control as these programs are usually designed and implemented by the state. While biological control has potential benefits, insects should be a small part of a larger vegetation management program (Newton and Dost 1984).

Cultural

Cultural methods of weed control are management techniques that increase the ability of conifer seedlings to outcompete the vegetation. Many activities are considered cultural treatments, and more often than not foresters may not realize that they are practicing cultural vegetation management.

Seedlings

Production of conifer seedlings is a common cultural treatment that foresters can manage. Any variable that the forester can manipulate in the nursery to give the conifer seedling a competitive advantage over vegetation in the field is a cultural treatment. For example, stock sizes are a choice that foresters make, but different-sized seedlings behave differently depending on geography. In wetter, high-site climates, several researchers have shown that larger Douglas-fir stock sizes increase growth and survival (Newton and Cole 1993; Ketchum and Rose 2000). Other studies have shown that the stock-size effect is additive when combined with vegetation management and fertilization (South et al. 2001). In drier Mediterranean climates, however, Fredrickson (2005) showed that growth differences due to initial stock size were short-lived and varied by species, and all initial size differences disappeared by year 5.

In drier climates, shoot-to-root ratio is an important variable to manage in the seedling nursery. Seedlings will compete better with vegetation in the field if they have a balanced shoot-to-root ratio. Large tops and small root systems cause the seedling to transpire faster than the root system can acquire water, resulting in growth loss or seedling mortality. The nursery manager can manage seedling heights and the shoot-to-root ratio by regulating photoperiods, thereby tricking the tree into thinking the day length is getting shorter, which causes the tree to set bud and harden off earlier.

Seedling nutrition

Nutrition is another critical factor that can give seedlings an initial advantage over competing vegetation. Timmer (1997) showed that exponential nutrient loading of seedlings in the nursery can induce a steady-state buildup of nutrient reserves; this study consistently showed greater growth and increased nutrient uptake after planting compared to conventionally fertilized seedlings of the same stock size. Powers and Reynolds (1999) demonstrated the benefit of nutritional amendments in the field for ponderosa pine growth, but only in combination with weed control. If weeds were not controlled, any nutrients added to the site were taken up by the competing vegetation and potential gains to conifers were lost. Powers and Reynolds (1999) also noted that fertilization success in the field depended on moisture availability and water holding capacity. Others have shown water to be a limiting factor regarding fertilization response in the field (Rose and Ketchum 2002).

The idea of incorporating slow-release fertilizer into soil media in the nursery initially showed increased growth responses in the field with ponderosa pine (Fan et al. 2002). However, when operational testing and planting was conducted in California, severe root mortality occurred from salinity buildup in the plug media, especially during storage. These problems are exacerbated in hot and dry climates where flushing of the root system from spring rains is sparse. This method of fertilization is not recommended for dry California climates.

Grazing

Grazing is a cultural treatment that has been practiced for centuries, and it occurs in forestry primarily with ungulates such as cattle, sheep, and goats. Ungulates are usually effective in reducing the amount of herbaceous and woody brush cover, depending on the species present (Thomas 1983; Krueger and Vavra 1984; Fullmer 1986; Sharrow 1992). Reductions in vegetative cover are short-term, however, and vegetation eventually recovers (McDonald and Fiddler 1993). Grazing has also released nonpalatable vegetation that actually increased the percentage cover after grazing (Fullmer 1986).

Reductions in vegetative cover do not necessarily mean increased conifer growth or survival. Research results regarding the benefits to seedling growth and survival are mixed. In many cases, no beneficial effect of grazing was seen (McDonald and Fiddler 1993; Milliman 1999), while others have documented increases (Krueger and Vavra 1984).

The timing and intensity of grazing play a significant role in damage to crop trees. Milliman (1999)

reported that browse damage on conifer seedlings was greatest with the highest intensity of grazing pressure and in June when early-season forage was maturing but late-season forage had not yet begun to grow. Fullmer (1986) also reported that sheep had browsed 49 percent of ponderosa pine and sugar pine (*Pinus lambertiana*) buds at one site when browsing occurred prior to conifer bud-set in the summer. Grazing was delayed on a second site until after bud-set and browsing of conifer buds was reduced to 10 percent.

Managing grazing effectively can be labor-intensive. Fences must be constructed, maintained, and moved as needed and herds rotations limited to prevent overgrazing. Water can also be a concern if none is present on-site.

Fire

Historically, fire was one of the most common cultural treatments for managing vegetation in forestry site preparation. With increasing constraints and regulations regarding air quality and smoke management along with general liability concerns, cultural burning is used much less frequently. Historical uses of fire involved reducing postlogging slash and residual vegetation on-site. The biggest advantage of fire is the potential to treat on steep slopes where heavy equipment cannot be used. Fire can improve accessibility for hand crews when planting, spraying, and thinning, thereby reducing costs (Newton and Dost 1984). Substantial gains in vegetation control have been shown when burning is used in combination with herbicides (Powell 1992). Burning without herbicides can actually release fire-adapted species such as deerbrush (*Ceanothus integerrimus*), snowbrush (*Ceanothus velutinus*), blueblossom (*Ceanothus thyrsiflorus*), and knobcone pine (*Pinus attenuata*) (Newton and Dost 1984; Weatherspoon 1987).

Fire has been shown to increase conifer survival and growth, especially in combination with herbicides. Taylor et al. (1991) looked at piling, broadcast burning, and spraying; burning alone; and all treatments with and without disking. Two years after treatment, the spray-plus-burning treatment had greater consumption of fuels compared to burning alone, and better vegetation control and seedling growth than either burning alone or the piling treatment.

Underburning is also a valuable tool to clear away understory slash, vegetation, and smaller, unwanted, submerchantable conifers. Arno et al. (1996) and Newton and Dost (1984) noted the importance of thinning in combination with fire, along with utilizing other vegetation management options including herbicides to maximize effectiveness. Burning is not a one-time treatment for fuels reduction; reducing fuels

or creating fuel breaks without maintaining them is a waste of time and money. Vegetation will come back rapidly after fire and needs to be managed to prevent an even greater buildup of fuels (Newton and Dost 1984).

Using fire for vegetation management has several disadvantages. The liability associated with burning is significant due to the risk of escape and associated suppression costs. It is essential to develop and follow a detailed prescription for any planned fire. The forester must also have the experience and ability to call off a potentially high-risk burn when conditions are not right. Cutting, clearing, and walking fire lines on steep slopes can also be dangerous, although Kauffman (1992) demonstrated that the incidence of worker injury and workers compensation claims during post-burning activities such as planting, backpack spraying, and thinning was less on units that had been broadcast-burned compared to units with heavy slash and brush loads.

Chemical weed control

As noted in *Forests and Right-of-Way Pest Control* (Dreistadt 2013), published by UC Agriculture and Natural Resources, herbicides are the most commonly used pesticides in forests because of their effectiveness in controlling competing vegetation. Pacific Northwest Weed Management Handbook also states that reforestation success depends heavily on weed control:

“In the past 20 years, research has made clear that virtually no other practice will produce as much gain in plantation performance as reducing competing cover, and that careful application of the appropriate chemicals exceeds other methods in safety, cost, and habitat protection for most operations” (Kelpas and Landgren 2018).

The use of chemicals for weed control in California forest settings is highly regulated by both the U.S. Environmental Protection Agency and the California Department of Pesticide Regulation. Table 8.1 summarizes the herbicides used in forestry by active ingredient, type of activity, and uses. The following sections describe the types of herbicides used in reforestation, resource and applicator protection measures, and logistical issues of application.

Types of herbicides in forestry

Several types of herbicides are currently used in forestry including growth regulators, acetolactate synthase (ALS) inhibitors, photosynthesis inhibitors, protoporphyrinogen oxidase (PPO) inhibitors, and the newest mode of action, cellulose biosynthesis inhibitors (CBI). Each controls plants in a different way.

TABLE 8.1. Properties and uses of herbicides registered for forestry use in California*

Active ingredient	Type of activity	Uses*
2,4-D ester	Foliar	Site preparation/directed release
Aminopyralid	Foliar and soil	Site preparation/directed release
Atrazine	Soil	Site preparation/release
Clopyralid	Foliar and soil	Site preparation/release
Fluroxypyr	Foliar	Site preparation/directed release
Glyphosate	Foliar	Site preparation/release
Hexazinone	Soil	Site preparation/release
Imazapyr	Foliar and soil	Site preparation
Oxyfluorfen	Soil	Site preparation/release
Penoxsulam	Soil	Site preparation/release
Sulfometuron methyl	Soil	Site preparation/release (California coast only)
Triclopyr ester	Foliar	Site preparation/directed release

*Directed-release herbicides have no over-the-top conifer tolerance.

Growth regulators

Growth regulators used in forestry include triclopyr, 2,4-D, aminopyralid, clopyralid, and fluroxypyr. Growth regulators control plants by causing rapid cell-wall expansion and collapse. Typical symptoms of growth regulator herbicides include the twisting and curling of foliage, stems, and roots.

Growth regulators come in both ester and amine formulations. Rather than water-soluble amine formulations, oil-soluble ester formulations are typically used in forestry due to their superior weed control and better penetration into leaf surfaces. However, the use of esters is typically limited to the spring and fall due to their volatility in hot summer temperatures. The amine formulations are nonvolatile, and fluroxypyr ester is much less volatile than 2,4-D or triclopyr ester.

The growth regulators triclopyr, fluroxypyr, and 2,4-D are primarily used to control woody brush and herbaceous broadleaves. Aminopyralid and clopyralid are only active on herbaceous broadleaves and some annual grasses, but they have both foliar and soil activity. Conifer tolerance with triclopyr and 2,4-D is high when applied as a preplant application since they are

not soil-active, but neither can be used over the top of conifers in California. Aminopyralid also cannot be applied over the top of conifers, but it has some conifer tolerance when applied as a preplant treatment. Seedlings will occasionally be injured by soil uptake of aminopyralid as a result of preplant treatments, but if damage occurs at all the trees usually recover quickly. Clopyralid has excellent conifer tolerance applied pre- or postplant over the top of seedlings.

Acetolactate synthase (ALS) inhibitors

ALS inhibitors stop the formation of acetolactate synthase, an enzyme necessary for the formation of essential aromatic or aliphatic amino acids that are only found in plants. These herbicides tend to be highly systemic and travel readily through plant tissues. ALS inhibitors used in forestry include glyphosate, imazapyr, and sulfometuron methyl. ALS inhibitors mainly occur as water-soluble amines; ester formulations do not exist, and volatility is not an issue.

ALS inhibitors can have both foliar and soil activity. Glyphosate is strictly foliar-active, imazapyr has both strong foliar and soil activity, and sulfometuron methyl is strictly soil-active. The three have a mixed range of conifer tolerance as well. Glyphosate may be applied over the top of seedlings that have been established for 1 year following bud-set in the late summer or as a preplant application, but applications made over the top of seedlings during the active growing season will cause significant damage or mortality.

Release applications with imazapyr in California, with a few exceptions, are not possible due to low conifer tolerance from both foliar and soil uptake. Even preplant site preparation treatments the year prior to planting may result in significant conifer injury from soil uptake. Imazapyr is mainly used as a pre-harvest treatment prior to logging in California.

Sulfometuron methyl may be applied as a pre- or postplant application over redwood seedlings on the California coast, but significant root suppression, top stunting, and even mortality occurs in conifers in the interior parts of the state where climate is drier. This is mainly due to the inhibition of root growth and, as a result, seedlings are not able to capture available soil moisture.

Photosynthesis inhibitors

Triazine herbicides control plants by inhibiting photosynthesis. The triazines hexazinone and atrazine are both soil-active herbicides, which are absorbed by plant roots and require rainfall to activate. Atrazine is primarily a preemergent herbicide. Once grass and herbaceous broadleaves grow to 3 or 4 inches tall, their efficacy is reduced. Hexazinone is more powerful and

can be applied as a pre- or postemergent herbicide, and it has some activity on woody brush that atrazine doesn't. Conifer tolerance with atrazine is excellent. Applications can be made pre- or postplant to native California conifers. Hexazinone, on the other hand, has good tolerance on ponderosa pine but moderate-to-no tolerance on other native California conifers.

Protoporphyrinogen oxidase (PPO) inhibitors

PPO inhibition is a new mode of action in California forestry. PPO inhibitors prevent plants from making the enzyme protoporphyrinogen oxidase, which results in the destruction of cell membranes. They kill via lipid peroxidation, the process in which free radicals take electrons from the lipids in cell membranes and, in turn, destroy the membrane. The only PPO inhibitor currently registered in California is a component of Cleantraxx, a combination herbicide with two different active ingredients and two different modes of action: oxyfluorfen, a PPO inhibitor, and penoxsulam, an ALS inhibitor.

The two active ingredients work well together. Oxyfluorfen and penoxsulam both have soil and foliar activity. Oxyfluorfen controls herbaceous broadleaves and annual grasses only. Penoxsulam is a relatively new active ingredient and the list of plants controlled is still being determined, but it appears to have some activity on herbaceous broadleaf plants and weaker activity on woody brush. It does, however, inhibit the germination of several woody brush species from seed. The product works best as a preemergent application, but it has some selective knockdown of existing vegetation as a postemergent application. Tolerance is excellent as a pre- or postemergent application on all conifers tested in the Northwest.

Cellulose biosynthesis inhibitors (CBI)

Cellulose biosynthesis inhibitors are a new mode of action to California forestry, and have only recently entered the forestry market through the active ingredient indaziflam. CBIs control plants by inhibiting cellulose synthesis as well as germination and root development. Indaziflam is solely soil-active, and a true preemergent application. If vegetation is already on-site, another product must be added to achieve knockdown.

Indaziflam mainly controls annual grasses and herbaceous broadleaf plants, but it does not have any activity on woody brush. Tolerance is high even on western larch (*Larix occidentalis*), sugar pine, and redwood seedlings, which are the most herbicide-intolerant conifers in the western United States. Conifer safety is maximized with preplant applications. Indaziflam is currently registered for forestry use in California.

Differences between soil- and foliar-active herbicides

Soil-active products are taken up by the roots and require rain to activate, while foliar-active products are taken up through the leaves and in some cases stem tissue. Products with soil activity tend to have longer residual control because they are more persistent and have longer half-lives in the environment than foliar-active products. Some soil-active herbicides, such as hexazinone, tend to be mobile in the soil, whereas others such as atrazine and oxyfluorfen are much less so. Foliar-active herbicides are generally not mobile in the soil. It is possible for an herbicide to have both foliar and soil activity; imazapyr, for example, has strong activity for both.

Soil-active herbicides are heavily influenced by soil type, texture, and percentage of organic matter. Those that readily adsorb to soil particles are less available for plants to uptake, which can negatively affect control. Adsorption to soil particles is measured by the soil adsorption coefficient, known as Koc. The higher the Koc, the more herbicide adsorbs to soil particles and the less mobile it is in the environment. This measurement in combination with the herbicide's solubility can indicate its potential mobility in the environment; highly soluble herbicides are generally more mobile.

However, mobility in the environment is heavily influenced by forest soils. In clay or clay loam soils, which have higher levels of organic matter, herbicides are generally less mobile than in loamy sand or sand (Dreistadt 2013). Several of the soil-active herbicides, such as hexazinone, strongly adsorb to organic matter, thus hindering plant uptake (Neary et al. 1983). Herbicides with high Kocs or solubility aren't necessarily mobile in any given soil; results are highly variable in the field and slope also can have a major influence on mobility.

Nonsynthetic herbicides

Nonsynthetic herbicides are naturally occurring materials occasionally used for weed control in place of synthetic herbicides, mostly in organic agricultural programs. They include compounds such as acetic acid (vinegar), citric acid, clove oil, cinnamon oil, and corn gluten meal. These compounds are not true herbicides but rather are desiccants that accelerate the drying of plant tissue. The herbicidal symptoms they produce are limited to desiccating aboveground plant tissue. They do not control the root systems of plants or translocate as true herbicides do.

In some cases, these materials can control small, freshly germinated herbaceous seedlings. They will not control brush or mature herbaceous vegetation adequately. Plants not killed by these treatments

recover rapidly after initial symptoms appear (Owen 2002; Brevis et al. 2004; Chase et al. 2004; Curran et al. 2005; Moran and Greenberg 2006; Chandran et al. 2009; Evans and Bellinder 2009). While these types of treatments are completely inadequate for forestry use, they are considered herbicides and must be registered for use by the California Department of Pesticide Regulation.

Herbicide behavior in the environment

Degradation rates, solubility, soil sorption capacity, climate, soil type, and organic matter all play a role in how herbicides behave in the environment. Some herbicides are more mobile in the soil than others, and it is the land manager's responsibility to make sure water, wildlife, and humans are protected. Potential negative effects of herbicides may be mitigated by using buffers, understanding how the herbicides behave in the environment, adhering to the label, and knowing what the appropriate herbicide should be for a given site. Herbicides have high margins of safety regarding toxicity when used at label rates. Knowing how herbicides behave and understanding their toxicology will significantly add to your skill set.

Degradation

Herbicides break down in the environment in two main ways. The first is microbial (Dreistadt 2013); microorganisms in the soil rapidly break down most herbicides and in some cases soil arthropods actually utilize them as a food source (Busse et al. 2000). The second way is via photolysis, when light causes them to degrade. Not all herbicides photodegrade in soil, but most break down in water via photolysis fairly rapidly, as photolysis is enhanced in the presence of water (Rhodes 1980). Herbicides are also degraded in other ways, including metabolization by plants, hydrolysis, oxidation, reduction, and volatilization; they break down into simple organic molecules and inert compounds.

An herbicide's half-life is the amount of time it takes for 50 percent of the active ingredient to degrade in the environment (Dreistadt 2013). Half-lives can range from a couple of days to 6 months or more depending on the product, the environment, and microbial populations. Typically, soil-active herbicides have the longest half-lives as they are designed to last longer to provide residual control.

Mobility

Water quality is of the utmost importance during herbicide applications. Mitigating any potential contamination of water through leaching or overland flow of water is critical, mainly with soil-active herbicides. How mobile herbicides are in forest soils depends on

the properties of the herbicide and the environment. Soil mobility is influenced by solubility, degradation rate, ability to adsorb to soil particles, soil texture and type, pH, organic matter, slope, and precipitation (Neary et al. 1983; Beaudry 1990). Sandy, well-drained soils are the most prone to herbicide leaching and clays are the least. Foliar-active products pose little risk from leaching due to their rapid degradation rates, while soil-active herbicides are more prone to movement depending on the product. Mobility is strongly influenced by site, and all sites are different. Looking at one or two lab-derived indicators of mobility may not give an accurate depiction of what may occur under field conditions.

Toxicity

Herbicides must pass more than 150 tests to be considered for federal registration, in addition to California's own testing requirements. Every herbicide's toxicity is carefully evaluated for potential harm to human, animal, insect, and aquatic life. Toxicity is evaluated for both acute (short-term) and chronic (long-term) exposure hazards. Most toxicity information can be found on the product's safety data sheet, which includes its carcinogenicity, teratogenicity (the ability of a substance to cause fetal abnormalities), mutagenicity (the ability of a substance to cause genetic mutations), reproductive effects, endocrine disruption, and eye and skin hazards.

Toxicity is usually measured in milligrams of active ingredient per kilogram of body weight. Two frequently used terms to define the toxicity of an active ingredient are the lethal concentration in water required to kill 50 percent of an aquatic organism's population (LC50), and the lethal oral dose required to kill 50 percent of a terrestrial organism (LD50) (table 8.2). The no observable effect level (NOEL) is defined as the highest concentration of pesticide that did not produce any negative health effects. When used as labeled, today's herbicides pose little threat to the environment.

Resource protection when applying chemicals

Land managers may want to or be required to protect resources and sensitive areas from pesticides. A variety of methods are available to protect resources, wildlife, and property. One of the most valuable documents in a forest management plan is the list of mitigation measures regarding pesticide applications. Documenting what you do in practice is both a requirement and a necessity, from both a best management practice and liability standpoint.

It is also important to remember that the label is the law! Labeled use rates for herbicides are developed

TABLE 8.2. Relative toxicities of forestry herbicides compared to several common chemicals (blue)

Active ingredient	LD ₅₀ * (mg/kg oral rat)	Source material safety data sheet
2,4-D ester	1,380	Weedone LV-6
Aminopyralid	> 5,000	Milestone
Aspirin	200	Aspirin
Atrazine	> 5,000	Aatrex 4L
Caffeine	192	Caffeine
Clopyralid	> 5,000	Transline
Fluroxypyr	> 5,000	Vista XRT
Glyphosate	> 5,000	Accord XRT II
Hexazinone	1,310	Velpar DF
Imazapyr	> 5,000	Polaris AC
Nicotine	50	Nicotine
Oxyfluorfen	> 5,000	GoalTender
Penoxsulam	> 5,000	Sapphire
Salt	3,000	Salt
Sulfometuron methyl	> 5,000	Oust XP
Triclopyr ester	2,966	Forestry Garlon XRT
Vitamin D	42	Vitamin D

*LD₅₀ = lethal oral dose that will kill half of test animals (rats).

with a significant safety factor built in that gives an extra layer of protection so as not to approach any significant exposure level to humans, animals, or the environment.

Buffers

Buffers are a designated distance or area of land designed to protect resources, people, and property from contact with pesticides. Buffers are not necessarily pesticide-free zones; the goal of buffers is to protect an area of concern. A 100-foot buffer, for example, may be used to protect a stream course. The applicator may stop spraying at 100 feet, allowing some residue to drift into the buffer zone, but the stream course will still remain pesticide-free. There is a major difference between a buffer and a pesticide-free zone; buffers are the simplest way to protect areas of concern (fig. 8.1).

In general, aerial buffers are larger than buffers for ground applications, and buffer sizes differs between foliar- and soil-active chemicals. Soil-active herbicides tend to have larger buffers than foliar-active products because they can move in the soil profile, but foliar-active products cannot. For soil-active herbicides, buffer sizes tends to range from 50 to 150 feet for aerial applications and 50 to 100 feet for ground applications.

Photo: John Mateski, Western Helicopter.



Figure 8.1. Aerial buffer along a stream course.

Foliar-active buffers can range from 25 to 100 feet for aerial applications and as close as 10 feet or less for ground applications. These distance examples provide examples of buffers used in the past, but actual buffer sizes may be more or less depending on the landowner, topography, soil type, sensitivity of what is trying to be protected, and product label requirement.

Drift mitigation

Drift is a major concern with pesticide applications. Drift can be mitigated in several different ways, which should be described in detail in a written plan. This plan not only helps foresters in the field but serves as a living document in legal matters.

Drop size. Drop size has a major impact on drift. Volume median diameter is defined as the point where 50 percent of the spray volume is droplets with smaller diameters and 50 percent is droplets with larger diameters. As volume median diameter decreases, the percentage of smaller spray droplets increases. Drop sizes less than 154 micrometers (μm) are the most prone to drift (Barry 1984; Akesson et al. 1985). By minimizing small droplets, drift can be substantially reduced.

Spray nozzles. The proportion of fine drops can be minimized by adjusting spray factors such as nozzle size, nozzle angle, air or ground speed, pressure, boom length, and humidity at the time of spraying. The size of the spray nozzle orifice is the most obvious way to manipulate drop size. Larger nozzle orifices result in higher volume median diameters, and hence fewer small drops prone to drift. It is important to know which nozzle system spray applicators are being used and what drop size range they produce. Nozzle angle also has a major effect on drop size. In wind tunnel tests used to simulate aerial application conditions, nozzles angled straight back (zero degrees) on an aerial spray boom produced a volume median diameter

roughly double that of nozzles angled back at 45 degrees (Akesson et al. 1985).

Air and ground speed. Faster air or ground speeds increase the number of fine drops due to greater shear of the spray solution at the nozzle. Increases in pressure will have a similar effect. As pressure goes up, fracturing of the spray solution increases, producing more fine drops. Boom lengths limited to three-quarters of the rotor length for helicopter applications will reduce the number of fine drops by reducing rotor wash at the ends of the spray swath. Making applications in higher humidity ranges that reduce the amount of droplet evaporation during flight will also reduce the amount of smaller drops (Barry 1984).

Split booms. One of the most important features on modern helicopter boom systems is the split boom, which allows half the boom to be shut off during applications (fig. 8.2). As a result, the part of the swath directly under the helicopter's body in the center of the boom is free from rotor wash, causing a spray pattern that falls virtually straight down (fig. 8.3). Buffer strips can be flown with the working half of the boom on the opposite side of the area of concern so that any rotor wash is concentrated on the side of the helicopter farthest away from the protected area.

Drift control agents. Drift control agents can also be added to the spray solution to reduce drift by increasing the formulation's volume median diameters. Drift control agents reduce the number of fine droplets primarily by increasing the surface tension of the spray solution (Sparks et al. 1988). Drift control agents may consist of polyacrylamides, polysaccharides, paraffin, or petroleum-based oils, or products that encapsulate the herbicide. Spray additives can be a cost-effective and inexpensive way to reduce drift,



Photo: John Mateski, Western Helicopter.

Figure 8.2. Example of a split-boom application.

Photo: John Mateski, Western Helicopter.



Figure 8.3. The outside edge of the sprayed area was treated with a split-boom pass, demonstrating the precision achievable with aerial applications.

but conifer tolerance may also be affected due to the surfactant-like properties in most drift-control agents, which increase herbicide penetration and efficacy (Fredrickson 1994).

Weather guidelines

To ensure safe and effective pesticide applications, a clearly defined set of weather guidelines is critical. The weather guidelines should clearly define limits on wind speed, temperature, humidity, and precipitation, as well as conditions in which inversions may occur. Foresters managing spray projects should also have forms in the field to document conditions at the time of application. Portable, handheld weather gauges should also be available to accurately document weather conditions on-site. Weather can also help to mitigate potential concerns, for example, by spraying when light winds are blowing away from areas of concern to limit non-target drift.

Project layout and planning

The importance of proper project layout and planning to mitigate any potential issues cannot be overstated. After developing spray plans for a given area, foresters must complete detailed reconnaissance of the spray areas on the ground, identifying areas of concern such as water courses, springs, wells, property lines, ditches, residences, and other areas requiring protection.

All heliports, water sources, and herbicide mixing areas should be identified and mapped ahead of time. Drive all roads and check for hazards prior to the start of the project and make detailed contract maps that include all spray units along with any water courses, lakes, ponds, heliports, roads, batching areas, property lines, and other areas relevant to the project. The contract must include strict guidelines regarding weather

and spraying conditions, chemical handling and storage, production rates, safety, and record-keeping responsibilities. Detailed unit prescriptions regarding pesticide products and rates must be provided in writing. Most importantly, safety mitigation measures must include a written spill plan and the availability of spill kits in case of emergency, clearly defining procedures, personal protective equipment, and contact information in the event of a spill or human exposure.

Developing a field packet for both the forester on the ground and the spray applicator ensures that everyone has all of the pertinent information they will need to complete the project safely and effectively. Field packets should include a copy of the contract, unit maps, spray recommendations and prescriptions, restricted materials permits and site identification numbers, pesticide labels and material safety data sheets, the spill plan, any necessary permits, and weather and application summary forms. Weather and application records with all pertinent pesticide use data and conditions should be kept daily. Foresters also must read and follow all label directions for any pesticide products they are using.

The final and perhaps most important mitigation measure is to physically show the applicator or pilot the units to be sprayed and any areas that require protection. Do not rely on word of mouth or pictures on a map to convey the message. The potential liability is too great not to take the time to ensure that the applicator is fully aware of all sensitive areas and unit boundaries that must be avoided. Having radio communication with the pilot also helps with answering any questions during the application. Portable radios should be supplied to the forester, pilot, and batch truck driver to further reduce potential risks.

Onboard global positioning systems (GPS) are commonly used to refine targeted aerial applications of herbicides so that sensitive areas and those with desirable vegetation can be avoided. Aerial applicators that use GPS technology should be supplied with geographic information system (GIS) shapefiles showing the application area, buffer zones, and heliports used for the job. Shapefiles show where the helicopter applied material during the application on the map, allowing the pilot and the forester to review the application and correct skips before leaving the site.

Chemical site preparation versus release applications

The type of application and chemical choices foresters make are largely based on whether the needed treatments are preplant (site preparation) or postplant (release). Once conifers are established on a site,

chemical choices and application methods are much more limited due to conifer tolerance issues (table 8.3).

The most effective and efficient vegetation control is usually achieved via chemical site preparation. The cost of release treatments on a per acre basis is generally much higher than preplanting treatments, and effective control is often lower.

Site preparation

Chemical site preparation occurs prior to or immediately after planting conifer seedlings. These treatments are used to control any vegetation that would prevent initial seedling establishment. Site preparation treatments may be applied by air or ground and can be done prior to or after logging operations occur. Any vegetation management done after the seedlings are successfully established is considered release. (See chapter 10 for more information on release.)

Preharvest site preparation

Preharvest site preparation is one of the most effective and efficient methods of forest weed control. It was adapted from midrotation release treatments in the southeastern United States and vegetation management research conducted on bear clover with glyphosate in the northern Sierra Nevada of California (Jackson and Lemon 1986; Fredrickson 1994). The process involves treating the most difficult-to-control woody brush species such as tanoak, golden chinquapin (*Chrysolepis chrysophylla*), snowbrush, and whitethorn (*Ceanothus*

cordulatus) at least 1 year prior to logging as an understory treatment in the stand that will be harvested.

Preharvest site preparation offers many benefits. The choice of chemical at this stage of the reforestation effort is basically open to any product registered in forestry for site preparation because conifer tolerance is not a concern. The Weed Control Methods Handbook is a useful online reference for herbicides described in this chapter (Tu et al. 2001).

Imazapyr. Imazapyr is the primary herbicide used in forestry applications due to its unparalleled efficacy with difficult-to-control brush. Since imazapyr has conifer tolerance issues from both foliar and soil activity, it is well suited for preharvest application where it will not damage young conifer trees. Prior to imazapyr's registration in California and the development of preharvest applications, no registered herbicide could completely control any of the most difficult woody brush species. Treatments with glyphosate, triclopyr, 2,4-D, and hexazinone would cause initial desiccation but not completely kill root systems, and retreatments were often necessary due to rapid resprouting. Fredrickson (2004) showed that units pretreated with imazapyr saved \$200 per acre on average due to a decrease in release treatments needed during the first 10 years of plantation establishment compared to units that were not pretreated and those pretreated with herbicides other than imazapyr.

The registration of imazapyr in California in both the original water-soluble (Arsenal AC) and oil-soluble (Chopper) formulations provided new tools that

TABLE 8.3. Conifer tolerance to forestry herbicides by activity type and season

Active ingredient	Soil-active conifer tolerance	Foliar-active conifer tolerance	Timing of highest tolerance
2,4-D ester	N/A	Low	Dormant season
Aminopyralid	Moderate	Low	Spring/fall
Atrazine	High	High	Spring/fall
Clopyralid	High	High	Spring/fall
Fluroxypyr	N/A	Low/moderate	Dormant season
Glyphosate	N/A	Low/high*	After bud-set in fall
Hexazinone	Moderate**	Moderate	Spring/fall
Imazapyr	Low	Very low	Preharvest
Oxyfluorfen	High	High	Spring/fall
Penoxsulam	High	High	Spring/fall
Sulfometuron methyl	Low/moderate	Low/moderate	Spring/fall (California coast only)
Triclopyr ester	N/A	Low	Dormant season

*Conifer tolerance to glyphosate is low until bud-set and hardening off in late summer to fall.

**Hexazinone tolerance varies by conifer species; see also table 8.4.

could completely manage the most difficult-to-control species. Since imazapyr will also kill conifer seedlings, it cannot be sprayed over the top. Postplanting release treatments with imazapyr are also not possible due to soil uptake of the long-lasting herbicide in most California soils. Postlogging site preparation applications made the year prior to planting can still cause significant damage from soil uptake in planted seedlings. Even worse damage can occur from foliar contact. Therefore, the only practical application timing is prior to harvest.

Other herbicides. Preharvest applications can be made with other herbicides depending on the type of vegetation present. For example, if understory vegetation is dominated by manzanita or mahala mat (*Ceanothus prostratus*), 2,4-D or fluroxypyr applications will suffice. For heavy deerbrush or snowberry (*Symphoricarpos albus laevigatus*) populations, glyphosate can be used. The use of imazapyr broadens the spectrum of control so much and so effectively that it is rare for it not to be part of the prescription alone or in combination with other products. Tank mixes with imazapyr, glyphosate, and a methylated seed oil greatly broaden the control spectrum and are commonly used in preharvest site-preparation applications, with good results. When using imazapyr, the oil-soluble formulation should be used for evergreen brush in combination with a methylated seed oil. The water-soluble formulation does not work well on evergreen brush but can be used for hack-and-squirt treatments or foliar treatments on deciduous brush.

Two application methods are predominantly used for preharvest treatments. Foliar treatments are typically used to control smaller woody brush, while large, woody brush and sprouting hardwood clumps or hardwood trees can be controlled with hack-and-squirt treatments, where herbicide is injected into fresh cuts on the tree (fig. 8.4).

Foliar treatments. Foliar applications should be timed during the late spring to late summer when deciduous woody brush is fully leafed-out and the maximum amount of vegetation has germinated on the site. Hack-and-squirt applications can be done almost year-round, with the exception of the spring sap-flow period.

With preharvest applications, foliar herbicides can be applied as broadcast treatments, directed treatments, or a combination. Broadcast applications can be applied using the waving-wand method with gun-jets, off-center (OC) nozzles, or adjustable tips, depending on the size and density of understory vegetation. Gun-jet or adjustable-tip applications are ideal when the brush is small and the understory is open and free of obstruction from submerchantable conifers or large



Figure 8.4. Typical forestry hack-and-squirt setup.

brush. Broadcast applications with off-center nozzles can occur in denser brush, which usually provides better coverage. Directed-spray applications with flat-fan nozzles are usually the best choice when there is too much interception from conifers, large brush, or understory comprised of more difficult-to-control woody brush species. Often the crew will do a hybrid broadcast and directed application, with a broadcast application in areas where stands are open and brush is small, and then directed treatments of larger brush as encountered. Off-center or flat-fan nozzles are usually appropriate in these conditions.

Hack-and-squirt. When stands have a large component of hardwood trees, sprouts, or saplings, hack-and-squirt treatments are usually required on top of the foliar treatment (fig. 8.5). Hack-and-squirt applications are much more efficient and effective in a preharvest situation than treating resprouting hardwood clumps after logging, and issues with conifer tolerance can be avoided. Depending on the density of hardwoods in the stand, crews can either apply foliar treatments first and then go back through with the hack-and-squirt



Figure 8.5. Hacks should be spaced evenly around the circumference of the tree and hacked deep enough to penetrate through the bark to the cambium.

treatment; or, if there are not many hardwoods, several people on the crew can be designated to hack-and-squirt while the others do the foliar application.

Complicating factors. Preharvest applications may be complicated by the logistics of the harvest plan, logging schedule, and accessibility. In California, the timber harvest plan approval process and all botanical surveys must be completed prior to herbicide treatments. Unit boundaries, stream courses, exclusion areas, and property lines must all be marked as well. In many cases, new roads have not been built or road reconstruction has not occurred yet. Crews may have to walk or use an off-road vehicle for access where roads are not available, and in some cases it may not be possible to pretreat some units. To be as efficient as possible, the treatment schedule should address all of these variables and anticipate adjustments as changes in the logging plan occur. Once a harvest plan is complete and units are ready for treatment, it is best to treat all of them in the same year. If and when logging plans change, the forester who tries to only treat units that will be logged the following year may end up with untreated logging units.

Benefits of preharvest site preparation. Despite the logistical complexity, preharvest site preparation has many benefits. First, the long-term reduction in release treatments also means a reduction in overall chemical use while maximizing vegetation control. A secondary benefit is reducing the amount of chemical needed for herbaceous treatments before planting. Prior to the use of preharvest treatments, hexazinone was often applied at 2.5 to 3.0 pounds active ingredient per acre; at those rates, some woody brush could be controlled along with herbaceous vegetation. Since preharvest treatments control woody brush, rates of hexazinone needed may be significantly reduced because the only target is herbaceous vegetation, which is easier to control.

Preharvest herbicide applications also increase soil moisture for fall planting. Since all of the unit's vegetation has already been treated, available soil moisture is significantly improved after logging since the units sit fallow through the summer, free of trees and vegetation that would otherwise remove soil moisture. This allows for earlier fall planting, with more water available for planted seedlings (Fredrickson 2002). Preharvest herbicide can also reduce or altogether remove the need for mechanical site preparation (piling). Treated brush in the understory has a full season to die and becomes brittle by the time logging operations occur. Often the disturbance from heavy logging equipment is enough to crush existing brush, making the site plantable without any further mechanical site preparation.

Postharvest site preparation

Postharvest treatments were much more common prior to the advent of preharvest site preparation. The disadvantage of treating brush after harvest operations is that the majority of plants that survive logging are damaged and do not translocate herbicide as effectively, resulting in reduced control (Newton and Knight 1981). Woody brush resprouting from existing root stocks is another problem because the limited leaf area available after logging is unable to absorb enough chemical to translocate to the existing root system. To obtain good control, 2 to 3 years of regrowth is usually required to match the leaf area aboveground with the root system belowground. Usually by the time the new seedlings are to be planted not enough time has elapsed from logging disturbance for brush to recover or achieve the ideal size for treatment.

Resprouting brush. If postharvest site-preparation applications must occur, it is usually best to let damaged or resprouting brush recover prior to treatment. Treating brush before it achieves adequate leaf area will most likely result in resprouting and the need for repeat treatments. The downside of waiting is losing a year or more on the rotation of the new stand. In situations where woody brush germination is primarily from seed, it will be most cost-effective to treat immediately after germination occurs. Treating seedling woody brush when it is small is significantly more cost-effective and efficacious than waiting until brush gets larger. With some species on some sites, treatment prior to germination with a soil-active herbicide may also be effective.

Wildfires. Another challenge of postharvest site preparation is that wildfires promote the germination of woody brush. Brush seedling populations can be dense and intermingled with surviving damaged brush or woody brush that has resprouted from previously existing root systems. In these instances, foresters have no option but to deal with woody brush after harvest.

Vegetation competition. Whether or not woody brush has been controlled pre- or postharvest, treatment to control herbaceous vegetation prior to planting also is necessary. The ability of herbaceous vegetation to compete with seedlings for survival and growth is well documented (Newton and Preest 1988; Peterson et al. 1988; White and Newton 1989; White et al. 1990; Rose and Ketchum 2002). Even in the wetter climates of western Oregon, Douglas-fir seedlings experienced a 217 percent gain in volume when herbaceous vegetation was controlled during the first 3 years. Vegetation control on drier sites has been shown to triple the volume growth of ponderosa pine (Powers and Reynolds 1999).

Application methods. Postharvest site preparation treatments can be applied by hand or with broadcast aerial applications. The suitability of aerial applications on brush depends on its type and size. Usually, hand applications are more effective with controlling evergreen species of woody brush. Imazapyr treatments by air are highly effective on evergreen brush, but they should not be applied the year prior to planting due to potential conifer damage from soil uptake; treatments applied earlier should not have residual effects on conifers. Glyphosate applications by air over species such as deerbrush or snowberry can be highly effective, as well as 2,4-D over smaller manzanita. When dealing with seedling woody brush, the smaller the plants, the more efficacious the herbicide treatment will be. Larger or resprouting brush from root stocks is likely better suited to hand treatments.

Hand treatments of woody brush can be applied by either broadcast or directed methods, depending on the species and its size. Similar to aerial applications, broadcast treatments by hand should focus on easier-to-control woody brush species such as deerbrush, snowberry, and manzanita. The more difficult-to-control evergreen brush or hardwood sprout clumps are best treated with directed hand-sprays, unless imazapyr is used more than 1 year prior to planting. Hardwood sprout clumps should also be treated with a directed hand-spray or basal treatment, depending on the species.

Herbaceous treatments by air or hand should be applied with a broadcast method. Soil-active herbicides are used almost exclusively for broadcast herbaceous treatments. Occasionally glyphosate can be used in a postemergent setting, but this is not preferable because it doesn't provide any soil residual effectiveness.

Soil-active herbicides depend on rain for activation. Application timing is critical to maximize the chances of getting the correct amount; too much or too little rain can severely impact efficacy. Usually between 3

and 20 inches of rain is ideal for soil-active products. The application timing depends on total seasonal rainfall, elevation, snow level, access, and soil type. Low-elevation units that receive high total seasonal rainfall should be treated in the spring, when the forester thinks the necessary amount of rain can be achieved. High-elevation units that receive mostly snow should be treated in the fall to assure adequate moisture. Access to these sites may be impossible in the spring due to snow, after rains are over. Areas on the east side of the Cascade or Sierra Nevada should also be treated in the fall because these high-elevation, low-rainfall sites may only receive 15 to 20 inches of precipitation annually. A general rule of thumb is that residual herbicides should be applied to units under 4,000 feet in the spring and over 4,000 feet in the fall.

Conifer herbicide tolerance. When treating with soil-active herbicides, it is extremely important to know which species of conifers will be planted on the site and what their tolerance is to the chemicals used (table 8.4). While hexazinone provides the best overall control of the soil-active herbicides, Douglas-fir, white fir (*Abies concolor*), sugar pine, incense cedar (*Calocedrus decurrens*), and western larch are all intolerant to some degree. Reducing application rates can help to mitigate tolerance issues in species such as Douglas-fir and white fir, but other species such as sugar pine or incense cedar have almost no tolerance. The use of sulfometuron methyl in interior California and southwest Oregon can cause the inhibition of root growth in almost all conifer species. Atrazine and oxyfluorfen plus penoxsulam are the only two soil-active herbicides registered for use in California that have virtually no tolerance issues.

Herbicide treatments for site preparation, both pre- and postharvest, allow the most flexibility due to the lack of issues related to conifer seedling tolerance. Good site preparation is the best money a forester can spend. Controlling competing vegetation correctly

TABLE 8.4. Tolerance of commercial conifers for main soil-active herbicides used for site preparation

Conifer species	Hexazinone	Atrazine	Sulfometuron methyl	Oxyfluorfen plus penoxsulam
Ponderosa pine	High	High	Low	High
Douglas-fir	Moderate	High	Low/moderate*	High
White fir	Low	High	Low	High
Incense cedar	Low	High	Low	High
Sugar pine	Very low	High	Low	High
Red fir	Moderate	High	Low	High
Redwood	Very low	High	Moderate	High

*Douglas-fir tolerance to sulfometuron methyl is low in interior California and moderate in coastal areas.

from the start will reduce the number of applications, reduce herbicide use, increase seedling survival and growth, reduce applicator exposure, and save thousands of dollars for the landowner. Remember this quote from Professor Emeritus Michael Newton of Oregon State University: “If you have a large release program, you’re probably screwing up.”

Release treatments

Weed control treatments after seedlings have successfully established are referred to as release treatments, meaning that the trees are being released from the competitive effects of vegetation. These treatments can be the most expensive investment of any reforestation effort. Chemical choices are limited due to conifer tolerance issues, and many treatments must be applied by hand (see table 8.4). Some woody brush species often cannot be effectively controlled because the ideal herbicides are not available for release.

Release treatments are most beneficial early in a plantation’s life. Delaying release treatments increases costs as well as diminishes the growth response of crop trees (Newton and Knight 1981; Fiddler and McDonald 1999). Herbicide-based release treatments result in well-documented, significant increases in survival, stem diameter, height, and volume in California (McDonald and Everest 1996; McDonald and Fiddler 1999; Fiddler et al. 2000). While release treatments are usually necessary during plantation establishment, a truly successful reforestation program will minimize release needs as much as possible through good site preparation.

Chemical release treatments have several advantages over mechanical, manual, or other methods. Effectiveness and cost are major advantages of herbicide treatments. In addition to major advantages in effectiveness and cost, herbicide treatments have less impact on forest soil in terms of generating erosion and subsequent germination of weedy species compared to mechanical or manual treatments (Newton and Knight 1981).

Aerial

Aerial herbicide applications are the most cost-effective release method but also the most limited, due to conifer tolerance issues with over-the-top applications. Soil-active herbicides including atrazine and oxyfluorfen plus penoxsulam can be applied over the top of all conifers, but options with hexazinone and sulfometuron methyl are more limited. Surfactants are not usually needed with soil-active products but should be avoided in release applications because they can reduce conifer tolerance, with the exceptions being atrazine or oxyfluorfen plus penoxsulam.

Most foliar-active herbicides are not registered for or do not have sufficient conifer tolerance to apply over the top of seedlings, with the exception of clopyralid and glyphosate. With glyphosate, timing is critical to avoid conifer injury. Broadcast applications must be applied to conifer seedlings in the summer or early fall after bud-set and hardening off for the year. Earlier applications will result in conifer injury or death. Over-the-top glyphosate applications with newly planted conifers is not advisable and restricted on most labels.

The type of glyphosate product applied is also critical, as most formulations do not have an aerial release label approved for over-the-top applications. Rodeo is a nonsurfactant formulation of glyphosate labeled for aerial release treatments. Since no surfactant is formulated into the product, one must be added to achieve adequate efficacy on the vegetation. Additional care must be taken when choosing a surfactant as most will increase conifer injury when added to a glyphosate formulation. Historically, only tallow-amine surfactants have had enough conifer tolerance to be safely added or formulated into glyphosate. Penetron is the only tallow-amine surfactant currently labeled in California for aerial release treatments with glyphosate. Other adjuvants such as drift-control additives, acidifiers, and oils can also increase the risk of conifer injury. When choosing among the large number of generic formulations of glyphosate, make sure that the product chosen is labeled for aerial release.

By hand

When aerial applications cannot be used or foliar herbicide tolerance to conifers is a concern, treatments must be applied by hand. All hand application methods are available for release needs. Similar to aerial applications, broadcast hand treatments are limited to herbicides with conifer tolerance that can be applied over the top, such as glyphosate in the fall or soil-active herbicides.

Where difficult-to-control evergreen brush species such as tanoak, snowbrush, golden chinquapin, and live oak (*Quercus chrysolepis*) are present, foresters are faced with tougher challenges. While these species would be easily controlled with imazapyr in preharvest applications, conifer tolerance issues prevent it from being used for release in most areas. In such cases, the forester must determine the most efficacious and cost-effective method. The type of herbicide chosen is dictated by the type of vegetation needing control. It is important to identify the complex series of weeds present in the application area. For example, for a unit dominated by manzanita, snowbrush, and chinquapin, the best herbicide choice for a release treatment may

be 2,4-D plus triclopyr in the fall. If the vegetative complex also includes cherry and deerbrush, applying glyphosate with a methylated seed oil during the growing season may be prudent. Application timing and chemical choice sometimes differ in separate regions of California. It is best to consult local foresters who are licensed Pest Control Advisors in any given area.

For difficult-to-control evergreen species, directed-spray applications of growth regulator herbicides or a high-concentration glyphosate treatment may be the best option in some areas, while in other areas basal bark or spot-gun applications may be preferable.

Glyphosate. When glyphosate became generic the price dropped significantly. Most glyphosate products were labeled for high-concentration, directed-spray applications in the solution range of 5 to 10 percent, but prior to going off-patent it was cost-prohibitive to treat anything but scattered black oaks (*Quercus kelloggii*). The cost savings of generic products allowed foresters to treat larger areas and more species with higher rates of glyphosate, usually in combination with a methylated seed oil. Glyphosate is one of the safest and shortest-lasting herbicides in the environment. It is also nonmobile and poses little risk to fish or wildlife when applied according to the label.

Timing is critical when treating with glyphosate. Late spring to midsummer is most effective for treating evergreens such as snowbrush, whitethorn, and manzanita. Treatments later in the season are less effective in September and ineffective after the onset of cold weather. Tanoak and golden chinquapin are only partially controlled with glyphosate. These glyphosate treatments can reduce the amount of resprouting by snowbrush and whitethorn compared with growth regulators. Early-season glyphosate treatments also allow foresters to control herbaceous vegetation with lower volumes and rates.

High-concentration glyphosate treatments can provide a broad spectrum of control, but there is a tradeoff. The volume of solution required to control the more-difficult evergreen species can increase labor costs significantly, making them inefficient from a labor standpoint. Applicators should also be careful not to exceed maximum label rates. Another drawback is that timing for the best efficacy occurs when tree seedlings are actively growing and most intolerant of the chemical. Seedling protection is required when these applications occur. Applicators should shield seedlings and carry a spray bottle filled with water to wash trees that are accidentally sprayed.

High-concentration glyphosate treatments are effective for resprouting black oak clumps that are not too large. Ten-percent solutions of glyphosate will adequately control black oak clumps at extremely low

application volumes, making them highly cost-effective. Clumps can usually be treated safely to a height of about 5 or 6 feet. Once stump sprouts grow larger too much overspray occurs, which may potentially injure conifer seedlings. The high-concentration glyphosate treatments are not as effective on other deciduous hardwoods such as dogwood (*Cornus nuttallii*) or big-leaf maple (*Acer macrophyllum*). Lower-concentration glyphosate applications should be used if the target vegetation is mainly herbaceous and deciduous woody brush other than hardwood sprouts. Seedling protection is still required.

Growth regulators. Growth regulator herbicides such as triclopyr, 2,4-D, and fluroxypyr can be used for directed-spray applications when evergreen woody brush is present. Foliar applications with growth regulator products on deciduous brush are not recommended due to high rates of resprouting following application. Growth regulators provide excellent desiccation of most vegetation and complete control of some woody evergreens such as manzanita and mahala mat. On most woody evergreen species, at least some resprouting occurs, and repeat treatments may be necessary on species such as snowbrush, chinquapin, tanoak, and whitethorn. Seedlings are also highly sensitive to triclopyr and 2,4-D and slightly less so to fluroxypyr, but seedling protection is required in all cases. Volatilization is also a concern, and applications at temperatures over 75°F should not occur.

Where both deciduous and evergreen woody brush occurs, growth regulator herbicides should never be mixed with systemic products such as glyphosate or imazapyr. The growth regulators do so much damage to the translocating tissue in the deciduous plants that neither glyphosate nor imazapyr can translocate to their site of action in the plant. Deciduous plants will resprout much like they do when treated with growth regulators alone.

Spot treatments. Spot-gun treatments with liquid hexazinone can provide a highly effective and efficient treatment if the brush is not heavy; they are especially effective with snowbrush. Spot-gun treatments can also be used on other brush such as deerbrush, whitethorn, and manzanita. If cover is heavy, directed applications with glyphosate or growth regulators may be necessary.

More difficult-to-control hardwood sprouts such as bigleaf maple, dogwood, and live oak can be treated with basal bark or hack-and-squirt applications, depending on their efficacy in the region and the conifer tolerance of species planted on-site. In general, hack-and-squirt should not be done with imazapyr where ponderosa pine is planted. Damage may not appear immediately, but imazapyr flashback can show up several years afterward, and basal bark

or high-concentration glyphosate applications may be more appropriate. Flashback occurs when active imazapyr in the treated plants is released back into the soil as the treated plant material breaks down; this imazapyr can then be taken up by conifer roots, often 3 to 4 years after the initial treatment. Without imazapyr, controlling hardwood sprouts other than black oak is difficult.

Cut-stump applications for release are rarely used in forestry due to the cost but may occasionally work if the amount of saw work is light.

Achieving adequate vegetation control with release applications may seem difficult, but it is possible. The presence of conifer seedlings severely limits management options compared to site preparation treatments. By controlling the more-difficult evergreen species effectively during site preparation, overall costs, the amount of chemical used, worker exposure, and vegetative cover can all be reduced while enhancing conifer survival and growth.

Choosing a chemical control method

When choosing a chemical control method, the most important information is to know the species of vegetation that must be controlled. There are no magic bullets. In defining treatment objectives, evaluate the vegetation complex and identify species that present the greatest potential problems, then determine the most efficacious method. Aerial applications are not appropriate for many species, hand treatments are limited to certain species, and for others, a suitable control technique may not be available. The goal is to determine what the main treatment needs are and to find the best approach based on cost, effectiveness, logistics, and other factors.

Cost

When choosing an application method, budget often dictates which is chosen. Aerial applications are the least-cost option due to the amount of area that can be covered in a short period of time. Aerial forestry applications are limited to helicopters due to topography, but where large tracts of flat clean ground exist, fixed-wing aircraft applications may be possible. Ground treatments with a tractor or other ground equipment can be cost-effective, but are also limited due to topography, slash loads, and stumps. In increasing order of cost, application methods range from fixed-wing aircraft to helicopter, then to tractor or other types of ground machine, with hand applications usually the most expensive.

Much of the cost of hand applications depends on the type of treatment. Directed (or spot) treatments of individual plants are the most expensive. Broadcast

applications by hand are efficient and can rival helicopter costs for certain types of treatments. Familiarity with different application methods and their availability is critical. When conducting sprays by hand, finding a crew that can apply them efficiently and effectively often reduces costs more than anything else.

Effectiveness

Different application methods have varying results based on the coverage provided by each. This is mainly true for foliar applications, where coverage on leaf surfaces is critical. Coverage from aerial applications is not as consistent or thorough as from hand applications. When foliar-contact herbicides such as glyphosate, imazapyr, triclopyr, fluroxypyr, and 2,4-D are used, efficacy is usually best with hand treatments rather than aerial applications, depending on the vegetation type.

The type and size of vegetation also determine the effectiveness of an application technique. As woody brush gets larger, it becomes more difficult to control by aerial methods. Deerbrush is fairly easy to control by air with glyphosate when it is small. If large deerbrush is treated by air, it may only top-kill plants and resprouting may result. Evergreen brush such as tanoak, golden chinquapin, and snowbrush are difficult to control with aerial methods, depending on the herbicide used.

Coverage for soil-active herbicides such as hexazinone, sulfometuron, oxyfluorfen plus penoxsulam, indaziflam, and atrazine is less critical than with foliar-applied herbicides. Soil-active products tend to spread in soil when in contact with moisture and are much more forgiving if coverage is incomplete. The application method makes much less of a difference with soil-active products, provided that the application is done correctly. The greatest risks with hand applications and soil-active products are untreated skips from spray swaths being too far apart and proper equipment calibration.

Conifer tolerance

Herbicide choice and conifer tolerance also dictate the application methods that may be used. Broadcast applications over the top of established seedlings by aerial or ground methods are not possible with herbicides that do not provide conifer safety. In these cases, directed hand treatments may be the only option. Time of season may also dictate when over-the-top applications can occur with herbicides such as glyphosate. Conifers are tolerant to over-the-top applications of glyphosate in the fall, after buds have hardened off. If treatments occur earlier, conifer damage or mortality will occur.

Project scope

The application method chosen may depend on the project size and availability of local applicators. Aerial applications are well suited for large projects. Helicopter applications can usually treat up to 300 or more acres per day. Hand crews trained to do efficient broadcast applications can treat between 100 and 150 acres per day. If directed hand-spraying is required, production rates may drop down to between 30 and 60 acres per day, depending on the size and density of brush, access, and other logistical factors. It is critical to schedule out the project with a production plan to ensure that all objectives are completed, including requirements that contractors complete a designated number of acres per day, weather permitting.

Logistics

Logistical concerns can influence the choice of application method. Without good access for ground-spraying operations, costs can rapidly get out of control; in these cases, aerial applications may be more appropriate. To make aerial applications efficient, heliports, road access, water sources, staging, and storage areas all must be available and in good condition for a successful program.

Liability

Liability is a potential concern with any spraying operation. The land manager's responsibility is to anticipate and mitigate these concerns, in order to minimize the landowner's liability and environmental risks. The risk of litigation can also dictate the type of application method chosen. When spraying close to adjacent dwellings, a detailed analysis of the application method should be conducted, and aerial applications will not likely be the method of choice. Ground applications are a good choice when spraying around areas with water, wells, domestic ditches, and property lines, and where required herbicide buffers must be precisely applied. Often a combination of hand and aerial treatments can be used, with hand treatments applied around sensitive areas and aerial methods used on the remaining areas. Aerial applications can be made precisely, but alleviating concerns utilizing alternative methods can go a long way toward gaining trust and ensuring that future projects progress according to plan.

Site-specific issues with chemical vegetation control

Many issues can affect chemical applications, any one of which may negatively impact the outcome if not considered and planned for. Weather is perhaps the most important physical influence on spray operations,

affecting everything from efficacy to drift. As a land manager, knowing the conditions needed for a safe and successful application is imperative.

Weather

As temperatures increase, smaller spray particles are suspended in the air for longer periods of time and can drift away from the application site (Barry 1984). In general, the risk of off-site movement increases as temperatures go up. Ester formulations of triclopyr and 2,4-D have higher volatilization rates as temperature increases and humidity decreases. Volatilization occurs as temperatures rise, turning the ester formulations from liquid into gas (Gratkowski and Stewart 1973). The gas phase of the herbicide maintains its phytotoxic properties and can move off the application site, damaging desirable vegetation. Volatilization can be exacerbated on open rocky sites or sites with light-colored soils and little ground cover.

Applying volatile ester formulations during extended periods of hot, dry weather may not be feasible. The herbicide labels of volatile esters often restrict applications if the temperature is over 75°F or is expected to exceed 75°F immediately after application. Most herbicide formulations of 2,4-D and triclopyr are now either low-volatility esters or amines. Low-volatility esters still have the potential to volatilize and cause off-site movement of the herbicide under adverse conditions, but they are less likely to do so than regular ester formulations. Volatilization with amine formulations of herbicides is negligible, and they are more suitable for use in areas or under conditions where volatilization would have adverse effects. New choline salt formulations of 2,4-D and triclopyr volatilize even less than amine formulations.

Spray drift increases as humidity decreases and winds increase (Gratkowski and Stewart 1973), and if spray particles move off-site, both the efficacy of on-site target vegetation and potential damage to off-site vegetation can be greatly affected. In general, winds less than 5 miles per hour are acceptable for aerial applications, and winds should be less than 10 miles per hour for ground applications.

Pesticide labels frequently refer to temperature inversions, a weather condition that prohibits herbicide applications. In a temperature inversion, cold air is trapped under a layer of warmer air. This phenomenon typically occurs in valleys or basins during periods of calm winds. If an herbicide application is made during a temperature inversion, spray particles can get trapped in the inversion layer and move great distances horizontally. Spraying under these conditions should not occur due to the high potential for off-site movement (Dreistadt 2013).

Rainfall can also influence spray applications. For foliar-active products, rainfall too soon after application can wash the active ingredient off plant surfaces before penetration occurs, reducing efficacy. Several hours are usually needed for herbicide residues to adequately dry on plant tissue, but this time can be reduced with the addition of a spray adjuvant that increases penetration into leaf surfaces.

Soil-active herbicides require rain for activation, with rainfall being a necessary part of the equation for successful applications. Too much or too little rain can have a major effect on efficacy and possibly conifer tolerance.

Timing

Timing is a factor contributing to successful herbicide applications that is often overlooked. Target vegetation susceptibility varies depending on the time of year, and different herbicides have different application windows. Woody deciduous brush is usually most susceptible to systemic herbicides in late summer to early fall (Cole and Newton 1989), whereas woody evergreen brush is usually more susceptible to systemic or growth regulator herbicides from late spring to early summer (Paley and Radosevich 1984; Jackson and Lemon 1986). With foliar-active products, herbaceous vegetation has a small treatment window in early spring before senescence occurs in early summer.

The timing window for soil-active herbicides—which require rainfall for activation—depends on soil moisture availability, which is influenced by elevation, geography, and annual precipitation patterns (White et al. 1990). Ideally, soil-active products are applied in the spring at lower elevations to avoid winter precipitation, whereas high-elevation sites where snowfall is the predominant precipitation are treated in the fall. It is essential to understand how much precipitation is too much or too little and base application timing on the period that will come closest to receiving the proper amount.

For broadcast foliar herbicide applications over the top of existing conifers, the proper timing depends on when trees are hardened off and tolerant to the herbicide. Conifer tolerance to foliar herbicides is usually greatest in late summer or fall after buds have hardened off (Radosevich et al. 1980). The least tolerant period is when trees are actively growing. Since soil-active herbicides are usually applied in late fall or early spring when trees are still dormant, most soil-active products can be applied over the top of planted seedlings without foliar injury.

Soil type

Soil type plays a major role in how soil-active herbicides work. The active ingredient in many herbicides adsorbs to organic matter in forest soils. When percentages of organic matter are higher, more active ingredient is tied up in the soil and unavailable for plant uptake. Soils with high organic matter content may require higher rates of herbicide, or the organic content may be so high that soil-active herbicides do not work at all (Johnson 1987).

Soil texture also plays an important role with soil-active herbicides, which are more mobile in porous, well-drained soils with higher sand content and less mobile in soils with higher clay content (Johnson 1987). Well-drained soils with low organic matter content also carry a higher risk of conifer damage because herbicide is more available for plant uptake. The risk of leaching also increases as organic matter decreases and porosity increases. Land managers should take particular care when spraying on steep slopes with well-drained soils where sensitive areas are at risk from leaching.

Topography

Topography also plays a role in how herbicides behave and can affect the quality of an application. Steep slopes are more prone to leaching, especially in well-drained soils or rocky sites, and they are more hazardous for applicators, with both ground and aerial applications. Steep slopes usually require slightly larger buffers to avoid the contamination of watercourses. Even aspect can play a role regarding efficacy. Under drought-stress conditions, hot, south-facing slopes can stress plants to the point that herbicide uptake is negatively affected.

Herbicide formulations

Herbicide formulations can affect their efficacy. The herbicides used in forest applications are either liquid, granular, or dry-flowable formulations soluble in water. Liquid herbicides are formulated either as amines or esters. Esters are soluble in oil, and amines are soluble in water. Esters can penetrate the thick, waxy cuticle layers on leaf surfaces more easily than amine formulations, which is why esters tend to be more efficacious on difficult-to-control woody evergreen brush than amines. However, ester formulations have higher vapor pressure than amines and will volatilize at higher temperatures. Amines may be used at higher temperatures, but their efficacy may suffer. Amines have excellent efficacy on deciduous woody brush and herbaceous broadleaf plants and grasses, and their efficacy on woody evergreen brush has improved since the advent of methylated and ethylated seed-oil adjuvants.

Dry formulations present a different challenge. With granular products that are spread over the landscape surface and rely on rainfall to activate, the only real concern is making sure that the distribution of material through the application system is adequate for even coverage. Dry-flowables are finely ground powders that are added to water to form a suspension. When dry-flowable products are used, constant agitation during mixing and application is critical to achieve consistent rates. Today's dry-flowable formulations go into solution well compared to older formulations.

Spray application technology

Understanding the interactions between application variables such as drop size, volume, rate, and adjuvants is complicated and varies greatly by active ingredient and species to be controlled. However, understanding the basic principles of spray application technology can greatly improve both the efficiency and efficacy of herbicide treatments.

Drop size

With foliar applications, as drop sizes get smaller more of the plant's surface area comes into contact with the spray solution. While efficacy does not necessarily increase as drop size gets smaller, plant surfaces are covered more efficiently (Fredrickson and Newton 1998). The tradeoff is that smaller drops tend to drift, while large drops reduce drift significantly but coverage declines (Akeson et al. 1970). For soil-active herbicides, drop size does not affect efficacy so it makes sense to use larger drop sizes to reduce the risk of off-site movement.

Of several physical factors influencing drop size, nozzle size is the most obvious. It is extremely important to know exactly which nozzles the spray applicators are using for ground and aerial applications. The choice of nozzle will vary depending on the type of application. Certain applications require smaller or larger droplets depending on the objective. Aerial applications present the greatest potential liability from small drops, making it imperative that land managers do all they can to minimize the risk of off-site movement. Small drops should be avoided with aerial applications unless the risk of off-site movement is minimal.

Pressure at the nozzle can also affect drop size; as pressure increases, drop size decreases. Air and ground speed also affect drop size through shear at the nozzle. The faster that application equipment moves, the smaller drop sizes will be. Nozzle angle can also influence drop size with aerial applications. Drop size is decreased as the nozzle angle increases from horizontal in the direction of travel. The greatest drop size is achieved with nozzles angled straight back, which

reduces shear (Akeson et al. 1985). With helicopter applications, boom length controls drop size and spray deposition patterns. The shorter the boom relative to rotor length, the less rotor wash and liquid shear occurs at the nozzle. As boom length increases, a significant vortex occurs from downward airflow created by the rotors, decreasing drop size.

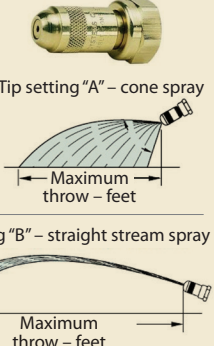
Nozzle characteristics

Nozzle types differ depending on the type of application (table 8.5). Nozzles selected for aerial applications differ from those used in ground treatments, with some overlap depending on the application method. There are many nozzles to choose from (including specialty nozzles) and the designations vary, but they all work under the same general principals. The choice of nozzle can have a significant effect on the success or failure of an application. The volume, rate, efficacy, deposition, and cost per acre are all affected by nozzle choice. If a hand crew is applying herbicides and the crew members do not all have the same nozzles, application rates between applicators can vary dramatically. The same is true for a helicopter boom fitted with different-size nozzles. It is imperative to pay close attention to these application parameters.

Flat-fan nozzles. Flat-fan nozzles, which are the most commonly used nozzles in hand-directed spray treatments, come in a wide range of sizes that produce very small to very large drops. They are designated by a series of numbers: the first two or three are the angle of the liquid emitted from the nozzle orifice and the last two are the gallons per minute put out through the nozzle at a set pressure, usually 40 pounds per square inch (psi). An 8003 nozzle, for example, has a liquid spray angle of 80 degrees, and each nozzle puts out a spray volume of 0.3 gallons per minute at 40 psi. The larger the last two numbers are, the greater the drop size. Flat-fan nozzles are also made in two different spray patterns, tapered or even. Even flat-fan nozzles maintain the same spray width from the center to the ends of the spray pattern. Tapered nozzles are widest in the center and get narrower at the ends of the spray pattern to allow for overlap of the spray solution. Even flat-fan nozzles are primarily used for banded applications in agriculture, whereas forestry applications mainly use tapered nozzles. Their specifications may vary somewhat depending on the nozzle manufacturer.

Off-center nozzles. Off-center nozzles are one of the most commonly used for broadcast applications by ground in forestry. These nozzles produce a different spray pattern than flat-fan nozzles. The spray solution is emitted from one end of the nozzle and thrown out away from the applicator in an arcing pattern. This nozzle produces excellent coverage when the nozzle

TABLE 8.5. Common nozzle types used in forestry applications and their spray patterns

Nozzle	Type	Pattern	Uses
11004	Tapered flat-fan		Directed hand-spraying, broadcast applications on fixed boom
8004	Even flat-fan		Band applications
OC-12	Off-center		Waving-wand hand broadcast applications, roadside boom
D-6	Disk		Aerial broadcast, hand broadcast with gun-jet, spot-gun applications with meter-jet
5500	Adjustable tip		Basal treatments, hardwood clump sprouts, waving-wand hand broadcast applications

is attached to a handheld spray wand and waved side to side for broadcast applications. The nozzles are designated with two letters followed by a number. A popular off-center nozzle used in forestry is an OC-12; the number designates the gallons per minute emitted from one nozzle at 40 psi. In this case the 12 stands for 1.2 gallons per minute, whereas an OC-06 emits 0.6 gallons per minute. Similar to flat-fan nozzles, nozzles with larger numbers produce larger drop sizes.

Disk nozzles. Aerial applications in forestry primarily use disk or disk-core nozzles that rely on air speed and nozzle angle as well as orifice size to manipulate the spray pattern and drop size produced. Disk nozzles produce a spray pattern in the form of a stream, and when a disk core is added to the nozzle the spray pattern is a cone. The cone pattern produced by disk-core nozzles can either be hollow in the center (hollow) or completely covered (full cone). Many aerial applicators choose to apply pesticides without a core and just use

the disk orifice to produce a stream from the nozzle. In this case, the applicator relies on air speed and nozzle angle to shear the stream and produce a desirable spray pattern. This significantly reduces drift by creating larger drop sizes, but coverage may be affected.

D-series disk nozzles. D-series disk nozzles are probably the most popular nozzles for helicopter applications. The D stands for disk nozzle and the number refers to the orifice size. The number does not specifically correspond to a certain volume per minute, only the orifice diameter. For example, a D-8 disk nozzle puts out significantly more volume and larger drop sizes than a D-4 nozzle. The drop size produced by a nozzle on the ground while not moving is going to be much greater than when it is attached to a boom at a certain angle and traveling at a relatively fast air speed. As air speed and the mounted nozzle's angle from horizontal increase, drop size decreases. D-series nozzles can be used for both aerial and hand applications, and they are the main nozzle chosen for broadcast hand applications with gun-jets.

Application volume

Changing the application volume per acre can effect several spray parameters, including cost. In general, volume per acre has little effect on efficacy (with a few exceptions); for example, glyphosate is more effective at low volumes per acre (Ambach and Ashford 1982; Buhler and Burnside 1987; Cranmer and Lindscott 1990). Rather, volume per acre affects coverage. Higher volumes per acre can negatively affect efficacy, due to large droplets bouncing off leaf surfaces reducing the amount of chemicals absorbed into leaf surfaces (Young et al. 1987). Volume per acre is best managed by adjustments to nozzle size and travel speed.

The main drawback of using high spray volumes is cost. As spray volume increases, the time required to spray a given area increases as does the cost per acre. This is most dramatic with hand applications, which can easily double labor costs just by doubling the spray volume. Foresters often mistakenly attribute increased efficacy to increases in the volume of herbicide solution applied. In reality, this is actually due to an increase in herbicide rate from higher volumes applied. The efficiency of applications can be significantly improved with higher rates and lower spray volumes (Fredrickson 1994).

Rates

The most important variable affecting efficacy is product rate (Fredrickson 1994; Fredrickson and Newton 1998). Many times, an increase in volume is mistakenly credited for increased efficacy with directed-spray applications, when the rate increase inherent with

increasing volume was actually responsible. The challenge for foresters is to use the lowest rate possible for maximum efficacy, thereby increasing efficiency. Most herbicides are expensive, and making applications as efficient as possible easily justifies the effort.

Adjuvants

Adjuvants are any type of additive to the spray mixture that changes the physical properties of the spray solution. Surfactants, spreaders, stickers, and buffering agents are all adjuvants; we mainly discuss surfactants here. Water has a high surface tension that causes droplets to bead up on leaf surfaces. Surfactants reduce surface tension, causing spray droplets to spread over leaf surfaces, thereby maximizing coverage (Hess and Faulk 1990). Surfactants also aid in the penetration of waxy leaf cuticles, increasing the amount of active ingredient absorbed into the plant. Rain-fastness can be improved with the use of adjuvants by speeding up absorption rates into plant tissues (Stevens and Zabkiewicz 1990; Sundaram 1990a, b).

The main types of surfactants used in forestry are nonionic, cationic, silicone-based petroleum distillates and methylated or ethylated seed oils, which all reduce surface tension and cause droplets to spread. The silicone-based surfactants reduce surface tension the most and result in the greatest droplet spread. However, this doesn't necessarily correspond to increased control (O'Sullivan et al. 1981; Fredrickson 1994). Many herbicide products are formulated with adjuvants, although in many cases adding a surfactant to a product that includes surfactant adds no additional benefit (Babiker and Duncan 1974; Brewster and Appleby 1990; Fredrickson 1994).

Historically, nonionic and silicone-based surfactants were mainly used with water-soluble amines. Petroleum or seed-oil-based adjuvants were primarily used with oil-soluble esters. This has changed in recent years; the seed oil products tend to work well with either amines or esters. Adjuvants are usually cheap to use but it shouldn't be taken for granted that they increase efficacy. Furthermore, surfactants can also have a negative effect on conifer tolerance (Fredrickson 1994).

Application methods

The chosen application method influences the physical properties of the application, but mainly from a spray deposition standpoint. Treatments made by hand will directly deposit spray solution exactly where it needs to go, and the risk of off-site movement is minimal. Aerial applications disperse spray solution the most widely, but deposition of the spray solution is not as accurate as hand applications. Ground applications

with tractors or off-road vehicles fall somewhere in-between. The main tradeoff between the methods is cost, with hand applications the most expensive and aerial applications the least.

Aerial

Aerial applications are the most efficient method of applying herbicides, enabling large areas to be treated in a short period of time. Rough topography, poor access, lower cost, and large acreages are all factors that favor aerial applications. Generally, helicopters can carry 8 to 10 acres worth of herbicide per load depending on the elevation. Applications with fixed-wing aircraft are only possible on flat, open ground, but they are more efficient than helicopter applications and can apply 50 or more acres per load. The following discussion refers primarily to helicopter applications.

Targeting vegetation

Developing prescriptions for aerial applications requires a good understanding of what can and can't be controlled by air. Since the quantity of material applied is less with aerial applications compared to hand treatments, controlling hard-to-kill brush species is more difficult by air. Hand directed spray treatments have better coverage than aerial treatments, resulting in better efficacy. Herbaceous vegetation can be controlled equally well by air or ground methods.

Herbaceous vegetation can be controlled with either foliar- or soil-active products, which differ in their duration of control. Any of the foliar chemicals—such as glyphosate, triclopyr, 2,4-D, imazapyr, fluroxypyr, or clopyralid—will cause mortality of established herbaceous vegetation via aerial applications. With the exception of imazapyr, these products have little or no soil activity to prevent further germination, and herbaceous vegetation will rapidly reoccupy the site following application.

Soil-active products such as hexazinone, atrazine, indaziflam, sulfometuron methyl, and oxyfluorfen plus penoxsulam, have residual activity in the soil and will extend the duration of control. Hexazinone, atrazine, and oxyfluorfen plus penoxsulam have excellent conifer tolerance and can be applied pre- or postplanting. Conifer tolerance issues with sulfometuron methyl prevent it from being used in interior California, but applications on coastal sites in the redwood range are possible. Hexazinone has the best knockdown of emerged herbaceous vegetation. Atrazine, indaziflam, and oxyfluorfen plus penoxsulam are best suited to preemergent applications unless another herbicide can be added. Knockdown of existing herbaceous vegetation with oxyfluorfen plus penoxsulam is better than

atrazine and can be improved with the addition of a methylated-seed-oil adjuvant.

Controlling brush with aerial applications is more difficult. The size and type of brush, product and rate, timing, and adjuvant have major influences on control. Deciduous brush such as deerbrush and snowberry are fairly easy to control with glyphosate. As deerbrush gets larger, control by air becomes more difficult. This is true for most woody brush. Deciduous hardwood sprouts are also difficult to control by aerial methods. The use of imazapyr alone or in combination with glyphosate dramatically improves the control of larger, woody deciduous brush, and the addition of methylated or ethylated seed oils further improves control.

Scheduling these treatments in late summer is usually better than earlier due to carbohydrate movement down into the root system later in the season. Due to conifer tolerance issues with imazapyr, only preplant applications are possible in the year prior to planting, and seedlings still may show some symptoms of damage. Deciduous brush and hardwood sprouts should usually not be treated by air with growth regulators such as 2,4-D or triclopyr. These growth regulators cause rapid brownout of deciduous foliage and heavy damage to the plant's translocating tissue, resulting in rapid resprouting. Deciduous woody brush and hardwood sprouts treated with growth regulators usually require retreatment with a different method and product to achieve satisfactory control.

Evergreen brush such as tanoak, golden chinquapin, greenleaf and whiteleaf manzanita, whitethorn, and snowbrush can be difficult to control by air. Again, small plants are much easier to control by air than larger ones. The best control of evergreen brush is usually achieved with the oil-soluble formulation of imazapyr (Chopper or Polaris AC), alone or in combination with glyphosate plus a methylated seed oil. These two systemic herbicides work well in combination. Both are ALS inhibitors, but they each inhibit three different amino acids (Ahrens 1994). Imazapyr inhibits valine, leucine, and isoleucine, while glyphosate keeps plants from producing tyrosine, tryptophan, and phenylalanine. They both translocate well within the plant and do little damage to the translocating tissue. Coverage is usually the critical factor when aerial applications are used. Evergreen brush is easily controlled with this herbicide mix by hand applications, while aerial treatments are usually less effective but still acceptable.

Triclopyr ester, fluroxypyr, and/or the 2,4-D ester formulation can also be used on evergreen brush species, but results are slightly less effective than the glyphosate plus imazapyr combination. Applications of fluroxypyr and 2,4-D ester plus a methylated seed oil control manzanita species well. The application timing

for evergreen species is different than deciduous brush, with early summer usually providing the best control by either the glyphosate and imazapyr combinations or growth regulator applications of 2,4-D, fluroxypyr, or triclopyr esters. When applying the ester formulations of 2,4-D and triclopyr, volatility is a concern if temperatures exceed 75°F. If temperatures are warm, these products should not be used near neighbors or crops as off-site damage may occur.

Project planning

Planning is the first step of any helicopter application program. Foresters must first evaluate each site unit by unit to determine which can be applied by aerial methods and which are better suited to ground treatments, as well as what herbicide prescriptions are needed. Most units can be treated by air unless water courses, sensitive areas, or neighbor issues limit the amount of ground that can be treated. From a cost perspective, large steep units with poor access are ideal for helicopter applications since hand treatments may be cost-prohibitive.

Define project boundaries. During initial site visits, foresters must define unit boundaries and identify suitable heliports, staging areas, water sources, access, potential hazards, and sensitive areas in need of mitigation. The pilot will be flying 50 to 100 feet above ground, traveling at roughly 50 miles per hour, so unit boundaries should be clearly defined and obvious. Boundaries are usually defined by the edge of mature timber or roads. However, in many cases, such as when dealing with large burns and multiple landowners, boundaries will not be clear. Unit boundaries, property lines, exclusion areas, and the like may be difficult to see, especially when different landowners have treated their ground in relatively the same ways. Defining property and boundary lines as well as exclusion areas can be done by painting large spots (at least 2-foot diameter) with bright marking paint on rocks, stumps, or logs, about every 50 feet. Blue marking paint shows up especially well from the air. Large, reflective pieces of foil or heavy, high-visibility flagging can also be used.

Identify heliports. Suitable heliports can be difficult to find. Large landings work well, provided there are no obstructions such as larger trees, saplings, or landing piles to hinder ingress and egress. Heliports need to be large enough to accommodate the helicopter, batch truck, and a pickup truck, with adequate room for maneuverability. Heliports should have at least two clear directions for takeoffs and landings. Helicopter pilots prefer to take off and land into the wind so multiple options are helpful. Ideally, some slope helps the helicopter pilot to drop off the heliport,

which also should be smooth, level, and not so dusty that the pilot's vision is impaired; treating heliports with water during dry conditions may be necessary. Good access to heliports is a must because the batch truck will need to be within about 50 feet of the helicopter to fuel and load with the spray solution. The number of heliports needed for a project depends on the size and number of units. The maximum distance flown from each heliport should be roughly a 1-mile radius unless no other options are available. Ferrying long distances is extremely expensive for the contractor, and if there are no other options the lack of nearby heliports needs to be made clear in the contract negotiation as it will affect the price.

Find water for mixing. The ideal and easiest way to obtain water for mixing is from a mill site, log yard, office, or other property under your control. Creeks may be used, provided the drafting equipment on the batch truck is equipped with antibackflow devices to prevent contamination. It is prudent to avoid drafting from streams or ditches that supply domestic water. If you are unfamiliar with the water sources, test them for pH and cations, as high cation content indicated by a high pH can tie up active ingredients in the solution, affecting efficacy. Never batch near your water source. Whenever possible, batching should be done on the spray site.

Map mitigation areas. It is critical for foresters to locate and define areas within the spray project area such as water courses, springs, wells, domestic ditches, lakes, ponds, property lines, and other resources that need protection. Once located, they should be mapped and well defined on the ground so that the pilot is fully aware of their presence.

Contact neighbors. If the project occurs near residences or other neighboring landowners, make contact with them ahead of time. A written neighbor notification program is a valuable tool for training foresters and improving their ability to communicate what you are trying to accomplish, while addressing any concerns that neighbors may have. Many problems can be avoided through good communication. Showing up unannounced at their doorstep with a helicopter first thing in the morning is not the best way to meet your neighbors.

Drive roads. Roads are often an overlooked aspect of spray operations. All roads accessing the project area should be driven before spraying operations occur. Roads must be cleared of debris and passable for a 4,000-gallon batch truck. Water bars must be lowered or removed if present, and any rolling dips or other drainage structures need to be passable. Helicopter time and auxiliary equipment are expensive, and unexpected delays can't be tolerated.

Secure equipment. Establish a secure staging area for storing the helicopter and batch truck when not spraying, where the spray equipment is watched or in an area restricted to company personnel.

Deliver and store chemicals. Chemicals for the project should be delivered ahead of time to avoid potential delays. In favorable conditions, helicopters can apply as much as 600 acres per day. Transportation and storage of chemical must be addressed before the project starts. The storage area must be a locked, secure, placarded area. As much as possible, minimize the distance that chemicals must be hauled to the project area.

Map units. GPS and GIS should be used to ensure accurate mapping. Unit boundaries, roads, stream courses, lakes, ponds, ditches, protected areas, and property lines should all be accurately mapped using GPS and downloaded directly into the GIS. Most helicopters are equipped with GPS guidance systems. Shapefiles for layers from the landowner's GIS system can be downloaded directly into the helicopter's GPS system. The GPS system not only shows the pilot an accurate map of all the layers in the system, but also maps the spray swaths and helicopter position as the application occurs. This provides a mapped record of areas that were and weren't sprayed, including aerial buffers, exclusion areas, and the unit itself.

Complete spray contracts. Spray contracts must be prepared and contain all the necessary information and instructions to complete a successful project. Contracts should include a unit summary and treatment list, price per acre or other unit, project maps, application parameters, acceptable weather conditions, weather and application record-keeping requirements and forms, licensing requirements, mitigation measures to follow, production schedules, chemical handling and transportation procedures, use reporting guidelines, container disposal guidelines, and any other pertinent guidelines or information.

Project implementation

When an aerial project is ready for implementation, it's helpful for the forester in charge of the project to have two to three people working with them in the field. These extra people can check weather conditions on units in advance of spraying, make sure units are clear of people, block access into the spray area, lead equipment in and out of spray units, and keep weather records. By knowing what the weather conditions are on units yet to be sprayed, the project manager can efficiently move from one spray area to the next, saving valuable time and money.

When the helicopter arrives, go over the spray plans, herbicide mixes, application volumes, mitigation

measures, policies, and calibration with the pilot and batch truck driver. To achieve the desired application rates, it is critical to ensure that the helicopter is calibrated prior to starting. For reference on aerial calibration, see Dreistadt (2013). Check the nozzle setup on the helicopter and make sure it is acceptable for your objectives. Based on the contract specifications, the helicopter should be set up the way you want it, but don't take that for granted.

Batching should be done on the spray unit at the start of each day to minimize traveling with a load of chemical in the batch truck. Batching on the unit also provides the opportunity to assess weather conditions and batch amounts that can easily be finished. Whenever possible, avoid letting chemical sit overnight in the spray tank, which reduces problems with settling and potential vandalism.

Determining where to start your project may not make a difference much of the year, but occasionally in the fall with large projects bad weather could influence your program. In the fall, start at the highest elevations and work downhill to avoid potential snowfall. The opposite is true with large projects beginning in the spring, when it usually makes sense to work from low to high elevations as snow melts. Understanding local weather patterns, especially wind patterns, will help to save time and money on figuring out where to start each day. Wide temperature swings during California days often cause dramatic changes in wind patterns and directions. Storm fronts bring in their own wind patterns, both before and after. While all of these factors can effect spray operations, the wind patterns are fairly predictable.

Before spraying begins, the forester should conduct reconnaissance of all units with the pilot. The forester should show the pilot unit boundaries, water courses, property lines, sensitive areas, and anything else of concern, as well as provide special instructions such as when and where to utilize a split boom. The forester should document the instructions for the pilot in their daily spray records. Written notes are critical documentation in the event of legal actions concerning spray applications.

Finish spraying one unit before starting the next. As part of the project record keeping, the forester should track each load and the volume applied for each unit. It is imperative to know how much spray volume went on each unit. If the pilot is flying more than one unit at a time it may not be possible to accurately record the volume of herbicide applied on individual units. Keep in contact with the pilot during the application but try to keep radio traffic to a minimum.

Be observant during the spray operation. Watch as creeks and drainages are flown to assure proper

buffering is done and split-boom applications are used. Make sure all the nozzles on the boom are working. Keep a watchful eye out for people or vehicles entering the spray area.

Accurate record keeping is invaluable, allowing you to keep track of the herbicide volume used, time, rates, mitigation measures used, costs, weather conditions, and personnel. At minimum, the forester should have two data sheets for record keeping, one for weather and another for each unit's spray record. At minimum, the weather should be recorded at least every hour, if not more often, as well as time, wind speed and direction, temperature, and humidity. California law requires the pilot to keep weather records. The unit summary should include the unit's name or number, acreage, personnel present, contractor, herbicides used and rates applied, volume per acre, mitigation measures used, number of loads flown, volume used per load, total gallons flown, time each load was flown, pilot name, and any other pertinent application notes.

Hand applications

Many application techniques and types of equipment can help improve efficiencies and reduce the cost of hand applications. Making effective and efficient applications by hand is an art. As a result, labor is an important area for the reforestation forester to focus on to reduce the cost of hand-spraying.

Having the right equipment

Hand-spray crews usually have 10 to 14 people, so any time the crew is waiting around and not spraying is costly. Efficient application equipment should be built around the concept of reducing that time. If a crew has to spend time waiting for more water or walking back to the batch truck to fill up their backpacks, costs can skyrocket.

The batch truck and associated equipment are key to reducing costs in the field. Batch trucks should be set up with a spray tank large enough (about 500 gallons) to carry a sufficient supply of chemical. Having an adequate water supply is key to reducing downtime. A water-tender trailer is essential to reduce application costs. To work with the batch truck, a trailer fitted with at least a 750-gallon water tank is generally enough to supply a crew for an entire day. The water-tender trailer should also be fitted with lockable metal storage bins to carry chemical and drafting and other spray equipment. Drafting equipment should be kept in a separate, chemical-free storage container. Herbicide-contaminated equipment should never be used for drafting water. Storage containers should be large enough to carry several 30-gallon containers of

chemical; having enough chemical onboard to last several days also helps reduce costs.

Reducing the amount of time a crew spends walking without spraying also helps to keep costs down. Reforestation units are often large, and when crews run out of spray solution in their backpacks, the time required to walk back to the batch truck to fill up can be substantial. Any efficient spray operation should have batch trucks set up with a power-take-off–driven pump-and-hose system to bring the chemical to the crew instead of the crew to the chemical. A hose reel capable of holding at least 1,200 to 1,500 feet of high-pressure hose with the ability to pump uphill as well as down can save time that would otherwise be spent walking. The hose reel itself needs to be set up with a powered reel-up system, as hose with a full load of chemical can be heavy. Hydraulic-powered systems are usually best.

Good communication between the crew foreman and the batch truck driver is essential. Each should have a portable radio for telling the batch truck where to move and when to pull or reel up the hose, which also saves time.

In certain instances, such as large wildfires with poor access, an off-road vehicle equipped with a spray tank and delivery system can help to fill backpacks in the field. In remote areas where hose reels cannot supply enough hose to reach the crew, an off-road vehicle is an efficient alternative.

Managing access to units is critical. Too often roads that provide access to reforestation units are decommissioned immediately after logging operations cease. Communicate with logging managers and plan writers about the importance of leaving access to units open at least until reforestation efforts are complete, which may be several years. Poor access affects the cost of all reforestation activities, not just spraying.

Spray crews must be supplied with a wide variety of application equipment to achieve the desired reforestation objectives. Besides standard backpacks and spray wands, crews should be trained and have equipment for broadcast, spot-gun, gun-jet, and hack-and-squirt applications. An extensive selection of nozzles including flat-fan, off-center, and adjustable-tip nozzles also allows for wide flexibility in the types of applications crews can do.

Directed hand-spraying

Hand applications include individual plant treatments and broadcast applications where 100 percent of the ground area is treated at a specific rate per acre. Directed-spray applications are the most common type of individual plant treatments, used primarily to control difficult woody brush. Individual plants are

sprayed with a standard backpack and wand, usually equipped with a flat-fan nozzle. Nozzles with narrower angles give the applicator more control over which plants are covered. Occasionally adjustable-tip nozzles can be used for taller brush such as hardwood sprouts, allowing the applicator to reach up higher on the plant.

Directed-spray applications are used when the herbicide cannot be applied over the top of existing conifer seedlings without injury and protecting seedlings is necessary. Usually, each applicator carries a shield with a handle to cover seedlings while the applicator sprays surrounding vegetation, protecting them from any chemical contact.

With directed-spray applications, knowing the target volume per acre is important because maximum label rates must not be exceeded; plus, as volume per acre increases, crews slow down and, in turn, costs increase. By observing the crew spray a small, known acreage at the beginning of the project, the forester can determine the volume per acre and adjust accordingly. Foresters should observe the spray pattern so that they know whether crews are applying too heavily or lightly. With directed applications, the use of dye is required to see what has been sprayed.

Directed-spray applications are usually batched on a percentage solution basis. If so, the forester must convert from percentage solution to rate per acre to determine if the application is within designated prescription rates. For example, if the maximum rate per acre of an herbicide is 1 quart per acre and the crew applies the mix at 25 gallons per acre spray volume, the percentage solution rate cannot exceed 1 percent to avoid going over the maximum label rate. To correct the volume per acre, nozzle size can be adjusted or the crew members can change the volume they put on each plant.

With smaller brush, applying less volume translates into lower costs for labor and chemicals. The crown volume of woody brush grows at an exponential rate from year to year. If spray projects are delayed until brush gets large and dense, application costs can easily reach several hundred dollars per acre for labor. Small seedling brush can be controlled more easily with lower labor costs and less herbicide applied. However, foresters should be careful not to treat woody brush that has sprouted from old root systems too early, before the plants are able to put on enough crown to absorb enough chemical to control the existing root system.

Directed spraying is not usually done to treat herbaceous vegetation, with one exception: occasionally landowners may want to apply glyphosate as a foliar treatment after planting. Glyphosate must be applied as

a directed treatment since freshly planted conifer seedlings are intolerant to over-the-top applications. Since glyphosate does not have soil residual activity, weed seeds will not be controlled if the treatment is made before they have germinated. Likewise, if the application is made after germinated plants have set seed, new seed will be present to germinate in subsequent growing seasons. For these reasons, controlling herbaceous vegetation with glyphosate must be considered critically and carefully timed. Longer-lasting herbaceous treatments can be applied as a broadcast treatment with hexazinone, atrazine, indaziflam, sulfometuron methyl, or oxyfluorfen plus penoxsulam as a preplant application, unless conifer tolerance or company policies dictate otherwise.

Directed-spray treatments can be effective around sensitive areas such as watercourses, lakes, ponds, property lines, and other sites needing protection. Herbicides can be placed accurately with this method with minimal risk of off-site movement.

Broadcast hand treatments

The most efficient method for hand-applying herbicides is as a broadcast treatment, similar to a helicopter application. With broadcast applications, 100 percent of the ground area is treated in a systematic, calibrated fashion. Depending on the conifer tolerance of the herbicide used, broadcast treatments may be applied pre- or postplanting. Broadcast is the most cost-effective method of hand application. Depending on the equipment used, costs are close to those of a helicopter application.

Several methods can be used to apply broadcast treatments except for boom spraying, which is possible but not practical with a large crew and requirement for heavier volumes of spray solution than individuals can carry cost-effectively.

Most broadcast treatments by hand are applied with the waving-wand technique (Newton et al. 2009), which can use either a conventional spray wand or a gun-jet application system. The wand is waved side to side at moderate speed so that the stream from the nozzle overlaps, creating a solid swath as the applicator moves forward. To apply this method properly, the applicator must know the width of the swath they are producing, wave rapidly enough that coverage is solid, and calibrate the walking speed to achieve the target volume per acre.

The crew must be calibrated prior to making the application. To calibrate the waving-wand method, first stand in one spot and spray, waving the wand back and forth until the effective swath (excluding scattered large droplets visible on each end of the swath) is visible on the ground, then measure its width. Measure

an amount of water (such as 1 gallon) and put it in the backpack. Walk at a comfortable pace that can be maintained across an entire spray unit. Spray out the gallon of water walking at the chosen pace and waving the wand back and forth exactly as when the swath was measured. Measure the distance traveled from where spraying started to when the backpack ran out of water. Calculate the area covered in square feet (swath width times distance traveled, in feet). Divide that number by 43,560 (square feet in an acre) to get the percentage of an acre sprayed, then divide that percentage into the volume sprayed out (in this example, 1 gallon). That will tell you how many gallons per acre of spray solution was applied at that walking speed.

This walking speed and waving technique must be replicated by all of the crew members, and they must be spaced apart evenly so that swaths do not overlap too much or too little. Crews that are not properly calibrated or trained in application procedures can result in the wrong rates being applied, conifer injury, or excessive skips across the spray unit. This method is highly effective and efficient but should only be applied by a properly trained and experienced crew.

It is important to distinguish the difference between the volume of solution applied per acre and the rate per acre of the herbicide being used. In general, 5 to 10 gallons per acre of solution are applied (water and chemical) with waving-wand applications, depending on the method. The rate per acre of herbicide is designated separately. For example, 2 quarts per acre of a glyphosate product can be applied in either 5 or 10 gallons per acre of total solution. The 2 quarts of glyphosate remain the same, but the dilution changes.

Several application setups can be used. For maximum production, use gun-jet applicators. This wand looks different than a typical backpack wand and uses disc nozzles similar to those used in helicopter applications. The gun-jets can be adjusted so that the spray output ranges from a straight stream down to a fine mist. To properly set the nozzle, open the nozzle all the way so that it emits a straight stream and then close it down to the point where the stream is just starting to become fractured. When waved side to side, swath widths of up to 30 feet can be achieved. Care must be taken to point the gun-jet away from the applicators so that they do not walk into the spray material. The gun-jet system is better suited for soil-active herbicides as coverage is slightly variable. It is also highly sensitive to wind, and worker exposure can occur if not properly applied. Adjustable-tip nozzles can also be used with a normal spray wand that simulates a gun-jet application, but crew production and swath widths will be slightly lower. This method is slower, but it is safer regarding worker exposure and drift.

Wands fitted with off-center nozzles are the most effective and controllable. The off-center nozzle puts out an elongated spray pattern, which when waved side to side provides superior coverage over other waving-wand methods. Applicators are also least likely to be exposed to herbicide spray, as the nozzle spray pattern is pointed downward and thrown away from the worker as it is applied. This method can be used with either foliar- or soil-active products. Off-center nozzles with smaller orifices should be utilized for foliar applications to achieve better coverage. Swath widths are reduced to about 12 to 15 feet with off-center nozzles compared to gun-jet systems, but production rates are only slightly lower. Swath width and walking speed increase as the size of the nozzle orifice increases, in turn reducing application costs.

Topography can severely affect the spray crew's pace during waving-wand applications. Crews have a tendency to slow down on steep slopes or in units with heavy slash loads. The forester and foreman must be aware of changing conditions that affect the volume per acre applied. Altering the nozzle size is a good way to deal with changes in topography. Using smaller nozzles on steeper slopes or units with heavy slash will adjust for a slower walking pace and maintain the same volume per acre as applied on easier ground.

Another limitation of the waving-wand method is the height and density of brush. When brush gets to more than about 3 or 4 feet tall and is dense, waving the wand, maintaining the right pace, and keeping crew members together becomes more difficult. To do these applications effectively, crew members must stay together and maintain an organized line so that each one can see where the next has sprayed. The last applicator in line, or the foreman, needs to flag the outside spray line so the crew knows what has already been sprayed when they turn around to make another pass.

A crew well-trained in broadcast application techniques is an invaluable asset to a reforestation forester. Application costs can range from \$40 to \$65 per acre for labor, depending on the application and site. Broadcast waving-wand treatments should not be contracted out as a low-bid application; they are complicated, and results can be poor if the herbicide is not applied properly. Foresters should be aware that crews may cover large acreages in one day, but if the treatments are not applied properly they could be ineffective, resulting in additional costs.

Hack-and-squirt

Hardwood trees and sprout clumps are competitive with young conifer seedlings in California (Jackson and Lemon 1988). Sprouting hardwoods from cut stumps can occupy large areas within a reforestation

unit in a short period of time, depriving seedlings of valuable light, nutrients, and water (DiTomaso et al. 2004). Where hardwood populations are heavy, reforestation units can be entirely dominated by hardwood cover if not managed. It is wise to designate a certain number of hardwood trees and clumps for wildlife habitat, but if left totally unmanaged they can cause significant problems for reforestation efforts.

The hack-and-squirt is a simple but efficacious, efficient, and cost-effective treatment that allows land managers to maintain hardwoods at a chosen density. The tools required are a hatchet, small gravity-fed backpack, and calibrated veterinary syringe that can deliver specific amounts of liquid herbicide (see fig. 8.4). In most cases the delivery amount is set at either 0.5 or 1 milliliter of liquid. The number of hacks made per tree is either a specific spacing around its circumference or one hack per certain number of inches of tree diameter at breast height (see fig. 8.5). For example, a hack can be placed every 6 inches around the tree circumference. When using diameter as a guide, a tree can be injected using one hack for every 3 inches of diameter at breast height. For example, a 9-inch tree seedling would receive three hacks. Once hacked, the appropriate amount of (usually) undiluted chemical is injected into each hack using the veterinary syringe.

When treating hardwood clump sprouts with stems that are too small to hack on a circumference or diameter basis, the number of injections is usually determined by selecting a certain number of stems to inject per clump. Stems may either be hacked with a hatchet if large enough or snapped by hand and the chemical injected into the broken stem.

Trees and clump sprouts can be injected most of the year, but spring treatments are not recommended when sap is flowing. At that time, chemical injected into the cuts can be pushed out of the hack area to the extent that it makes the treatment ineffective. Bigleaf maple will begin flowing sap as early as late January in Northern California. The most effective timing is usually late summer through the entire winter for most hardwoods (DiTomaso et al. 2004).

The most widely used and effective herbicide for injection treatments is imazapyr. Conifer tolerance precludes using imazapyr as a release treatment in many situations, but it is ideal for preharvest or preplant site preparation. However, it's important to note that imazapyr has soil activity and translocates well with plant systems. Many hardwood species growing in close proximity to one another form root grafts. Any tree that is root grafted to a treated tree may show visible symptoms or even death; this is important to consider when treating near property lines. Buffer zones may be needed to prevent inadvertent mortality across

property lines or to trees intended to be retained for wildlife habitat (DiTomaso et al. 2004). Imazapyr may also be exuded through the roots of treated trees into the soil, where conifer seedlings can absorb it and be damaged.

One of the benefits of hack-and-squirt treatments is that crews can operate when it is windy or other weather precludes foliar spraying. The only weather condition that prohibits hack-and-squirt applications is heavy rain, as freshly injected chemical may be washed out of the cuts. Having the option of utilizing the crew for hacking when weather prohibits other application methods provides a more consistent work supply in treatment programs.

Application costs depend on the density and type of hardwood treatment. Labor costs with hack-and-squirt in interior California for a typical black oak stand average between \$20 and \$50 per acre. Hack-and-squirt treatments on the California coast can be much higher due to heavy densities of tanoak or dense understories of other hardwood sprouts. Herbicide rates per acre should be closely monitored in stands that have high stem densities, because the maximum rate per acre could easily be exceeded. Treating hardwoods prior to planting is preferable to postplant treatments, and the benefits include lower costs, better conifer tolerance, and higher efficacy.

Cut-stump treatments

Cut-stump treatments are seldom utilized in forestry due to their cost and the availability of other more efficient and effective methods. Trees or brush are treated by first severing the stem or bole with a chainsaw or other cutting tool, then applying either a high-concentration solution or undiluted herbicide around the cambium of the stump with a squirt bottle. Herbicide need not be applied to deadwood in the center of the stump. The key to cut-stump applications is to treat immediately after cutting because delays will dramatically reduce translocation and efficacy.

Triclopyr, glyphosate, and imazapyr are the most commonly used herbicides for cut-stump applications. It is imperative to use the amine formulation of triclopyr in warm weather because the ester formulation will volatilize. Take care not to treat stumps with imazapyr along property lines or rights-of-way where adjacent vegetation may be root-grafted to treated stems. Cut-stump applications are most effective in the late summer to winter but may be used most times of the year other than during spring sap flow.

The major deterrent to cut-stump treatments is the labor costs associated with cutting vegetation. Chainsaw removal of large brush can cost as much as \$300 to \$400 per acre in dense stands. These

treatments are often used when brush is too tall for foliar sprays, but the land manager wants to treat vegetation before clearing the ground for planting to avoid resprouting. Where vegetation is so large that it cannot be foliar-treated before mechanical site preparation, it may be more cost-effective to pile the vegetation first and then manage resprouting. In general, it is best to treat vegetation prior to removal to maximize efficacy and reduce costs.

Basal-bark treatments

Basal-bark treatments are used primarily to control resprouting hardwoods and larger woody brush. The herbicide solution, usually triclopyr ester and imazapyr, is applied to the bark of the plant's lower stems, near the ground. With basal treatments, herbicides are mixed with a basal-bark oil as the carrier instead of water to get penetration through the bark. Bark thickness increases as plants get older, and, therefore, basal treatments are limited to stems with a maximum diameter at the ground of 3 inches or less.

The types of basal-bark treatments are conventional, low volume, and thin-line. With conventional basal treatments, the stems of treated plants are sprayed around the entire circumference from the ground up to a height of 18 to 24 inches, depending on the land manager's preference. To ensure control, completely cover the circumference of every stem and heavily cover the root collar area on the stump. Low-volume basal treatments are applied the same way, but the herbicide concentration is significantly higher than in conventional basal treatments and stems are only treated to 6 inches above the ground line, reducing the total volume used.

Thin-line treatments are also applied to the base of stems, but with the highest concentration and lowest volume of herbicide solution compared with other methods. The spray solution is applied through a nozzle that produces a straight stream, which is arced across the base of the stems from left to right to a height of about one foot above the ground line from three or four sides of the plant. The idea is to connect all of the arcs so that all stems receive some coverage. Unlike conventional or low-volume basal treatments, complete coverage around the entire circumference of the stem is not necessary due to the high concentration of herbicide solution.

Labor costs are most expensive for conventional basal treatments, followed by the low-volume and then thin-line treatments. The efficacy of basal-bark treatments varies dramatically by geographic region. In interior California, basal treatments do not typically work as well as those designed to treat hardwood sprouts, such as foliar or hack-and-squirt with

imazapyr. Heavy resprouting usually occurs with basal applications on species such as black oak and dogwood. In Oregon, basal treatments with triclopyr ester are most effective on species such as tanoak and bigleaf maple (Mark Gourley, personal communication).

Spot-gun applications

Spot-gun (also called meter-jet) applications are an efficient technique for controlling woody vegetation that is sensitive to the herbicide hexazinone, such as snowbrush, whitethorn, deerbrush, and greenleaf manzanita. Spot-gun treatments are applied using a meter-jet application system to individual plants, or on a grid system if cover is too heavy to treat individual plants. The device delivers a measured amount of chemical with each pull of the trigger and can be adjusted to deliver a range of rates. The herbicide is applied undiluted to the soil about midway between the root collar and branch tips. Generally, 3 milliliters of the liquid formulation of hexazinone per spot are applied. The number of spots a plant receives depends on the plant size, and most plants receive a minimum of two spots. The spot where the herbicide is applied must be free of litter or other debris that could tie up the chemical.

An experienced crew is required to properly apply spot-gun treatments. Crews must always be careful not to exceed the maximum label rate. Crop trees may be damaged or killed if too much hexazinone is applied in any area. Spot-gun applications are best suited to low brush densities. If vegetation is too heavy to treat individual plants, grid applications will not be nearly as effective and another treatment method should be considered. Due to root uptake, conifers can also be severely injured or killed in stands adjacent to treated areas. Large cedars and sugar pines in close proximity to the treatment area are at highest risk and may be killed if not given a large enough buffer. On steep slopes, spots should be placed around the upper sides of the plant so that the herbicide does not move downslope away from the root system.

Hexazinone requires rainfall to activate. The majority of spot-gun applications are applied in the fall, as the main target is snowbrush, which occurs at upper elevations. To work correctly, the herbicide must not get too much or too little precipitation. Generally, hexazinone needs between 3 and 20 inches of rain to be effective. Lower elevation species such as deerbrush may theoretically be treated in the spring if there is an adequate moisture window. Spot-gun applications are highly effective and efficient from an application standpoint, and the cost per acre is generally low with labor costs ranging between about \$25 and \$35 per acre.

Tractor and off-road vehicle applications

Opportunities to utilize spraying systems mounted on tractors or off-road vehicles are minimal in forestry, because terrain, stumps, brush, rocks, snags, and residual conifers prohibit their efficient use. Instances where they may be used include roadsides, pasture conversions, or flat and clean clear-cuts that are relatively free of slash.

Where possible, spray applications using tractors or off-road vehicles are similar to aerial treatments. They are primarily broadcast applications applied at specific volumes per acre. System calibration and traveling speed are critical for tractor-mounted systems (Dreistadt 2013). The choice of herbicides depends largely on the vegetation on-site and whether or not conifer seedlings are established. Pre- or postplant applications can be made with a tractor or off-road vehicle system, provided that tree height and conifer tolerance are not concerns.

Tractor and off-road vehicle applications are delivered primarily via mounted booms, with shorter booms being better for forestry applications. Unique configurations of flood-jet and off-center nozzles can also be used to reduce boom lengths and increase maneuverability in reforestation units. Roadside applications usually have either a handheld nozzle system mounted to the spray tank or a half-boom with off-center or flood-jet nozzles.

The main benefit of systems mounted on tractors and off-road vehicles is control of the spray deposition, as they allow the spray solution to be accurately placed along stream buffers, property lines, and other sensitive areas so that contamination does not occur. Application costs are relatively low and are along the lines of broadcast hand applications.

Conclusion

Chemical vegetation management is the most critical step to a successful reforestation project. While mechanical, manual, biological, and cultural treatments may complement chemical vegetation control, they are not effective substitutes for chemical weed control on their own. This is especially important in Mediterranean climates where water is the main limiting factor.

When developing a reforestation program, it is important to remember that good vegetation control is most critical at planting. Good chemical site preparation is the most important step in growing a new forest. Chemical site preparation should completely control herbaceous and woody vegetation and include a residual herbicide to be effective. Too many times foresters try to save money by minimizing chemical

vegetation management inputs only to result in complete failure, resulting in even higher costs to fix a problem that could have been avoided in the first place. By doing a good job of chemical site preparation, release treatments in the future will be minimized.

Monitoring reforestation projects after planting is critical to ensure success. No matter how well reforestation foresters do their jobs, there will always be issues to contend with such as vegetative competition, animal damage, insects, and disease. Most issues can be effectively dealt with if observed early. Ignoring reforestation units after planting will only end in failure or results that are less than desired.

When managing competing vegetation, be aggressive, effective, and efficient and your program will be successful. There is nothing more satisfying than seeing your reforestation efforts 20 or 30 years in the future. It is truly something to be proud of.

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Chapter 9

Planting

Bob Rynearson, Land Department Manager with W. M. Beaty & Associates in Redding, CA

Prior to implementation, it is important to consider how planting fits with other key steps to a successful reforestation plan. These key steps are based upon the five principles of successful reforestation developed and refined by reforestation foresters over the past several decades in California's Mediterranean climate.

1. **Plant species from known, appropriate seed sources.** Typically, this means tree species that are native to the site using seedlings grown from native, adapted seed (Buck et al. 1970; see also chapter 5, "Seeds").
2. **Use quality seedlings.** As described in chapter 6 ("Seedlings"), seedlings must be grown using excellent, up-to-date nursery practices. Seedlings must be vigorous enough to grow roots down to permanent soil moisture during the first growing season of establishment and to withstand sun, wind, cold, and any other environmental conditions (Rose and

Haase 1995). This chapter describes commonly selected seedling species, stock types, and planting seasons for the general regions and elevational bands within California.

3. **Control competing vegetation.** During the critical first year of establishment in a typical Mediterranean climate (fig. 9.1), planted seedlings need all the available water in the soil that is within reach of their rapidly expanding root systems. The main cause of soil moisture depletion at the rooting level during long, hot, and dry summers is not evaporation, but transpiration from competing vegetation (Powers and Ferrell 1996). Experience over the past few decades has shown that with good control of competing vegetation, soils retain sufficient moisture to allow for high survival rates, even on dry sites during prolonged droughts. Mechanical and hand-control methods (as described in chapter 7,

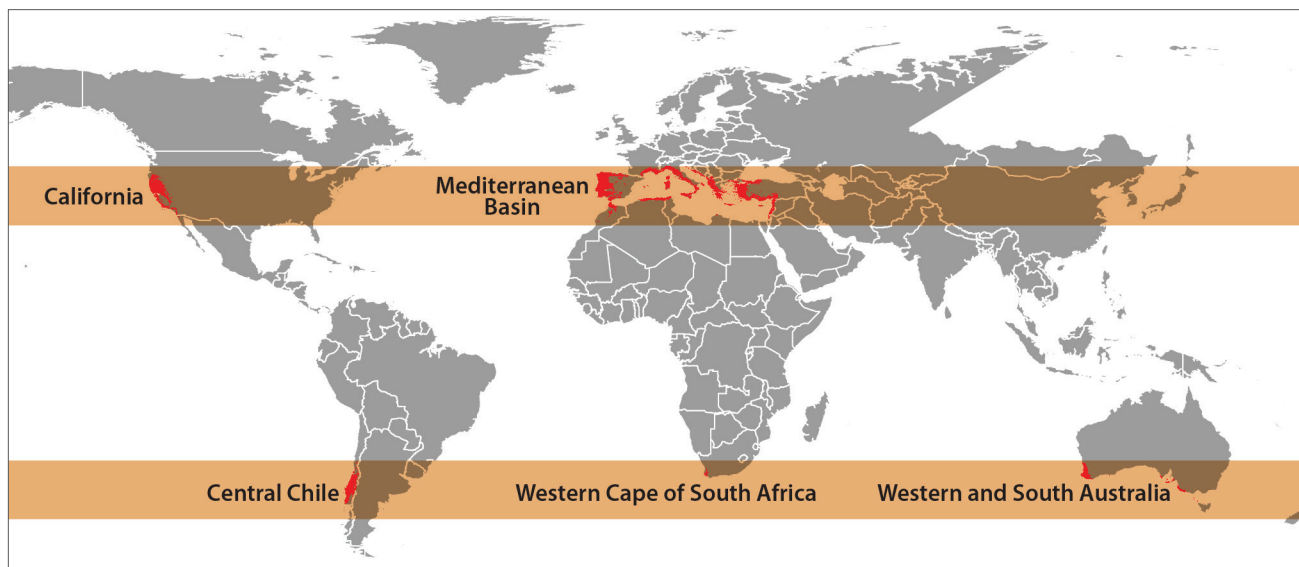


Figure 9.1. A Mediterranean climate is characterized by warm/hot, dry summers and mild/cool, wet winters. Soil moisture is the limiting factor for conifer seedling establishment.

“Site preparation”), can also be used to control competing vegetation but are most effective in combination with herbicides to minimize erosion or topsoil disturbance, and to effectively constrain costs. The carefully planned and regulated application of registered herbicides is a cost-effective method of vegetation control (McDonald and Fiddler 2010; see chapter 8, “Vegetation management”).

4. **Properly handle, transport, store, and plant seedlings.** This chapter describes the critical reforestation steps of handling, transporting, storing, and planting seedlings developed and refined by many California foresters with decades of experience in planning and implementing successful reforestation projects. The most common and cost-effective method for successful planting in California, especially in the interior, is using hoedads to plant relatively small, container-grown stock. However, other stock types and methods are appropriate in certain other climates, soil types, and situations. For example, on coastal sites where competition for light is more critical and transpiration stress less significant than on interior sites, larger seedlings are often planted with shovels rather than hoedads. Proper handling includes minimizing seedling exposure to drying and high temperatures prior to and during planting. Proper planting includes planting deep enough so that the growing media is completely covered by moist mineral soil and ensuring that seedling roots are not bent over in the hole or have air pockets around them. Proper timing means planting only when soil moisture and soil temperatures are adequate for root growth on the site.
5. **Protect seedlings from damage by animal and insect pests as necessary.** As described in chapter 11 (“Damage”), many control methods are available depending upon the specific animal and insect pests and reforestation site characteristics. Maximizing early tree growth by adhering to the previous four principles can greatly reduce the number of years that seedlings will need protection from possible browse damage by livestock or other animals. This chapter describes pest protection measures that might be conducted in conjunction with planting and also methods and scheduling of post planting monitoring.

Planting season

The most appropriate times of the year to plant vary for different ecoregions in California. Even within regions the optimal planting window varies by elevation, aspect, climatic conditions, soil and ground conditions, and planting site access. Depending upon these

site-specific factors and the region, planting typically occurs in California from fall through late spring. Since 2010 a few successful operational-size planting trials have been conducted in late summer (Mark Gray, personal communication). These successful summer plantings were completed on sites with good soil moisture due to recent thunderstorms and excellent control of competing vegetation throughout the spring and summer. Additionally, smaller container seedlings were grown in the nursery for a shorter period of time and lifted and packed in proper physical and physiological condition for summer planting. Late summer plantings should be done with caution until ongoing success can be demonstrated in specific regions. The following region-specific factors should be considered when scheduling planting times, especially if the forester has multiple planting projects to complete.

Central and northern coastal areas

Ideal planting times are determined by the species, distance from the coast, climatic conditions, elevation, and aspect (personal communications, Mike Alcorn, Brian Lindstrand, and Bill Morrison). Areas not planted in late fall or winter are typically planted as early as possible in spring. Since south and west slopes typically dry out before east and north slopes, they should be planted first.

Planting true fir at higher elevations of the North Coast region typically starts in November and progresses until access to and planting of the units is impeded by snow, usually in late December. Planting can then resume in spring after snowmelt, sometimes as late as May if snowpack persists into spring. In general, redwood planting within its typical coastal range starts in November and continues into April or early May, with the majority planted January through March. When redwood is planted at more inland and higher elevation sites at the fringe, near the edge, or outside of its typical range, planting is typically delayed until later in the season to avoid desiccation of newly planted seedlings from exposure during the coldest months of midwinter. Once redwood seedlings are established with deep roots at the end of the first growing season, winter desiccation is not usually a problem.

West and east sides of Sierra Nevada and Cascade ranges

The variable elevation, aspect, soil, and climatic conditions dictate planting schedules for specific locations within this broad, mountainous region. Latitude can also affect planting timing, with southerly latitudes opening sooner for planting than northerly latitudes at the same elevation (personal communication, Ed Fredrickson, Mark Gray, Craig Ostergaard, and Jeff

Webster). Planting in this region occurs primarily in the spring planting season, from late winter through the advent of drier late-spring conditions. However, where seedlings can be insulated during harsh winter weather by snow, fall planting is becoming increasingly common and successful at higher elevations, primarily on the westside but also in limited situations on the eastside.

Typically, spring planting on the westside Sierra and Cascades ranges extends from February to late March or early April at lower elevations (1,500 to 3,500 feet), March through April at middle elevations (3,500 to 5,000 feet), and mid-April to late June at higher elevations with late snowpack melt. On the eastside, planting season is typically from April to late May, and any high-elevation sites (above 5,000 feet) may not be accessible until May to late June. These time frames depend on local conditions such as aspect and site conditions, which vary from year to year depending on weather patterns (table 9.1).

Spring planting in the Sierra, Cascade, and eastside regions should begin as soon after snowmelt as possible and when soil temperatures are at least 38°F to 40°F and rising. For large, spring planting projects that require several weeks to complete, lower elevations should be planted first; and within any particular elevation, south-facing aspects should be prioritized, followed by west-, then east-, and lastly north-facing aspects. Also, within these elevational and aspect considerations, soils with relatively lower water holding capacities should be prioritized.

Fall versus spring planting in the Sierra Nevada, Cascades, and eastside

The principle behind fall and spring planting is that most conifer species have two primary root-growth periods in a year. The spring growth period is stimu-

lated by climatic conditions favorable for root and shoot growth, including increasing day length, warming atmospheric and soil temperatures, and an abundance of moisture from seasonal rains. This period of conifer growth is characterized by the highest rapid extension of both roots and shoots as seedlings grow rapidly, with root growth initiating before shoot growth.

Conifers can grow roots in late summer and early fall when temperatures start to moderate, and days become shorter. Transpiration in deciduous trees and herbaceous vegetation is also reduced in the fall, which allows soil moisture levels to rise. Planting in fall has historically yielded unpredictable results, at least in part due to unpredictable winter weather conditions. Wind or exposure to sunlight without adequate snow cover can result in seedling desiccation, particularly since no root uptake occurs in cold soils. All these factors typically make spring planting the safest and most common planting timing for reforestation. In recent years, however, reforestation foresters have developed more expertise on when, where, what, and how to plant in the fall. Several factors should be considered when making the decision to plant in the fall, and certain strategies can help to maximize success and minimize risk.

Planning a fall planting project requires focus on the basic reasons for choosing not to plant during the safer spring planting window. Four justifications for planting in the fall include:

1. Planting is on high-elevation sites that will likely be covered in winter snowpack until very late spring or the onset of summer drought.
2. Planting is on sites where access may be blocked by high passes normally covered in snowpack until late spring or by snow that persists on significant distances of roads shaded by forest cover. Snowpack on planting units exposed to direct sunlight typically melts off weeks before shaded or high-elevation access roads are open for travel to the planting site.
3. Planting in the fall decreases the extended seedling storage time required when planting in late spring.
4. Planting must be divided between two planting seasons due to the operational challenges of large planting projects.

The conditions required for fall planting are the same as other planting timings: adequate soil moisture, warm soil temperatures, mild diurnal air temperatures, and adequate humidity. Timing is even more critical in the fall. Ideally, seedlings should be in the active root-growing phase typical of the late summer and early fall. The fall planting window is

TABLE 9.1. Approximate planting dates in California Sierra and Cascade regions

Area	Elevation	Planting dates
Westside low elevation	1,500 to 3,500 feet	February through early April
Westside middle elevation	3,500 to 4,500 feet	March through April
Westside high elevation	Over 4,500 feet	April through June or September through October
Eastside low elevation	3,200 to 5,000 feet	April through May
Eastside high elevation	Over 5,000 feet	May through June or September through October

Source: Personal communication with numerous experienced reforestation foresters

generally late August through October for most sites. Ideally, high-elevation sites should be planted when enough growing season is left for adequate root growth. Planting in mid- to late October may result in little or no root growth at high elevations (Fredrickson 2003). Plantings this late can be successful if seedlings are covered with snow during the winter, by which they are essentially being stored under a blanket of snow until the spring thaw. If seedlings are protected from desicating winds and low humidities by winter snow, then they will get an earlier start on establishment and growth in the spring than similar seedlings planted later in the spring.

In general, the best time for fall planting is early, when soil is still moist, provided that soil temperatures are still high enough for root growth or an insulating winter snowpack is imminent. The uncertainty that suitable late summer or early fall rains will occur during any given planting year can be significantly mitigated with effective weed control. Although late summer or early fall rains can provide necessary soil moisture, the complete control of competing vegetation during the entire growing season prior to planting is an effective strategy to retain the necessary soil moisture for fall planting. Most forest soils, especially at higher elevations, can maintain adequate soil moisture within the lower rooting zone of seedlings, even by the end of summer if transpiration from competing vegetation has been completely controlled on the planting site. If vegetation control has not been completed throughout the entire growing season, then sufficient late summer or early fall rains are necessary to ensure adequate soil moisture for early fall planting.

Fall planting should be avoided in areas prone to drier conditions, due to the risk of desiccation. Eastside sites, especially at relatively low elevations (less than 5,000 feet) can be risky due to the high probability of low humidity (less than 20%), high winds, or soil temperatures too cold for water uptake by existing seedling roots. These conditions can desiccate seedlings before they have time to grow new roots. When planting at higher elevations, south-facing aspects or windswept areas may not have adequate snow cover in the winter, exposing newly planted seedlings to extreme low temperatures and drying winds. North-facing slopes that are likely to be snow-covered all winter are generally safer for fall planting. Small regeneration units with surrounding mature trees that provide winter shade on most of the unit will retain more snow than large units open to direct winter sunlight.

Fall planting should also be avoided in areas with high populations of deer or elk in the late fall or winter, which historically browse on conifer seedlings.

Areas that are traditional wintering grounds for these herbivores should not be planted in fall, since the only succulent green vegetation at this time of year may be the newly planted conifer seedlings.

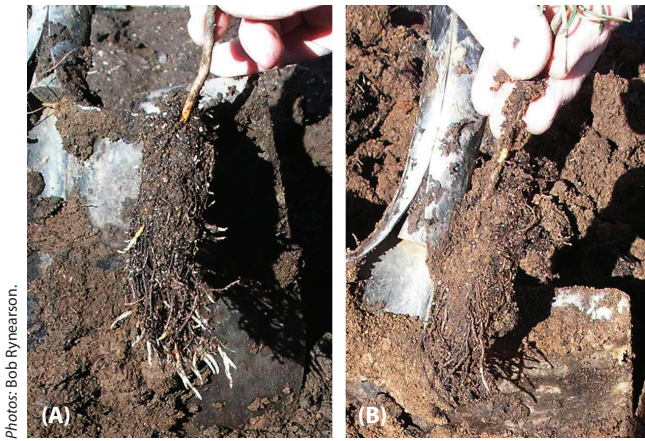
When placing the sowing order, it is important to communicate to the nursery manager that you plan to lift the seedlings for a fall planting program if site conditions are suitable. The nursery manager should make sure that the seedlings are sown early enough to achieve the suitable maturity for lifting (packed for storage and transportation) between late August and early October (depending upon species and elevation of planting site) if site conditions are favorable. The nursery must also plan ahead to accommodate fall packing, and this should be discussed with them early in the growing season. At the time of lifting in the nursery, seedlings should be actively growing roots and kept in that condition until planting time. This is considered “hot” planting, and fall-planted seedlings should not be placed in cold storage. Storage temperatures should not be less than 40°F or the trees may be pushed into dormancy and not grow roots.

As planting time nears, the nursery should be instructed to only lift and pack the number of seedlings that can be planted in a week or less. The nursery should not put liners around the boxed seedlings, as carbon dioxide (CO₂) may build up rapidly due to the trees’ high respiration rate. All seedlings lifted and packed for fall planting must be planted at that time because they will not be capable of surviving long-term storage when lifted and packed at that time of the year. Seedlings do not reach a high level of cold hardiness and low metabolic rate—which are necessary for long-term storage—until mid-November, the start of the normal lifting window for long-term storage (Bigras et al. 2001). Container stock is preferable to bare-root stock for fall planting because it can be lifted and shipped on short notice for 1 week’s production or less and also because it is difficult to lift bare-root seedlings while the roots are actively growing without damaging the roots (by stripping the cambium layer away from the root).

Advantages of fall planting

The advantages of fall planting include:

- Seedlings planted in the fall will initiate root growth before winter if planted in September or early October (fig. 9.2A). Even if seedlings are planted later in the fall (fig. 9.2B), they will initiate spring root growth sooner than seedlings planted in the spring.
- Fall root growth can occur immediately after planting if the seedling and site conditions allow planting in September or early October (Fredrickson 2003).



Photos: Bob Rynearson.

Figure 9.2. Significant new fall root growth on white fir (A) within 2 weeks of planting in early October. By comparison, white fir planted (B) a week later have almost no new root growth 2 weeks after planting; both are at 5,500-foot elevation in Plumas County, on private land burned in the Moonlight Fire of 2007. Although seedlings planted after mid-October did not initiate new growth until the next spring, they survived the winter and initiated vigorous new root growth in spring, much sooner than root growth was initiated in seedlings planted that spring.

- The costs of plowing snow or long seedling storage are eliminated, as are the risks of late spring–early summer planting, and more time is available to conduct the entire annual planting program if needed.

Challenges and risks with fall planting (especially east of the Sierra and Cascade ranges)

The challenges with fall planting include:

- Coordination and scheduling with the nursery and planting contractors for seedling packing, transportation, and planting is more complex due to hot planting, with no more than 1 week's production for each pack out.
- On the eastside, the normal summer dry season sometimes extends into fall with the first significant precipitation in the form of snow, especially above 5,000- to 6,000-foot elevations.
- Low relative humidity on the eastside in the fall can exacerbate transplant shock or subsequent stress on seedlings.
- Wind or extreme temperatures with no protective snowpack after fall planting can damage or kill newly planted seedlings.
- On sites where mechanical subsoiling or ripping has been conducted, planting should not occur until significant precipitation has settled the disturbed, loose soil. Reforestation projects have experienced higher-than-acceptable mortality rates when fall planting was preceded by such mechanical treatments in summer of the same year. It is now standard practice to either avoid subsoiling and/or rip-

ping on sites scheduled for fall planting, or to schedule fall planting at least one full winter after subsoiling/ripping in order to allow the disturbed soil to properly settle prior to planting. If it is necessary to subsoil/rip in the same year as fall planting, then seedlings must be planted in the undisturbed, firm soil between the subsoiled/ripped rows.

- A scheduled fall planting program may be reduced in scope or cancelled due to unanticipated delays in scheduled logging or site preparation activities. This risk can be mitigated by scheduling fall planting a year or more after logging or site preparation to provide more certainty in scheduling the prescribed reforestation activities; for example, it allows for a spring herbicide treatment, which helps with the retention of adequate soil moisture throughout the summer and early fall, regardless of the amount of late summer and early fall rains.

Species, stock types, and spacing

Seedling species and stock types are discussed in detail in chapter 6 (“Seedlings”). We offer some practical lessons from decades of experience with reforestation projects in Northern and Southern California.

Sierra, Cascades, and eastside

Species. Species selection by landowners and managers is more variable in these interior regions of California than in the areas dominated by coastal redwood (personal communications, Ed Fredrickson, Mark Gray, Craig Ostergaard, and Jeff Webster). Generally, landowners and managers will plant a mix of species adapted to survive and grow well on the site. Planting a diversity of adapted species increases the health of the forest stand, since most pests are host-specific, and it also provides marketing options for the future trees, which will take several decades to grow. On many sites in these regions the percentage of shade-tolerant species far exceeds the presettlement, more fire-adapted mix with a higher proportion of shade-intolerant species, especially at low- to middle elevations on the westside and most of the eastside.

Decades of partial harvesting, the in-growth of more shade-tolerant species, and fewer wildfires have often resulted in the distribution of species not necessarily well-suited to future climatic conditions. Although seed disseminated from adjacent shade-tolerant species, such as white fir and incense cedar, typically becomes established in group selection (maximum size 2.5 acres) and even clearcut (less than 30 acres) regeneration units, natural regeneration may not occur after much larger, stand-replacing wildfires. Douglas-fir is much more susceptible to frost damage in late spring than other conifer species, so other suitable species

should be planted in frost pockets that may occur within a planting unit.

Where natural regeneration of shade-tolerant species such as white fir and incense cedar is expected over time, planting may focus on less shade-tolerant species such as ponderosa pine, sugar pine, and Douglas-fir. This is especially true for landowners and managers who primarily practice single-tree selection silviculture, which favors the natural establishment of incense cedar and white fir over ponderosa pine, sugar pine, and Douglas-fir.

Species should be selected that are adapted to anticipated site-specific climatic conditions as the stand grows for the next several decades, for resiliency to drought, fire, pests, and pathogens. In some areas, this may mean shifting toward a species mix of more drought-tolerant pine species, even if the site is currently dominated with white fir and incense cedar.

Soil-type characteristics such as available water holding capacity, depth to bedrock, and texture can also influence the best mix of planted species. Although a site may be within the general location and elevational range to normally plant a 50:50 ratio of ponderosa pine and Douglas-fir, if soils have a relatively low available water holding capacity, it can be planted with a higher percentage of more drought-resistant ponderosa pine, especially on south aspects or sites with relatively low average annual precipitation.

At lower elevations (such as below 3,000 feet and up to 4,500 feet on the eastside), 50 to 100 percent ponderosa pine (or Jeffrey pine where appropriate on the eastside and on less-productive ultramafic, or serpentine, westside soils), with some Douglas-fir and incense cedar seedlings, may be an appropriate seedling mix, depending upon objectives. A typical seedling mix from 3,000 to 4,000 feet on the westside is 50 percent ponderosa pine and 50 percent Douglas-fir, with some incense cedar as appropriate.

At middle elevations (4,000 to 5,000 feet) on the westside, the species mix commonly planted is 35 to 50 percent ponderosa pine, 5 to 20 percent sugar pine, 5 to 20 percent incense cedar, 20 to 35 percent Douglas-fir, and 10 to 20 percent white fir. At elevations above 5,000 feet, increasingly more white fir or red fir are planted, with red fir replacing white fir as elevations increase above 5,500 feet, and Jeffrey pine replacing ponderosa pine. Ponderosa pine or Jeffrey pine are often not included in the species mix at all above 6,000 feet depending upon the specific location. Some landowners have not only planted giant sequoia within its current narrow range but also up to 5 percent on suitable sites in the Northern Sierra—well outside its current range—but where giant sequoia grows well and may be better adapted to future climates. Sites

selected for planting giant sequoia typically are characterized by relatively high site class and soils with high water holding capacity.

Stock type. The selection of stock types in the Sierra, Cascade, and eastside regions is based on several factors, including the following considerations to ensure that seedlings can survive the critical first year of establishment during these regions' typical long, dry, hot summers:

- Minimize foliage height to reduce transpiration stress.
- Maximize first-year root growth (to below the depth of late summer soil moisture).
- Select stock types small enough to plant with hoe-dads and with sturdy stems and buds and healthy foliage.

To reduce transpiration stress and promote rapid, deep, root growth during the critical first growing season, almost all seedlings planted in interior California are relatively small, 1-year-old, container-grown stock with vigorous, juvenile roots. For the past few decades styro-5–sized seedlings have been the most common ponderosa pine stock planted by foresters, although in recent years they are increasingly planting even smaller styro-4 ponderosa pine. Styro-6 ponderosa pine are planted to a far lesser degree than in the past, and styro-8 ponderosa pine are planted even less frequently. Styro-6 is the most commonly planted sugar pine seedling. Styro-6 and styro-8 are the most common stock sizes for Douglas-fir, true fir, and incense cedar because these species, especially Douglas-fir, are more susceptible to sun scald on the basal stem compared with ponderosa pine. Although more expensive, the slightly larger stem diameter and more pronounced lateral branching of styro-8 Douglas-fir provides more shade on the stem, which is especially important at lower elevations. If a larger Douglas-fir seedling with even more lateral branching is needed, then more expensive styro-10-77s, which are grown in Styrofoam containers that have only 77 cavities, are planted. On eastside ponderosa pine sites in northeastern California, some landowners still plant 2-year-old, bare-root ponderosa pine seedlings using shovels or hoedads with relatively long, wide blades.

Spacing. Seedling spacing in the Sierra, Cascade, and eastside regions depends on factors such as landowner objectives and their commitment to follow up with precommercial thinning, site quality and conditions, risk of mortality from animals (for example, gophers), seed availability, levels of competing vegetation, funding availability and window, and anticipated first-year seedling survival rates by species. When harvesting healthy trees on private land, compliance

with minimum stocking standards of the California Forest Practice Rules must be considered. As of 2020, minimum stocking standards in the California Forest Practice Rules were updated to consider the decades-long improvements in seedling survival, improving alignment with stocking standards on private lands in other Western states.

No reliable pulp markets are currently available in the Sierra, Cascade, or eastside regions of California, and wood fuel chips and small logs are low (or negative) value byproducts of final harvests or intermediate forest thinning projects. As a result, the primary objective of most private forest landowners when determining seedling spacing at planting or precommercial thinning is to facilitate future growth without thinning until trees reach sawlog or peeler size with diameters at breast height of 12 to 18 inches. Although the ideal density will vary by species and site, it should generally be 100 to 180 trees per acre by ages 10 to 15 years to reach desired tree sizes for the first commercial thin at ages 35 to 50 years. This was historically accomplished by planting at higher densities of approximately 258 to 436 trees per acre, depending on species mix, followed by a precommercial thin at 7 to 10 years. However, due to improved seedling survival rates, some landowners began planting seedlings at wider spacing, often from 135 to 222 trees per acre after wildfires and other catastrophic stand-replacing events that did not require restocking under the Forest Practice Rules. In the 2020 California Forest Practice Rules, stocking standards were revised to reflect successful reforestation experiences after wildfires that used less seed and seedlings and reduced costs and future fuel loading.

Planting fewer initial trees per acre can reduce immediate costs as well as some or all of precommercial thinning costs to achieve the desired density of commercial trees. In these cases, especially in low-elevation Sierra and Cascade ponderosa pine as well as eastside pine sites where excellent survival is anticipated, planting 135 trees per acre (18 by 18 feet) to 170 trees per acre (16 by 16 feet) became more common. This is due to exceptionally high survival rates of ponderosa pine and Jeffrey pine, and the desire to minimize seed use and reduce the costs of seedling, planting, and future precommercial thinning, as well as fire hazards from slash.

North Coast region

Species. The larger redwood companies typically plant 75 percent redwood and 25 percent Douglas-fir mixes on upland sites and pure redwood on flat, alluvial sites. When determining the species mix for a particular reforestation project, foresters must always consider

the availability of suitable seed by species, climate, soil types, site elevation and aspect, appropriate species, and unplanned natural in-growth. Sites with soils that have lower available water holding capacity or south-facing aspect experience more moisture stress on seedlings and may do better with more Douglas-fir and less redwood. Conversely, sites with consistently more fog can support more redwood (personal communication, Mike Alcorn, Brian Lindstrand, and Bill Morrison).

Stock type. For many years, stock types for redwood seedling production consisted of 2-year-old bare-root or plug-1 stock, which have woody stems that are far more resistant to damage from animal browse than seedlings with succulent green stems. However, it is now difficult to find a bare-root nursery in locations where the minimum winter temperatures are mild enough for redwood production. Improvements in container nursery technology have allowed foresters to shift much of the production to 2-year-old containerized styro-15s. These large container trees do not sustain as much damage to the fine root systems when lifting as bare-root seedlings. Since the coastal redwood climate results in relatively less soil moisture loss and transpiration stress than interior climates (where much smaller stock types are preferred), the larger foliage does not create as much transpiration stress on seedlings during the first growing season. However, it is common practice to mow the tops of containerized redwood seedlings to keep the crown from getting too large, in order to reduce transpiration stress after planting.

It is fairly common to see redwood seedlings turn reddish brown the first few years after planting, particularly on colder sites. Sometimes the tops will even die off. However, even if the top appears completely dead, the trees will often resprout from the root collar the next season. In these situations, foresters typically dig up a few such seedlings to inspect and determine if they are still alive below ground level. Inspection is done by scraping the cambium at the base of the stem and looking for moisture or creamy color, signs that the seedling is alive. Before investing in a replant, it is important to take the time and monitor whether the seedlings are still viable or foliage dieback is fatal.

Common stock types for Douglas-fir in the coast region are 1-year-old styro-8 and styro-10 container seedlings. These are commonly grown at a greenhouse nursery in interior Northern California, where colder temperatures and careful control of temperature and light within the greenhouse condition these seedlings to withstand planting site conditions. Douglas-fir stock types as small as styro-6 have also been successfully planted by some landowners. Container nurseries

can provide much more flexibility in the timing of lifting and packing seedlings than bare-root nurseries, which is important when scheduling a planting project around specific planting site conditions. Also, Douglas-fir can be forced into dormancy by the use of dark-out technology in the greenhouse. This method of inducing dormancy does not stress the seedlings, unlike withholding water and nutrients. Two-year-old bare-root and plug-1 transplant Douglas-fir seedlings are still used on the coast, especially on sites where sunscald or animal damage is a problem. Although plug-1 stock is more expensive than 2-0 bare-root, less damage to fine roots occurs when lifting and packing.

Spacing. Since planted seedlings are often outnumbered by redwood sprouts, it is more cost-effective on units that are sufficiently stocked with sprouts to avoid planting redwood or plant no more than 50 redwood seedlings per acre. Approximately 5 percent of regeneration units can meet redwood stocking objectives solely with coppice regeneration. However, in redwood units with few sprouts, typically as many as 200 redwoods are planted per acre with up to 150 redwood clones and 50 redwood seedlings, totaling 200 planted trees per acre. Although the range of planting density varies with the level of resprouts, approximately 120 seedlings per acre are planted on average within redwood units. Redwood planting has expanded into some areas of Douglas-fir and tanoak timber type at higher elevations than redwood occurs naturally, but still generally within the redwood region. Outside of the redwood range, Douglas-fir is commonly planted in the coast region at 300 to 435 trees per acre depending upon ownership and site.

Southern California mountains

Located at lower latitudes, Southern California's dry season is longer and temperatures are generally higher than in Northern California forests. Considering Southern California's generally lower average annual precipitation, the timing of planting projects in this region is even more critical and usually involves shorter planting windows (Cuyamaca Rancho State Park 2013). If the five principles of successful reforestation (described in the introduction to this chapter) are followed—especially the elimination of competing vegetation to extend the window of suitable soil moisture during seedling establishment—a suitable planting window should be available to complete a successful planting project.

Planting in Southern California mountains occurs primarily from December through February but at higher elevations can extend later into spring. Ideal planting times are determined by distance from the coast, climatic conditions, elevation, and aspect. Since

south and west slopes typically dry out before east and north slopes, they should be planted first. The periodic occurrence of extremely dry warm spells and, especially, east winds known as “Santa Anas” must be taken into consideration when scheduling planting operations, and avoided.

Receiving seedlings from nursery and cold storage

The importance of monitoring growing, packing, and storage practices at the nursery is discussed in chapter 6 (“Seedlings”) along with what the forester should look for when visiting the nursery. Seedlings should be inspected upon receipt from the nursery, placed into a cold storage facility, and monitored periodically until the day of planting.

Nursery

Upon receiving seedlings from the nursery, the forester should inspect them for the following conditions.

Identification. Boxes or bags must be properly labeled with name of the forest owner/manager, seed lot number, species, stock type, seed zone, and elevation. The quantities of each seed lot should be verified against the nursery's packing list. In addition to a label on the outside of each seedling box, it is important for the nursery to place a label inside the box in case the label on the outside detaches during later transport or handling.

Morphological standards. Seedlings should meet the morphological specifications in the nursery growing contract (such as stem height and caliper, and root length). On rare occasions, accepting seedlings that do not meet specifications, particularly stem height, may be preferable to delaying planting for a year or more, which usually also creates the need for an additional site preparation treatment.

Acceptable root pruning. Roots of bare-root seedlings should be consistently pruned to specified lengths, with the root cambium remaining intact (not stripped away or otherwise damaged during lifting or packing).

Moist but not waterlogged condition. If seedling roots or shoots appear to have dried out, plant moisture stress should be measured. Seedlings and roots should be moist but not immersed in standing water within bags or boxes.

Signs of physical damage. This includes examining foliage, terminal buds, stem cambium, and roots. Bare-root seedlings should be carefully inspected to ensure that the stem or root cambium of seedlings was not stripped during lifting, pruning, or packing.

Signs of destructive molds or fungi. It is critical to inspect seedlings for destructive molds or fungi upon

receipt from the nursery and also periodically during cold storage. Botrytis and other destructive fungi can severely weaken or kill seedlings regardless of how well they are subsequently planted and cared for (Haase and Taylor 2012). Destructive molds or fungi may appear dark or slimy or cause the bark and cambium to easily dislodge from the stem. However, some fungi that typically show as a whitish fuzz connected to the foliage of seedlings that have been in long-term cold storage are not harmful. Mycorrhizal fungi that appear on roots are even beneficial. When in doubt, immediately consult with an experienced reforestation forester or nursery manager to properly determine if fungi appearing on seedlings are destructive or harmless. Planting seedlings with destructive molds or fungi such as botrytis is putting “good money after bad” and not worth the cost and effort, even if the seedlings otherwise appear alive and green.

Cold storage

After receipt from the nursery and inspection, seedlings must be placed in cold storage facilities immediately and monitored periodically until the day of planting (Landis et al. 2010), unless they were lifted and packed for fall planting, in which case they should be kept in shaded storage above 40°F to prevent root dormancy. Such seedlings must be planted within a week after lifting to maintain good health and vigor and prevent botrytis infestation. For seedlings that should be kept dormant until winter or spring planting, cold storage should meet the following specifications.

Temperature. The storage facility temperature should be 33°F to 35°F. If the facility does not have a functioning commercial hydrothermograph, then strategically placed high-low thermometers or a continuous digital recording device is helpful for daily monitoring of the cold storage unit. A long probe thermometer is useful to monitor temperatures inside the seedling boxes or bags. Modern digital data recorders are small enough to be placed inside seedling boxes and are capable of recording temperature data remotely for many days.

Seedling boxes or bags. Boxes or bags should not be open in order to avoid drying out the seedlings.

Air circulation. The storage facility should have proper air circulation with seedling boxes stored at least 4 inches away from walls and stacked on pallets (if feasible), and with at least one side exposed to circulating air.

Refrigerated vans. If diesel-powered refrigerated vans are being used for temporary cold storage, then the oil and fuel levels of the motor supplying power to the refrigeration unit should be monitored, along with the refrigeration coils and fan. The temperature in both

diesel and electric-powered refrigerated vans should be checked daily, as refrigeration units break down periodically and should be repaired within 24 hours. Foresters using refrigerated storage, especially vans, routinely arrange for mechanics skilled in refrigeration to be ready and available for repair work on short notice. Caution should be used when placing seedling boxes immediately in front of the refrigeration unit, as colder temperatures from air blown by fans can sometimes lead to frozen seedlings.

Frost and drying. Refrigerator coils should be checked daily for excessive frost, which can impair proper functioning, especially in refrigerated vans. The higher the relative humidity in a cooler, the more likely that excessive frost can occur. Icing of the refrigerator coils has been observed to occur more frequently after wet seedling boxes are loaded into cold storage on rainy days. Although electric defrost coils installed in storage units can reduce icing problems, the coils still must be monitored. Excessive drying of seedlings in cold storage rarely occurs due to the use of container seedlings and current packaging techniques with all seedling stock types; but it is important to make sure that seedlings, especially bare-root seedlings, are not directly exposed to drying air. Once seedling roots dry out, they are dead. If the packaging and seedling stock type do not keep seedlings sufficiently moist, buckets or barrels of water can be placed in the cooler with burlap sacks placed over the sides to soak up and wick the water and increase humidity.

Long-term storage. Although long-term storage is not ideal, seedlings that were cooler-stored and never frozen can last for 3 to 4 months if lifted and packed at the proper time and stored properly. Alternatively, as discussed in chapter 6 (“Seedlings”), seedlings can be put in freezer storage if a longer storage period is anticipated. However, once freezer-stored seedlings are thawed, they do not cooler-store as well as those that were never frozen. Seedlings should be placed in cold storage immediately after thawing and then planted as soon as possible, preferably within a week.

Seedling care in transport, handling, and field storage

As described in chapter 6 (“Seedlings”), proper handling and cold storage (refrigerated or freezer) of seedlings at the nursery and transport to, and storage at, a temporary refrigerated or freezer storage facility (if not available at the nursery) is critical. Conifer seedlings must be in the best physiological shape to survive and thrive in the harsh field conditions that may be encountered during establishment in the first growing season.

Physically damaged seedlings expend resources to repair the damage. Seedlings exposed to temperatures above 35°F are subject to undue respiration, which depletes carbohydrate reserves that are otherwise needed for survival and growth. Foresters must plan, communicate, and coordinate well with nursery and storage facility managers and planting crews to ensure that seedlings are packed, stored, transported, and planted at the best time and under optimum conditions. Although it is critical to maintain container-grown stock free from physical damage and at proper storage temperatures, bare-root seedlings are even more susceptible to climatic stresses during field transport, handling, and planting. Without soil media surrounding the roots, bare-root stock is especially susceptible to root damage or death by desiccation.

Seedling health and vigor must be carefully maintained from the time they are transported from the nursery (or local refrigerated or freezer storage facility) to planting in the ground.

Transportation from nursery or storage to planting site

To minimize seedling stress and loss of vigor, only the number of seedlings to be planted that day should be picked up and transported to the planting site. Seedlings scheduled for planting later are best left in cold storage. Seedling boxes and bags should be handled with care (no dropping, excessive sliding, or impacts) to avoid damage to seedlings. Seedlings are typically transported from cold storage to the planting site in the bed of a pickup truck or trailer. In situations where road access to the planting site is not available, seedlings may be further transported using yarders, helicopters, or all-terrain vehicles. Since crews typically start planting at first light in the morning, seedlings must be picked up and transported to the planting site before sunrise.

However, if transportation occurs while the sun is shining or in low relative humidity (generally less than 30%), seedling boxes or bags should be placed in an insulated tree box with a reflective outer surface. If no such storage compartment is available, the boxes or bags should be covered with a planting tarp, which typically consists of a silver reflective layer on the inside (placed against the boxes or bags) and a white reflective layer on the outside (facing away from boxes and bags). Never cover seedlings with a regular plastic or canvas tarp that is not constructed specifically for planting (known as a planting tarp) as ambient temperatures around the seedling containers could increase rather than decrease by absorbing rather than reflecting radiant heat. Seedling container temperatures should be checked upon pickup from the cooler

and monitored throughout the day until seedlings are placed in planting bags. Particular care should be taken if the weather is sunny, hot, windy, or dry, especially when planting bare-root seedlings.

Handling seedlings at the landing or daily storage site

Tree seedlings should be kept sealed in their container boxes or bags until placed in the planting bags.

Seedling containers must be kept out of direct sunlight at the planting site and stored under secured planting tarps. If shade is available, parking the pickup truck or trailer in the shade is advisable, even if an insulated seedling trailer or storage box is used. If a pickup truck with a reflective planting tarp is used and cannot be parked in the shade, then the seedling boxes or bags should be removed and placed in the shade of trees or in the pickup and covered with the protective planting tarp.

Planter handling at the landing or other daily storage site

Planters should use planting bags specifically made to carry small conifer seedlings.

Container seedlings

Container-grown seedlings are often packed in small plastic bags containing 15 to 20 seedlings each, which are then packed together in a larger container, usually a box lined with a large plastic bag. Seedlings should be placed in the planting bags either with or without their plastic seedling bags, such that the roots are protected from sunlight and dry air. Avoid packing seedlings in the planting bags so tightly that they are damaged or prone to accidental spillage when an individual seedling is pulled out for planting. Seedling roots must not be allowed to dry out. Planters should not bag up until they are ready to plant, including after, not before, taking a break. Planters should only pack planting bags with enough seedlings that can be planted within an hour on days that are warm, dry, windy, or sunny.

Bare-root seedlings

Consider packing up fewer trees per bag when planting bare-root seedlings on hot, dry, or windy days. Bare-root seedlings should be dipped in water prior to placing them in bags. On warm, dry days some foresters mix vermiculite or another additive such as Terra Sorb planting gel (manufactured by Lebanon Seaboard Corporation) in the water to retain moisture. However, the literature is not conclusive on the benefits of using additives in the dipping water. Drain excess water from the bottom of planting bags so that roots are not

immersed in water long enough to be damaged by asphyxiation.

Seedling handling during planting

Each seedling should be pulled gently from the planting bag one at a time and only after the planting hole has been prepared using a planting tool for placement. Holding multiple seedlings in one hand outside of the bag or holding a seedling while preparing the planting hole (for example, by holding the seedling and planting tool in same hand) is a common cause of cambium damage and weakened seedling vigor. In addition to risking stem or root cambium damage, holding seedlings outside of the planting bag any longer than necessary can expose roots to desiccation and possible death.

Planters should not prune individual bare-root seedling roots in the field. Although all bare-root seedling roots should be pruned to the proper length at the nursery just prior to packing, if some seedlings were not properly pruned then any subsequent root pruning should be done under the supervision of the forester at the landing site (where boxed or bagged seedlings are stored for the day and distributed into planting bags). Heavy-duty paper cutters or sharp machetes can be used on the rare occasions that pruning at the landing is necessary.

Planting methods

Proper planting methods must be followed to ensure success. The following steps are essential to any reforestation project:

Storage. Store trees prior to planting in an area selected by the landowner's representative and under conditions specified and monitored by the landowner or manager's representative.

Moist root system. Keep the root systems of all planting stock moist at all times between storage and planting. Only remove one seedling at a time from the planting bag immediately prior to planting—and only after opening the planting hole with the planting tool.

Organized planting. Plant the area in an organized manner so that systematic inspection can be maintained.

Scalping. Scrape each planting spot down to bare, moist mineral soil to remove dry soil, slash, snow, and other dead and live vegetation. No duff or debris should be allowed to enter the planting hole. Prior to starting the planting hole, the edge of the hoedad or shovel should be used to scalp an area of sufficient size (approximately 1-foot diameter) down to moist mineral soil such that only moist mineral soil falls into the planting hole when it is opened and then closed around the seedling roots.

If not instructed otherwise, planting contractors (and some reforestation foresters) sometimes do not require crews to spend the extra time to scalp when the surface of the soil is wet or it's raining. Besides making sure no dry soil or snow can fall down into the planting hole, scalping also clears away woody debris, grasses, forbs, and surface rocks that could potentially fall into the planting hole around the seedling roots. Also, scalping live grasses and forbs prior to planting helps to protect tree seedlings during follow-up release spray treatments. Grasses and forbs rooted at the base of planted seedlings are likely to be missed when seedling protectors are placed to protect them during release spray. Heavy, deep accumulations of slash can make it difficult to plant with a hoedad, which should be taken under consideration when planning and implementing site preparation activities.

Planting holes. Break out each planting hole by opening it to the extent necessary to assure that only friable soil is packed around the roots of each seedling.

Root positioning. Plant each tree in an erect, vertical position so that the tops and roots are perpendicular to the horizontal plane. Ensure that the roots are not twisted, tangled, matted, or curled at the ends (no J or L roots) and only moist soil is placed against the roots. The entire root system must be covered with moist soil.

Root collars. Plant each tree so that the root collar is at the natural, undisturbed ground line of the planting spot. When container-grown nursery stock is used, the top of each plug must be covered with soil to prevent exposure of the potting mix to the atmosphere. Allow the planting hole to backfill with moist soil and minimal rock, without woody debris or snow, and leave no air pockets.

Soil compaction. Compact soil around the root system by lightly tapping the ground (do not use a hard stomp that would cause too much compaction) so that the tree does not pull loose by a tug strong enough to detach a group of needles.

Spacing. Maintain the desired spacing and trees per acre.

Planting near roads. Do not plant seedlings in a road drainage facility or within 8 feet of any road. Consider leaving the log landings and other selected areas unplanted to facilitate equipment and personnel access and safety for future management activities and fire suppression efforts.

Culls. Field-culled seedlings should be laid on the ground alongside a planted tree so planting inspectors know they were intentionally left unplanted because they were considered cull and were not otherwise intentionally or accidentally abandoned. If feasible, require the planter to tie the stem of the field-culled

seedling in a knot to show that it was placed on the ground intentionally.

Root pruning. Root pruning should be allowed only when trees are being placed in planting bags and under the direction of landowner or manager's representative.

Species mix. Plant seedlings of each species uniformly throughout the planting area or as directed by the landowner or manager's representative. This is especially important when planting a mix of species at wide spacing, as planting contiguous areas solely with less hardy species may result in an unacceptably large hole if they experience low survival.

Micrositing. Where feasible, true fir and Douglas-fir should be planted on the north side of snags, tree stumps, slash, dead brush skeletons, and other shade-producing objects and close to the spot that fits into the spacing pattern. Ponderosa pine can be planted in full sunlight. Examples of micrositing are shown in figures 9.3, 9.4, and 9.5.

Planting tools

Various tools are used to properly plant seedlings with methods specific to seedling stock type and site conditions (such as soil, slash, snow, and other dead and live vegetation). Regardless of the tool used, the proven methods summarized previously must be followed to make sure seedlings are properly planted. Almost all operational reforestation projects in California now use a type of hoedad or shovel to plant seedlings.

Hoedads

The hoedad is by far the most common planting tool used in California. This tool is used almost exclusively for planting in the Sierra, Cascades, and eastside where relatively small, container-grown seedlings are the preferred stock type. When used by well-trained and experienced planters on most sites in interior California, the hoedad is the most productive and cost-effective tool for planting seedlings. An experienced planter can average more than 1,000 seedlings per day using a hoedad on prepared sites.

A hoedad consists of a metal blade typically 3 to 4 inches wide by 16 to 19 inches long, which is attached to a 36-inch-long wooden handle with a metal bracket that is either angled at 90 degrees (straight blade) or at a slightly wider bracket angle of approximately 100 degrees (angled blade). Due to hand position and the mechanics of holding and swinging a hoedad downward, using an angled blade makes it easier for the blade to enter the ground at a 90-degree angle on relatively flat ground (fig. 9.6). This angle facilitates planting the seedling with the roots straight down and deep rather than at an angle. On steeper slopes, however, using a hoedad with a straight blade when planting



Photo: Bob Rynearson.

Figure 9.3. Douglas-fir (right) in the shade of a dead tree and a nearby ponderosa pine planted (left) in full sunlight, 1 year after micrositing planting.



Photo: Bob Rynearson.

Figure 9.4. A Douglas-fir on the north side of a tree stump that provided adequate shade during a portion of the day in the previous summer of the first critical year of seedling establishment, 1 year after micrositing planting.



Photo: Bob Rynearson.

Figure 9.5. Dead brush skeletons provide suitable shade for Douglas-fir and white fir seedlings during the critical first summer growing season after planting. Crews are instructed to plant ponderosa pine in openings and Douglas-fir and white fir in partial shade of dead brush where it is feasible to reduce direct solar radiant heat on sensitive basal stems. By the time winter snow crushes down the brush skeletons, Douglas-fir and white fir seedlings will be sufficiently developed to withstand direct sunlight.

uphill makes it easier to dig a 90-degree hole that facilitates proper placement of the roots.

Hoedad blades come in various lengths and shapes, which are selected depending upon the size of the planting stock or rockiness of the soil. The effective length of the blade (the distance between the tip of the blade and the location of where it is attached to the

bracket) should be at least a few inches longer than the length between the root collar and bottom of the roots of the seedlings being planted. It should be long enough that it can loosen soil in the planting hole a few inches deeper than where the bottom of the seedling roots will be planted. It should be wide enough to properly break up the soil and open a planting hole that can accommodate seedling roots. In friable, relatively rock-free soil, a longer and wider blade can be used without negatively affecting planting quality, but it could slow down individual planter production or increase fatigue compared to a shorter, narrow-bladed hoedad.

A hoedad with a relatively short, narrow blade can be used in surprisingly rocky soil to plant small, container-grown seedlings or even a compact 1-year-old bare-root seedling (sidebar 9.1, fig. 9.8). This is done by holding the butt of the handle with one hand, or sometimes both hands, very close to the blade and applying pressure to wiggle the blade down between the rocks, deep enough to open a small planting hole. Even if the ground is not too rocky, the use of a shorter, narrow-bladed hoedad can facilitate better production without a reduction in quality, provided that it can still open a planting hole of sufficient width and depth to properly plant the seedling stock type and size being planted.

Shovels

A short-handled shovel specifically designed and manufactured for planting or a regular long-handled shovel with footpads of sufficient size and strength can be used in certain situations (sidebar 9.2, fig. 9.9). Shovels can be used for planting in soil that is relatively friable and free of rocks and on well-prepared sites that consist of sufficiently exposed mineral soil such that scalping is not needed. On sites with a lot of slash that limits the effectiveness of hoedad planting, shovels can be used to plant without scalping. Although rarely used in the Sierra, Cascades, and eastside regions, shovels are commonly used on the coast where larger seedlings are typically planted and sites may have heavy slash. In suitable soils, shovels can be used to properly plant large 2- or 3-year-old bare-root or plug-1 seedlings more easily than hoedads. However, shovel planting is often less productive and therefore costlier than hoedad planting when the seedling stock type is small and slash loads relatively low. In some circumstances, shovel planting may require more site preparation to loosen and expose the soil, such as with mechanical ripping or subsoiling, or the use of a separate labor step and tool to scalp to bare mineral soil prior to opening the planting hole.



Figure 9.6. When planting flat or relatively gentle slopes, the 100-degree-angled bracket hoe-dad (as shown by the hoedad in the left hand) facilitates setting the blade into the ground at a right angle more easily than the hoedad with a 90-degree-angle bracket, which causes the planter's right hand to contact the ground when setting the blade at a right angle (A). 100-degree-angled bracket in foreground and 90-degree-angled bracket in background (B).



Commonly used planting shovels are steel and short-handled with D-shaped grips and handles ranging from 26 to 29 inches long and attached spades or shanks from 12 to 15 inches long and 6 to 7 inches wide. Bolt-on foot pads are usually sold separately.

Power auger

Although rarely used in operational reforestation projects, power augers have been used in limited situations such as planting in hard-packed soils or those with a shallow and thin hardpan layer. Typically, an auger is mounted to a chainsaw-type power head, and it can dig a 4- to 6-inch-diameter hole to any depth needed for tree planting (fig. 9.10). However, augers cannot operate on areas with many large rocks and roots. Operator fatigue and maintenance time is typically much higher with a power auger than a hoedad or shovel. Also, in heavy clay soils, using an auger can glaze the walls of the planting hole, restricting future lateral root growth.

Thorough scalping prior to making the auger hole is critical to keep dry soil, woody debris, rocks, vegetation, and snow from falling into the planting hole. After bare, moist mineral soil has been exposed by scalping, it is important to auger the hole perpendicular to the ground surface and in the middle of the scalped area. Care must be taken to power the auger slowly enough so that moist soil is mounded close around the top of the planting hole and not thrown too far away from the hole. After the auger is used to make a hole, the seedling must be planted before any portion

Sidebar 9.1.

Hoedad planting

Hoedad planting starts by (fig. 9.7A) using the long side of the blade to scalp away dry soil, competing vegetation, woody debris, snow, and any other material that must not fall into the planting hole. Next, (fig. 9.7B) the hoedad blade is inserted into the ground at a right angle to a depth at least a few inches below where the end of the seedling roots will be placed; then (fig. 9.7C) breaking out the planting hole by lifting the top of the handle up and away from the planter such that only the soil between the planter and hoedad blade is loosened and the soil against the bottom side of the hoedad blade is undisturbed. Depending on the soil, sometimes the process of inserting the blade and breaking out the soil is repeated until the blade reaches sufficient depth.

Breaking up only the soil between the planter and the hoedad blade allows the planting hole to remain open upon pulling back the hoedad blade in order to place the seedling in the hole properly (fig. 9.7D). After the seedling is placed in the opening, the hoedad blade is removed so the loosened soil falls back into the planting hole, enclosing the seedling in bare, moist mineral soil. The hoedad blade is then (fig. 9.7E) inserted at a slight angle approximately 6 inches away from the seedling with the blade tip angled slightly toward the seedling roots so that a slight straightening of the blade as it is pushed toward the seedling will then secure the soil against the seedling, leaving no air pockets. Only a gentle step with the toe of the planter's boot is done to (fig. 9.7F) level out the soil around the seedling and make sure there is no loose soil or air pockets around the seedling roots.



Photos: Bob Ryneason.

Figure 9.7. Planting with a hoedad.

of the mounded soil surrounding the hole becomes dry. On sunny or dry, windy days, the auger operator should not get too far ahead of the planter. Following these steps will facilitate planting of the seedling with its roots straight down and allow for only moist mineral soil to be placed back in the hole around the roots.

Machine planter

Many thousands of acres of gentle terrain were machine-planted from the 1980s through about 2010, with good success on private lands in Siskiyou and Modoc counties in California. These projects were primarily on relatively flat ground in areas destroyed by wildfires in the 1970s, where stumps had decayed enough so as to not interfere with the planting machine. However, this method has not been used in

Photos: Bob Rynearson.



Figure 9.8. Hoedad with a relatively short, narrow blade (A) can be used in surprisingly rocky ground to plant small container grown seedlings (B). Although the surface is covered almost 100% with rock scree, survival and growth can be excellent due to proper planting technique with the right tool and quality seedlings as shown (C) 2 years after planting on the Moonlight Fire in Plumas County.



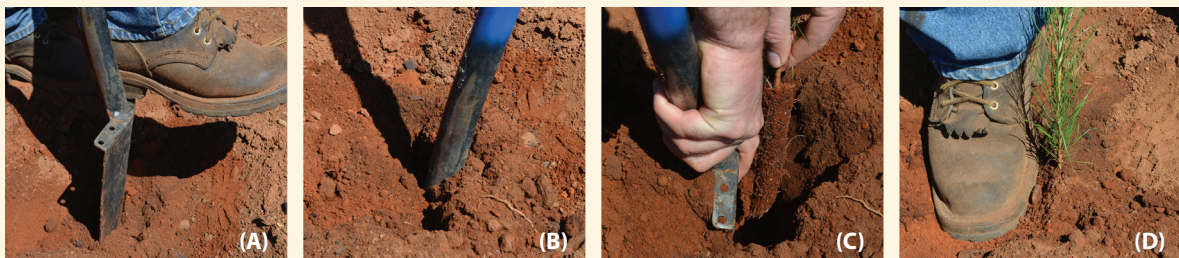
Photo: Bill Morrison, Soper-Wheeler Company.

Figure 9.10. Auger-planting of redwood cultivars.

Sidebar 9.2.

Shovel planting

Shovel planting steps are similar to hoedad planting (fig. 9.9). These include scalping to bare mineral soil and then inserting the shovel blade at (fig. 9.9A) a right angle to the ground to a depth at least a few inches below where the end of the seedling roots will be placed; then (fig. 9.9B) breaking out the planting hole by pressing the top of the shovel handle away from the planter such that only the soil between the planter and shovel blade is loosened and the soil against the front of the shovel blade is undisturbed. Breaking up only the soil between the planter and planting spot (fig. 9.9C) allows for the planting hole to be kept open for proper placement of the seedling upon pulling back the shovel blade. Then, once the shovel is removed (fig. 9.9D), the loosened, friable soil falls back into the planting hole enclosing the seedling in bare, moist mineral soil with no air pockets.



Photos: Bob Rynearson.

Figure 9.9. Planting with a shovel.

California for several years, since the reforestation backlog was caught up on these old burns.

A properly modified machine planter pulled by a small crawler tractor equipped with a V-blade (fig. 9.11) was a cost-effective method of planting on relatively gentle terrain with suitable soils in old burn sites that had few solid, fresh stumps remaining. Since soils on these sites consisted of live brush roots and decaying tree roots instead of bare plowed soil, the most critical modification made to the manufacturer's planting machine was to replace the trenching tool, such as a coulter wheel, with a custom-made cutting blade. This modification allowed for a much cleaner and debris-free opening of a planting trench, which was critical so that each seedling fed into the trench could be planted properly as the packing wheels then closed the trench. The V-blade attached to the front of the crawler tractor would scalp away a 5- to 6-foot-wide band of grass, brush, and woody debris down to moist mineral soil, allowing the planting machine attached to the back of the tractor to plant 5,000 to 8,000 seedlings per day.

This was a cost-effective method because site preparation of grasses, forbs, and light- to moderate-sized brush could be accomplished in the same operation as planting. Unlike piling brush into piles or windrows a substantial distance away from where the trees are planted, the V-blade left the scalped material within the future rooting zone of planted trees, providing organic matter to the soil as it broke down. The planting machine, however, was not efficient at planting wide spacing within a row, and only 8- to 9-foot spacing between seedlings within a row was feasible. Therefore, after early machine planting at high densities resulted in excellent survival rates, typical plantings by the mid-1990s consisted of 8- to 9-foot spacing within a row, with rows located 16 to 18 feet apart. Precommercial thinning 7 to 10 years later consisted of thinning out every other tree in each row for a resulting density of 135 to 170 trees per acre.



Figure 9.11. A V-blade attached to the front of a crawler tractor (A) scalps away grass and brush, making a level surface of moist mineral soil in preparation for planting 2-0 bare-root ponderosa pine seedlings with the planting machine attached behind the crawler tractor (B).

Contracting

Selecting a planting contractor is a critical step in the implementation of a successful reforestation project. The increasing importance of skilled, experienced planters available during a relatively short timing window, coupled with increasing reliance on the time-sensitive work visa process, means that foresters now plan and secure agreements with planting contractors from several months up to a year prior to planting.

Experienced reforestation foresters do not limit their criteria in selecting a planting contractor simply to the lowest bidder with the cheapest labor. Paying the compensation necessary to retain skilled, highly motivated planters is critical to ensure the careful and proper seedling handling and planting necessary for survival and growth. In addition to cost, the crew, foreman, and contractor's experience are important considerations when selecting a planting contractor.

Crew

Successful reforestation foresters understand that the person who actually handles and plants each tree seedling plays a critical role in the reforestation program. They look for indications that crew members have expertise, a good work ethic, and take pride in their role in a successful project. Although inexperienced planters periodically join a planting crew and require one-on-one training, the majority of the crew should be experienced, proven planters. Select a planting contractor with a low turnover rate and crew members who are highly motivated. Although training new planters occurs, minimizing turnover and maximizing the use of experienced planters allows the planting contractor's foreman to focus on the details necessary for proper organization and oversight of the handling and planting of several thousand seedlings each day. Important questions to ask of a potential planting contractor include:

- What percentage of the planting crew has one full season or more of experience planting?
- What do you do to motivate your planters to produce efficiently and with care and pride in their work?
- What is the average tenure with your company?

Responses to these questions will provide an indicator of how well a planting contractor retains employees that have the expertise and motivation to do quality planting and take pride in their work.

Foreman

A good planting crew foreman communicates well with each member of their crew as well as with the refor-

estation forester, takes pride in the crew's work, and pays attention to detail. They are highly organized and are eager to implement all of the steps necessary for a successful reforestation project. A foreman should be transparent and open with the reforestation forester about any problems or potential problems that may arise during planting operations.

Experience, reputation, and references

Information about a planting contractor's experience and reputation can be obtained from other experienced reforestation foresters that have used the one you are considering. A list of reforestation projects completed in the past 5 years can be requested from prospective planting contractors, with a description including the number of seedlings, stock types, planting methods, and list of references (such as landowners, forest managers, and reforestation foresters). References should be contacted and inquiries made as to how they would rate the planting contractor in terms of the criteria listed here.

Production and timing

The planting contractor should have adequate personnel to meet daily production goals for comfortably completing planting within the planting window. Also, the planting contractor must be available to start planting with sufficient crews and foremen by the date needed. This is very important and should not be overlooked, because postponing completion of a planned planting project until the next season usually results in wasted seedlings and the need for additional site preparation of the unplanted area. If an otherwise qualified contractor quotes a cheaper price but cannot guarantee that they will be able to start and complete planting within a suitable time frame, preference should be given to another qualified contractor who commits to completing on time, even if they quote a higher price.

Contractors should be willing to execute a written planting agreement indemnifying the landowner or manager, and they should have adequate commercial general liability and auto insurance naming the landowner or manager as additional insured. Contractors should also have workers compensation and employer liability insurance and comply with all state and federal laws and regulations, including but not limited to employment practices, occupational health and safety, and environmental laws and regulations. A written agreement should also include terms and conditions that meet the landowner's objectives, including enforceable inspection guidelines.

Enforceable inspection guidelines

Although enforceable inspection guidelines should be developed based upon the methods and objectives of

each specific planting project, the planting contract should list enforceable inspection items that address the steps listed in the "Planting methods" section above.

Production targets

Specifications for production targets should include the minimum average daily number of trees per crew to comfortably complete the project within the scheduled time frame. Weather conditions, access, or harsh conditions on particular portions of the planting area may justify planting less than the minimum on some days, but overall average daily production targets should be established.

Production targets should also include the maximum number of seedlings that can be planted daily per planter to maintain planting quality and minimize fatigue and shortcuts on proper handling and planting techniques. This number depends upon the seedling stock type and size, planting tool, spacing, site, and soil conditions.

Penalties and incentives

Typical planting agreements specify a minimum percentage of seedlings inspected that must have a satisfactory rating for all planting criteria, below which the contractor is docked payment. However, if the percentage of seedlings inspected that do not pass as satisfactory goes much below this minimum, then the contractor could be held in breach of contract, assessed more severe penalties, and possibly face termination of the contract. The forester's daily inspection report can serve as the basis for any payment reduction computed on a daily basis, should such reductions be necessary.

Penalties and possibly a breach of contract could also apply to noncompliance with contract terms not related to the inspection of individual seedlings, such as improper storage and handling of seedlings in the field, poor distribution of species, failure to meet production targets, and abandonment of seedlings. The excessive abandonment of seedlings, such as stashed trees (intentionally discarded in slash or buried, typically in bundles) should result in stiff penalties. For example, some planting agreements specify that any tree that is stashed will be paid for by the contractor at 10 times the landowner's purchase price, and that the contractor will not be paid for planting that tree. Tree stashing may be the cause, at the sole discretion of the landowner's representative, for immediate suspension of work for the day or termination of the planting contract.

Payment methods and rates

There are three general methods for paying planting contractors. By far the most common is to pay the con-

tractor based upon the actual number of seedlings planted, usually calculated daily and subject to reduction depending upon contract penalty specifications. This form of payment requires careful monitoring and documentation of seedling inventories, deliveries to the planting site, and seedlings planted on a daily basis.

Another method is to pay the contractor based upon the number of acres satisfactorily planted. This requires an accurate calculation of actual acres planted in compliance with the spacing and planting specifications, as determined by a sufficient number of sample plots. Although the latter, less-common payment method is a more turnkey form of payment, it could cause logistic challenges that lead to delays in payment, disagreements, or uncertainty on the amount of payment. These potential issues may create more risk of uncertainty for the contractor and lead to higher bids and costs.

A third method involving hourly payment is useful in situations where significant variables make it difficult to estimate and then bid or negotiate on a fixed cost per seedling or acre basis. For example, sometimes the planting contractor is paid by the hour that each laborer works when a project has many small units and significant travel time between units. Use of this payment method should be reserved for trusted contractors and should include agreement on a not-to-exceed amount in the contract, with clear knowledge of crew performance and production levels.

Organizational needs

It is important to prepare for organizational needs well ahead of the anticipated commencement of planting operations because once planting starts, the reforestation forester will be spending long busy hours overseeing operations.

Inspectors

If the reforestation forester is overseeing multiple planting projects or a large planting project that requires more than one 10-person crew, trained planting inspectors should assist the forester in administering the planting contracts and conducting systematic daily planting inspections. A rule of thumb is to have at least one inspector for every 10- to 14-person planting crew, but in many situations an additional inspector is helpful. If enough inspecting personnel are available, it is a good practice to have one inspector in the field with the crew at all times and one on the landing. The inspector at the landing can also assist in field inspection as the landing duties allow.

Inspections are considered either “hot” or “cold.” Hot inspections are more common in California,

especially on the property of small, nonindustrial landowners. Hot inspection involves taking random plots of planted seedlings immediately behind a planting crew and interacting directly with the crew supervisor while the crew is planting. This allows for problems to be corrected in a timely manner and also provides timely direction to the crew supervisor for any matters or questions that might come up. This type of close inspection is preferred when a forester contracts with a planting contractor to plant on several small units or for several small landowners.

“Cold” inspection involves reviewing plots after the crew has completed planting a unit with no direct interaction with the supervisor while the crew is planting. The ideal type of inspection and number of inspectors depends upon specific site conditions, the size and number of units planted each day, access, caliber of the planting contractor, and planter-to-foremen ratio. The reforestation forester should conduct a preoperational meeting with the planting inspectors to train them in the contracted planting techniques, including actual field planting if needed, and to go over all aspects of the planting project (including those described below).

Seedling deliveries

Seedling deliveries from the storage location to the planting site via pickup trucks or trailers and, if needed, further transport via all-terrain vehicles, yarders, or helicopters must be scheduled and coordinated.

Inventory

It is essential to monitor the rate at which the seedling inventory in the storage facility is being depleted by planting. Sometimes seedlings for a project are not stored at the location from which daily seedlings are loaded. In this situation, seedlings would need to be transported from a separate storage facility to replenish the inventory in the on-site or local cold storage. Planning ahead to anticipate the time required for shipping seedlings to the local storage must be factored in to avoid running out of seedlings. Failing to provide a planting contractor with seedlings may result in losing the contractor to another job during the already short planting window.

Field considerations

Unit layout. Before planting begins, it may be necessary to identify unit boundaries with flagging or other suitable means. Situations where this may be useful include units in which vegetation control via the site preparation spray is not yet clearly evident, areas where planting will be deferred, and special treatment areas. Identification of unit boundaries ensures that planting crews do not waste time trying to determine

the planting area and that seedlings will not be planted outside of the designated planting area.

Maps. Project and unit maps that show the planting area as well as all access roads should be readily available on-site. Maps are essential for clear communication with the planting contractor. These maps should be used to document the daily planting progress, unplantable areas, areas requiring additional treatment, and other project issues.

Detailed unit-by-unit planting plans. Often different seedling species mixes, spacing, or other constraints may be prescribed for a specific planting unit or within a particular aspect of a planting unit. Considering any issues related to each unit prior to planting and conveying this information to the planting contractor will help to streamline the planting project. If the planting project has more than one unit or is large enough to be divided into units, the number of seedlings per unit should be calculated. Seedlings should be allocated and reserved for each unit to ensure that an adequate number is available for the last units to be planted.

Unit planting folders. A folder should be available at the cold storage area and landings, which includes documents such as instructions, unit maps, daily planting inspection and summary forms, and inspection cards.

Trash disposal. The collection, storage, loading, transport, and disposal of refuse generated from planting should not be underestimated. Often on large planting projects, a substantial quantity of empty seedling boxes, pallets, seedling bags, banding material, and other trash accumulates. Some seedling nurseries will accept the return of seedling boxes and pallets. The remaining trash must be disposed of by relocating to a refuse facility or burning on-site, if that can be done safely and local regulations allow the burning of seedling boxes, bags, and pallets.

Preoperational meeting. A preoperational meeting with the reforestation forester, planting inspectors, and the planting contractor is critical to discuss terms of the planting agreement and logistical and organization aspects relevant to the planting contractor. These preoperational meetings facilitate much smoother operations because once planting starts, inspectors will be spending long, fast-paced days (often starting a few hours before sunrise and ending well after dark) keeping the planting crews supplied with seedlings, inspecting planting operations, maintaining accurate daily records, and making periodic reports.

Planting inspection

Number of inspectors per crew. Generally, one inspector will oversee each 10- to 14-person crew, but

in many situations an additional inspector may be helpful to handle landing duties and assist in field inspections, especially during the first few weeks of a planting project or planting with a new or inexperienced contractor.

Inspection procedures. Conducting timely inspections is important so that problems can be corrected and adjustments made as soon as possible. Besides general observations to monitor the planting crew's proper handling of seedlings, inspectors should conduct sampling to check on seedling health, spacing, species distribution, microsites, and planting techniques (such as scalp, depth, and root placement). Inspectors should run transects perpendicular to the direction the planting crew has traveled in order to randomly check all planters instead of following one or two planters as the crew progresses.

At least 1 percent of the seedlings should be inspected by first measuring for spacing and then checking to make sure seedlings are not too loose (should not pull up by tugging on a few needles), scalping was adequate, seedlings were planted at the proper depth, and proper planting microsites were selected (if applicable). After checking these items, the inspector should carefully dig up the seedling and check for proper planting angle, roots straight down and not stuffed, no J- or L-rooted seedlings, and all roots surrounded by moist mineral soil. Dry soil and woody matter that dropped into the planting hole indicates there was no or poor scalping prior to opening the planting hole. Air pockets near seedling roots indicate either that snow fell into the planting hole (for example, poor scalp) or the planting hole was not properly closed around the seedling roots.

Documentation. Documentation is critical, such as the use of daily inspection forms (fig. 9.12) printed on waterproof paper (if wet conditions are anticipated) with boxes to fill in and symbols indicating satisfactory or unsatisfactory results for each seedling checked. For example, this might be a "0" for satisfactory, and if unsatisfactory then symbols for which criteria were not met, such as poor scalp (S), loose seedling (L), poor angle (A), or J-root (J). The header of each form should include the names of the inspector, contractor, foreman, planting project, and landowner, as well as the date and any other information the forester deems important. A line at the bottom should be available to fill in the number of trees inspected and the percentage planted satisfactorily. A place should also be included at the bottom of the form for both the inspector and the crew foreman to sign, acknowledging the daily inspection results. Weatherproof electronic devices are

increasingly being used that document this information along with the mapping of daily planting progress.

Seedling inventory. Seedling information should be included on the daily inspection form or a summary form if multiple inspection forms are filled out in one day. This should include the number of seedlings planted by nursery, stock type and seed lot, and species. Planting inspectors should take the time when loading trees in the morning to count and record the number of seedlings of each lot loaded (by number of boxes and number of seedlings per box). Although it is good practice to plant all seedlings removed from the cooler and transported to the planting site, if unplanted seedlings remain at the end of the day they should be counted so the net number of seedlings planted is carefully recorded daily. Of course, any unplanted seedlings should be returned to the cooler at the end of the day and be the first seedlings removed and planted the next day. Even though days can be long and hectic, taking the time to accurately keep daily records can greatly benefit accounting later and be used in tracking progress to schedule timely seedling shipments if more are needed.

[illegible]

Figure 9.12. Planting inspection form.

Installing protection measures in conjunction with planting

Animal pest control measures and mulching are covered more fully in chapter 8 (“Vegetation Management”) and chapter 11 (“Damage”), respectively, but a few measures may be installed in conjunction with or soon after planting operations, often by the same crews.

Artificial shading devices

With proper species and stock type selection, seedling handling, planting practices (including micrositeing), and other methods, artificial shading devices are rarely required. Occasionally, however, the installation of artificial shading devices can improve seedling survival or health in some specific site and species situations (Livingston and Black 2011). For example, shade cards were effectively used in reforestation portions of Cuyamaca Rancho State Park in the arid mountains of Southern California after the 2003 Cedar Fire (personal communication, Lisa Gonzales-Kramer).

The purpose of artificial shading is to protect susceptible seedlings of sensitive species from solar radiation on one or more of the following surfaces:

- The main stem of the seedling that can damage young, developing stem surfaces and kill the underlying cambium
- The soil surface material that is in direct contact with the seedling stem and root collar or close enough to radiate damaging levels of heat
- The seedling foliage that can lead to excessive transpiration, especially on hot, dry sites during the first summer's growing season while the seedling roots are getting established into the soil profile

In addition to protection from solar radiation, artificial shading devices can provide protection from the desiccating effects of wind in limited situations.

Ponderosa pine seedlings, even when planted on harsh sites, are resilient to the effects of solar radiation, and artificial shading devices are very rarely, if ever, necessary. On certain sites, especially south- or east-facing aspects, the stems and underlying cambium of Douglas-fir and, to a lesser degree, true firs, are susceptible to direct solar radiant heat damage or damage from excessive soil surface temperatures, especially smaller, 1-year old, containerized stock sizes. Relatively larger 1-year-old Douglas-fir and fir container stock (styro-15 or greater) and 2- or 3-year-old bare-root or plug-1 stock not only have more developed, hardened stems but also more lateral branch foliage to shade the seedling stem, so less artificial shading is needed. However, larger stock with more foliage are subject to

much more transpiration stress during the critical first year of root establishment on hot, dry sites typical of Southern California and much of interior California, especially on south-facing aspects at relatively lower elevations.

Artificial devices are generally comprised of photo-degradable, black polyolefin mesh envelope and a wire wicket. They can provide a shade factor of approximately 80 percent, and the mesh allows for air passage. The mesh degrades in approximately 5 years and the wire wicket will begin to degrade in approximately 5 years. In most situations where shading devices are used, shading is only needed for the first, and maybe second, year of seedling establishment, when the seedling is developing a root system that is deep and extensive enough to reduce transpiration stress, a hardened stem to protect the cambium, or lateral branching to shade the seedling stem from direct sunlight. Devices that are only used during the first year or two of seedling establishment can be reused until they degrade.

Mulch materials

Mulch mats manufactured from synthetic fiber, sod, or paper are commercially available, or a mulch can be created using materials such as bark, pine needles, or straw. These mulch products can reduce evapotranspiration from the soil and control competing vegetation. Except in areas where competing vegetation is otherwise controlled or in areas that receive sufficient summer rainfall, mats should cover approximately a 5-foot-diameter area around planted seedlings for adequate effectiveness. Mulch mats must be secured to the ground with rocks, stakes, spikes, or woody debris (fig. 9.13). It is important to periodically monitor mats, especially after significant wind events, as seedlings be killed or damaged by mats which have been dislodged by the wind. The material and installation costs for mulch mats are typically much greater than chemical vegetation control methods and can be cost-prohibitive. Mulch mats deteriorate naturally over time but should be removed once they are no longer needed in order to eliminate the risk of wind or other events dislodging the mat and covering the seedling.

Animal pest protection materials and methods

Sometimes, in conjunction with planting operations, rigid (solid or mesh) protection tubes, mesh netting, or bud caps are installed to protect newly planted seedlings from animal damage. Seedling protection is generally only installed in areas with known pest problems. The cost of the materials and labor is typically as much, or more, than the cost of seedlings and planting. When visiting a planting site to see if it is ready for planting in order to schedule planting crews, the for-



Figure 9.13. Properly installed mulch mat.

Photo: Bill Morrison, Soper-Wheeler Company.

ester can plant several test seedlings and monitor them to see if animal damage occurs. Then the forester will be better prepared to arrange for the installation of seedling protection devices in conjunction with planting operations. The two most common types of animal damage that can be mitigated by installing protection devices are rabbits, which clip small seedling stems at about an inch above ground level, and deer, which browse the seedling foliage or main stem bud and sometimes tear off a very tender main stem.

Rabbits. Rabbit damage is easily diagnosed because rabbits make a clean cut of the main stem at a 45-degree angle about an inch above ground level. Since this is done not for consumption of the seedling but rather simply to keep their teeth from growing too long, the clipped seedling is typically laying close to the tiny stump. Small, 1-year-old container stock are mainly attacked early in the growing season, and older seedlings or newly planted 2-year-old bare-root stock are rarely attacked. One of the most cost-effective and maintenance-free methods for protecting newly planted seedlings from rabbits (as long as deer browse is not also an issue) is installing plastic mesh buried a few inches below ground level and extending 4 to 6 inches aboveground (fig. 9.14).

Deer and elk. The least expensive method to discourage deer browsing is to install mesh netting, but unlike installation for rabbits, the netting must cover the tops of the seedlings and still allow for seedling growth and/or the netting must be monitored and maintained through the growing season. This method works best when deer browse is not too heavy or is temporary for just a few months. For elk or heavy deer browse, plastic mesh tubes anchored with bamboo stakes are more effective (fig. 9.15). Although more expensive, this method lasts longer and requires less maintenance, especially during the first growing season.

Although not commonly used in California, bud caps are a relatively inexpensive treatment to protect terminal buds, if browsing pressure is limited to the winter and early spring when more palatable forage is not available to deer or elk present. Bud caps can be installed prior to spring flush, or in fall after the growing season for overwintering and the following spring. Proper installation can allow for early terminal growth of approximately 2 inches inside the cap, when it is most desirable for the browsing animal. Bud caps should be monitored and removed if terminal growth is negatively impacted by them later in the growing season. Lightweight, degradable mesh bud caps, such as Pacforest Supply Company's Breathe Easy bud cap, can be left to break down in most situations but should still be monitored (fig. 9.16).

Seedling protection tubes and mesh netting are generally not effective against gophers and other burrowing animals. Control treatments for gophers and other pests that are not done in conjunction with planting operations are described in chapter 11 ("Damage").

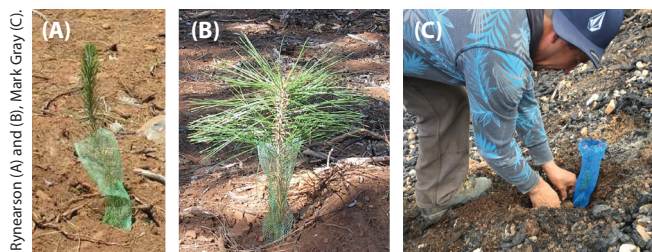


Figure 9.14. One of the most cost-effective and maintenance-free methods to prevent rabbits from clipping seedling stems is installing plastic mesh buried a few inches below ground level and extend 4 to 6 inches aboveground, shown after planting (A) and at the end of the first growing season (B). To protect seedlings from deer browse, netting must be anchored in soil (C) and extend over the top of the seedling and monitored for maintenance needs.



Figure 9.15. Plastic mesh tubes are typically buried a few inches below ground level and anchored by bamboo stakes.

Planting follow-up

Timely follow-up is critical in order to monitor the success of a reforestation project and, if needed, identify and schedule timely site preparation and interplanting activities or pest control treatments. Monitoring first-year seedling survival and vigor can facilitate more timely decisions and actions if needed. Early detection and diagnosing of problems with competing vegetation (including its effect on depleting soil moisture) or animal and insect pests can facilitate more timely decisions and actions that reduce damage and costs. Also, monitoring provides important information for lessons to learn and incorporate in future reforestation projects.

Stocking survival surveys

Systematic, statistically useful surveys to determine first-year seedling survival and vigor and estimates of seedlings per acre should be conducted after the first late summer or fall rains. The person conducting the seedling survival surveys should also record conditions of competing vegetation by type (grass, forbs, and brush) and species of brush, and whether or not the brush is a germinate (approximate age) or a resprout.

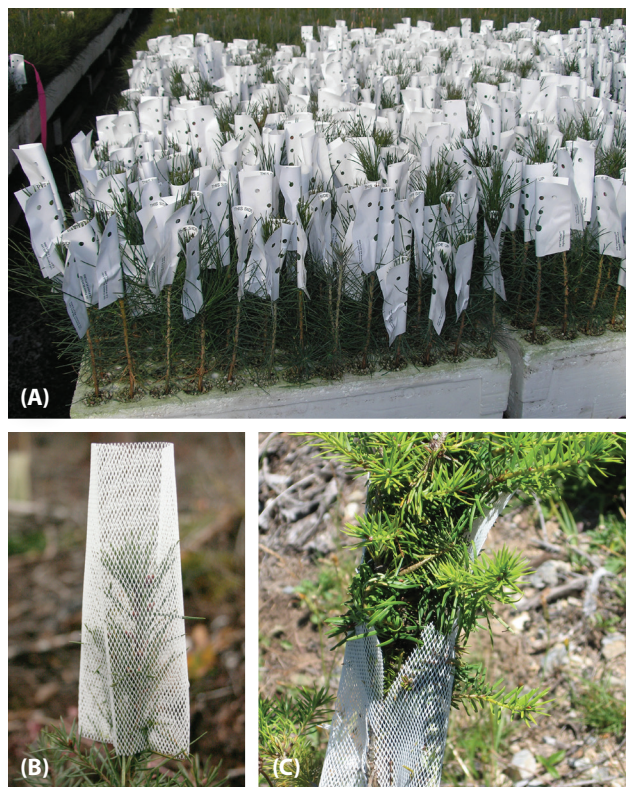


Figure 9.16. Solid bud caps are installed at a nursery prior to lifting and packing (A). Lightweight, semi-rigid, poly-mesh slip (B) on a Breathe Easy bud cap (Pacforest Supply Company) is applied after planting to protect seedling from winter deer and elk browse; typically, they are not removed (C) (as pictured, in the second growing season).

Also, notes should be taken on any herbicide, insect, or animal damage observed in each plot or while travelling between plots.

Typical first-year surveys consist of 1/100-acre plots (11.78-foot plot radius) established at 2-chain (132 feet) intervals on 5-chain (330 feet) to sample about 1 percent of the area. The intensity of the sample depends on funds and time available and the degree and uniformity of survival. A good first-year stocking survey will aid in scheduling interplanting, release treatments, and other pest control treatments, if needed the following year. Depending upon results of first-year stocking surveys and the reforestation forester's experience with the site and planting stock, a second-year survey may be necessary.

Although a systematic survey is not warranted until the end of the first growing season, ocular (visual) walk-throughs should be conducted about 2 to 4 weeks after planting, which include digging a few trees of each species and stock type to monitor root growth (figs. 9.17 and 9.18). Additional ocular walk-through inspections should occur monthly until the year-end stocking survey is conducted. These periodic, brief inspections are necessary to monitor the health and vigor of seedling foliage, stems, buds, and roots; evaluate competing vegetation; and aid in diagnosing any problems. For example, if seedlings that looked morphologically good were physiologically dead or severely weakened at the nursery or during cold storage, they usually will show signs within 2 to 4 weeks after planting. Also, most animal damage problems occur within the first month or two of planting. If there are problems with seedling survival or vigor and the reforestation forester waits until the end-of-season stocking survey to look at the seedlings, it is much harder to diagnose the myriad of potential causes and at which step they occurred, whether at the nursery or storage facility, or after planting. Also, early detection and diagnosing can facilitate more timely decisions and actions that reduce damage and costs.

Interplanting

Ocular or systematic stocking surveys may reveal areas that are understocked or not uniformly stocked, which may need to be interplanted to achieve the desired level of stocking and uniformity. The need for interplanting should be carefully considered before committing. Sometimes a unit or project may appear understocked and be interplanted, only to discover in 5 to 10 years that it is actually overstocked. In this situation, the interplanted trees are often just cut later in the precommercial thinning to achieve the desired trees per acre. Interplanting is more expensive than standard planting due to the time required to find the holes or



Figure 9.17. Fall-planted white fir seedling (A) dug up to check for root development at the beginning of next growing season. New root growth on a ponderosa pine seedling (B) a few weeks after planting.



Figure 9.18. New root growth on a styro-5 containerized ponderosa pine seedling 2 weeks after spring planting in Modoc County, where average annual precipitation is 24 inches.

gaps where seedlings need to be planted. Additionally, the seed transfer, seedling growing, packing, transport, and storage must be accounted for. If interplanting is delayed, an additional site preparatory or release treatment may be necessary to ensure survival of the interplanted seedlings.

Vegetation and pest problem surveys

Plantation surveys can determine the extent of competing vegetation and pest damage. Often a few dead seedlings or competing vegetation can be alarming and lead to the conclusion that treatment is needed. Systematic surveys can be invaluable to quantify the extent and spatial distribution of damage and aid in determining if treatment is warranted. These surveys can be used as a follow-up to earlier stocking surveys that indicate the occurrence of problems.

Diagnosing problems

Periodic monitoring during all phases of the project, including lifting and packing at the nursery, cold storage, transportation to the site, planting, and postplant-

ing will greatly aid in diagnosing problems that may occur. In addition to monitoring planted seedlings aboveground (including stems, branches, needles, and buds, and the presence of competing vegetation), it is important to dig out some seedlings within a few weeks to a month after planting and then excavate the soil around some seedling roots in the late summer or early fall to check on the depth of root growth and availability of soil moisture at rooting depth.

In addition to checking on root growth, examining the depth to soil moisture and presence of competing vegetation roots within the seedling's rooting zone in the late summer are good indicators of whether or not competing vegetation was adequately controlled. Even during periodic drought cycles on relatively dry conifer sites, proper vegetation control should provide for sufficient soil moisture at the end of summer within the rooting depth of quality conifer seedlings. A minor level of vegetative cover (10 or 20%) near a conifer seedling can deplete soil moisture enough to affect seedling vigor or survival. Also, when diagnosing problems with seedling survival and vigor one must realize that when using spray circles or mulch mats to control vegetation, the roots of adjacent vegetation grow into the soil underneath. If a problem with seedling survival or vigor occurs where an insignificant amount of competing vegetation is present or when an adequate radius of a spot spray or mulch mat treatment were used, the area should be checked to ensure that adequate soil moisture is available for the seedling roots.

The main key to seedling survival in a Mediterranean climate is vigorous root growth down to soil moisture available at the end of the summer. Checking early-season root growth and later checking end-of-summer root depth and soil moisture are important monitoring techniques for diagnosing problems and prescribing possible treatments.

A useful and relatively inexpensive technique to monitor and diagnose potential problems is to plant short monitoring rows of each seedling lot at a few different elevations and soil types with labeling that will last at least a few years. Generally, these monitoring rows are planted at convenient locations on the project area, in side-by-side rows of about 20 seedlings of each lot and at approximately 4- or 5-foot spacing. This can provide a quick and simple periodical check for vigor, top, and root growth by seedling lot as the summer progresses. Although a more thorough survey may be needed if problems with a particular stock type, species, or nursery arise, the ease of monitoring these rows can alert one earlier to any problems with a particular lot and give a rough indication of seedling health and vigor by lot. Although samples of these trees can be dug up and replanted early in the first

season to check for root growth, the close spacing allows for destructive sampling to measure root growth at the end of the first and second growing seasons.

Conclusion

Planning and implementing successful reforestation projects is critical to sustain and enhance California's forestlands, but these are challenging endeavors. The various methods and steps described in this book have been developed and refined over the past several decades. Understanding the critical steps of seed and stock type selection; transporting, storing, handling, and planting seedlings; and follow-up monitoring and treatments will help improve the success of any planting operation.

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Chapter 10

Precommercial thinning

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Precommercial thinning, defined as the “removal of trees not for immediate financial return but to reduce stocking to concentrate growth on more desirable trees” (Helms 1998), plays an important part in the reforestation process. It is typically applied between stand establishment and the first commercial thin or harvest. In addition to altering planting density and competition from noncrop vegetation, the selection of which trees remain after precommercial thinning affects the timing and average tree size attainable at the next harvest. A higher-intensity precommercial thinning will shorten the time needed to grow trees large enough to produce commercial products but will also reduce the total amount of wood fiber (but not necessarily the wood value) available for removal in the first commercial thin.

Planning a precommercial thinning involves the following decision factors:

- Timing (early versus late)
- Intensity (heavy versus light)
- Thinning method (selecting favorable trees for retention)
- Implementation (tools and equipment used)

Precommercial thinning influences the risks associated with disturbances such as wildfire (Pollet and Omi 2002), bark beetles (Fettig et al. 2007), windthrow and snow damage (Powers and Oliver 1970), and bear damage. These risks change over time, before and after or with and without precommercial thinning. On occasion, precommercial thinning plays a role in naturally regenerated even-aged and multiaged stands, and it is commonly applied in young, artificially regenerated (planted) even-aged conifer forests in California.

Outcomes of precommercial thinning

The decision to conduct precommercial thinning comes with the expectation of positive and negative outcomes for the treatment. We review possible outcomes and how they are influenced by choices made at the time of implementation.

Enhanced growth

Thinning results in the redistribution of tree growth to fewer stems, increasing the growth rates of remaining trees (Ashton and Kelty 2018, 395). When growth rates on residual trees accelerate, the time until the retained trees reach harvestable size shortens. The increase in tree growth is achieved at some loss to the stand's overall volume growth per acre and will delay the culmination of mean annual increment (Curtis 1994, 1995).

Growing stock improvement

Precommercial thinning may improve growing stock by removing trees that are unhealthy, damaged, low vigor, or less valuable. Sometimes the largest trees have poor form and heavy branching. Failure to remove malformed trees at precommercial thinning preserves trees that will continue to increase in size but perhaps have little value if their logs are defective or become downgraded by large knots. Growing stock can also be improved by removing species that do not meet management goals. For example, prescriptions can be tailored to maintain and promote trees that provide critical wildlife habitat such as black oak (*Quercus kelloggii*). On the other hand, a management goal of maximizing conifer growth and yield would necessitate removing most hardwoods during precommercial thinning.

Wood quality

It is difficult to generalize about the impacts of precommercial thinning on wood quality because of differences among species, their end uses, and innovations in sawmill technology. Maintaining lower stand density will likely reduce wood quality to some degree. Trees with wider spacing can keep low branches alive and growing longer, resulting in low crown-base height, larger branch size and knots, lower height-to-diameter ratio, and more conical form than trees grown at higher densities (Maguire et al. 1991; Briggs et al. 2008; Weiskittel et al. 2009). These attributes can lead to problems such as the downgrading of logs with excessive knot size or reduced recovery of sawn timber from tapered logs.

Conversely, postponing precommercial thinning keeps lower branches in the shade longer, where they grow slowly or die; and being smaller, these low branches may fall sooner to allow for the production of more knot-free clearwood. However, species may be more valuable if they grow rapidly and attain larger log sizes that contain more decay-resistant heartwood, while maintaining live lower branches that produce intergrown knots, which preserve the integrity of sawn timber for exterior applications (Ashton and Kelty 2018, 424). The problem of branches growing unabated into large openings can be mitigated by maintaining even spacing after precommercial thinning and reducing the amount of stand-edge versus interior stand area, where branch size is controlled by interaction with neighboring trees.

Wood properties. Enhanced growth after thinning has been linked to changes in wood anatomy and wood product performance in some species but not others. Markstrom et al. (1983) found that growing-stock levels in ponderosa pine (*Pinus ponderosa*) had no impact on the performance characteristics of resulting structural lumber, including factors that affect stiffness and strength of wood such as specific gravity, percentage of latewood, tracheid length, or microfibril angle. Rapid diameter growth produces wider annual rings that some consider unsightly and can have slightly lower specific gravity in some species, such as Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) (Jozsa and Brix 1989; Filipescu et al. 2014) and ponderosa pine (Echols 1971). However, the wide rings themselves were not the cause of performance problems. Early precommercial thinning to promote rapid diameter growth (and wide rings) at a young age tends to increase the proportion of crown wood in the butt log of conifers (Maguire et al. 1991). Crown wood typically has lower density, stability, and stiffness than the outer wood that surrounds it. Therefore, structural lumber sawn from

outer wood is expected to perform better than crown wood (Ashton and Kelty 2018, 388).

Pruning. In concert with precommercial thinning, pruning can improve wood quality, although the expense limits its applicability in many situations. Pruning enhances wood quality and value when branches are removed over an entire log length (such as up to 18 feet aboveground for a 16-foot log) and this is done early enough to allow clearwood to form over many years after pruning. The economics are more favorable after timely precommercial thinning on better sites where rapid growth in diameter at breast height (DBH) facilitates earlier harvest to recoup pruning costs incurred years earlier. Only a subset of crop trees designated for retention to attain large sizes should be pruned for the production of clearwood timber. During precommercial thinning, additional unpruned trees should also be retained to allow for subsequent commercial thinning of knotty sawlogs, while pruned trees are allowed to continue growing larger to produce enough clearwood for the adequate recovery of knot-free lumber during milling (Ashton and Kelty 2018, 432). Pruning can also lower the risk of white pine blister rust (caused by the fungus *Cronartium ribicola*) entering the lower branches of young pines (O'Hara et al. 2010) or reduce ladder fuels and facilitate fire suppression efforts in locations such as fuel breaks, high-value landscapes, and buffers along main roads. Pruning for forest health and fire hazard reduction can be restricted to 8 to 10 feet up from the ground to limit cost, but this restricts clearwood production to an unusually short butt log that may not be saleable at a premium. Pruning for fire hazard reduction is commonly applied strategically within 100 to 200 feet of main roads.

Timing and intensity. To improve operational efficiency and reduce fuel loading, pruning can be done in 2 or 3 separate operations, or lifts, conducted a few years apart, leaving 40 to 50 percent live crown upon completion of each lift. Pruning wounds recover better when pruning occurs on live rather than dead limbs, on smaller branches to create smaller wounds, and on rapidly growing trees where the stem can encapsulate wounds quickly.

The following considerations should also be accounted for when planning precommercial thinning and pruning treatments:

- fuel loading from thinned and pruned material
- thinning shock; in Douglas-fir and white fir, for example, consider delaying pruning until after precommercial thinning
- epicormic branching response to precommercial thinning or more severe pruning; in coast redwood,

for example, consider delaying or adjusting the season of precommercial thinning to limit epicormic sprouting (O'Hara and Berrill 2009)

- insect attack potential; delaying thinning until the fall and winter can reduce risk of insect attack in some species

Timing may be better during the growing season to limit epicormic sprouting or during the fall and winter to avoid insect attack in some species.

Insect and disease impacts

Managing the density of trees can also reduce the likelihood of mortality from bark beetles. Low tree vigor is related to bark beetle attacks (Larsson et al. 1983), and thinning has long been proposed as a method to reduce the risk of bark beetle attack (Sartwell 1971; Sartwell and Stevens 1975).

***Dendroctonus* bark beetles** are the primary long-term concern in California (table 10.1). While many trees are too small at the time of precommercial thinning to be susceptible to *Dendroctonus*, an increase in tree vigor is expected to limit the mortality from bark beetles over time as the trees approach a size where commercial thinning may be considered (Oliver 1995; Fettig et al. 2006, 2007; Egan et al. 2010).

TABLE 10.1. Bark beetle (*Dendroctonus* species) of concern for California native pines

Insect species	Host species	Impact
<i>D. brevicornis</i> , Western pine beetle	<i>P. ponderosa</i> <i>P. coulteri</i>	Usually attacks trees more than 6 inches diameter at breast height
<i>D. jeffreyi</i> , Jeffrey pine beetle	<i>P. jeffreyi</i>	Usually attacks where bole is more than 12 inches diameter at breast height
<i>D. ponderosae</i> , mountain pine beetle	<i>P. ponderosa</i> <i>P. contorta</i> <i>P. lambertiana</i> <i>P. monticola</i> <i>P. coulteri</i> <i>P. flexilis</i> <i>P. balfouriana</i> <i>P. monophylla</i> <i>P. longaeva</i>	Usually attacks trees more than 5 inches diameter at breast height
<i>D. pseudotsugae</i> , Douglas-fir beetle	<i>P. menziesii</i> <i>P. macrocarpa</i>	Will infest recent mortality or windthrown trees; can spread to living trees
<i>D. valens</i> , red turpentine beetle	<i>P. ponderosa</i> <i>P. contorta</i> <i>P. lambertiana</i> <i>P. monticola</i> <i>P. jeffreyi</i>	Usually not a tree killer in California, but may weaken trees; is often active after fire

***Ips* beetles.** The *Ips* genus of bark beetles can be a more immediate concern to managers conducting precommercial thinning (Sartwell 1970). The primary species of concern in California are pine engraver (*Ips pini*) and California five-spine ips (*Ips paraconfusus*). Hosts include most pine species in California. Both *Ips* species will readily infect green logging slash, so the season when precommercial thinning takes place and the distribution and amount of slash generated are concerns. Lower levels of slash and more widely scattered slash that dries quickly tend to inhibit *Ips* populations. Lopping felled trees may facilitate drying but can be cost-prohibitive, with cost increases of 50 percent or more. In some instances, foresters may choose to accelerate the drying of felled trees by delimbing the top side to let direct sunlight reach the stem or leaving the cut tree intact in hopes that transpiration via foliage helps purge moisture from inside the stem and branches (Mark Gray, personal communication). Thinning pine in late summer or early fall may also inhibit population growth of *Ips* (Kegley et al. 1997). *Ips* produces several generations per year, and with high levels of slash emerging adults can attack small green trees and the tops of larger trees.

Other insects and root disease. While precommercial thinning may improve tree vigor in relation to beetles, it may also exacerbate problems with insects such as shoot borers (Robertson and Dewey 1983; Ferguson et al. 2011). This problem is most pronounced when heavy thinning removes more than half of standing trees (Mark Gray, personal communication). Disturbance may also create an environment favorable to root bark beetles such as *Hylastes nigrinus*, which can vector black-stain root disease (Goheen and Hansen 1993; Hessburg et al. 2001). Interactions between thinning and root disease may differ among host tree species; in ponderosa and Jeffrey pine forests, for example, thinning has been observed to reduce the occurrence of black stain (Woodruff et al. 2019), whereas thinning in Douglas-fir plantations appears to increase the spread of the pathogen (Harrington et al. 1983; Hessburg et al. 2001).

In general, the presence of root disease in plantations is not necessarily an impediment to thinning (Filip and Goheen 1995; Filip et al. 2009, 2015). General thinning guidelines for pathogen management are to favor retention of species that are less susceptible to the disease while minimizing soil disturbance. Care should also be taken to impede the spread of pathogens by washing equipment.

Fire and fuels management

Precommercial thinning has the potential to create—via accelerated growth and increased bark thickness—larger trees that are more resistant to fire (Ryan and Reinhardt 1988; Odhiambo et al. 2014; Zeibig-Kichas et al. 2016; Berrill, O'Hara et al. 2020). In the short-term, however, trees cut and left on-site elevate surface fuels that can increase fire severity. Early implementation when trees and their branches are smaller will reduce this surface load and increase the rate that slash breaks down. Pruned limbs also become surface fuels, which can be scattered or piled to avoid leaving them concentrated at the base of crop trees. Busse et al. (2009) observed that slash fuel loads of small material (less than 3 inches in diameter) subsided over a 5-year period.

Because surface fuels influence fire behavior, managers may consider mitigation by chipping or pile-and-burn treatments. Some precommercial thinning prescriptions may call for lop-and-scatter treatments to minimize fuel concentrations and reduce the height of fuel beds. Contract language for lop-and-scatter could simply prescribe a single cut at a specified stem diameter or a maximum fuel-bed depth achieved by cutting fuels into progressively smaller pieces. Achieving lower fuel-bed depths is more costly, but the expected benefits include mitigating extreme fire behavior due to the faster decomposition of smaller fuel pieces closer to the ground, where warmth and moisture support decomposition (Jain et al. 2012, 136). However, until lopped surface fuels decompose, they pose a risk of severe fire behavior (Stephens 1998). Keyes and O'Hara (2002) recommend an integrated strategy combining pruning, low thinning, and surface fuel management to mitigate the risk of crown fires.

Understory vegetation development

Lower stand density encourages the development of understory vegetation including shrubs and herbaceous plants (McConnell and Smith 1970; Thomas et al. 1999; Dagley et al. 2018, 2023). Numerous studies show the long-term impacts of competition from shrubs in reducing the growth and yield of conifer trees (Barrett 1973; White and Newton 1989; Oliver 1990; Monleon et al. 1999; Powers and Reynolds 1999; Zhang et al. 2006). For this reason, the growth effects of precommercial thinning will be more pronounced when done in concert with the effective management of competing vegetation (Barrett 1982; Oliver 1984); for example, a masticator can be used to both thin and masticate brush simultaneously. Effective site preparation and early release treatments tend to minimize competition from shrubs. Alternatively, delayed or repeated light thinning can mitigate this problem by

reducing growing space available to understory vegetation.

Decision-making about precommercial thinning

The implementation of precommercial thinning involves numerous decisions on the method, timing, and density of retained trees; species selection; and tree selection for size or vigor. In the simplest case of a single-species stand, a nondiscriminatory approach such as cutting entire rows of planted trees may be considered. With this type of thinning, decision-making is focused on the timing and intensity. However, more discriminatory thinning practices are more complex and require greater levels of understanding by the operators.

Thinning timing

Timing has direct and indirect impacts on the costs for precommercial thinning. In general, thinning in a younger stand is easier and less costly than culling a more mature stand. Thinning later increases costs because trees are larger and therefore take longer to cut; likewise, more slash is produced, which is often considered hazardous surface fuel that must be dealt with at extra cost. Early thinning reduces or eliminates the need for slash disposal (Powers et al. 2013). Figure 10.1 shows that early thinning by removing 100 to 125 trees per acre when they are 2 inches in diameter will generate about 1/20th as much biomass and new surface fuels as waiting until the trees are 5 inches in diameter. Some foresters prefer to wait and conduct precommercial thinning when the trees are around 5 inches diameter so that they have more time to express favorable traits such as superior growth and form. Later thinning also provides more opportunity to remove defective trees, such as those damaged by bears, shoot borers, or woodrats. However, future dominance may be expressed quite early, allowing for early thinning focused on retaining fast-growing trees. Oliver and Powers (1971) found that ponderosa pine expressed future dominance by the time trees reached breast height.

For coastal Douglas-fir, Reukema (1975) suggested a thinning window with tree heights between 10 and 15 feet and between ages 10 and 15 years on high- and medium-quality sites (Reukema 1975; Reukema and Bruce 1977). Earlier thinning when trees are smaller is common in other areas. For example, many owners of conifer forests in California thin when the stand is between 7 and 10 years old. For pine or pine and Douglas-fir mixtures that are planted at 300 trees per acre, the average site can be expected to be ready for thinning in year 7 or 8, whereas high-site-index areas

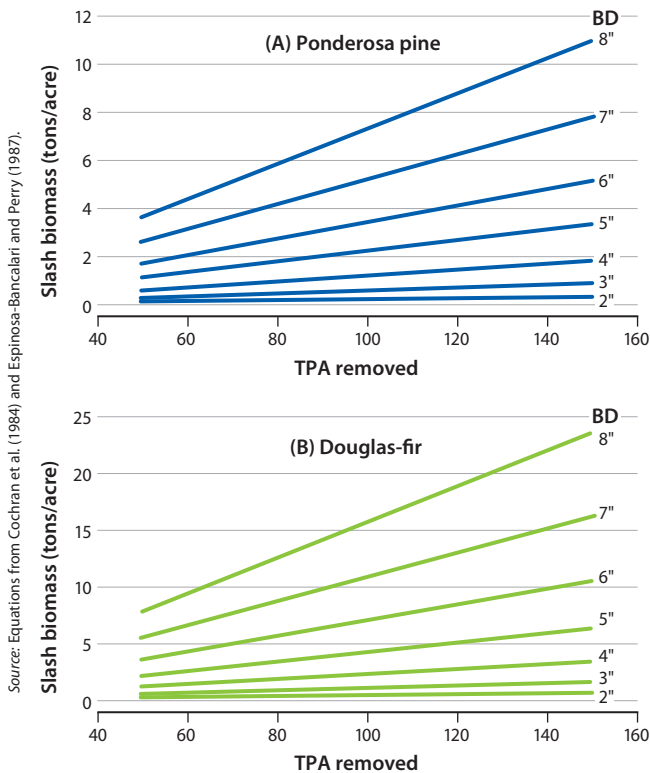


Figure 10.1. Douglas-fir aboveground total biomass estimates in tons per acre for thinning slash as a function of average basal diameter (BD) at 6-inch stump of trees removed and number of trees per acre to be removed for (A) ponderosa pine and (B) Douglas-fir.

(high quality sites with rapid height growth) planted to pine may be ready at year 5 (Mark Gray, personal communication). The rationale for waiting until this time instead of conducting precommercial thinning earlier is to ensure that crop trees outsize weeds (any unwanted vegetation) such that after thinning the residual trees are capable of quickly reoccupying available growing space instead of prolonging the stand initiation phase by ceding more growing space to weeds (Oliver and Larson 1996).

Intensity of thinning

The number of trees per acre retained after precommercial thinning influences the time when the first harvest, or commercial thinning, can happen for any market or site quality. The residual density (number of trees retained per acre) can be defined to meet a goal of growing specific tree sizes at the next thinning or some other type of harvest; this is often determined by the stand's average tree size by diameter, known as quadratic mean diameter (QMD) at the next thinning (Reukema 1975; Webster 1997). As the target quadratic mean diameter for commercial thinning increases, the residual tree density from thinning should decrease by growing fewer, larger trees. The number of trees per acre and mean tree size determine the density thresh-

old; density management diagrams, described below, can help guide decisions on residual density to achieve the forest manager's specific objectives.

It is natural for timberland owners and foresters to want to leave stands at higher densities; it can be difficult to cut your own trees or watch thinning crews cut trees you have planted and cared for (Mark Gray, personal communication). But the correct timing and intensity of thinning is an integral step in density management prescriptions designed to maintain the desired balance between rapid individual tree growth (low stand densities) versus high-volume production per acre annually (higher stand densities).

The **OP-Yield tool** can help guide decision-making on the timing and intensity of early stand development in ponderosa pine (Ritchie and Zhang 2018). This [spreadsheet adaptation](#) of the yield tables for ponderosa pine plantations in Oliver and Powers (1978) gives users the flexibility to evaluate thinning options with varying establishment densities and anticipated commercial thinning targets.

Species selection

In planted stands, the natural regeneration of commercial species such as white fir (*Abies concolor*) or non-commercial species such as tanoak (*Notholithocarpus densiflorus*) can add a considerable number of trees to the stand's density. Precommercial thinning provides a window of opportunity to adjust the species mix available for subsequent harvests. Due to natural regeneration, competition, climate, disturbances, and other factors, the early status of a stand may not reliably describe the long-term development of individual species.

Figure 10.2 illustrates a crossover effect: although species A is favored due to an early size advantage, it may not produce the desired long-term results. For example, 9 years after planting at Caspar Creek watershed in Mendocino County, Douglas-fir seedlings were shorter than redwood seedlings, which were much shorter than redwood stump sprouts. However, dominant Douglas-fir were expected to overtake dominant redwood in height after a slow start (Jameson and Robards 2007).

In stands managed primarily for timber production, thinning to promote evenness in tree spacing is a high priority. Thinning contractors are therefore usually given a target average spacing to aim for, and their success in achieving this goal is assessed by foresters who count residual stems per unit area in small, fixed-area plots. In mixed stands, the forest manager should provide thinning contractors with guidelines on which species are higher or lower priorities for retention, along with exceptions for situations when a

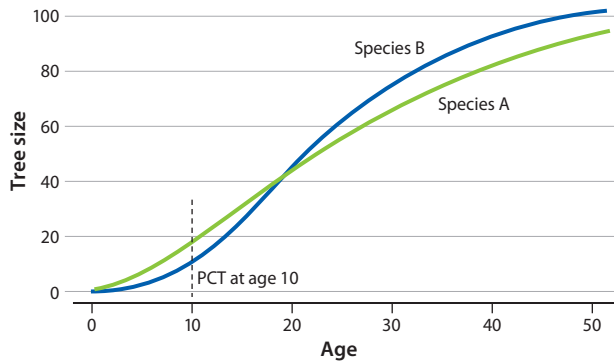


Figure 10.2. Tree-growth forms with crossover where species A is larger than species B at time of thinning (dashed line).

high-priority species tree is much smaller and less vigorous than a nearby tree of lower species priority. The simplest strategy is to allow a lower priority species to replace a higher priority species only when it reaches a size that thinning contractors can easily judge, such as, for example, “twice as tall” or “50 percent taller” than the smaller individual of higher species priority. Any such prescription implies that the forester does not expect much-smaller individual trees to be released by thinning and maintain competitiveness until the next stand entry (for example, for operations such as commercial thinning or final or partial harvest that transform the stand from even-aged management of one age class of trees to multiaged management of two or more age classes).

Health, vigor, form, and defects

Typically, trees selected for retention are the healthiest and most vigorous, and free of serious defects such as broken or dead tops; stem defects such as lean, sweep (for example, curved stem), crookedness, or forking; and stem damage such as bark stripped by animals. The spatial distribution of leave trees (any trees not cut at thinning) is also an important consideration; the best trees may not be well distributed throughout the stand. Variability within stands can be handled by ordering or weighting priorities for individual tree retention in the precommercial thinning prescription. For example, if even spacing is a priority, then it can be emphasized ahead of other important factors such as tree vigor or size. Straightforward retention guidelines for thinning contractors should include priorities, for example: (1) species choice, (2) evenness of spacing, and (3) tree growth and form. Species choice can be listed explicitly according to individual species names or groups, such as, “Prioritize retention of redwood, then Douglas-fir, then other whitewoods, then hardwoods other than tanoak.”

Thinning methods

The thinning method defines which trees are cut according to their position within the stand, often according to relative tree crown position ranked from highest to lowest: dominant, codominant, intermediate, and suppressed/overtopped. The thinning method selected helps to refine and communicate the precommercial thinning prescription using professional terminology, as follows:

- **row thinning, also called geometric or mechanical thin:** no discrimination based on size, so trees from all diameter classes are cut, maintaining the same tree diameter distribution
- **low thinning, also called thin from below:** focus cutting on smaller trees
- **crown thin:** focus cutting mainly on codominant trees to keep larger trees while also releasing smaller trees with desirable properties
- **selection thinning, also called thin from above or dominant thin:** focus cutting on largest trees, which is acceptable when cut trees are unhealthy or of undesirable species or form
- **variable-density thinning:** for objectives other than timber production, cut patches to different spacing, creating a mosaic of different densities throughout the stand
- **crop-tree release, also called localized release:** cut trees only in the vicinity of crop trees selected for retention and release from competition
- **Free-form thinning:** combinations of any of these thinning methods for specific objectives

Row thinning is simple and economical. By felling trees in one direction along a row of plantation trees, row thinning facilitates the efficient felling of trees by creating open spaces for trees to fall into and avoid the likelihood of trees getting hung up in the crown of adjacent trees. In dense, naturally regenerated stands, cutting or crushing strips of trees is simpler and less costly than most other thinning methods. Row thinning is typically the first in a sequence of planned thinnings (for example, row thin followed by commercial thins using more sophisticated methods).

Low thinning reallocates growing space to the largest, most vigorous, and wind-firm trees. It preempts the natural mortality of weaker trees, but cutting only smaller trees requires that many trees be cut to sufficiently reduce competition and thus achieve the desired release from competition among residual crop trees. Low thinning in mixed stands can be detrimental when slower-growing species are inadvertently targeted. The numerous small cut trees can create a spatially continuous fuel bed that is less desirable than

a discontinuous fuel bed, but they usually decompose more rapidly than relatively larger trees cut during selection or crown thinning.

Crown thinning involves thinning in the middle and upper canopy to create space for promising crop trees of any size. Removing neighboring trees with crowns that interfere with the development of crop trees usually involves cutting codominants, but cutting some dominants or intermediates may also be needed. Crown thinning may be more economical because it requires cutting fewer (larger) trees than low thinning, while at the same time making fuel beds less uniform or continuous, and in turn, less hazardous. In a stand with trees approaching merchantable size, a crown thinning could be performed in lieu of low thinning of smaller, nonmerchantable trees.

Selection thinning is used to remove dominant trees of poor health, form, or value, such as low-value pioneer species overtopping the desired crop trees. Unfavorable genetics may predispose a vigorous tree to form problems such as heavy branching and forking. Stem or leader damage caused by pests is also common among the most vigorous trees. Timely selection thinning helps to cull such trees before they overtop and suppress desirable crop trees.

Variable-density thinning encourages nonuniform tree spacing, which results in differences in crown size, growth rate, and tree form within stands. Trees in uncut reserve patches grow slowly while others grow rapidly at wide spacing and adjacent to patch cuts. This medley of densities can promote the heterogeneity and complexity of natural, older forests. Variable-density thinning is suboptimal for timber production because of inefficiencies related to the range of tree sizes and form problems such as heavy branching and crown asymmetry.

Crop-tree release requires cutting only a few large trees with crowns in direct contact with each crop tree. Smaller trees overtopped by the crop tree can remain as trainers, restricting the lower branch growth of crop trees. Crop-tree release usually removes crown competition on all four sides of each crop tree, but “three-sided release” can be used to reduce costs, albeit at reduced benefit in terms of crop-tree growth (Dagley et al. 2018). After the localized release of well-formed, desirable trees, much of the stand remains unthinned, making the crop-tree release method cost-effective, especially in dense stands and when low retention densities are prescribed (Leonard et al. 2017).

Free-form thinning combines any two or more of these thinning methods. Within a plantation, for example, row thinning can efficiently removing entire rows in combination with low thinning along adjacent rows of retention trees, to leave a well-spaced stand

of superior trees. Free-form thinning is also useful in stands with irregular species composition and structure, where the precommercial thinning prescription can list different localized conditions matched with the desired thinning methods. For example, patches of desirable or valuable hardwood or tolerant conifers could receive crown thinning to release them, while areas dominated by intolerant conifers receive low thinning.

For more detail and examples of thinning methods, see Ashton and Kelty (2018, 461–485).

Implementation methods

Options for implementing precommercial thinning include hand treatments, chemical and mechanical treatments, and prescribed fire.

Hand treatments. Hand treatments (chainsaw, brush-saw, or loppers) offer potentially high selectivity but can be slow and therefore more costly, particularly in older stands or those with dense, competing vegetation. Hand-felling allows the land manager to be specific about which trees to remove and leave, enabling the treatment to target disease, insect, or mechanical damage, or the ingrowth of undesirable species. At the same time, this type of thinning can help to retain and protect or promote the growth of critical elements such as snags, mast-producing hardwoods, and trees with features offering habitat value. If possible, the stem should be completely severed below the lowest live branch or foliage, otherwise this foliage may survive and turn upward to become a replacement stem. The same applies to trees pushed over by other falling trees; the down tree should be cut, otherwise its branches may grow upward as new, unstable tree stems.

Tree size affects the choice of thinning tool. For very-small-diameter trees (less than about 3-inches basal diameter), options include loppers or a brush or clearing saw; the latter is a motorized tool has a blade mounted on a pole, similar to a string trimmer but with a circular saw blade on the cutting end. Clearing saws do not work well for larger trees but may effectively deal with dense pockets of natural regeneration.

The backpack chainsaw is ergonomically designed specifically for thinning smaller saplings, with the backpack’s powerhead running a chainsaw bar and chain mounted to the end of a handheld pole. Keyes et al. (2008) reported that when thinning crowded redwood sprout clumps, brush saws and hedge trimmers were not effective because they could not cut larger, older stems, while smaller chainsaws performed adequately and resulted in less operator fatigue than larger, slightly faster saws. Common chainsaw sizes used for thinning are 60 to 70 cc and power output of 3.5 to 4.0 kilowatts or 4.7 to 5.4 horsepower (Mark

Gray, personal communication). Professional-grade chainsaws have slightly higher power-to-weight ratios, which can reduce fatigue.

Chemical treatments. Chemical thinning uses herbicides to kill selected trees. Spray applications can help remove unwanted trees that have seeded into a planted stand or germinated after planting as may occur with serotinous species such as knobcone and lodgepole pine. Spraying can be a useful tool in these young stands, but as the stand grows it loses effectiveness. Hack-and-squirt applications involve stem injections of herbicide; they can be used for thinning when the plantation trees reach appropriate thinning age and beyond. With hack-and-squirt, a small quantity of herbicide is injected or sprayed into cuts (sometimes named frills) that go through the bark and into the cambium of the target tree. While most conifer stumps will not resprout after cutting, redwood and most hardwood stumps can sprout vigorously in response to thinning (Roy 1955). This problem can be solved by spraying a small quantity of herbicide on the freshly cut stump using a handheld spray bottle. Chemical thinning requires a licensed applicator and in-depth knowledge of the best chemicals and application timing. For example, injecting chemicals in spring may be less effective than late in the season. Although hack-and-squirt is most commonly used to remove unwanted hardwoods, it may be useful for removing unwanted conifers. Glyphosate, imazapyr, and triclopyr will kill most conifers when applied at the proper dose (Mark Gray, personal communication).

Using herbicides for thinning may increase risks to the remaining stand. For example, imazapyr remains active in soil for months and is sometimes translocated to adjacent trees of the same species through root grafts, so testing on a small scale is advisable. Chemical applications to conifers don't kill the treated tree rapidly and in some cases only cause the tree's health to decline over a long period of time. This can lead to insect outbreaks and increases in disease in an otherwise healthy plantation (Mark Gray, personal communication).

Basal bark spraying is another chemical thinning approach where an oil-based penetrant carries the herbicide through the thin bark of young trees; triclopyr ester is commonly used. This is an efficient way of treating multistemmed clumps of resprouting hardwoods quickly with a small amount of herbicide. For more information on chemical weed control, see chapter 8 and Tu et al. (2001).

Mechanical treatment. Another option for thinning is mechanical treatment. Mechanical chippers or masticators, which are boom-mounted or mounted on the front of a wheeled or tracked vehicle, may be used for

thinning (USDA Forest Service 2009). These tools are well suited for row thinning, especially in extremely dense young stands, or for thinning stands of advanced age where hand-felling is too slow. Mechanized harvesters such as feller-bunchers can cut trees and place them in bundles to be skidded to a landing, where the material is made available to firewood cutters, piled and burned, or chipped and hauled to a cogeneration plant for the production of electric power. In multi-aged stands, feller-bunchers can be used to quickly thin young trees (such as dense patches or unwanted species) in conjunction with harvesting merchantable trees. Excessively steep or rocky terrain will limit mechanical treatments. For more information on mechanical treatments, see chapter 8 and Jain et al. (2012).

Prescribed fire. Prescribed fire is another option for thinning (Windell 1998), although fire is an unpredictable thinning tool with uneven results. Prescribed fire may be feasible in young plantations when the fire intensity is controlled (Bellows et al. 2016). Tree mortality can be highly aggregated (fig. 10.3). If conditions are too cool or wet, the fire may not remove enough trees; if too hot and dry it may take out more than desired. Generally speaking, prescribed fire is better suited to thinning from below in a stand with larger, older trees, which are more fire-resistant. The probability of surviving fire varies among tree species and according to the burn season. The chances of tree survival may be slightly enhanced by pruning and raking fuels away from young trees (Bellows et al. 2016).

Cost considerations

Cost is a key consideration for any precommercial thinning project. So just how much will precommercial thinning cost? Even if we could produce estimates they would quickly become obsolete, and costs are significantly influenced by the particulars of a given project.



Figure 10.3. Prescribed fire thinning of a dense cluster of naturally regenerated ponderosa pine saplings at Blacks Mountain Experimental Forest.

Photo: Martin Ritchie, U.S. Forest Service.

The best approach to budgeting for precommercial thinning is to consult with professionals in your area with recent thinning experience.

The costs for precommercial thinning will be higher when it is delayed, the materials being cut are large (Webster 1997), or the contractor is required to pile or lop-and-scatter material. The time to think about thinning is before you plant: cutting more trees per acre increases costs, as does overplanting. These cost considerations are critical, since it will be decades before any returns on the reforestation investment occur.

The equipment used to thin also influences operation costs, while the choice of tools depends on size of trees being cut. For example, Jamnick (1989) compared a brush cutter with a machete and chainsaw for precommercial thinning in an 8-year-old, mixed-conifer plantation and found that productivity was lowest with the brush cutter (which might be an efficient tool for cutting smaller trees).

Access is another important cost consideration. Is there easy access or will workers have difficulty getting to the site? Any time crews have to walk some distance, costs increase. Steep slopes slow productivity and increase costs per acre because workers and machines can generally move more effectively on flat ground. Are there other obstructions to be dealt with like high shrub cover or slash that will slow workers down? Anything that slows the rate of work will increase costs.

Density management

Precommercial thinning plays a critical role in long-term density management, as stand structure and growth after thinning affect the timing of subsequent entries. The ability to manipulate the number and distribution of trees in a stand over time is one of the silviculturist's primary tools.

We often think about precommercial thinning prescriptions in terms of simple metrics of density such as trees per acre retained. However, as stands develop over time, the metrics necessarily become more complicated and trees per acre no longer adequately describes growing space occupancy in the stand. For example, 200 trees per acre of small trees occupy less growing space than the same number of large trees in the same space.

The following sections explain how density metrics and density management diagrams can be used to help develop guidelines for establishing the optimal target densities for precommercial thinning.

Density metrics

The generic definition of stand density is the number of individual trees per acre. For very young planta-

tions, particularly those with uniform survival and distribution, trees per acre is a sufficient descriptor of stand density. In instances where tree survival lacks uniformity—as may occur with natural regeneration—trees per acre may need to be augmented with a stocking measure (Stein 1978, 1992). Stocking reflects the amount of a stand that has adequately regenerated, often expressed as a percentage. It may be possible to derive estimates of stocking for natural regeneration from estimates of trees per acre (Lynch and Schumacher 1941; Ritchie 2020).

To assess development of a stand over time, density-related metrics must incorporate the effect of tree size, particularly related to growth and mortality. Basal area per acre, the cross section of all trees in the stand at breast height (4.5 feet), is a metric used as a target for late-entry thinning as well as in later commercial harvests (Oliver 1979a, 1979b). Basal area per acre can be expressed as a function of quadratic mean diameter (the diameter of a tree of mean basal area):

$$BA = k \times TPA \times QMD^2 \quad (1)$$

Where:

BA = basal area in square feet per acre

TPA = trees per acre

QMD = quadratic mean diameter in inches

$k = 0.005454154$

For example, if *trees per acre* is 300 and *quadratic mean diameter* is 3 inches, basal area is 14.7 square feet per acre.

Reineke's stand density index (SDI) is a widely applied density metric, especially for western North American forests (Reineke 1933). This metric was derived by Reineke for even-aged forests, and it takes the general form of:

$$SDI = TPA (QMD/10)^{1.605} \quad (2)$$

Stand density index is referenced to the number of trees in a stand with a *quadratic mean diameter* of 10 inches. The effect of indexing this metric is similar to indexing dominant height with site index, in which a stand's dominant height is referenced to that of the stand at base age. Therefore, if two stands have *quadratic mean diameters* of 7 and 15 inches and both have a *stand density index* of 135, both are at the same level of density in Reineke space; they both are equivalent in density to a stand with a *quadratic mean diameter* of 10 inches and *trees per acre* of 135. A reexpression of equation (2) yields:

$$SDI = a \times TPA \times QMD^{1.605} \quad (3)$$

This expression (where $a = 0.0248$) then has a form nearly identical to (1); the only important difference is the value of the exponent on *quadratic mean diameter*.

While the exponent of 1.605 is widely applied, it is not universal. Some studies in ponderosa pine have used a value greater than the Reineke (1933) constant of 1.605. Edminster (1988) used 1.66 and DeMars and Barrett (1987) and Cochran (1992) used 1.7653. Rounding this to two decimal points yields 1.77, which has been employed for ponderosa pine as well (Oliver and Powers 1978; Cochran and Barrett 1995; Ritchie and Zhang 2018). As a result, it is important to understand which value is in use for any application. The example presented above of 3 inches *quadratic mean diameter* and 300 *trees per acre* yields a *stand density index* of 43.4, when an exponent of 1.605 is employed.

Because Reineke's *stand density index* was developed for even-aged stands, it may not be appropriate for uneven-aged or multicohort stands. For this reason, Long and Daniel (1990) proposed a modified version of *stand density index* using a summation method. The summation form of *stand density index* can be expressed as:

$$SDI_s = \sum TPA_i \times (DBH_i/10)^c \quad (4)$$

where DBH_i is the breast height diameter; TPA_i is the expansion factor, for the i th tree in the sample; and c is the *stand density index* exponent, again usually 1.605 although sometimes rounded to 1.6. This expression has the advantage of being additive, so the metric can be compartmentalized by individual tree, size class, or species cohort. The two different expressions for *stand density index*, equations (3) and (4) produce metrics that are very close to one another for stands with a symmetric diameter distribution (Curtis 2010; Curtis et al. 2016), as is the case in most plantations. However, with multimodal or long-tailed distributions, the value obtained for *stand density index* in (4) can be substantially less than that for equation (3).

A case can be made for excluding very small trees by setting a minimum diameter limit for calculating equations (3) or (4), particularly in cases where ingrowth of natural seedlings is present in the understory (Curtis 2010). For Douglas-fir in the Pacific Northwest, Curtis (2010) recommends basing this restriction on one-quarter of the *quadratic mean diameter* of the 40 largest *trees per acre*. It isn't clear if this method translates well to other species.

Density management diagrams

One approach to decision-making about thinning is to first determine an upper limit to density for a managed stand. Observed *stand density index* is often divided by the upper limit for that species (SDI_{UL}) to develop a

relative density (RD) metric bounded by 0 and 1: $RD = SDI/SDI_{UL}$. A relative density value near 0.6 is sometimes defined as the upper limit of the management zone (UMZ). For example, if the SDI_{UL} is assumed to be 400 and one wishes to establish the upper limit of the management zone at a relative density of 0.6, then the upper limit of the management zone is 240: 0.6 times 400. In turn, density management would be conducted to ensure that the stand remains below this threshold. Note that this threshold relative density as well as the SDI_{UL} value may vary by species. The lower limit of the management zone is typically associated with the point where the stand approaches crown closure.

So how does precommercial thinning, which is generally specified by a trees per acre or spacing target, relate to the *upper limit of the management zone*? First assume a quadratic mean diameter that will define a stand that can support a commercial entry at some time in the future. One example would be to assume that the desired *quadratic mean diameter* is 11 inches, meaning that the goal is to precommercially thin a stand to a level which assures that it can reach a *quadratic mean diameter* of 11 inches without exceeding the *upper limit of the management zone*. In other words, the *upper limit of the management zone* should not be reached until the next harvest after the precommercial thinning, and that harvest should be a commercially viable timber sale. Using 240 as an upper limit, this would be calculated as $TPA_{pct} = 240(11/10)^{-1.605} = 205.95$, meaning that no more than 206 trees per acre should remain in the stand after the precommercial thin.

In this context, density management diagrams can be helpful for visualizing the timing and intensity of thinning. Often a *density management diagram* is an expression of *stand density index* with mean tree size (QMD) on the y axis and *trees per acre* on the x axis, using a log-transformation (fig. 10.4). In addition to the lines for fixed values of *the stand density index*, additional isolines may be included for volume (cubic feet per acre) and dominant height (feet). These can be used to estimate the status of the stand in the future. By assuming a site index system, such as the Biging (1985) curves, one can then also imply the age at a given point in stand development in the density management diagram.

Other expressions have been developed for density management. Some present average tree size as mean tree biomass (Drew and Flewelling 1977, 1979). Drew and Flewelling (1979) used relative densities of 0.15 and 0.55 to bound the management zone within which they expected an acceptable compromise between lower densities (fosters individual tree growth and

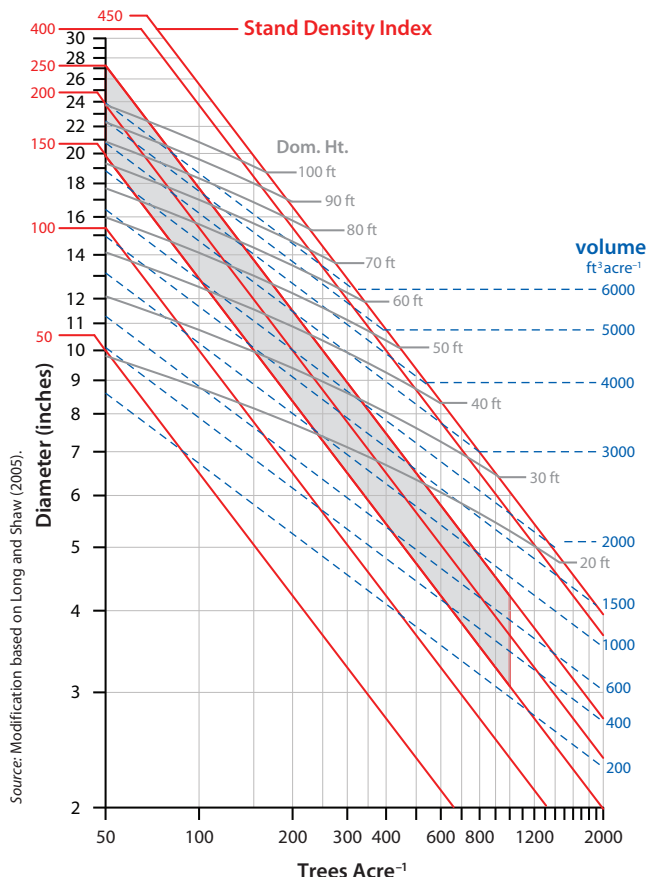


Figure 10.4. Density management diagram with management zone from stand density index (SDI) with 150 to 250 for ponderosa pine (shaded).

vigor) and higher densities (greater stand growth per acre).

Another common form of density management diagram employs stand basal area per acre (Edminster 1988; Cochran 1992). This approach uses the same technique, deriving a management zone as a proportion of a limiting *stand density index*. Figure 10.5 shows Edminster's (1988) work on ponderosa pine in the southwestern United States and Rocky Mountains.

Both types of density management diagrams can be constructed with the [standview package in the R computing environment](#). The package comes with help files and detailed guidance on the application. A dynamic application of the *standview* package, which does not require knowledge of R, can also be found online at <http://bcgov-env.shinyapps.io/SDMD/>.

Precommercial thinning and establishment density

To a large extent, planting density drives the need for thinning. High planting densities, or stands with excessive natural regeneration, put stands on a trajectory where precommercial thinning will be needed to main-

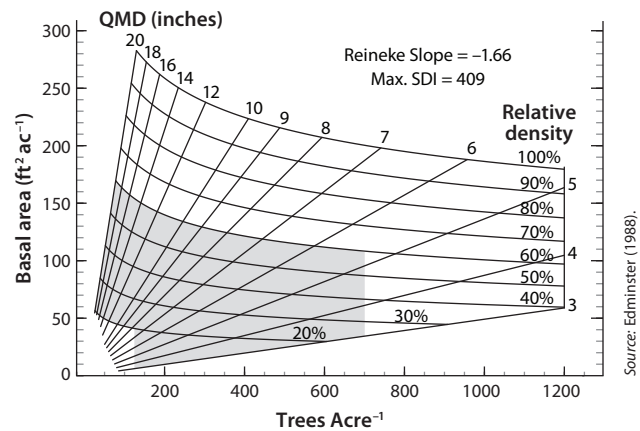


Figure 10.5. Density management diagram for ponderosa pine in the southwestern United States and Rocky Mountains, with management zone (shaded).

tain tree health and vigor and to reach merchantable size in a reasonable time frame. Without thinning in these stands, tree growth slows, and mortality eventually ensues before trees attain sizes where commercial thinning is possible.

For plantations established after a regeneration harvest, the current California Forest Practice Rules were modified in 2020 to lower the required stocking. These new standards impact the need for precommercial thinning because lower planting densities will have an impact on stand density as the planted stand approaches the commercial thinning window.

To illustrate this, a ponderosa pine plantation at 12-foot spacing with 90 percent survival rate would produce approximately 273 trees per acre. We would then anticipate *stand density index* of 318 when the stand reaches a *quadratic mean diameter* of 11 inches. A ponderosa pine stand with a site index of 100 at base age 50 will achieve this stand density in about 25 years (Oliver and Powers 1978). However, a *stand density index* of 318 exceeds the suggested *upper limit of the management zone* for ponderosa pine, indicating that precommercial thinning will be needed if we desire the stand to reach a quadratic mean diameter of 11 inches, with minimal mortality, before a commercial thin may be executed.

Precommercial thinning could be employed to allow the stand to reach the commercial thin target of 11 inches at a lower stand density, thus reducing risk of mortality. One could also achieve this outcome with a lower initial density. With a lower planting density of 14-foot spacing and 90 percent survival (about 200 trees per acre), we would then anticipate the stand will achieve a quadratic mean diameter at a stand density index of 235, perhaps avoiding the need for precommercial thinning.

Table 10.2 shows the *stand density index* associated with various establishment densities or spacings (assuming no mortality) at different points of stand development, expressed as *quadratic mean diameter*. Under earlier regulations, precommercial thinning was often not a management option but rather a silvicultural necessity. Planting a mix heavy with Douglas-fir on a westside stand may also raise the *upper limit of the management zone* and thus delay the stand's exceeding this limit (Drew and Flewelling 1979; Long 1985).

Regional considerations

Tree species and their productivity are substantially different across California, which must be considered when managing the density of young stands. Managers must also consider local and emerging issues. Local issues may include elevated risks of wind-throw after heavy late thinning in exposed areas, or the risk of large wildfires after creating a continuous fuel bed by thinning over vast, contiguous areas. Emerging issues include elevated risks of loss due to drought in a changing climate, prompting thinning to retain fewer *trees per acre*; and sudden oak death, prompting the

removal of hardwoods. Managers may also incorporate language into contracts requiring the cleaning of equipment to prevent the spread of unwanted seed or fungal pathogens or actions taken when diseases such as root rots are present. For example, in areas with black-stain root disease, managers should seek to minimize tree injury during thinning operations, soil compaction, and fuel loading, and thin later in the year after insect flight has occurred.

California Coast Range forests

The forests of California's Coast Range are known for their highly productive coast redwood (*Sequoia sempervirens*) forests located on alluvial flats and lower slopes with deep soils and favorable climate moderated by coastal fog. Further inland and upslope, redwood shares growing space with Douglas-fir, tanoak, and other associated conifer and hardwood species, which eventually give way to Douglas-fir and tanoak or true oak-dominated forests characterized by climate extremes with high vapor pressure deficits. At the southern limits of its range, redwood is found in patches on cooler, north-facing slopes where soil moisture is sufficient for it to survive the hot dry summers. Efforts

TABLE 10.2. Stand density index associated with establishment density (trees per acre) or average tree spacing (feet) and average tree size (quadratic mean diameter) combinations*

Trees per acre	Quadratic mean diameter (inches)											Average tree spacing (feet)
	8	9	10	11	12	13	14	15	16	17	18	
50	35	42	50	58	67	76	86	96	106	117	128	29.5
75	52	63	75	87	100	114	129	144	159	176	193	24.1
100	70	84	100	117	134	152	172	192	213	234	257	20.9
125	87	106	125	146	167	190	215	240	266	293	321	18.7
150	105	127	150	175	201	229	257	288	319	352	385	17.0
175	122	148	175	204	234	267	300	335	372	410	450	15.8
200	140	169	200	233	268	305	343	383	425	469	514	14.8
225	157	190	225	262	301	343	386	431	478	527	578	13.9
250	175	211	250	291	335	381	429	479	532	586	642	13.2
275	192	232	275	320	368	419	472	527	585	644	706	12.6
300	210	253	300	350	402	457	515	575	638	703	771	12.0
325	227	274	325	379	435	495	558	623	691	762	835	11.6
350	245	296	350	408	469	533	601	671	744	820	899	11.2
375	262	317	375	437	502	571	644	719	797	879	963	10.8
400	280	338	400	466	536	609	686	767	850	937	1,027	10.4
425	297	359	425	495	569	648	729	815	904	996	1,092	10.1
450	315	380	450	524	603	686	772	863	957	1,055	1,156	9.8

*Assuming negligible mortality.

to expand the range of redwood by planting further inland at higher elevations have been successful (Dagley et al. 2017). It is still unknown whether these redwoods will reproduce by seed to become naturalized or, more likely, just resprout from cut stumps. High early survival in these plantations suggests they will benefit from precommercial thinning.

Natural regeneration, which is usually prolific in Coast Range forests after harvesting, may be dominated by less-desirable conifers, advance regeneration (shade-tolerant seedlings or saplings that establish naturally, independent of the harvest), and stump sprouts of tanoak and other hardwoods (Thornburgh et al. 2000). Redwood stumps can have over 100 resprouts after cutting (Neal 1967; Wiant and Powers 1967), which may all die in low light or self-thin when sufficient light is unavailable (O'Hara et al. 2007; O'Hara and Berrill 2010). Jameson and Robards (2007) stated, "Considering that redwoods tend to sprout when cut or destroyed, a high-density planting of redwood, coupled with the naturally high density of native sprouts, may make precommercial thinning more of a necessity than an option to avoid overcrowding and to maintain a reasonable rate of diameter increment ... More recently, land managers have begun to reduce the number of trees planted, recognizing that a significant portion of the regeneration will ultimately consist of both redwood sprouts and natural fir seedlings."

Redwood sprout clumps should be thinned to promote good growth and form among the best individual sprouts (Boe 1974; Cole 1983; O'Hara et al. 2017). Thinning also provides enough space between sprouts so their stems do not grow together over time and fuse, causing deformities and making future thinning more difficult (O'Hara et al. 2015).

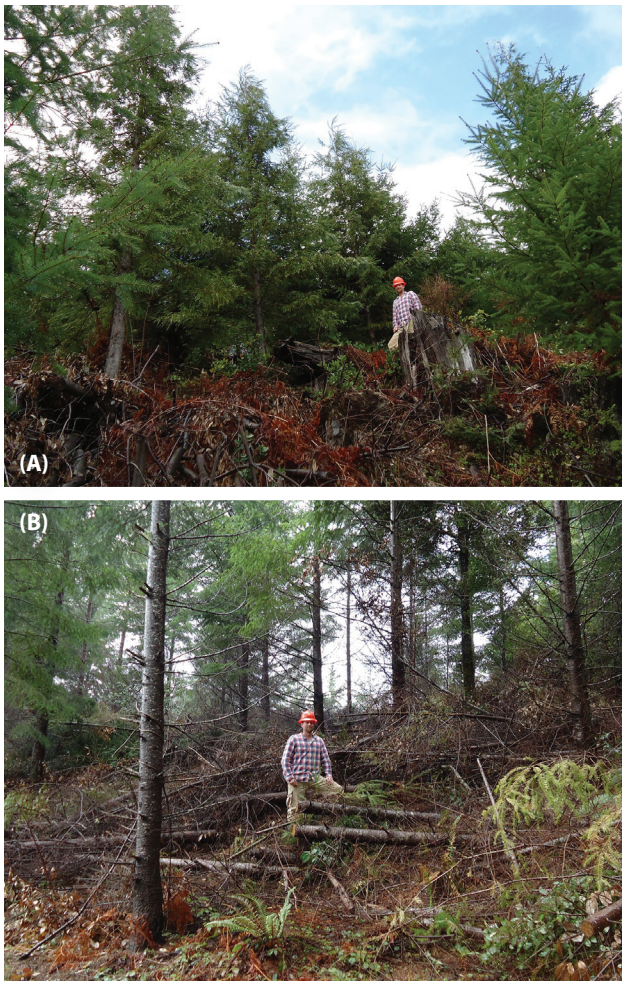
The time and cost of thinning have been shown to increase as redwood sprout clumps get larger (Keyes et al. 2008). However, an early thinning can stimulate another regeneration event, which would be counterproductive. Ingrowth comprised of sprouts arising from stumps cut during thinning as well as prolific natural seedling regeneration may counteract or lessen the benefits of thinning that were originally designed to reduce competition and promote the growth of selected trees (O'Hara et al. 2015).

Leaving sprouts that originate from the root collar or low down on the stump is recommended, since the taller, straighter sprouts located higher on the stump may eventually separate from the decaying stump and topple over. If left unthinned, the process of self-thinning within each sprout clump will proceed, and these tall, unstable sprouts will likely come to dominate; they have been observed toppling at up to age 100.

Thinning studies conducted in north coastal California on the Coast Range include timber management (Oliver et al. 1994; Lindquist 2004, 2007; Webb et al. 2012, 2017; O'Hara et al. 2015) as well as thinning for restoration objectives such as developing stands that resemble old-growth forests (O'Hara, Nesmith et al. 2010; O'Hara 2012; Teraoka and Keyes 2011; Berrill et al. 2013; Dagley et al. 2018, 2023). A long-term study of stand development after precommercial thinning to retain 100, 150, 200, 250, and 300 *trees per acre* compared with unthinned controls continues to yield data as the redwood-dominated study area surpasses a harvestable age of 50 years (Webb et al. 2017). The most recent analysis of study data found that precommercial thinning had a lasting effect on growth in young redwood stands, but that growth was highly variable and sensitive to differences in species composition and small-scale variations in site quality (Webb et al. 2017).

Site quality varies over short distances in the redwood forests of California's Coast Range. Trees in a sheltered gully may be twice as tall as trees on an adjacent ridge and have smaller or greater *DBH* depending on other site characteristics (Berrill and O'Hara 2014, 2015, 2016). Therefore, the timing of thinning or residual stand density may be adjusted to better suit patches of forest with similar productivity. If the objective of management is to grow trees of uniform size for commercial harvest at the next stand entry, then areas of poorer site quality can be thinned to lower densities (wider spacings) to promote the growth in *DBH* of individual trees; or, to foster more stand production at the expense of growth in *DBH*, the stand can be thinned to leave higher densities in better-quality areas where trees grow faster.

Similarly, multiaged redwood stands of differing site quality can be expected to have different optimal harvest return intervals or residual stand densities if the same harvested tree sizes or harvest return intervals are desired (Berrill and O'Hara 2009). Thinning in the youngest cohort of multiaged stands will accelerate tree size development and therefore shorten the time until the next harvest. It may also result in the harvest of larger trees, provided that sufficient growing space is made available to the understory cohort (O'Hara et al. 2007; Berrill and O'Hara 2009). Cole (1983) noted sprout mortality after early thinning (age 2 years) of redwood sprout clumps in low light, another caution against very early thinning in this forest type. Thinning around stand age 10 years is common in mixed redwood and Douglas-fir stands (fig. 10.6).



Photos: Christa Dagley.

Figure 10.6. One year after precommercial thinning in redwood and Douglas-fir plantation outside of redwood's range with tanoak resprouting from cut stumps (A) and light branching after late thinning (B) in homogenous Douglas-fir that generated deep slash layer.

Thinning shock in Douglas-fir

Thinning shock, a period of reduced height and diameter growth after thinning, can be a legitimate concern in Douglas-fir plantations (Staeble 1956). The problem seems most acute when thinning is delayed (Reukema 1975) and on poor-quality sites (Harrington and Reukema 1983). The reductions in growth can be quite severe in the short term, but trees will generally recover, resulting in long-term growth increases in response to thinning. DeBell et al. (2002) reported very short-lived thinning shock in a 10-year-old southwestern Washington plantation, suggesting that thinning early may be the best way to avoid it.

Thinning of coastal Douglas-fir has been decreasing (Talbert and Marshall 2005) due to the prevailing view that Douglas-fir can often make it to harvest without the need for precommercial thinning. This may be acceptable in stands comprised solely of Douglas-fir but not in overstocked stands or mixed plantations

where more desirable species are being outcompeted. Suppressed Douglas-fir with smaller crowns are unlikely to respond well to thinning at any age (Tappeiner et al. 2007).

Density management in mixed stands

By setting a goal for tree size (*QMD*) at the next harvest, the number of trees to retain after precommercial thinning can be back-calculated. Since redwood tolerates about two-thirds higher stand density than Douglas-fir (*stand-density-index* upper limits of 1,000 and 600 trees per acre, respectively) (Reineke 1933), redwood can be retained at tighter spacing than Douglas-fir. In single-species stands, 150 *trees per acre* of redwood (17-foot spacing) should reach a 24-inch *quadratic mean diameter* when the stand is at the *upper limit of the management zone* of 0.6 relative density (600 *SDI*), but only 90 trees per acre of Douglas-fir (22-foot spacing) should be retained if the goal is to reach a 24-inch *quadratic mean diameter* in a timely manner (for example, when the stand reaches an *upper limit of the management zone* of 0.6 relative density for Douglas-fir) (Long 1985).

Planning a commercial harvest at a lower quadratic mean diameter allows for the retention of more *trees per acre* at precommercial thinning. For example, when planning for commercial thinning once the stand reaches 20-inch *quadratic mean diameter*, the thinning would leave either 120 trees per acre of Douglas-fir or 200 *trees per acre* of redwood. This would translate into the following prescription for a mixed stand: thinning to leave approximately 19-foot spacing between Douglas-fir trees and 15-foot spacing between redwoods. Subsequently, if 50 percent of these stems were cut during commercial thinning, the remaining stems should have 30-inch *quadratic mean diameter* the next time relative density returns to the *upper limit of the management zone*. Alternatively, cutting fewer than 50 percent of stems would allow for a shorter harvest return interval but with smaller harvested tree sizes at the next stand entry.

Thinning in mixed stands with redwood sprout clumps

Redwood stump sprouts use their advantage of an established root system to outcompete planted or natural seedling regeneration. Redwood stump sprouts form dense clumps surrounding one or more cut stumps associated with the same root system. Depending on the size of the sprouting stumps associated with each clump and the size of the entire clump of sprouts, a small clump might be thinned down to one sprout, whereas thinning in a large, multistump clump might leave two or three well-formed sprouts

spaced 10 feet or more apart. Rather than considering this spacing too tight to meet the density management objectives of a given plantation, greater spacing can be allowed between these sprouts and other trees in the vicinity.

This precommercial thinning prescription would dictate spacing-off a certain distance from sprout clumps to allocate the appropriate amount of growing space to each sprout retained in the clump. This can be done by calculating the amount of growing space needed for each clump. If the spacing goal is 17 feet between redwoods (17 feet multiplied by 17 feet equals 289 square feet of growing space), three sprouts should be allocated 867 square feet of growing space (an area of about 30 feet by 30 feet or a 16.6-foot radius circular area). Growing space would be allocated to each neighboring tree adjacent to this sprout clump, so the spacing-off distance for each redwood clump would depend on the growing space needs of neighboring trees selected for retention. The amount of growing space needed depends on species, and, if the neighbor is another redwood sprout clump, the number of sprouts retained in that clump.

A simpler approach is to define the tree-size goal for the subsequent stand entry (for example, 20-inch *quadratic mean diameter*), then prescribe the number of sprouts to be retained per stump (for example, average two sprouts per clump, range one to three) and the amount of growing space allocated to each species (for example, half redwood and half Douglas-fir, noting that more redwood than Douglas-fir would be retained on a *trees-per-acre* basis at this growing space allocation). The precommercial thinning prescription then becomes 19-foot average spacing between individual Douglas-fir trees and/or redwood clumps (averaging 2 stems per clump). The resulting stand would have 60 Douglas-fir and 100 redwood for a total of 160 *trees per acre*, assuming that the redwoods experience higher stand densities in their stump sprout pairs than the Douglas-fir, which are well spaced to reach 20-inch *quadratic mean diameter*. Theoretically, the Douglas-fir and redwood stand components should each attain about 20-inch *DBH* and 0.6 relative density at around the same time. This is because more growing space was allocated to Douglas-fir than to redwood, which can tolerate higher densities. Thinning to 15-foot average spacing in a single-species redwood stand or thinning to 16-foot spacing in a redwood-dominated stand should give trees enough growing space to reach a 20-inch *quadratic mean diameter* at the next stand entry, when relative density reaches the 60 percent *upper limit of the management zone*.

In practice, density and tree spacing are difficult to control due to the inherent variability in spatial

patterns of tree locations in mixed stands (O'Hara et al. 2015). Deviation from the prescribed spacing to retain better trees is the norm, requiring the operator to compensate by leaving wider or narrower spacings nearby to meet the overall goals for *trees per acre*. After thinning, higher *trees per acre* overall will lessen the time to reach the desired *stand density index* for commercial thinning, but when that time arrives average tree sizes will be lower; for example, smaller trees can be harvested sooner by retaining more trees at precommercial thinning. Foresters can be very helpful to contractors with decision-making in these complex and variable mixed stands, along with acknowledging and accommodating variability by prescribing a range of spacing for retention trees. One such prescription accommodates variability by requiring contractors to leave the best individual tree every 14 to 20 feet, while redwood clumps are handled differently by leaving 2 stems every 10 to 14 feet or one stem every 6 to 10 feet within clumps (Mike Alcorn, personal communication).

Reducing competing tanoak

Tanoak nuts are an important source of food for wildlife, but tanoak have low to no commercial value so retaining many tanoak per acre is generally not advisable. Tanoak competes with conifers and influences their development (Harrington and Tappeiner 2009; Berrill and O'Hara 2014, 2016). Ideally, regenerating tanoak should be treated as soon as possible while they are small and easily sprayed. However, if tanoak are not overtopping the commercial conifers, waiting until thinning to remove them may be more efficient and economically advantageous.

Tanoak also compete with planted and naturally regenerated young conifers after variable retention and selection harvests (Berrill, Dagley et al. 2018; Berrill, Schneider et al. 2018; Berrill, Webb et al. 2020; Muma et al. 2022). Berrill and Han (2017) modeled thinning in 2.5-acre group selection openings 10 years after harvest, enhancing the future growth and yield of merchantable conifers. The thinning focused on removing hardwood and retaining Douglas-fir and redwood in the openings. Berrill and Howe (2019) found that eliminating above- and belowground competition by killing tanoak with herbicide resulted in substantial growth response in *DBH* of neighboring redwood.

Treating tanoak by stem injection or spot spraying smaller individuals and clumps leaves deadwood standing for several years (Krieger et al. 2020). This is generally considered beneficial to mitigate fire hazard, as opposed to cutting unwanted hardwoods and leaving the cut biomass as surface fuels (Valachovic et al. 2011). Precommercial thinning at Headwaters Forest Reserve changed forest structure and fire hazard by

increasing surface fuel loading and altering the microclimate at the forest floor, lowering relative humidity by 4.6 percent and raising air temperature by 2.9°F (Glebocki 2015). The low cost of chemical thinning relative to cutting or girdling makes it an attractive option for a wide range of culled-tree sizes.

Bear damage and thinning intensity

Bear damage to conifers is widespread in Del Norte and Humboldt counties and has been noted farther south. Bears strip bark from trees to feed on sugars in the cambial layer located immediately inside the bark. Perry et al. (2016) found that thinning resulted in higher incidences of bear damage compared to neighboring unthinned stands. Generally, redwood sustained more damage than Douglas-fir. Bear damage is typically concentrated on larger, fast-growing trees (O'Hara, Nesmith et al. 2010; Perry et al. 2016; Berrill et al. 2017; Dagley et al. 2018, 2023). Redwoods near forest roads were a little more likely to be damaged by bears than redwoods farther away (Giusti 1990; Hosack and Fulgham 1996; Perry et al. 2016). These results suggest that refraining from thinning and retaining higher densities alongside forest roads, as well as thinning small parts of a landscape progressively instead of large areas, may help to deter bears. Another option is to implement a series of lighter thinnings instead of one heavy thinning that promotes rapid growth in *DBH*. When bears damage a young stand before thinning, the prescription should take into account how to prioritize culling trees that sustained damage.

Wood quality

Heavy thinning encourages branch development, especially on better-quality sites along the Coast Range, as tree crowns quickly expand to reoccupy growing space liberated by thinning. Douglas-fir branches were larger after thinning in Oregon and Washington (Weiskittel et al. 2007), with the largest increase in branch size after low thinning (Maguire et al. 1991). Low thinning removes smaller trees, which often have smaller branches, leaving larger trees with larger branches to reoccupy the growing space. In Mendocino County, branches of overstory trees in multiaged stands responded to partial harvesting (commercial harvest, not thinning) with greater response in the basal diameter growth of branches than after chemical thinning of neighboring tanoak trees, and branch growth was greater in Douglas-fir than redwood (Kirk and Berrill 2016).

The size, taper, and slenderness of a cut tree influence the number of logs it yields and the size and value of each log. More logs can usually be cut from taller trees. In general, height-to-diameter ratios are lower in

redwood than Douglas-fir, so Douglas-fir will be taller than redwood with similar *DBH* (Berrill et al. 2012). However, redwoods have a plastic physiology where they can alter their allocation of resources to height or diameter growth depending on conditions (Berrill and O'Hara 2016). Some evidence suggests that taller Douglas-fir trees encourage neighboring redwood from the same age class to allocate more resources to height growth, presumably to “keep up with” Douglas-fir or because less *DBH* growth is needed when redwood is sheltered (Berrill and O'Hara 2016). This suggests that frequent light thinning would promote a steadier growth rate of *DBH* and height in redwood when compared with a single heavy thinning that extends treatment longevity (time until next stand entry) but would also promote rapid growth in branches and *DBH*.

The timing of thinning influences residual tree growth and form. After precommercial thinning of redwood sprout clumps at age 2 years, the next 5 years growth of *DBH*, but not height, was enhanced by thinning more intensely (Boe 1974). After this time, both height and *DBH* were enhanced by early thinning, but there were no further benefits after a second thinning at age 15 years (Cole 1983). An alternative to frequent light thinnings or heavy early thinning is to delay the thinning until branches in the first one or two logs have become suppressed. Delaying thinning adds to the cost because larger trees must be felled and they tend to hang up, but in the meantime lower branches remain small and many die and fall or break off during late thinning operations. This may lead to the production of valuable knot-free outer wood. Branches may also be removed by pruning. However, thinning timed to coincide with the pruning of lower branches for clearwood production may stimulate a counterproductive epicormic branching along the pruned bole (O'Hara and Berrill 2009; O'Hara 2012).

Dominant redwoods have higher volume growth efficiency (stemwood growth per unit of growing space occupied by tree) than the lower crown classes (codominants, intermediates, and suppressed trees), so cutting the largest, most-efficient sprouts on a clump could reduce stand volume production (Berrill and O'Hara 2007). However, this effect may be offset by also cutting the smallest, least-efficient intermediate and suppressed redwoods. Future growth would then be concentrated on well-formed codominant stems, adding more valuable wood than small trees with low recovery of sawn timber or on large trees with large branches and knots (Plummer et al. 2012; Kirk and Berrill 2016).

Developing a modern density management diagram for redwood is problematic due to the lack of data from unmanaged stands. Reineke (1933) showed a limiting

stand density index of 1,000, consistent with old-growth redwood (Dagley and Berrill 2012), although a limit of 774 and an upper management bound of about 550 have been suggested for young redwood stands (Dan Opalach, personal communication). Figure 10.7 shows a density management diagram for coast redwood with management zone bounded by relative densities of 0.15 and 0.55 (Drew and Flewelling 1979) with an assumed stand-density-index maximum of 1,000. When thinning redwood, a narrower density management zone is advisable in most cases because thinning from 0.55 to 0.15 relative density involves removing 73 percent of the growing stock. This intensity of treatment leaves ample growing space for brush and is expected to result in the transformation to multiaged silviculture by regenerating a vigorous new age class of redwood (Berrill and O'Hara 2009; Berrill, Schneider et al. 2018; Muma et al. 2022).

California's eastside forests

Forests east of the crest of the Cascade or Sierra Nevada mountains are drier and colder than westside forests. These eastside forests generally have less than 25 inches of total precipitation per year. Due to shorter growing seasons and limited water, eastside forests are

less productive than those in other state regions. In an investigation of site classification (Dunning 1942), about 75 percent of eastside forests were classified as low site quality and average net growth was 104 Scribner board feet per acre per year (Bolsinger 1983).

One consideration for precommercial thinning is that rates of slash decomposition are generally slower than those on warmer, wetter sites in California. Slash loading is a pressing concern because higher loads reside longer, elevating fire hazards for a longer period of time. Precommercial thinning should not be delayed in eastside forests, in order to minimize the amount of slash and the size of material left after thinning. If thinning is delayed for some reason, slash mitigation measures may be necessary.

There are few guidelines for thinning in eastside forests dominated by ponderosa pine, and those that do exist were made at a time when planting densities tended to be higher. Barrett (1979) reported that even heavy thinning (reduction of 65 percent basal area) produced remarkably high volume growth compared to much lighter thinning in central Oregon. Cochran (1983) recommended precommercial thinning to 120 *trees per acre* on low-quality sites. Oliver and Trask (1983) found that ponderosa pine responded well after thinning even in stagnated stands. In evaluating a spacing study in central Oregon, Cochran and Barrett (1999a) suggested *trees per acre* of less than 246 for an assumed upper-limit stand density index of 270. This guideline was recommended to minimize the long-term risk of mountain pine beetle mortality, whereas Cochran and Barrett (1999b) suggested *trees per acre* of 134 (18-foot spacing) to maximize tree diameter growth.

Density management

In dry eastside forests, management efforts commonly focus on ponderosa and Jeffrey pine, and guidelines for managing stand density vary. Differences among published values for the upper limit of *stand density index* in ponderosa pine (table 10.3) serve as a reminder that the *upper limit of the management zone* is an estimated guideline, not an exact rule; it may also vary depending on specific management objectives.

Cochran et al. (1994) suggested that for poor sites the upper limit of the management zone should be adjusted as a function of site index, with lower site index associated with lower target values for the management zone. Precommercial thinning would in turn be adjusted, because of how the value assumed for the *upper limit of the management zone* influences tree retention.

For example, suppose that a stand with 300 *trees per acre* has a precommercial thinning at a *quadratic*

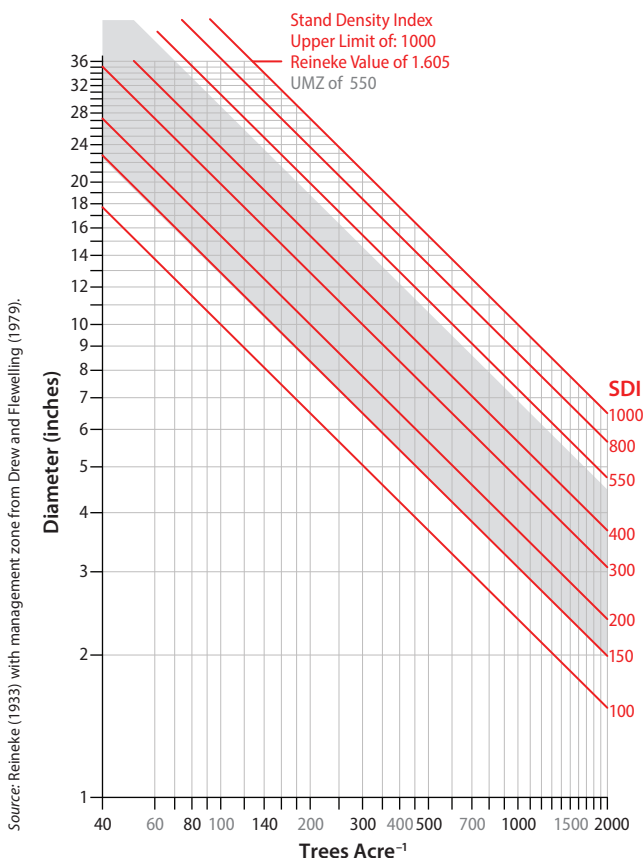


Figure 10.7. Density management diagram for coast redwood forests.

TABLE 10.3. Published upper limits of the management zone for ponderosa pine

Citation	Stand density index management limit	Exponent
Oliver (1995)	230	1.77
Edminster (1988)	270	1.66
Long and Shaw (2005)	250	1.60
Cochran et al. (1994)	124 at $SI_{100} = 70$	1.77
Cochran et al. (1994)	161 at $SI_{100} = 80$	1.77
Cochran et al. (1994)	197 at $SI_{100} = 90$	1.77
Cochran et al. (1994)	234 at $SI_{100} = 100$	1.77
Cochran et al. (1994)	270 at $SI_{100} = 110+$	1.77
Cochran and Barrett (1999a)	240–270 at $SI_{100} = 110$	1.77

Note: Exponents rounded to two decimal places; some are site index-dependent with lower SI_{100} (base age 100 years) having a lower stand-density-index limit for management. Site indices from Barrett (1978).

mean diameter of 3 inches, thereby removing 165 trees per acre, which results in an increased quadratic mean diameter of 3.5 inches (fig. 10.8). This is then followed by a commercial entry when the stand reaches a quadratic mean diameter of 15 inches at a dominant height of about 60 feet. At this point the stand has reached an *upper limit of the management zone* of 250. Commercial thinning takes the stand back to 79 trees per acre and increases the quadratic mean diameter to 17 inches, removing approximately 1,000 cubic feet per acre of stemwood volume (from 4,000 to 3,000 cubic feet). By thinning from below, the trees removed will mostly be smaller than the quadratic mean diameter of 15 inches. If future market conditions are not favorable or these trees are too small for a commercial thin, then the landowner will need to wait for a period of time during which some density-related mortality may be experienced as the stand grows past the *upper limit of the management zone*. Alternatively, a lighter precommercial thinning taking the stand back to 200 trees per acre instead of 135 would require a much earlier commercial thin at a smaller quadratic mean diameter. Conversely, a heavier precommercial thinning would leave fewer trees to grow larger before the stand becomes overcrowded or needs to be harvested.

In drier, less productive stands, the time between precommercial thinning and the first commercial entry will be considerably longer than on more productive sites, meaning that the return on investment expressed as a net present value will be reduced. As a result, decisions about precommercial thinning or any early cultural treatments during stand establishment will greatly impact profitability. In turn, early cost saving efforts

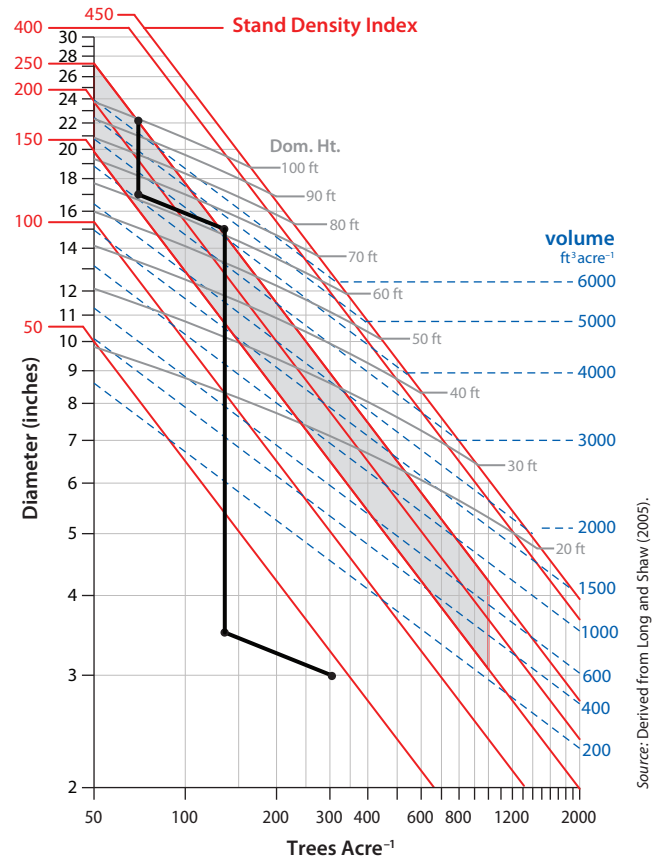


Figure 10.8. Ponderosa pine density management diagram with precommercial thinning at 3 inches of quadratic mean diameter to 135 trees per acre, followed by commercial thinning at quadratic mean diameter of 15 inches with an estimated volume for commercial thin of about 1,000 cubic feet per acre.

are critical. On low productivity sites, lower planting densities that reduce or eliminate precommercial thinning costs should be seriously considered.

Planning based on future commercial thinning requires assumptions about the quadratic mean diameter associated with a commercially viable timber sale, but the assumption of a target tree size comes with some uncertainty. For example, Webster and Fredrickson (2005) recommended a minimum quadratic mean diameter of 14 inches for commercial thinning in ponderosa pine, but market fluctuations, milling technology improvements, or even changes in the regulatory environment could change the minimum tree size that defines a commercial thin.

Sierra Nevada and southern Cascades

In contrast to eastside forests, the mixed-conifer forests west of the Sierra Nevada and southern Cascade mountain crests are generally more diverse and productive. Because of greater species diversity, the optimal species mix for planting and retention with precommercial thinning is more important.

Managed stands in this range are often comprised of a mix of conifers and hardwoods, most notably black oak with older plantations dominated by ponderosa pine and Douglas-fir. Because management philosophy has shifted over time, recent plantations may include conifer species such as sugar pine (*Pinus lambertiana*), incense cedar (*Calocedrus decurrens*), white fir, and occasionally giant sequoia (*Sequoiadendron giganteum*).

Research focused on precommercial thinning in this region is sparse. Recent studies have focused on the role of fire in young plantations (Bellows et al. 2016) and plant diversity (Thomas et al. 1999). Zhang et al. (2013) observed reduced mortality of pine plantations in response to thinning.

Planting practice in the California Sierra Nevada has called for square spacing ranging from 12 to 14 feet, with lower planting densities after wildfires in some areas. However, with the current California Forest Practice Rules allowing lower stocking levels after harvest operations, this is likely to shift toward wider spacing. Wider planting densities after harvest operations on private ground will reduce or in some cases eliminate the need for precommercial thinning, which in turn reduces the costs of planting and thinning as well as lowers the amount of slash that contributes to fire hazard.

With better planting stock and vegetation control, survival and growth in plantations has improved over time, allowing for tree dominance and favorable genetic characteristics to be revealed at earlier ages. In the California Sierra Nevada, plantations with a lot of ponderosa pine are often thinned between 5 and 7 years of age, and a few years later in mixed-species plantations. There are no guidelines for postfire artificial regeneration, so thinning may not be needed after planting at wide spacing, or it may be needed early in dense patches of natural regeneration.

Density management can be more complicated in the Sierra Nevada and southern Cascades because the species mix can vary considerably within the region and by ownership. The definition of an upper limit for the *stand density index* is problematic with any species mix. Reineke (1933) estimated the upper limit for *stand density index* in California mixed-conifer at about 750, but this value is considerably higher than the value of 550 that Long and Shaw (2012) derived empirically from an analysis of U.S. Forest Service Forest Inventory and Analysis data. Long and Shaw (2012) suggested that the upper limit for mixed-conifer stand density index should vary depending on species mix, with values ranging from 524 for ponderosa and sugar pine to a maximum of 671 for red fir (*Abies magnifica*) and white fir.

Using this method, the actual upper limit for any given stand is a weighted value derived from the particular species mix, expressed as a proportion of the stand. The presence of more shade-tolerant species tends to raise the upper limit of the *stand density index* and management zone, thereby tending to delay the need for *commercial thinning*. The species mix chosen for a given plantation along with the presence of natural regeneration may influence the need for and timing of subsequent thinning. As in other regions, thinning is typically prescribed when stands reach 0.55 to 0.6 relative density, equivalent to 55 to 60 percent of the *stand density index*'s upper limit. This coincides with the so-called self-thinning line, a value of *stand density index* above which the onset of competition-induced mortality increases significantly.

Long and Shaw (2012) show a mixed-conifer forest where full site occupancy was attained at a *stand density index* of 200, and the upper limit for management (onset of self-thinning) was assumed to be at a *stand density index* of about 300 (fig. 10.9). Given these values, if implementing a precommercial thinning in a stand with 400 *trees per acre* at a *quadratic mean diameter* of 3 inches, which results in *trees per acre* of 200 and quadratic mean diameter of 4 inches—and assuming minimal mortality thereafter—the stand will reach

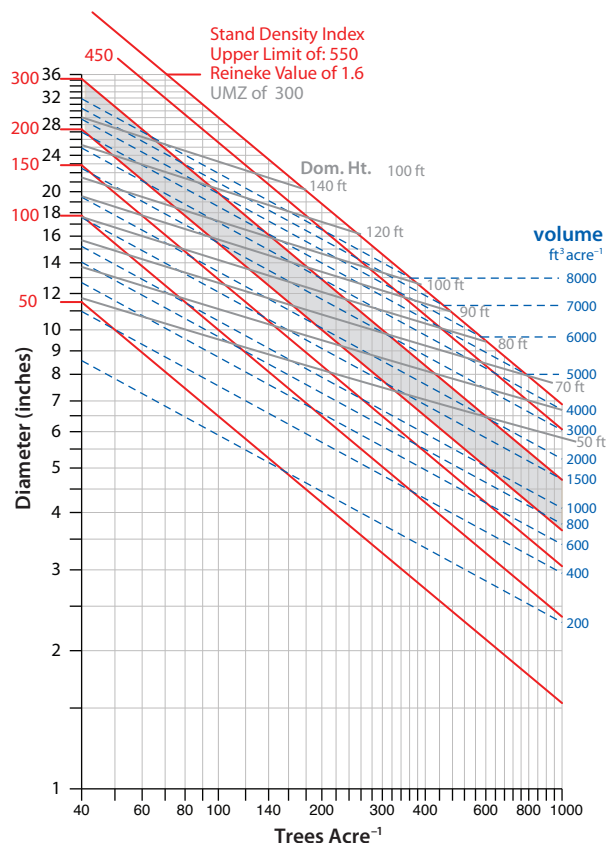


Figure 10.9. Density management diagram for California mixed-conifer forests.

Source: Derived from Long and Shaw (2012).

a *quadratic mean diameter* of 11 inches and *stand density index* of about 230. According to this *density management diagram*, the dominant height will be about 70 feet, and if the site index is 100 then this point will come at about tree age 35. For a site index of 80, an 11-inch quadratic mean diameter is reached at about tree age 45. If a *quadratic mean diameter* of 11 inches is sufficient for a commercial thin, then commercial thinning could be possible at this point. There is little risk of mortality since the stand is well below the upper limit for management (*stand density index* of 300), but a precommercial thinning to 200 *trees per acre* may be excessive with not enough *trees per acre* retained if the goal is for commercial thinning at *quadratic mean diameter* of 11 inches. More volume would be available for the commercial thin if the precommercial thinning retained 250 *trees per acre*, and the commercial thin could still take place at a *quadratic mean diameter* of 11 inches without exceeding the upper limit of 300 *stand density index*. If the proposed commercial thinning reduced density to 150 *trees per acre* proportional across size-classes—using nondiscriminatory row or geometric thinning to leave *quadratic mean diameter* unchanged—then shifting the thinning from 200 to 250 *trees per acre* would result in increased harvest volume from 715 to 1,460 cubic feet per acre. In this scenario, the volume of the commercial thin would be doubled.

These examples demonstrate how decisions on the timing and intensity of thinning can influence future growth trajectories and commercial harvests. Site quality must also be considered, because the optimal thinning age is reached earlier on better sites where height and *DBH* growth are achieved more quickly. A basic prescription for Sierra Nevada conifer plantations on medium-to-high site ground is to plant at 13-by-13-foot spacing, thin to 18-by-18-foot spacing at years 6 to 7, commercial thin to 28-by-28-foot spacing at years 25 to 30, and let grow to final rotation or subsequent thinning entries.

This prescription was developed using the G-space model (Cavallaro 1990; Ritchie 1999), which derives thinning schedules based on the principles of stand density management described here (Mark Gray, personal communication). Thinning would be delayed on poorer sites with slower growth, while on better sites it would be implemented earlier to achieve the desired goal of maximizing the growth of high-quality trees. Because true fir plantations can thrive at higher stocking levels, a suggested prescription using the G-space model would call for planting at 11-by-11-foot spacing followed by thinning to 16-by-16-foot spacing at year 10, then several years later commercial thin to 22-by-22-foot spacing and grow to rotation or extend

the time until final harvest by implementing a second commercial thin to 31-by-31-foot spacing (Mark Gray, personal communication).

Conclusion

The need for precommercial thinning is driven by planting density. If fewer trees are planted, the need for thinning could be eliminated. In 2020, the California Forest Practice Rules were modified to reduce density requirements, providing more flexibility in managing planting densities. When managing for wider tree spacing, effective control of competing vegetation is even more critical, as nature will often attempt to fill that space with vegetation that can lower tree growth rates and increase fuel loading.

Precommercial thinning improves stands by culling less-desirable trees, but properly identifying favorable trees early enough can be problematic. Delaying thinning increases costs as well as fuel on the forest floor. However, delaying may be desirable in some situations, such as when waiting for canopy closure to shade out weeds, or slowing tree diameter growth in an attempt to avoid bear damage to young trees that grow rapidly after thinning or secure a premium price for lumber with narrow growth rings or smaller knots. We have provided information and guidelines about precommercial thinning to support the manager's decision-making, but there are no hard-and-fast rules, and tradeoffs abound. If the management objectives are to maintain wide spacing between trees, such as to reduce drought stress or fire hazard, this can be achieved by adopting lower density targets. Higher rates of tree growth will be sustained with reduced competition and the trees may better resist insect attack, but wood production on a per-acre basis will be sacrificed.

Conversely, allowing stands to surpass relative densities of 0.55 to 0.6 can enhance wood production per acre, but with elevated tree mortality. This could prolong the time trees need to reach merchantable size and put crowded stands at greater risk of stand-replacing fire or forest health problems from reduced tree vigor. Likewise, self-thinning will occur as competition intensifies.

Precommercial thinning takes place in a dynamic environment. The need for precommercial thinning may be influenced by technological improvements that provide better seedling quality or tools and techniques that enhance the early growth and survival of planted stands. At the same time, changing market conditions or shifts in the regulatory environment can impact all phases of forest regeneration, and it is difficult to anticipate their influence on decision-making regarding the implementation of precommercial thinning in the future. Foresters must be attentive to such changes and

current research in order to make timely and effective decisions regarding density management in California forests.

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Web addresses

OP-Yield tool

woongsoon.shinyapps.io/OP_Yield

General technical report, OP-Yield Version 1.00 user's guide
fs.usda.gov/psw/publications/documents/psw_gtr259

Standview package in the R computing environment
fs.usda.gov/research/psw/products/dataandtools/tools/standview

Chapter 11

Damage

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Damage to young conifers comes in many forms. Pest organisms such as insects, pathogens, and vertebrates often are involved, but adverse environmental conditions can lead to damage without the involvement of any pests. Knowledge of what damage has previously occurred in an area or under similar circumstances can allow land managers to anticipate what might occur, recognize the source of the damage, and act accordingly. Ultimately, it is difficult to anticipate and recognize all the variables that might lead to damage. When damage does occur, land managers mainly want to know: “Will this damage continue and if it does, is there anything that can be done to prevent it?” To answer these questions, an accurate diagnosis of the situation is essential. Regardless of your level of skill or comfort at making diagnoses, the process of assessing damage is invaluable because it sharpens observation skills and enables a better understanding of the situation. You may then either feel confident to make a diagnosis or decide to consult an expert.

Assessing damage

A simple but useful model to keep in mind when evaluating damage is the pest triangle (fig. 11.1). Pests are strongly influenced by host and environmental conditions. All three points of the triangle interact to produce the damage and all three points must be considered when formulating a diagnosis, and, ultimately, a prognosis for what comes next.

Common mistakes made during diagnosis include an imbalanced interpretation of how points of the triangle are interacting, and a misidentification or lack of recognition of one or more of the factors contributing to the damage. If a pest organism is present or easily identifiable, it is not uncommon for most of the

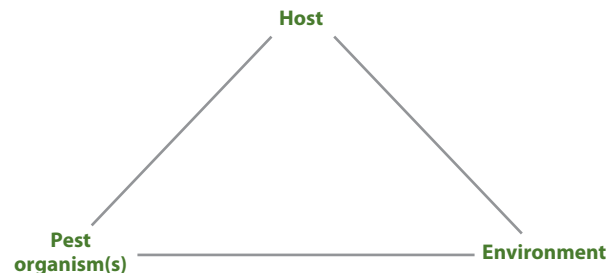


Figure 11.1. Pest triangle.

blame to be placed on it, with the belief that eliminating the pest will bring an end to damage. If a key pest organism is misdiagnosed or unrecognized, time and resources may be wasted trying to manage the wrong pest or condition.

It is important to thoroughly investigate both the damage and the context in which it occurs. Look for clues at multiple levels—on the damaged trees, within the stand, and across the region. Explore the patterns and extent of damage, associated environmental conditions, and other clues that may arise during an on-site assessment. Obtain as much background information as possible on site conditions such as soil properties, weather events, source of growing stock, history of damaging agents on-site, and management actions, including anything that could have a bearing on the damage. Context is invaluable since many types of damage are associated with predictable conditions.

Inspect damage on all or a representative number of trees and entire trees to the extent possible. The source of damage may not be obvious, especially if the damage is old or multiple organisms are present. It is common for insects and disease organisms to invade wounded or stressed tissue and, in doing so, mask more relevant signs and symptoms of damage. The

sooner an inspection is conducted after damage has occurred, the better. Roots should not be overlooked since aboveground symptoms can be caused by below-ground damage or conditions.

Trees respond to damage in a limited number of ways. Symptoms are the generic expression or consequence of damage. As such, they may allow an educated guess as to what is occurring, but they typically do not provide a definitive answer. For example, brown needles at the ends of branches are a symptom that can be caused by insects, diseases, vertebrates, or abiotic factors. Additional clues collected at the tree, stand, and regional levels may help to narrow the choices, such as the size and species of trees impacted, type of damage (for example, the length of brown needles), and distribution of damage within tree crowns and across the stand and region. Validate a diagnosis by looking for signs of a pest organism or evidence of a specific type of injury. Signs of biotic damage include evidence that a pest organism is or has been present, such as insect life stages or remains (for example, larvae, pupal cases, dead adults), tunnels and galleries, chewed tissue, frass, fungal staining, mycelium, zone lines, fruiting bodies, and parasitic plants (such as mistletoe). Signs of abiotic damage include physical wounds and tissue death that often occur in distinct patterns and are not associated with living organisms.

Damage that occurs to a cohort of trees over a relatively short or otherwise distinct period of time is usually caused by a specific set of conditions. It is important to mentally reference the pest triangle and look for patterns in the symptoms of damage, species and size of trees impacted, associated environmental conditions, and signs of pest organisms. If a pest organism is a principal contributor to damage, it should be possible to identify signs or symptoms of that organism on all or most of the trees inspected. Finding such evidence, however, may be limited by how thoroughly the tree is inspected. If evidence for a specific pest organism is inconsistent, consider that a different organism may be contributing to the damage or that pest organisms are primarily acting in a secondary role.

Certain pests are frequently found together in what are referred to as pest complexes. Bark beetles and root diseases are a good example of this. While bark beetles can kill trees on their own, quite often the success of their attack is facilitated by a preexisting condition that weakens the tree, such as root disease, injury, or drought stress. Awareness of pest complexes and investigating their presence is an important aspect of diagnosis.

In most cases, signs and symptoms will lead to a diagnosis in the field. Occasionally, samples of damaged tissue may need to be taken to a lab for

dissection, incubation, or some other diagnostic procedure (see “Additional resources” below). If the lab diagnostician has not seen the damage in the field, it is important that they be provided with as much relevant information as is possible, including geographical location, elevation, aspect, tree species, and tree size. A prognosis can only be made once damage is accurately diagnosed.

Damage caused by abiotic factors is often limited in duration, for example a late frost, hail, or herbicide treatment. It also tends to be more uniformly and widely distributed, both on individual trees, across tree species, and across the landscape. In some cases, damage may be vague and nonspecific, with no or inconsistent signs of pest organisms. Abiotic factors typically cause no further damage, although it may take time for damage to be fully expressed. Secondary insects and disease organisms may initially be absent, but they often invade damaged tissue over time. Usually, their contribution to damage is minimal.

Pest organisms vary widely in the damage they cause and their ability to persist on-site. A prognosis depends on the biology of the individual organisms as well as an accounting of factors that influence future pest abundance and damage. The probability of future damage coupled with management options makes a prognosis complete. Are pest organisms still present and at what level? Are they likely to increase or decrease? What factors, including treatment options, will influence their abundance and ability to cause additional damage? An initial evaluation may be sufficient to answer these questions, or it may be desirable to conduct follow-up surveys.

Preventing damage: Best management practices

A certain amount of pest damage is preventable, to the extent that it is related to management choices. We discuss generic considerations here and prevention practices specific to one or a small group of pests in the pest sections below. Prevention practices should be thought of as best management practices since the intent is to produce the best possible reforestation outcome.

Because tree genetics are closely aligned with environmental conditions, it is essential that locally adapted seed or seedlings are used for reforestation (see chapter 5, “Seeds”). Many off-site plantings can suffer from pest damage. While such trees may initially grow well, they are poorly suited for the site and often succumb to pest damage before reaching merchantable size.

Reducing competition between trees and associated vegetation improves tree growth and is an important factor in reducing pest damage on drier sites. Treatments include thinning (stocking control) of plantation trees and various methods of controlling competing vegetation. Precautions must be taken when thinning since it can lead to pest damage under certain pest or environment-specific conditions.

On forestlands that naturally support a mixture of tree species and ages, one of the challenges of reforestation efforts is to promote and maintain a diversity of these two characteristics. Reforestation following wildfire is challenging because only a limited number of tree species may be able to survive when planted into a postfire landscape. With large wildfires, finding sufficient amounts of seed or seedlings adapted to the local area is an additional challenge. Pest-caused damage often occurs in large plantations with little diversity in tree age and species. Planting stock that is not well matched with local conditions may further contribute to damage.

Mitigating damage: Options for response

Mitigation or management options usually depend on the specific pests and circumstances involved. The most commonly encountered plantation pests are discussed in the following sections, including information on identification, life history, and management. Direct control of a pest is one of many options that may be considered under the more holistic strategy of integrated pest management (IPM). Understanding the ecological relationships between hosts, pest, and the environment (fig. 11.1) is a central concept of IPM; as such, a variety of options are weighed and integrated into an ecologically sound response. Modern definitions of IPM also typically incorporate the concepts of economic efficiency and social acceptance. When thinking about mitigation, it is important to have realistic expectations of what is possible from both an ecological and cost-benefit standpoint. Some pest damage may be difficult to avoid or too costly to mitigate. Doing nothing is sometimes the best or only alternative.

Insect pests

Much of the insect damage that occurs to young trees is insignificant, not encountered, or simply different on older trees. Plantation insect pests are, for the most part, a distinct subset of the larger group of insects that damage trees.

Insects that attack roots and the lower stem of the youngest trees

Recognition and significance. The first year or two of a tree's life is a critical time for root damage from insects. The insects involved are rarely primary pests of conifers, but rather have largely been studied as agricultural or ornamental pests. Often they cause damage when conifer seedlings grow alongside of or replace vegetation that the insects were feeding upon. Sites where herbaceous vegetation is well established are prone to damage. Removing this and other competing vegetation by chemical or cultural means will result in insect populations dying out, but the effect is not immediate. See Cram et al. (2012) in the "Further reading" list below for coverage of the most common of these pests.

These insects come in many forms and typically do not need to be identified precisely. Common names include white grubs (larvae of beetles in family *Scarabidae*), cutworms (caterpillars of moths in the family *Noctuidae*), root weevils (beetle larvae in the genus *Otiorhynchus*), and sod webworms (caterpillars of moths in the family *Pyrilidae*). Immature stages of the insects (larvae and caterpillars) live in the soil and feed on roots, the lower stem, and sometimes foliage. An initial symptom of root or lower stem feeding is a change in the foliage color of seedlings. Heavily damaged seedlings continue to fade and die, while less damaged seedlings may survive with reduced growth. Some adult weevil species will girdle seedlings while their larvae feed on other plants.

Any time the entire top of the tree appears off-color or shows reduced growth, suspect an issue with the roots. These symptoms can be the result of poor planting (for example, J-roots), vertebrate pests, diseases, herbicides, or insects. Inspect the roots and lower stem for insect feeding damage, including missing bark, consumption of finer roots, or young shoots clipped at the soil line. Look for larvae, caterpillars, or evidence of insects such as frass and webbing in the soil near roots. Cutworms and weevils may also feed on needles. Be aware that vertebrates can cut or tear foliage and stems with their teeth, causing damage in the absence of insects or disease. Intact, apparently healthy roots combined with foliage discoloration may indicate herbicide or abiotic damage. Other signs and symptoms may indicate disease (see "Disease" section below).

Management options. While direct control of insects may be prescribed for seedlings in nurseries, it is rarely recommended for seedlings and young trees in forest plantations because damage is typically limited in scope and duration. Damage is rare when plantations are established soon after the harvest of overstory trees. Damage is possible if herbaceous

and other vegetation becomes well established, such as when a site remains free of trees for an extended period. On such sites, control competing vegetation and consider a fallow period before planting trees to reduce the possibility of insects surviving in the soil and feeding on seedlings.

Insects that attack the inner bark and cambium

These insects feed in the cambial region, girdling the stem and killing the entire tree or a portion of it. Bark beetles and some weevils can do this to advanced regeneration under drought stress, particularly to species of pine. Other factors that stress young trees potentially predispose them to attack by insects that attack the main stem.

Pine reproduction weevil

Recognition and significance. The pine reproduction weevil (*Cylindrocopturus eatoni*) kills young pines, in whole or in part (fig. 11.2). Ponderosa pine is the primary host, but Jeffrey, sugar, foothill, and other pines are attacked. Trees taller than 5 feet are rarely killed. The weevil life cycle is 1 year. Adults are tiny (about 2.5 millimeters long) (fig. 11.3) and emerge from dead trees in the spring (May to June), creating small exit holes in the bark. Adults do minor feeding on the host, creating diagnostic puncture wounds on needles (fig. 11.4). Females lay eggs one at a time on the stems of live trees in early summer. Larvae tunnel in the cambial region, girdling the stem, and eventually enter the wood or pith to overwinter (fig. 11.5A). A blue fungal stain discolors the wood (fig. 11.5B, C). Pupation occurs in the spring prior to adult emergence. Foliage of killed trees begins to change color (fade) in the fall or the following spring. Diagnosis is readily made based on these signs and symptoms.

A related insect, the Douglas-fir twig weevil (*Cylindrocopturus funissi*) is similar in appearance, life cycle, and the damage it causes, although mortality is



Photo: Donald Owen.

Figure 11.2. Ponderosa pines killed by the pine reproduction weevil.



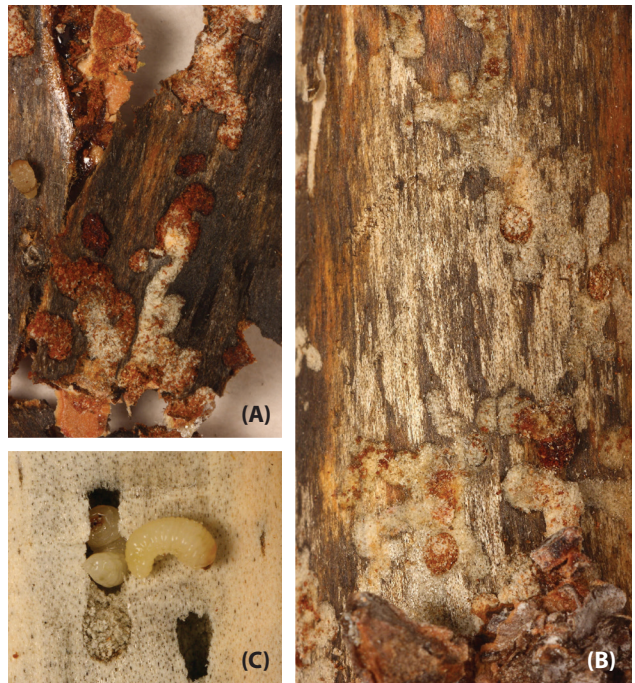
Photo: Donald Owen.

Figure 11.3. Adult pine reproduction weevil.



Photo: Donald Owen.

Figure 11.4. Ponderosa pine needles with puncture wounds from the pine reproduction weevil.



Photos: Donald Owen.

Figure 11.5. Evidence of pine reproduction weevil in a killed ponderosa pine. Inner bark surface (A) and surface of wood (B) show mines and staining. Larvae tunnel into the wood (C) prior to pupation with associated stained wood.

usually restricted to twigs and branches. Management is the same for both insects.

Management options. Direct control of weevil populations is done by destroying infested trees or applying contact pesticides to kill the adults, but these treatments do not produce lasting solutions. Weevils reinvade plantations where trees are under stress, allowing populations and damage to rebuild. Controlling vegetation that competes with trees for limited water is the recommended treatment, as it enables trees to better resist attacks by weevils and other insects. On sites that are marginal for conifer growth and survival, the costs of keeping planted pines alive may outweigh the benefits.

Bark beetles attacking young pines

Recognition and significance. Several bark beetle species can kill young conifers during drought. These beetles also attack older trees but are not primary killers of mature trees. Susceptible tree height and diameter are greater than for trees damaged by *Cylindrocopturus* weevils. Mortality events are typically short-term and often precipitated by thinning stressed host trees at an inappropriate time. In pine plantations, species of *Ips*, especially California five-spined ips (*I. paraconfusus*) can kill sapling and pole-size trees. The red turpentine beetle (*Dendroctonus valens*) can kill pole-size trees. Bark beetle attacks are distinguished from those of the pine reproduction weevil by the larger size of tree attacked and the presence of boring dust or pitch tubes on the main stem. Key factors in bark beetle–caused mortality are drought and a productive breeding site for the beetles. For *Ips*, the breeding site is cut green stems and larger limbs from within the plantation or nearby. Green material that is generated from winter through early summer and is greater than 3 inches in diameter presents the greatest risk. Red turpentine beetle breeds on fresh stumps.

Management options. To prevent mortality from either of these beetles, avoid thinning plantations during drought or thin later in the growing season, such as August through October, when risk is lower.

Other bark beetles

Other pole-size conifers, besides pines, will on rare occasions experience similar mortality from bark beetles. Douglas-fir attacked by the Douglas-fir engraver (*Scolytus unispinosus*) is an example. It breeds in green stems and larger limbs of Douglas-fir and may leave this material to attack nearby trees. Avoid creating large amounts of breeding material when drought-stressed Douglas-fir are nearby.

Winter storm damage—windthrow and stem breakage—also produces breeding material for bark

beetles. Most damage resulting from these events has not involved the beetles mentioned above or occurred to young trees. Beetles such as the western pine and Douglas-fir beetles, which attack older, larger trees, are more likely to be involved. Consider the potential for damaging bark beetle activity whenever large amounts of green slash are created and susceptible trees are nearby.

Insects that attack shoots

The most damaging insects in this group attack pines and include the western pine shoot borer (*Eucopina [Eucosma] sonomana*), ponderosa pine tip moth (*Rhyacionia zozana*), and gouty pitch midge (*Cecidomyia piniinopsis*). The latter two insects are recognized for killing shoots, while western pine shoot borer more often reduces terminal shoot growth. Weevils in the genus *Pissodes* occasionally kill terminal shoots of pine and spruce, but reports of damage are rare in California.

Western pine shoot borer

Recognition and significance. Western pine shoot borer typically restricts its attacks to the terminal shoot (leader) of the tree and completes its life cycle without killing the terminal. Attacks on lateral shoots are less common but more likely to kill the shoot. Ponderosa pine is the principal host, but Jeffrey and other pines are also attacked. The principal impact of western pine shoot borer is reduced height growth. Loss of dominance by the terminal shoot and stem deformity also occur. Chronic infestations can have a significant impact on wood production over the life of a stand of trees, especially on more productive sites. Because shoots are rarely killed, damage may be overlooked. The sex pheromone of western pine shoot borer has been identified, synthesized, and used in various treatments to disrupt mating and prevent damage.

Western pine shoot borer moths (fig. 11.6) emerge and begin flying in early spring, just as snow cover is disappearing from many sites. Eggs are laid singly on expanding terminal buds and shoots. One larva typically mines a shoot, but occasionally there may be two.



Figure 11.6. Western pine shoot borer moth length varies from ¼ to not quite ½ inch.

Photo: Scott Tunnick, USDA Forest Service, Bugwood.org

Mines follow the pith and are packed with dark-brown, somewhat resinous frass (fig. 11.7A). Larvae exit shoots in late spring near the lower end of the mine, leaving a small hole and resin droplet on the surface. They drop to the ground where they pupate and overwinter. There is one generation per year.

Infested terminals become stunted, causing needles to bunch together and shorten relative to needles on noninfested shoots (figs. 11.7B, C, D). The entire shoot may be impacted, or initial growth of the shoot may look normal, while later growth, for example, younger needles closest to the top, are clearly impacted. Suspect western pine shoot borer whenever terminal shoots exhibit these symptoms. Moths can be caught in pheromone-baited traps but otherwise are rarely seen. Larvae are off-white with a tan-to-brown head capsule and can be found in mines during the spring. The best time to recognize and survey for damage, however, is after trees have finished height growth and damage is finished for the year, from summer onward. Confirmation of western pine shoot borer is made by cutting into one or more symptomatic shoots and finding the characteristic mines.

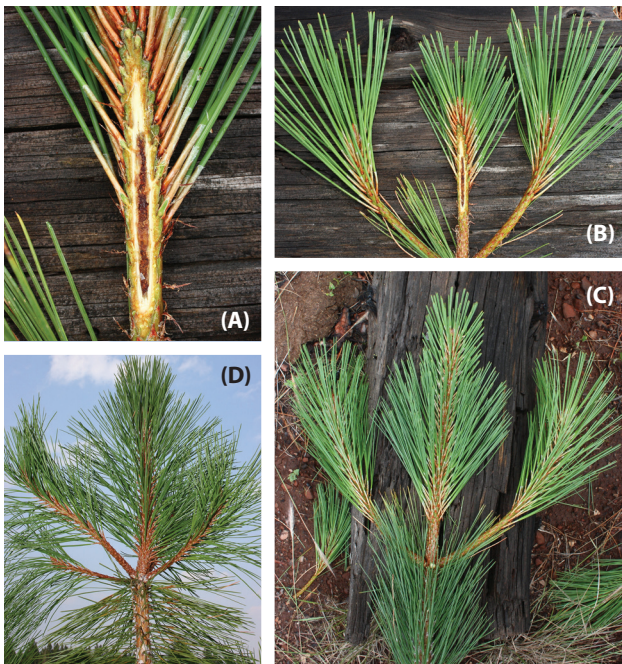
Damage is first noticed when tree height is 3 to 4 feet and can continue for a couple of decades or more. A good time to begin monitoring for damage is early in this period of susceptibility, since a steady increase in damage is likely as a plantation grows. A single infestation results in a one-time loss of height growth of about 25 percent. Trees with the largest terminal

buds are preferred for oviposition and may represent the best growing trees in a plantation. Multiple factors have bearing on the decision of when to control damage, including age of the stand, percentage of terminals infested, and cost of treatments versus benefit. Studies indicate that the greatest benefit is achieved when stands are treated at a young age after reaching a certain level of infestation. The benefits of control drop off for stands over 20 years old, are considered negligible for light infestation levels (25% or less) and will be greatest for heavily infested (50% and higher), high-value stands.

Management options. Infestation levels can be reduced by use of a commercial product (for example, MalEx ShootBorer), which utilizes the pheromone and a pesticide in a formulation that attracts and kills male moths. Treatment is applied by hand in the spring just before or as close to moth emergence as possible, which can be monitored. Thinning a plantation can cause the infestation level to increase significantly as damage is concentrated on fewer trees. To avoid this, application of the pheromone treatment in the spring following a thinning is recommended. This combination of thinning and pheromone treatment will help plantations to quickly grow through the time when they are most susceptible to damage. Because moths will reinvade a treated area, one or two additional pheromone treatments, 2 years apart, may be warranted.

Ponderosa pine tip moth

Recognition and significance. The ponderosa pine tip moth is one of several *Rhyacionia* species that mine buds and shoots of young pines, killing the shoots and stunting the growth of trees that are repeatedly attacked (fig. 11.8). As the name suggests, ponderosa pine is the principal host, although other pines including Jeffrey, lodgepole, and sugar may be attacked.



Photos: Donald Owen.

Figure 11.7. Terminal shoots of ponderosa and Jeffrey pines infested by the western pine shoot borer: shoot cut open to reveal a western pine shoot borer mine (A,B) and external symptoms of infestation (C,D).



Photo: Donald Owen.

Figure 11.8. Trees and shoots damaged by the ponderosa pine tip moth.

Damage is predominantly on trees less than 6 feet in height on dry sites.

Moths emerge in the early spring, overlapping with but starting slightly later than western pine shoot borer emergence. Eggs are laid on elongating terminal and side shoots. Larvae are initially found externally on shoots, where they form a bubblelike shelter of silk and resin and create a hole through which the shoot is entered for feeding. Eventually they stay within the shoot. Multiple larvae feed inside a single shoot, where they consume nearly everything, creating a maze of tunnels and frass (fig. 11.9). Needles on the shoot fail to develop and remain short. Needle color begins to fade in late spring and becomes more noticeable as the summer progresses. An occasional larva will pupate in a shoot, but most will leave and pupate at the base of the tree in midsummer. There is one generation per year.

Tip moth damage is often concentrated on individual trees and in certain areas of a plantation. It is easily recognized by the dead or dying shoots (fig. 11.10A, B) that are consumed on the inside. Slight pressure on a heavily mined tip causes it to crumble. Intact older dead tips may be present, but over time they disintegrate, leaving a resinous stub at the end of the damaged shoot. Larvae, present from late May through much of July, are orange-brown (fig. 11.11A) and

develop a slight rose color as they mature (fig. 11.11B). They are 10 to 12 millimeters (slightly less than one-half inch) when fully grown. Pupae are dark-brown and roughly half this length. An accumulation of tip moth cocoons can be found at the base of infested trees at or near the ground line. Cocoons are tightly lodged in gaps and crevices of the outer bark. They consist of loosely woven silk and dried resin, and depending on the time of year may contain pupae (late July through March/April) (fig. 11.12A, B).

Management options. The sex pheromone of *Rhyacionia zozana* has been identified and shown to be effective at disrupting mating and reducing damage from ponderosa pine tip moth. However, no



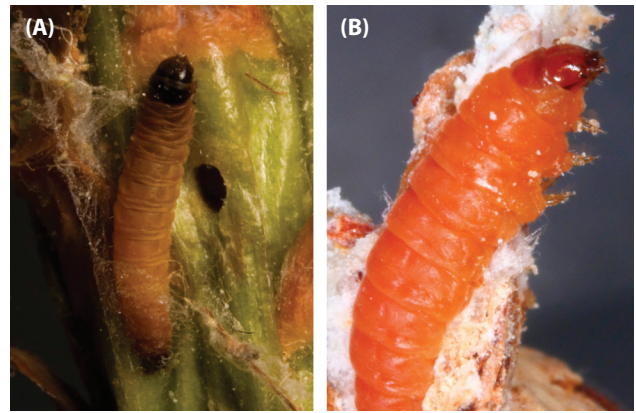
Photo: Donald Owen.

Figure 11.9. Mines of the ponderosa pine tip moth within a killed shoot show internal feeding damage.



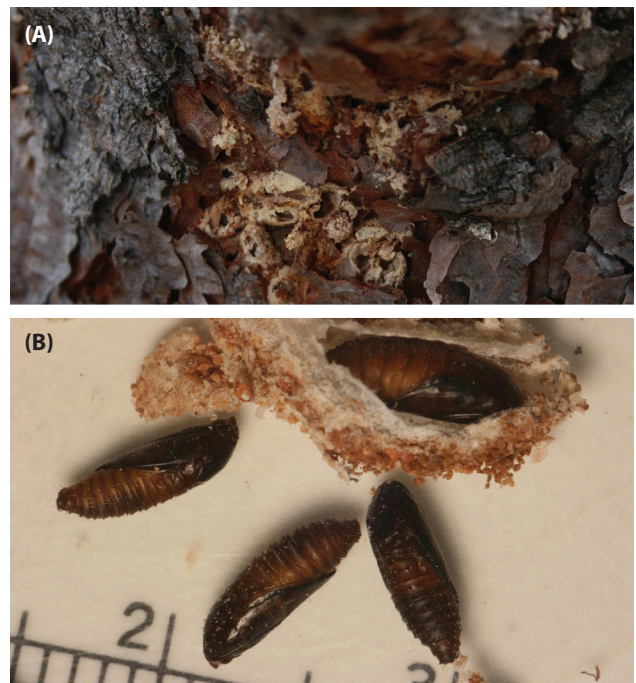
Photos: (A) Bugwood.org, Donald Owen; and (B) Donald Owen.

Figure 11.10. Trees and shoots damaged by the ponderosa pine tip moth.



Photos: Donald Owen.

Figure 11.11. Young larva of ponderosa pine tip moth (A). As larvae mature, the head and prothoracic shield lighten in color and the body takes on a slight rose-colored tinge (B).



Photos: Donald Owen.

Figure 11.12. Old cocoons on bark near ground level (A) and pupae of ponderosa pine tip moth (B).

commercial products for control are currently available. The western pine shoot borer pheromone attracts males of *R. zozana*, so there is speculation that pesticide treatments containing it may control tip moth damage, but this has not been tested. While both moths can be found in the same plantations, significant damage from the tip moth is restricted to drier sites. Most trees quickly outgrow tip moth damage and the fastest-growing trees appear to receive little damage from it. Any treatment that improves tree growth will help reduce damage.

Gouty pitch midge

Recognition and significance. Midges in the genus *Cecidomyia* form pits beneath the bark of new shoots or live in exuded resin masses on pines and are known as pitch or resin midges. The gouty pitch midge (*C. piniinopsis*) primarily attacks ponderosa pine. Damage ranges from scarring to shoot dieback, depending on the level of infestation. Chronic infestations can deform trees and retard growth.

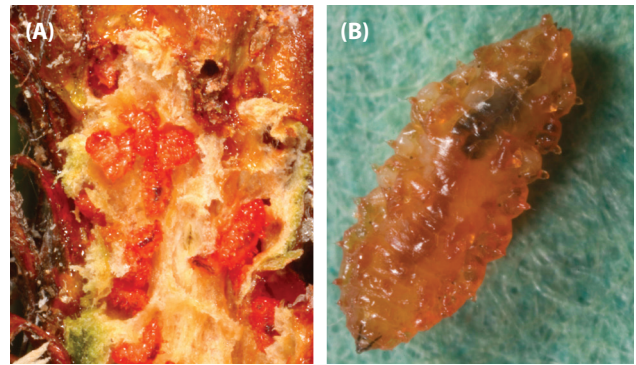
Confirming pitch midge as the cause of shoot dieback can be somewhat confusing because infested shoots are alive and then die after the insects have exited. There is one generation per year. In the spring, tiny adult midges emerge from cocoons on needles and females lay eggs on expanding pine shoots. Eggs hatch and salmon-colored larvae enter new shoots where they develop in resinous pits just beneath the bark. The cocoons are distinctive (fig. 11.13), but neither the adults nor eggs are easy to find. Fully developed larvae are 4 to 5 millimeters ($\frac{3}{16}$ of an inch) long (fig. 11.14A, B). Infestation may produce slight stem swelling, but shoots otherwise look normal and remain alive through the 1-year period of infestation. In late winter, larvae exit the shoots and make their way to needles where they pupate. The previously infested shoots can continue to live or may die in the spring.

Management options. Trees differ in their likelihood of becoming infested and damaged. Damage is heaviest on trees with viscid or sticky shoots, a heritable trait. Trees with dry or waxy shoots can become infested, but damage is less (fig. 11.15). In most plantations, damage is unlikely to be severe and trees will continue to grow at a normal rate. Selectively removing damaged



Photo: Donald Owen.

Figure 11.13. Cocoons of the gouty pitch midge.



Photos: Donald Owen.

Figure 11.14. Gouty pitch midge larvae within an infested shoot (A) and close-up (B).



Photo: Donald Owen.

Figure 11.15. Ponderosa pines with different levels of attack by gouty pitch midge. The tree on the left has viscid shoots, while the tree on the right has dry shoots.

trees is an option but is only recommended if height growth is being significantly impacted. Trees over 16 feet in height are unlikely to be damaged. Attempts to control the midge with pesticides have not proven successful. While it should be possible to breed resistant planting stock, low demand makes this impractical.

Insects that attack foliage

In general, this group of insects presents a limited threat to young trees. Insects with piercing and/or sucking mouthparts, such as aphids and scales, are unlikely to reach damaging levels. Populations of some other insects may reach damaging levels on occasion, but natural enemies—parasites and predators—play a significant role in controlling outbreaks and maintaining populations at endemic levels. Some of the more common insect defoliators are discussed here.

Grasshoppers

Recognition and significance. A small number of grasshopper species are a potential threat to seedlings

and young trees up to a few years in age. Trees are not a favored food, but grasshoppers will feed on and damage trees when their preferred food, green grasses and forbs, dries and becomes unpalatable. Endemic grasshopper populations are not a threat, but outbreaks can cause significant damage, including complete defoliation and mortality of young trees.

Grasshopper outbreaks are sporadic and difficult to predict. Similarly, outbreaks are not likely to be noticed until some level of damage is seen. Most grasshoppers have a 1-year life cycle, and it is the older stages that damage trees by consuming needles and buds. By the time damage is noticed, little may be done during the current year. Control, if it is needed, is aimed at the next generation, which hatches in the spring. Young grasshoppers are the easiest stage to control, and their numbers indicate the level of damage that may occur later in the season. Although they are easily recognized, young grasshoppers do not feed on trees, so look for them on adjacent vegetation.

Management options. No established economic thresholds exist for controlling grasshoppers in tree plantations. A logical approach, however, would be to survey grasshopper numbers at the time of damage to get an estimate of their density. The number of grasshoppers per square yard is a commonly used metric. Monitor grasshopper densities the following spring to determine if control is warranted.

Eliminating or reducing the levels of grasses and forbs in the spring will cause young grasshoppers to either starve or leave, reducing local populations. Alternatively, young grasshoppers can be treated with a pesticide to reduce their numbers. Because grasshopper populations may be an issue over a larger area, it is recommended that the situation be reported to and discussed with the county agricultural department.

Pine needle sheathminer

Recognition and significance. The pine needle sheathminer (*Zelleria haimbachi*) is a defoliator of two- and three-needle pines in California, including ponderosa, Jeffrey, and lodgepole. Outbreaks have periodically occurred in pine plantations where trees are 4 or more years old. Heavy defoliation can cause temporary growth loss and limited shoot dieback. Natural enemies play an important role in controlling populations.

Female moths lay eggs at one per needle on current-year needles in late spring to midsummer. They also may be laid on older needles, especially when populations are high and the complement of current-year needles has been greatly reduced by defoliation. Eggs hatch in summer, and the first two instars of the insect are spent as a tiny, threadlike caterpillar feeding within a needle until the spring. Individual needle mines are

barely visible with the naked eye and amount to insignificant damage (fig. 11.16A, B). As new shoots and needles begin to elongate, caterpillars exit these mines and begin feeding on developing needles by chewing a round hole through the needle sheath and eating the bases of needles (fig. 11.17). This feeding begins in May and lasts about 3 to 4 weeks. Needles are severed and die before finishing elongation and are easily pulled from their sheaths. Damage depends on the number of caterpillars feeding, and anywhere from a handful to all the needles on a shoot may be killed (fig. 11.18). Severed, green needles initially remain within the sheath but eventually fade and begin falling out.

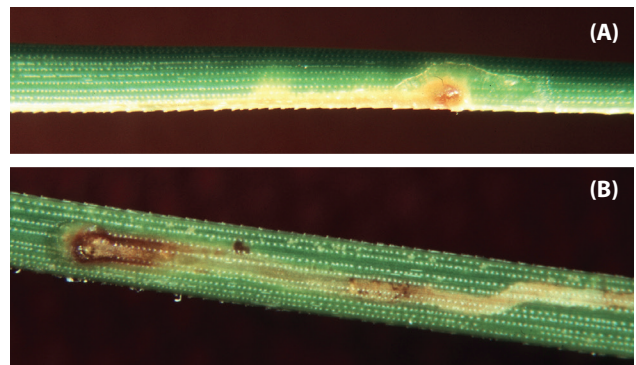


Figure 11.16. Close-up of mines of the pine needle sheathminer. The first instar larva mines along the edge (A) of a needle and then moves toward the center (B) during the second instar. Completed mines range in length from about 50 to 80 millimeters.



Figure 11.17. Holes mark where the pine needle sheathminer fed at the base of the needle fascicle.



Figure 11.18. Ponderosa pine shoot heavily damaged by the pine needle sheathminer.

During the sheath feeding phase, caterpillars are found on new shoots at the base of needles, along with silk webbing and frass. Caterpillars initially are tan but take on orange and green overtones as they develop (fig. 11.19A). They reach a length of 12 to 13 millimeters (about one-half inch). Pupae are half this length and found in silk webbing on damaged shoots in June (fig. 11.19B). Tiny white moths with tan markings begin flying in the latter part of June and may be present into August.

Outbreaks are not common and often short-lived. Natural enemies and host quality both likely contribute to this. Heavy defoliation kills the current year's needles, which are the preferred oviposition site for the next generation. If these needles are gone, eggs are laid on older needles, which presumably are less suitable for insect survival. Little information exists on impacts of defoliation, but what does exist indicates that most outbreaks are unlikely to cause significant damage. A rare worst case would involve multiple years of defoliation.

Management options. Direct control has been shown to be highly effective at reducing populations. Insecticide treatment is applied when most caterpillars have exited mines and entered the sheath feeding phase, usually in the latter half of May. Esfenvalerate, a synthetic pyrethroid insecticide, has been used successfully in aerial applications, but other insecticides are likely to be effective as well.

If direct control is being considered, an estimate of the population should be made by sampling trees in mid- to late April when caterpillars are still in needle mines. Shoots, including the full complement of last year's needles, are collected from a subset of trees. On each shoot, a portion (for example, 50%) of last year's needles are inspected for needle mines, which are relatively easy to see by April, but not before. The number of mines is counted and multiplied by the appropriate factor (such as times two if 50% of

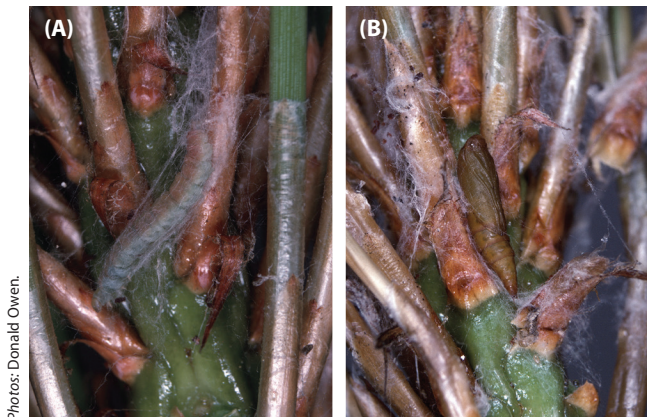
needles are inspected) to estimate the number of larvae per shoot that will enter the sheath mining phase. One or two caterpillars per shoot cause negligible defoliation. Slightly more, and defoliation begins to stand out. When numbers approach 10 caterpillars per shoot, defoliation is heavy. If most of the previous year's needles were killed, it will be necessary to look at the complement of needles from the year prior to that and to distinguish between old, unoccupied mines and those that contain caterpillars of the current generation.

White fir sawfly and Douglas-fir tussock moth

Recognition and significance. White fir sawfly and Douglas-fir tussock moth are two insects that defoliate white fir in distinctly different patterns. Sawfly larvae restrict their feeding to old needles, while tussock moth caterpillars initially feed on young needles and then may feed on needles of all ages as the caterpillars mature. It has been noted that if their outbreaks coincided, this would have a devastating impact on trees since defoliation would be rapid and nearly complete. While this is plausible, it is not likely. Both insects feed on trees of all sizes, but defoliation is heaviest on the youngest trees. This distinction is more pronounced with the sawfly.

Outbreaks of the white fir sawfly, a *Neodiprion* species, have occasionally occurred in stands of white fir. Damage is limited for two reasons: outbreaks typically are short-lived, generally a year or two, and feeding is restricted to old foliage (fig. 11.20). Feeding starts in the spring slightly before or when new growth begins. While feeding on old foliage can be heavy, new foliage remains undamaged. A major outbreak occurred in Northern California in the 1950s, but mostly minor activity has been noted otherwise.

The sawfly has a 1-year life cycle. Adult flight, mating, and oviposition occur from October to early November. Females insert eggs singly into needles



Photos: Donald Owen.

Figure 11.19. Pine needle sheathminer larva (A) and pupa (B).



Photo: Donald Owen.

Figure 11.20. Foliage damaged by the white fir sawfly. Newly flushed needles are untouched.

where they overwinter. Larvae hatch in the spring and feed gregariously. They are olive green, essentially hairless, and reach a length of slightly less than an inch at maturity (fig. 11.21). In contrast, tussock moth (*Orgyia psuedotsugata*) caterpillars are quite hairy and do not feed gregariously. By July, sawfly larvae stop feeding and begin to leave trees to pupate in the duff. An occasional pupa may be found among foliage.

Outbreaks of the Douglas-fir tussock moth are much more frequent and extensive than those of the sawfly, occurring somewhere in California on average about every 7 to 10 years. White fir trees of all ages can be heavily defoliated and put at risk for mortality. Douglas-fir trees receive little if any defoliation. In the past, treatments to control outbreaks were applied over large areas, but it is now recognized that heavy defoliation and damage is limited to local hot spots within larger outbreaks. White fir stands on ridge tops, upper slopes, and poorer sites are likely to receive the heaviest defoliation. Because trees can be killed or damaged by a single season of heavy defoliation, early detection and evaluation of building populations is critical.

Endemic populations of the tussock moth are virtually undetectable, except through monitoring with pheromone-baited traps. Depending on the area, the USDA Forest Service or CAL FIRE may be monitoring tussock moth populations. Such efforts provide areawide information on population fluctuations and

can be a cue of when to look more closely for tussock moth. Trap results can indicate if an outbreak is likely, but do not predict where it will occur. Aside from extensive sampling, a next best option for early detection is to keep an eye out for defoliation (fig. 11.22) or any other signs of the moth. This can be done during normal duties and by planned visits to high-risk sites. The tussock moth has a 1-year life cycle. The most visible stages of the insect are caterpillars (fig. 11.23), present from June through most of July, and egg masses (fig. 11.24), laid on foliage from late summer through October. Finding these or other evidence of the moth would be reason to request a local evaluation, which is best done by an entomologist or forest pest specialist.

Management options. Direct control of the sawfly might be considered for an outbreak of multiple years that coincided with other damage or stress to produce significant impacts. The 1950s sawfly outbreak was easily controlled with an insecticide, although natural enemies likewise exerted control in untreated areas. While direct control of the tussock moth is feasible, an evaluation is essential to determining an appropriate course of action. CAL FIRE conducts evaluations on state and private lands and the Forest Service on federal lands.

Photo: Donald Owen.



Figure 11.21. White fir sawfly larvae.

Photo: Donald Owen.



Figure 11.22. Light defoliation of white fir caused by the Douglas-fir tussock moth. Brown needles are partially eaten.

Photo: Donald Owen.

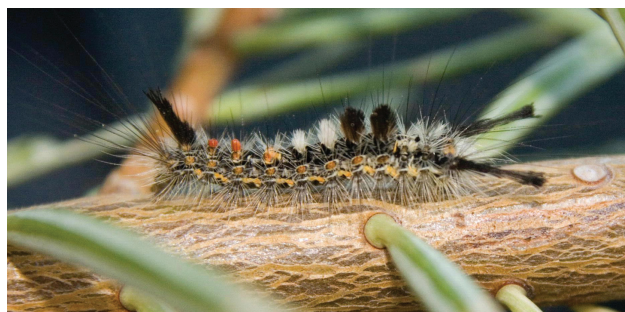


Figure 11.23. Douglas-fir tussock moth caterpillars come in different color variations. The distinctive tufts and other markings become more pronounced as the larvae mature.

Photo: Donald Owen.



Figure 11.24. Douglas-fir tussock moth egg mass and cocoon.

Diseases

Most diseases of significance in plantations are found on trees of all sizes and are a component of the environment into which young trees become established. Direct control of forest pathogens is rarely an option, but management strategies can reduce the incidence or impact of many tree diseases.

Many bark beetles and some woodborers and weevils attack trees under stress, including diseased trees. Some of these associations are well studied while others have been observed but not rigorously documented. If cambium-feeding insects are attacking a tree, the possibility of disease and other causes of stress should be investigated as well. The primary agent impacting the tree is deduced based on what is known of the organisms or other factors involved.

Root diseases

This group of pathogens infect the roots and lower stems of various tree species, causing mortality or, in the case of *Heterobasidion* on true firs, wood decay. The prevalence of root diseases is influenced by human activities, so it is important to recognize situations that contribute to disease, as well as preventative measures to avoid it.

Heterobasidion (Annosus) root disease

Recognition and significance. Most conifers in California are potential hosts for one of two fungi that cause *Heterobasidion* root disease. In live trees, the pathogen acts as either a decay that weakens root systems or as a root disease capable of girdling and killing trees. In the root systems of stumps or dead trees, the pathogen can persist for up to 50 years as a saprophyte. Young trees are infected and killed when their roots contact the roots of an infected stump or nearby live or dead tree. Once a tree is infected, the pathogen can grow and spread to adjacent live trees via underground root-to-root contacts. If the dead, infected roots in the soil are large and extensive, the pathogen can persist on-site and kill young trees for decades, creating an opening that is difficult to reforest.

Most openings or “disease centers” caused by *Heterobasidion* root disease are found in relatively pure ponderosa or Jeffrey pine forests, or true fir forests composed of white or red fir. Another characteristic of these centers is the presence of a single or multiple large, infected stumps. The diseases in pine and fir are different both in terms of the species of fungus that causes them and the damage done. Live pines are infected by *Heterobasidion irregulare* (formerly known as the “p” type of the fungus) and experience cambial girdling and mortality, whereas true fir are infected by *Heterobasidion occidentale* (formerly the “s” type of

the fungus), which causes wood decay in mature trees and may kill young firs. Diseased mature true fir are subject to wind-throw. Stress resulting from infection by either fungal species often leads to increased mortality from bark beetles, particularly during drought. Strategies to manage the disease in pine and true fir are slightly different. Note that the host specificity that is exhibited by *Heterobasidion* spp. in live trees does not apply to cut stumps. From a practical standpoint, *H. occidentale* can infect a pine stump and subsequently move to a live fir. Movement of *H. irregulare* from a fir stump to a live pine, however, is unlikely.

Management of *Heterobasidion* root disease is a matter of recognizing risk and implementing preventative strategies. Tree failure can be a significant risk to people and structures in all forest types where the disease occurs. On timberlands, mortality of young trees is primarily an issue in pine, especially on drier sites that are naturally suited to support a high percentage of pine. Such sites may have a history of *Heterobasidion* root disease and thus be recognized as higher risk for the disease. Aside from site conditions, larger pine stumps are an essential component of risk. A freshly cut stump surface can be an important route for the pathogen to become established on-site. Without large pine stumps to saprophytically harbor the pathogen, risk is nil.

Heterobasidion root disease can be diagnosed by a variety of signs and symptoms. One key symptom is the association of dead young trees with larger stumps. Fruiting bodies (conks) (fig. 11.25) of *Heterobasidion* spp. often can be found within old stumps or on the



Figure 11.25. Conks of *Heterobasidion occidentale* from white fir (A) in a stump and (B) close-up of the lower pore surface.

Photos: Donald Owen.

roots of killed seedlings and young trees. A perfectly formed conk is a semicircular shelf with a gray-to-brown top and an off-white pore surface on the bottom. Many conks, however, take on a more amorphous shape that conforms to their substrate and the space in which they developed. They vary in size from less than an inch to many inches across. They typically are hidden from view and must be revealed by removing duff and soil around the root collar or excavating decayed stumps. Wood with advanced decay is straw yellow, separates in a stringy or laminate fashion, and may have elongate white pockets and small black flecks (fig. 11.26). The roots of dead seedlings and young trees are discolored brown, often resinous, and may have tiny “popcorn” conks attached (fig. 11.27).

In mature stands, disease centers result in openings created by the outwardly expanding mortality of trees over the course of many years (fig. 11.28). Trees near the center of the opening have been dead the longest, while those on the edge may exhibit symptoms or be dying. Trees with advanced disease have thin, chlorotic crowns. Crowns thin from the bottom up, so the top of the tree may look relatively normal. It may be possible to find roots or portions of the root crown that have been killed by disease. Phloem turns brown, underlying wood may have light-brown streaking, and areas

Photos: Donald Owen.



Figure 11.26. Lower stem and root wood of a white fir decayed by *Heterobasidion occidentale* illustrating (A) laminate separation and (B) white pockets and black flecks.

Photo: Donald Owen.



Figure 11.27. Popcorn conks of *Heterobasidion irregulare* at the root collar of a young ponderosa pine killed by the fungus.



Photo: Danny Cluck.

Figure 11.28. Heterobasidion root disease center in a ponderosa pine stand.

of resin accumulation are common in both wood and bark. Tree reproduction within disease centers is poor because seedlings and young trees are killed. Often there are large, old stumps in the disease center that suggest the pathway by which the opening was initiated. Black-stain root disease causes similar crown symptoms and openings, but rarely kills young pines and produces very different signs within infected trees.

Management options. When cutting live pines on high-risk timber sites, stump surfaces can be treated with a borate fungicide to prevent colonization by *Heterobasidion* spp. Small stumps, generally less than 14 inches in diameter, present little risk for *Heterobasidion* root disease and can be left untreated. Stumps should be treated immediately or as soon as possible after cutting. If 2 days pass, the borate application will be ineffective. A benefit of treating true fir stumps on timber sites has not been proven for a variety of reasons: the pathogen is known infect true fir via other routes, infection is believed to be more common in true firs, and the impacts from infection are slower to develop in true fir versus pines. On sites where people or infrastructure are at risk from tree failure, consider treating stumps of all conifer species down to a 3-inch diameter.

Black-stain root disease

Recognition and significance. Black-stain root disease, caused by the fungus *Leptographium wagneri*, occurs in several pine species and Douglas-fir. Although trees of all ages may be killed, it is not a common disease of young pines. Pole-size and larger Douglas-fir are more readily infected and killed, especially in single-species plantations. Unlike *Heterobasidion* spp., *L. wagneri* does not persist well as a saprophyte. Hence, if an infected stand is cut and replanted, seedlings have limited exposure to the pathogen. As plantations age they become more susceptible to disease. Plantations of Douglas-fir apparently reach a susceptible age sooner than those of ponderosa pine.

The fungus is moved from one location to another by insect vectors, such as certain root-feeding bark beetles and weevils. Thinning or other disturbance in a plantation can attract vectors and result in the fungus becoming established. It then can move from tree to tree through root contacts and grafts, as well as insect transmission. Once established, no methods have been proven for slowing or stopping the disease. Of three different varieties of the fungus, the one that infects Douglas-fir will not infect pines and vice versa. Thus, planting nonhost tree species within a disease center is an option.

Recognizing black stain is usually straightforward. It is easiest to diagnose in dying or recently dead trees but can be difficult to diagnose in trees that have been dead for a few months or more. A progression of tree mortality over time (disease center) is one clue, although individual dead or dying trees are also common, particularly in Douglas-fir. Locate recently dead trees or, even better, nearby trees with thin crowns (fig. 11.29) or yellowing needles. Advanced black-stain root disease often causes a well-defined area of resin streaming on the bark surface at the base of the main stem (fig. 11.30). If the disease is the cause, a characteristic stain will be found in the sapwood beneath (fig. 11.31). Use a long-handled axe to cut into the wood. The stain is dark-brown and usually, but not always, resinous. In cross-section, it looks like a blotchy arc that roughly follows the curves of the outer growth rings. Longitudinally, it looks like dark-brown streaks coming up from the roots. Blue stain (fig. 11.32) is also found in dead and dying trees, but it is bluish



Photo: Donald Owen.

Figure 11.29. Douglas-fir with advanced crown thinning due to black-stain root disease.

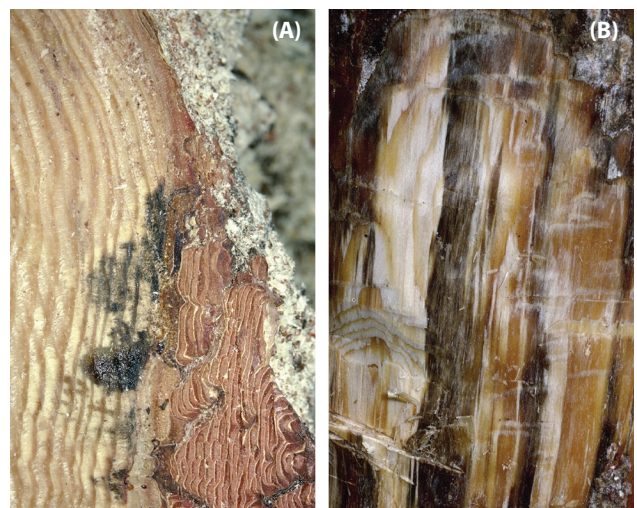
grey, usually not resinous, and radially oriented in the cross-section. A lack of resin streaming on the bark does not mean that black stain is absent. Checking the sapwood around the base of the tree and on larger roots may still yield stain. Once a tree dies, the invasion of the wood by other microorganisms and insects makes the stain more difficult to recognize.

Management options. Reducing the likelihood of disease establishment is the preferred option for plantations that have no evidence of black-stain root



Photo: Donald Owen.

Figure 11.30. Resin streaming at the base of the main stem associated with black-stain root disease on Douglas-fir.



Photos: Donald Owen.

Figure 11.31 . Typical stain produced by black-stain root disease in the lower stem of a ponderosa pine in cross-section (A) and longitudinal-section (B).

Photo: Larry Swan.



Figure 11.32. Characteristic blue staining in wood.

disease. Studies have shown that the timing of thinning and other disturbances is important to establishment. Thinning in spring and the months leading up to it create the greatest risk of disease establishment, while summer has the lowest risk. This is because spring is a peak flight period for insect vectors, paired with cool, moist soil conditions that favor infection. Fall and winter have elevated risk because cut or injured host tissues remain fresh and attractive to vectors into spring months.

If seedling survival is expected to be good, it may be desirable to avoid or minimize future thinning by planting at a lower density. On sites that will support it, consider planting nonhost tree species or a mix of host and nonhost species.

Other root diseases

Port-Orford-cedar root disease, caused by *Phytophthora lateralis*, and Armillaria root disease, caused by *Armillaria* spp., can both kill young conifers, but they are of concern primarily for other reasons. Port-Orford-cedar root disease is caused by a nonnative invasive pathogen that is spread via infested soil and water. Port-Orford-cedar trees are highly susceptible to this lethal disease. Timber operations and other human activities have contributed to disease spread and are primary routes by which long-distance spread occurs. Regulations and best management practices designed to prevent the spread of Port-Orford-cedar root disease are available and should be known to all who manage lands with Port-Orford-cedar.

For the most part, Armillaria root disease is a minor issue in California's conifer forests. This is mainly because the most virulent species of Armillaria do not occur in California. Most observed conifer mortality from the disease has occurred in situations where living, large-diameter oaks have been cut

adjacent to conifers. The residual oak stumps and roots become a reservoir for the pathogen, which then infects and kills conifers. Mortality is typically limited to the area immediately around the cut oak. Significant mortality was observed in one situation where all oaks were cut with the intent to convert to all conifers. Conifer mortality is less likely when large oaks senesce and die naturally.

Dwarf mistletoes

Recognition and significance. Dwarf mistletoes (*Arceuthobium* spp.) infect most conifer timber species in California, including species of true fir, pine, spruce, Douglas-fir, and hemlock, but not incense cedar. These parasitic plants rarely kill trees but can have a profound impact on growth or lead to secondary attack by other insects and pathogens. The greatest impacts occur where site conditions are less than optimal and added stress from dwarf mistletoe further weakens trees.

Recognition of dwarf mistletoe is simple, but it is not unusual for the disease to be overlooked or underestimated by land managers. Branch swelling and formation of witches' brooms are common symptoms. Dwarf mistletoe plants (fig. 11.33) or their remains confirm the disease. Propagation is by seeds that are forcibly ejected by female plants in late summer and fall. They only go a short distance, tens of feet or less, and have a sticky coat that adheres them to whatever they land on. New infections are thus initiated on the same tree or nearby trees. Birds and animals can transport seeds longer distances. Infection only occurs on young stem tissue, generally less than 5 years old, on an appropriate host. Mistletoe growth is initiated



Photo: Donald Owen.

Figure 11.33. Female dwarf mistletoe plants on lodgepole pine.

within the stem, and plants begin to emerge 2 to 5 years after initial infection. Swelling (fig. 11.34) of the stem is typical, and older branch infections lead to the development of witches' brooms (fig. 11.35). Plants are small, no more than a few inches tall, green to yellow in color, and sometimes difficult to see. They eventually detach, leaving behind small, round structures embedded in the bark called basal cups, which is another way to confirm the disease. Detached plants often litter the ground beneath heavily infected trees.

Individual infections have a limited effect on the tree, and it takes the cumulative impact of numerous infections, acquired over time, to have a significant impact. Disease severity rating is based on the amount of the tree crown infected. Infections remain active as long as the infected tissue remains alive. Infections are likely to spread and intensify over time, with stand structure having a significant influence. Bole infections, which are less common than those on branches, are of additional concern because they can lead to future stem defects. Several aspects of dwarf mistletoe



Figure 11.34. Branch swelling from dwarf mistletoe on lodgepole pine.



Photo: Donald Owen.

Figure 11.35. Witches brooms of dwarf mistletoe in a ponderosa pine.

biology are important to disease management: dwarf mistletoe species are highly host-specific, with only one or a few closely related hosts infected by each *Arceuthobium* spp.; spread of the pathogen is slow, and dwarf mistletoes are obligate parasites that only survive on living hosts.

Single-species, multistoried infected stands are a worst-case scenario. If young trees are overtopped by infected overstory trees, the chances of infection are high because mistletoe seeds will rain down upon the trees below. Single-species, single-storied infected stands fare better, especially if height growth is rapid. Upward spread of dwarf mistletoe within a tree crown is slow. If no mistletoe seeds are coming from above, this allows fast-growing infected trees to outpace this upward spread of the pathogen and thus produce substantial amounts of disease-free crown. A mixture of tree species slows the spread of dwarf mistletoe, but many infected sites are not well-suited to grow a mixture of trees or are difficult to regenerate as a mixture.

Management options. Tree harvest and reforestation practices can greatly influence future levels of dwarf mistletoe within a stand of trees. Infected single-species stands are typically regenerated using even-aged management, which includes clearcutting, group selection, seed trees, and shelterwood. Complete removal of infected overstory trees prevents the transfer of disease to regeneration; if residual seed and shelter trees are present, remove them as soon as is practical. The configuration and size of openings can be adjusted to minimize the likelihood of disease entering from adjacent infected stands. Align edges of the opening with natural barriers to disease spread, such as ridges, rock outcroppings, or groups of nonhost trees. When barriers are absent, larger openings will slow disease spread to the interior of the opening. Thin infected plantations to improve tree growth and maintain a canopy of uniform height. Remove slower growing trees, especially ones with infection.

Mixed-conifer stands are less likely to have high levels of dwarf mistletoe. When they do, it usually is in pockets where host trees are concentrated. With minor exceptions, dwarf mistletoe species are limited to a single host genus, and within a genus they are limited to one or a few species. Pine, Douglas-fir, and true fir are all infected by separate species that will not cross over to another host genus. Ponderosa pine shares dwarf mistletoes with other pine species, but notably does not share a dwarf mistletoe with sugar pine. A single species of dwarf mistletoe infects true fir in California, but different (subgeneric) forms of the mistletoe mean that the pathogen only occasionally spreads between red and white firs. These host differences provide

natural barriers to disease spread, which can be utilized when harvesting and regenerating mixed-conifer sites.

Rusts

Rusts are a group of fungal plant pathogens that produce yellow to orange/red spores, thus the common name of “rusts.” The rusts discussed here both produce stem infections.

White pine blister rust

Recognition and significance. This nonnative invasive disease, caused by the rust fungus *Cronartium ribicola*, is a serious threat to white pine—including sugar, western white, whitebark, and limber pines—in California. Resistance to the disease is low. Young trees often are killed, while mature trees may be damaged but survive. The blister rust pathogen requires an alternate host to complete its life cycle, and past control efforts were aimed at eliminating a principal alternate host, *Ribes* spp., without success. Currently, efforts by the Forest Service in California are aimed at identifying and breeding resistance in sugar pine, which may be the best option for protecting regeneration. Federal, state, and private land managers cooperate in the program.

As with many pathogens, weather can significantly influence the infection process. Widespread infections typically occur during “wave years” when environmental conditions are favorable, such as high humidity in late summer or early autumn. Infection occurs through a needle and progresses to the stem, where a canker is produced. Cankers take time to develop, but many will eventually girdle the stem, killing the distal portion (fig. 11.36). Cankers are spindle-shaped (fusiform) with cracked and sunken bark (fig. 11.37). Bright orange spores may be present within cankers in the spring. Limited numbers of infections may occur most years, but damage from infections that occurred during wave years can be dramatic. Older trees are protected somewhat because a high proportion of their stem tissue is not associated with needles and thus can’t be infected. Just the opposite is true for young trees. Trees that survive dieback will have evidence of cankers and may have thin, ragged crowns depending on the severity of damage. Young trees can be killed directly by a canker on the main stem or may die from the cumulative effect of cankers throughout the crown.

Management options. Except for the extreme southern end of the range of sugar pine in and south of the Tehachapi Mountains, most of the state’s white pine are potentially exposed to the pathogen, although damage has varied across sites. In areas where disease incidence is low to moderate, sanitation thinning and



Photo: Donald Owen.

Figure 11.36. Western white pine with upper stem girdled by blister rust.



Photo: Donald Owen.

Figure 11.37. Cankers of white pine blister rust on sugar pine stems.

pruning may be beneficial. Target the most-damaged trees for removal during thinning. Pruning infected branches from lightly infected trees can improve their chance of survival, provided branch cankers are no closer than 4 inches from the main stem. Prune from the bottom of the crown up, starting with infected branches. Removal of the lower-most, noncankered branches may also be beneficial, but no more than 50 percent of live branches should be removed overall. Once an infected tree or branch is cut, the pathogen dies as well. Individual trees that show limited, slow, or no disease development relative to other trees in the area may be candidates for resistance testing. For sites where disease has been severe, consider regenerating with nonhost tree species.

Western gall rust

Recognition and significance. Western gall rust is a native disease caused by the fungus *Endocronartium harknessii*. It infects many species of hard pines, but is most common on Monterey, lodgepole, and ponderosa pine. Like blister rust, heavy levels of infection occur during wave years and young trees are impacted the most. Mortality, however, is rare and restricted to the youngest trees. No alternate host is needed to complete the life cycle. The disease is most common in areas where moist air favors infection. Some higher levels of disease in ponderosa pine are seen in the northern Coast Ranges and west side of the northern Sierra Nevada.

Infection occurs on young shoots, producing a persistent, globose gall that gradually increases in size over time. Yellow-orange spores are produced by galls in the spring and early summer (fig.11.38). Branch ends distal to the gall may die, either directly from the expanding gall or from secondary pests that invade it. Infections on the main stem of young trees may persist for years, necrose, and be invaded by secondary pests. This produces a weakened, cankerous area on the stem of the mature tree that is subject to failure (fig.11.39A, B).

Management options. To avoid future impacts, remove young, infected trees from plantations, especially ones with high levels of disease or a main stem infection. Consider planting other conifers in areas with high risk for disease, such as riparian areas, around meadows, and other areas where moist air collects.

Needle diseases

Most needle diseases are of minor importance because widespread infection occurs infrequently, and impacts are limited to a complement of needles. Specific environmental conditions are needed for infection and



Photo: Donald Owen.

Figure 11.38. Western gall rust producing spores on ponderosa pine.

pathogen biology is tuned to take advantage of this, typically during a once-per-year window of suitability. Trees that experience a 1-year episode of infection and needle loss typically recover well. The youngest trees may be impacted the most, but also would be expected to recover. Recovery may be slower for trees suffering from other stresses. Rarely does widespread infection occur in consecutive years.

There are some exceptions to this scenario. Red band needle blight, caused by *Mycosphaerella pini*, can be particularly damaging to Monterey pine planted on the Northern California coast outside of its native range. Another exception is *Elytroderma* disease, caused by *Elytroderma defomans*. In addition to causing needle loss, the pathogen can persist within branches and result in long-term impacts.

Elytroderma disease

Recognition and significance. This disease of pines primarily impacts ponderosa and Jeffrey pine. Like other needle diseases and rusts, widespread infection occurs during wave years. Current-year needles are infected and die the following year. Widespread fading of these needles in the spring (fig. 11.40A) is what gar-



Photos: Donald Owen.

Figure 11.39. Stem infections of western gall rust that occurred when these ponderosa pines were young and continued to impact the trees throughout their lives; canker (A) and stem failure at an infection site (B).

ners the most attention, but unlike other needle diseases, previously infected trees harbor the fungus within branches, buds, and growing tips, causing other symptoms and impacts, including poor needle retention, witches' brooms, and reduced growth.

Initial infections are from airborne spores that infect through needles. Once the pathogen is established in a branch, it continues to grow along with the branch and can infect new needles directly. Branch infections thus allow the pathogen to colonize new needles when environmental conditions do not favor airborne infection. These infections also lead to witches' brooms. Internal infections persist on a branch but do not spread to uninfected portions of the crown.

Fruiting bodies of the fungus are dull black, elongate structures (fig. 11.40B) that may or may not be present on needles that died in the spring. Witches' brooms are relatively globose, compact, and have upturned branches. In contrast, brooms from dwarf mistletoe are more spread out, have greater branch swelling, and often have mistletoe plants. One of the most useful signs for identifying *Elytroderma* is the presence of brown necrotic flecks within the inner bark of infected twigs (fig. 11.41). Cut into tissue at least 3 years old to see it.

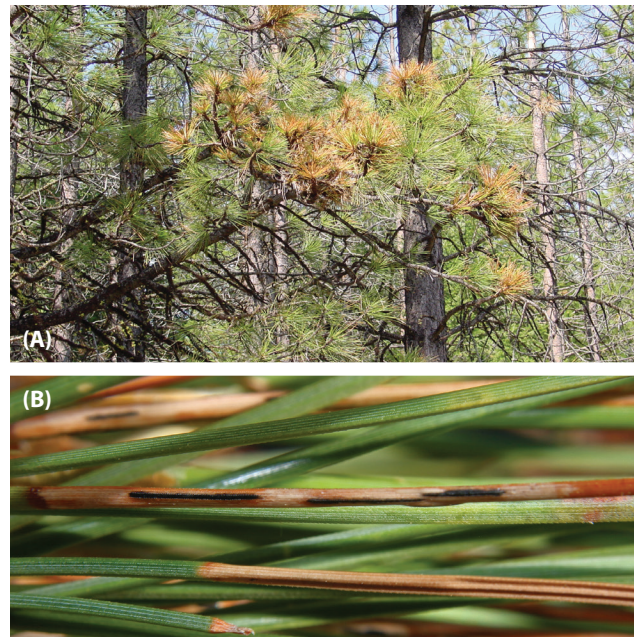


Photo: Danny Cluck.

Photo: Donald Owen.

Figure 11.40. Jeffrey pine infected by *Elytroderma deformans* show needles fading in the spring (A) and fruiting structures (B).



Photo: Donald Owen.

Figure 11.41. Brown necrotic flecks in the inner bark are a sign of *Elytroderma* disease.

Sites that favor a higher frequency of infection include areas around lakes, in canyons, and north-facing slopes. If mature trees in such areas show symptoms through much of their crown, this indicates repeated infection and high hazard for the disease. Young trees in high-hazard areas may experience growth loss and deformity and will have little opportunity for disease-free growth during their lives.

Management options. Tree mortality from *Elytroderma* disease is unlikely but may increase susceptibility to other pests. Little can be done to prevent the disease, but removal of highly impacted trees and thinning should improve the growth of residual trees. Off-site pine plantings should be avoided. Nonhost conifers can be favored on high-hazard sites. Needle loss can be widespread following wave years, but most trees outgrow the effects of disease on sites where infection frequency is low.

Cankers

A canker is a localized area on stems or branches where the cambium and adjacent bark has died, typically from fungal or dwarf mistletoe infection. Cankers can also be caused by abiotic factors, including weather extremes, fire, or mechanical damage. In contrast, the term canker is not applied to insect damage.

Fungi that cause cankers are not usually aggressive pathogens but can be damaging when the host is under stress. They enter susceptible tissues through wounds or other openings in the bark, such as branch stubs. Most canker fungi are restricted to bark and cambium tissue and do not penetrate the wood. As the dead tissue dries and shrinks, it becomes sunken relative to surrounding live tissue (fig. 11.42). Eventually the dead bark is sloughed off, and wood may be exposed. Callus forms at the edge of the canker and may close the wound with time unless the damaging agent girdles the stem or continues to expand. Secondary organisms may colonize the killed tissue.

Canker diseases are not a significant threat to young conifers, but two fungi, *Diaporthe lokoyae* and *Dermea pseudotsugae*, are notable for causing cankers on young, stressed Douglas-fir, especially those stressed by drought. These two fungi can girdle and kill stems. Most damage is limited and repairable by the tree, but the youngest trees may experience significant dieback or be killed. Thinning and vegetation control can help ease drought stress. Chronic dieback of Douglas-fir is a good indication that the site is better suited to more drought-tolerant species.

Pitch canker. Pitch canker, caused by *Fusarium subglutinans*, sp. *pini*, is an invasive disease primarily restricted to pines growing near the coast. Serious damage has occurred in natural stands of Monterey and Bishop pine, and to a lesser extent knobcone pine.



Photo: Donald Owen.

Figure 11.42. Phomopsis (*Diaporthe*) canker on Douglas-fir.

Young trees can be killed outright, while older trees experience dieback and may be killed by bark beetles. Although resistance occurs within native populations and damaged trees can recover, significant impacts still take place, especially in areas where the disease is recently introduced. Visit the [Pitch Canker Task Force](#) website for information on managing the disease and preventing its spread. Although work has been done to develop resistant stock, none is commercially available.

Phytophthora ramorum. *Phytophthora ramorum*, which causes sudden oak death, is another invasive pathogen that occurs near the coast, causing a wide range of impacts on trees and other plant species. Although direct impacts to conifers are minor, the disease has caused significant changes to some native ecosystems. Federal and state quarantines, and a zone of infestation established by CAL FIRE, are designed to prevent disease spread via human activities. See the [California Oak Mortality Task Force](#) website for more information.

Vertebrate pests

What is a vertebrate? Put simply, it's any animal with a backbone including fish, amphibians, reptiles, birds, and mammals. What is a vertebrate pest? A pest can be defined as any organism creating an unwanted condition, for example, invasive fish eating native fish, a rattlesnake in a wood pile, bird droppings on a park bench, or a roof rat living in an attic. In forests, it usually means an animal or population of animals creating undesirable conditions that negatively impact a reforestation outcome.

Vertebrate wildlife is a natural, vital, and desirable component of a healthy forest. Vertebrates provide many vital functions. Some voles and squirrels disperse mycorrhizal fungal spores throughout the forest floor, birds and many rodent species disperse conifer seeds, pocket gophers aerate soil and recycle soil nutrients, and ungulates recycle plant nutrients.

For a variety of reasons, however, there are times when vertebrate populations may inhibit reforestation efforts, requiring some level of human intervention to minimize negative impacts. As with any pest management scenario, *one size usually does not fit all*. Situations require thoughtful analysis and extent of the impact, a review of management options, and diligence in application and monitoring. The science of integrated pest management has emerged since the first printing of this publication back in the early 1970s, when most vertebrate pest management strategies focused solely on lethal options to remove the animals. The strategy back then was simply, “No animals . . . no problem.” Since then, political and social realities have changed, causing forest managers to address pest management

scenarios differently, resulting in more thoughtful—and challenging—ways to address vertebrate pests.

This section provides vertebrate management strategies for the 21st century as forests and their managers face the reality of increased droughts, wildland fires, urban encroachment, and legal requirements to protect threatened and endangered species.

Pocket gophers

Five species of pocket gophers (*Thomomys* spp.) occur in California:

- Mountain pocket gopher (*Thomomys monticola*) occurs in the Sierra Nevada above 5,000 feet, from Fresno County north to Shasta and Lassen counties.
- Western pocket gopher (*T. mazama*) is found in wet meadows and grasslands of the Klamath and western Cascade ranges.
- Northern pocket gopher (*T. talpoides*) occurs from Mono County north into Alpine, eastern Sierra, eastern Plumas, Lassen, Modoc and eastern Siskiyou counties, where it is abundant in juniper habitats.
- Townsend's pocket gopher (*T. townsendii*) is found only in the western portion of Honey Lake Valley in alkali desert shrub.
- Botta's pocket gopher (*T. bottae*) is by far the most widely distributed pocket gopher species in California, occurring in all habitats except the eastern Sierra Nevada and portions of Lassen, Modoc and Siskiyou counties above 5,000 feet. This species is responsible for most damage caused to both agricultural and forest trees. Optimal habitats are perennial meadows, and the grass and forb stages of most riparian deciduous and conifer forests. They are less common in mature stages of forest habitats.

In this section, we focus primarily on Botta's pocket gopher. Pocket gophers (fig. 11.43) are so named because of the fur-lined, external cheek pouches that they use to carry food back to their cache. They are herbivorous, feeding mainly on the roots, tubers,



Photo: invasive.org; Dave Powell, USDA Forest Service (retired).

Figure 11.43. Pocket gopher.



Photo: Greg Giusti.

Figure 11.44. Pocket gopher damage.

bulbs, stems, and leaves of forbs and grasses. They can and do damage young forest conifer seedlings (fig. 11.44). Pocket gophers prefer to forage from underground tunnels where they can chew on roots in tunnels and may pull entire plants into the tunnel. During winter they build surface tunnels above the ground through the snow to forage.

Reproduction and life traits. Pocket gophers nest in their burrows with deep chambers excavated for nurseries (females only). Litters are born in the spring, with juveniles dispersing and expanding their tunnel systems. Most forest populations have one litter per year, but in irrigated agricultural settings (for example, alfalfa) they are capable of several litters per year. Males are larger than females. Males grow throughout their lives, whereas females stop growing after their first pregnancy, so older males can be much larger than females. Pocket gophers live in small, local populations, spending almost their entire lives underground in their network of burrows (fig. 11.45). Pocket gophers are solitary animals that ferociously defend their tunnels from marauders in search of food from intersecting tunnel systems. Consequently, each tunnel has one resident animal at a time, except when a

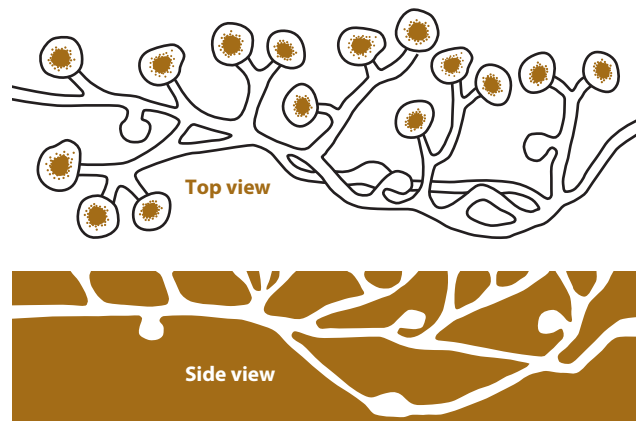


Figure 11.45. Example of a pocket gopher burrow system.

female is rearing her young. Pocket gophers do not hibernate and are active throughout the year.

Symptoms, signs, and significance of damage. The greatest risk to conifers from feeding damage by pocket gophers occurs in the early stages of reforestation when the trees are at their smallest stage. Gophers will eat the roots and main stems of seedlings, leaving the tops dead. During winter months, they strip twigs and bark from tree parts buried in snow. After the snow melts, long winding strips of soil on the surface show where pocket gophers have tunneled and backfilled with soil. They often kill trees in the first 3 years of planting and in severe cases can affect the stand's ability to achieve regulatory stocking standards.

Management options. Like all pest management strategies, diligence is required to detect and monitor centers of pocket gopher activity. Addressing a *potential* problem often results in less time, energy, and costs being needed to resolve the problem later.

Few viable, nonlethal options are available to address pocket gopher damage to conifers. Fencing, both above- and belowground, has not proven effective in minimizing damage, as gophers can dig beneath and climb over most fences. Live trapping of pocket gophers only results in moving the problem to a new location.

Lethal options to manage pocket gophers include:

- **Predator attraction** can be achieved by leaving or providing structure adjacent to the planting site. Trees, artificial perches, and snags can provide sites from which predatory birds can hunt for gophers. However, once a predator captures and consumes a gopher its dietary requirements will be addressed for some time until it needs to hunt again. Though predators will eat pocket gophers, they most likely will not achieve economic control without the aid of other management options.
- **Trapping** is an effective way to reduce populations while simultaneously monitoring efficacy. Trapping is only effective if the effort is given the time required to place sufficient numbers of traps per unit area to capture many animals simultaneously, check the traps daily, and relocate a trap to another burrow after an animal has been captured.
- **Toxic baits** provide a relatively time-conserving approach to covering large areas, but do not provide as quick and direct an evaluation of efficacy as trapping does. Toxic baits, placed underground in active burrows, rely on the animal consuming ample amounts to deliver a lethal dose. Bait acceptance can be affected by the composition of the bait, its age and freshness, and soil moisture, which can be absorbed by the bait, causing it to dissolve or mold.

- **Fumigants** can be effective if used properly and all registration, labeling, and safety requirements are followed. Soils need to contain some moisture to minimize the venting of fumigant gases through soil pores. Since pocket gophers do not hibernate, fumigants may prove useful throughout the year if soil conditions are right. Several types of fumigants are available:

- Incendiary devices such as smoke bombs and flares release sulfur gas, asphyxiating an animal belowground. Caution needs to be exercised during dry months when grasses may ignite.
- Carbon monoxide gas has been legal to control fossorial (belowground) pests since 2012. Both commercial and self-designed devices have been developed to deliver carbon monoxide gas to burrows.
- Aluminum phosphide tablets are a restricted materials pesticide requiring a permit from the county agricultural commissioner. A training certificate from the manufacturer or distributor often is required before the permit is issued.

Voles

Ten species of voles representing four genera (*Clethrionomys* spp., *Phenacomys* spp., *Microtus* spp., *Lemmus* spp.) are recognized in California. The five species affecting regeneration efforts are all members of the *Microtus* genus and are found regionally throughout the timber-growing regions of California.

Voles are stubby-bodied mice with tails shorter than their head and body. They have small, rounded ears and live in burrows (fossorial), but all their forage activities take place on the surface. Unlike pocket gophers, voles are gregarious and social. Vole burrow entrances are never closed, and several burrow openings are often found near each other. Burrow openings are about the size of a golf ball.

Reproduction and life traits. Nests are constructed of grasses belowground with breeding generally occurring in spring months between April and May, although the breeding seasons of some southern populations extend into the summer months. Litter sizes average four to five young, and some populations can have multiple litters in a year. Gestation is generally about 21 days. Females can reach sexual maturity in 30 days. Densities can achieve extremely high numbers in optimal habitats. Voles are crepuscular, meaning their daily rhythms are tied closely with dawn and dusk. Populations usually begin to increase with the first rains in autumn, peaking in the spring when grass growth is greatest. Voles do not hibernate.

Symptoms, signs, and significance of damage.

Voles generally prefer grassy habitats. Grass management is a key component in addressing vole population fluctuations. Seedlings planted in heavy grass cover in the presence of voles are at risk of feeding to the lower trunks where the damage often goes undetected until the seedling begins to fail (fig. 11.46). Field-grown seedlings in the absence of grass control are at risk of being heavily impacted by voles (fig. 11.47), often resulting in a major crop loss. If damage occurs in winter the signs can go unnoticed until plants are lifted.

Management options. Grass and other herbaceous management around seedlings is key to monitoring and evaluating vole damage. Voles are small, secretive animals susceptible to predation from snakes, birds of prey, foxes, mustelids (such as weasels, badgers, and wolverines), bobcats, and coyotes. They are not comfortable feeding in an exposed area. Creating a weed-free zone around a seedling is an important consideration when trying to minimize feeding damage.

Trapping. Trapping is a useful method of determining vole presence and abundance but may have limited application over a large area. Snap traps can be set (unbaited) perpendicular across the paths leading away from burrow openings. Voles are highly restricted

to movements within their pathways and will simply blunder into a set trap.

Toxic baits. Toxic baits are used most often to achieve population control. Zinc phosphide applied on a grain bait is the most commonly used toxicant. Since the baits must be placed above ground in the runways, prebaiting (using an untreated grain bait) is highly effective in preconditioning voles to bait sites. Once the prebait has been consumed, replacing it with toxic bait can achieve high efficacy while minimizing the chance of nontarget impacts by limiting the time toxic bait is exposed to the environment.

Exclusion. Vexar tubes and tree shelters are effective deterrents in field applications. To improve their effectiveness, tubes must be positioned tightly to the ground to prevent voles from going underneath and reaching the seedling.

Predator attraction. Attracting predators such as hawks and owls can be achieved by leaving or providing structures adjacent to the planting site. Trees, artificial perches, and snags can provide sites from which birds of prey can hunt for voles. However, once a predator captures and consumes a vole its dietary requirements will be addressed for some time until the animal needs to hunt again. Though predators will eat voles, they most likely will not achieve economic control without the aid of other management options.

Rabbits and hares

Rabbits and hares are members of the order Lagomorpha, distinguished from rodents by having a double set of front incisor teeth, one behind the front. Rabbits are burrowing animals, born in an altricial state, meaning that they are helpless at birth and fully dependent on the mother, much like puppies and kittens. Hares do not use burrows, are born aboveground in a precocious state with eyes open and are able to leave the nest within days of being born.

Eight species of Lagomorphs are found in California. The pika (*Ochotona princeps*) is not discussed in this chapter. There are four species of true rabbits, often called cottontails (*Brachylagus* sp., and *Sylvilagus* spp.); and three species of hares (*Lepus* spp.), the snowshoe hare (*L. americanus*), white-tailed jackrabbit (*L. townsendii*), and black-tailed jackrabbit (*L. californicus*).

True rabbits are not often associated with extensive damage in forestry restoration as they are closely associated with briar patches and other heavy cover, and they never stray far from cover. Hares, on the other hand, are mobile and wide ranging.

Reproduction and life traits. Female hares can have up to four litters per year with two to eight young per litter under optimal habitat conditions. Daily



Figure 11.46. Vole damage on coast redwood.



Figure 11.47. Redwood mortality from vole damage.

movements up to 2 miles are common when food and shelter resources are separated. Rabbits and hares are active day and night, though true rabbits tend to be crepuscular. Rabbits and hares do not hibernate.

Symptoms, signs, and significance of damage.

Hares will eat the foliage, stem, and twigs of seedlings, as well as young trees (fig. 11.48). Rabbit feeding can be distinguished from deer browsing, as rabbits turn their heads when biting a seedling leaving a distinctive 45-degree angle clean cut. Additionally, rabbit damage tends to be relatively close to the ground while deer feeding can occur from ground level up to 5 feet aboveground. They also can strip bark from seedlings, shoots, and stems. Hares can have severe impacts to young plantations and seedlings. Small trees can be completely consumed, and stripped bark often leads to the death of the seedling.

Legal status. Cottontails and snowshoe hares are considered small game mammals in California with a set season and bag limits requiring a hunting license to legally take rabbits. Jackrabbits may be taken all year and there is no daily bag limit, but a hunting license is required.

Management options. Vexar tubes and tree shelters are effective deterrents in field applications to exclude Lagomorphs. To improve effectiveness, tubes must be positioned tightly to the ground and checked regularly to insure proper positioning. Shooting and hunting may have applications in forestry settings and can help control localized populations. Hunting regulations must be consulted when using this method for rabbits.



Photo: USFS John Ghent.

Figure 11.48. Rabbit damage.

A number of commercially available chemical repellents are available, but little efficacy data exists for forestry applications. No toxic baits are currently registered in California for use on rabbits or hares.

Porcupines

The porcupine (*Erethizon dorsatum*) (fig. 11.49), like the beaver, is a large rodent. Once abundant, their numbers have plummeted in the state over the past 30 years for unknown reasons. Its historical range included all of the Sierra Nevada and Cascade ranges, and much of the Coast Ranges. Recent studies have shown that it is now uncommon at elevations below 6,000 feet. The porcupine is arguably one of the most recognizable animals in the forest.

Reproduction and life traits. Porcupines den in caves, crevices in rocks, cliffs, hollow logs, snags, and burrows of other animals. They are primarily nocturnal but can be seen in daylight. They are active all year and do not hibernate. When ambient temperatures become very cold (below 9°F), they become lethargic and limit their activity to a single tree. They mate in fall or winter with a gestation of 7 months. The usual litter size is one, and, rarely, two. Females are attentive and juvenile mortality is considered low. Porcupines have been documented to live up to 10 years.

Symptoms, signs, and significance of damage. Pole-size timber is at the greatest risk from porcupine feeding damage (fig. 11.50). Pines (ponderosa and Jeffrey) are preferred species, but they will feed on aspen, cottonwood, and willow. Porcupine will feed on herbaceous plants, inner bark, twigs, and leaves of host plants. Tooth marks often indicate porcupine feeding, and bark and wood chips can often be found at



Photo: Paul Bolstad, University of Minnesota. Bugwood.org

Figure 11.49. Porcupine.

Photo: Joseph O'Brien, USDA Forest Service, Bugwood.org



Figure 11.50. Porcupine damage.

the base of a tree that porcupines feed upon. The tops of pines are often killed, especially in winter months when an animal may limit its movements to a single tree or cluster of trees. Porcupine damage in young, open stands and plantations can be significant if left unchecked. Top-killed trees result in abnormal growth patterns, affecting timber values.

Management options. Historic methods of using aboveground, strychnine-laced salt blocks to reduce porcupine populations is no longer legal. Use of toxicants requires consultation with the local agricultural commissioner or U.S. Department of Agriculture Wildlife Services prior to use.

Tracking and shooting. During winter months when snow is on the ground, porcupine tracking is an effective, albeit time consuming, method of finding individual animals roosting in trees. Where legal, shooting is one method of population reduction.

Exclusion. Porcupines do not jump from tree to tree like squirrels. Trunk guards and wraps are effective in limiting their ability to climb trees.

Predation. Porcupines are susceptible to predation from mountain lions, bobcats, and fishers. Fishers, in particular, are adept at preying on porcupines and have been shown to reduce populations in some areas.

Ground squirrels

California has *at least* 23 species of ground squirrels, including marmots, ground squirrels (California, Belding, antelope, and golden mantle), and chipmunks. Fortunately, only a few species can be a problem in reforestation efforts.

Reproduction and life traits. Ground squirrels (fig. 11.51) are diurnal, social animals often living near their cohorts sharing burrows and food resources. All ground squirrels hibernate. This means that they are in their burrows during winter months, and population surveys can easily underestimate numbers. Burrows are obstructed (plugged) belowground when the animals



Photo: Terry Spivey, USDA Forest Service, Bugwood.org

Figure 11.51. Ground squirrel.

are hibernating, and they are difficult to control during this time.

Following hibernation, ground squirrels emerge from their burrows and establish and defend breeding territories. They are most active and visible during this time, which helps determine population distributions and densities. Young are born and tended belowground in a nursery chamber of the burrow. Litter sizes can vary between five and eight, with young emerging from the burrow at about 6 weeks of age. By 6 months, young resemble the adults.

Symptoms, signs, and significance of damage.

Damage by ground squirrels was a problem when reforestation used aerial seeding, as the conifer seeds were readily eaten by squirrels and other rodents. With the shift to planting seedlings, damage by ground squirrels is limited to a few species, including California ground squirrel (*Otospermophilus beecheyi*), Golden-mantled ground squirrel (*Callospermophilus lateralis*), and Belding's ground squirrel (*Urocitellus beldingi*).

Golden-mantled ground squirrel is considered the most potentially destructive to conifer seedlings. Damage is nondescript and variable, with newly planted seedlings at most risk from direct feeding (clipping) to the terminal or lateral roots or complete loss of the seedling. Some forest managers have observed that the soil matrix in which seedlings were grown can attract feeding by golden-mantled ground squirrels. It therefore may be worth investigating this with the nursery of origin.

Golden-mantled squirrels generally benefit from moderate timber harvesting that opens the canopy and allows greater food production. Seedlings would be considered another food source in this scenario.

Management options. Since ground squirrels hibernate, all management options attempting population control must be during times of activity (March to September).

Exclusion. Vexar tubes and tree shelters are effective deterrents in field applications. To improve effectiveness, tubes must be positioned tightly to the ground and checked regularly to insure proper positioning.

Trapping. Snap traps and conibear 110 bodygrip traps (for the larger California ground squirrel) traps can be effective in controlling ground squirrels. Traps need to be set during daylight hours, as leaving traps after dark increases the capture of nontarget predatory species.

Toxic baits. Diphacinone applied on a grain bait is the commonly used toxicant. Prebaiting (using an untreated grain bait) is highly effective in preconditioning ground squirrels to bait sites. Once the prebait has been consumed, replacing it with toxic bait can achieve high efficacy while minimizing the chance of nontarget impacts by limiting the time toxic bait is exposed to the environment. Homemade or commercially available bait stations are an effective way to minimize exposure to nontarget species. Baits are best accepted by ground squirrels late in the summer when their dietary focus shifts to seeds.

Fumigants. Fumigants can be effective if used properly. Soils need to contain some moisture to minimize the venting of fumigant gases through soil pores. Since ground squirrels hibernate, fumigants are only effective after the animals awake from hibernation. Several types of fumigants are available:

- Incendiary devices (smoke bombs, flares) often release sulfur gas, asphyxiating animals belowground. Exercise caution during dry months when grasses may ignite.
- Carbon monoxide gas has been legal to control fossorial (belowground) pests since 2012. Both commercial and self-designed devices have been developed to deliver carbon monoxide gas to burrows.
- Aluminum phosphide tablets are a restricted materials pesticide requiring a permit from the county agricultural commissioner. A training certificate from the manufacturer or distributor is often required before the permit is issued.

Shooting. Where safe, shooting can eliminate a small number of animals. It is often time consuming, and efficacy is dependent on the skill of the marksman.

Tree squirrels

The three native species of tree squirrels (*Sciurus*, *Tamiasciurus*, and *Glaucomys*) found in California's forests are western gray squirrel (*S. griseus*), Douglas squirrel (chickaree) (*T. douglassii*), and northern flying squirrel (*G. sabrinus*). Of these, the western gray and Douglas squirrels can damage conifers.

Reproduction and life traits. Tree squirrels are diurnal, except for the flying squirrel, which is nocturnal. Tree squirrels **do not** hibernate and remain active throughout the year. Whereas ground squirrels will climb trees, tree squirrels never go belowground. Tree squirrels are primarily herbivorous, feeding on conifers, seeds and fruits, and fungi. They will cache food for eating during winter months, foraging in trees or on the forest floor. Tree squirrels nest in abandoned woodpecker and snag cavities, or make a nest of branches lined with bark, grass, lichens, and moss. Young are born between March and June, with one litter of three to five per year.

Symptoms, signs, and significance of damage. Tree squirrel feeding and associated damage is most often near the top of pole- and saw-log-sized trees. Douglas squirrel feeding in seed orchards can be a problem if feeding is heavy and the seed cones are eaten. In winter months, tree squirrels often feed on and remove the tips of lateral branches. Generally, this is not considered a long-term impact to the tree and is not considered a negative impact to reforestation efforts.

Tree squirrels have been known to kill the tops of pines and coast redwoods. This feeding behavior often happens in the spring when sap flow is high. Bark is removed and feeding impacts the cambium. It's not clear if bark is also removed for nest building during this time. Impacted trees are not killed, but the damage can affect log quality and can lead to secondary pest problems in pine. The economic impacts from squirrel damage are not well documented in California, as the damage is often localized and transient.

Legal status. Tree squirrels are considered small game mammals in California with a set season and bag limits, and a hunting license is required to legally take them. California Fish and Wildlife regulations should be consulted prior to taking tree squirrels.

Management options. Given their legal status, few management options are available in forestry to control tree squirrel populations. No toxicants or fumigants are registered, and live or kill trapping is not allowed under California law. Under appropriate hunting statutes tree squirrels may be legally taken by shooting during the defined hunting season.

Younger stands are at greatest risk from squirrel damage. If damage is occurring and limiting regeneration efforts, concentrating control measures in these stands may lessen the threat.

Woodrats

Of the three species of woodrats found in California, only the dusky-footed woodrat (*Neotoma fuscipes*) may be of concern to coastal forest managers. Found primarily in the belt of coast redwood and Douglas-fir in

coastal California and the Sierra Nevada foothills, the species has been known to damage regeneration efforts in coast redwood stands. They are mostly nocturnal.

Reproduction and life traits. Woodrats feed on woody plants, fungi, flowers, grasses, and acorns; prefer moderate canopy cover; and are often abundant in chaparral habitats. They construct nests of sticks in or at the base of a tree and breed year-round (except in October and November), with peak breeding in the spring. Woodrat populations have been shown to be highest in coastal redwood stands between 15 to 30 years old. They are considered a primary prey species for the endangered northern spotted owl (*Strix occidentalis*) in coast redwood forests.

Symptoms, signs, and significance of damage. Woodrat feeding damage is often seen within the clumps of sprouting coast redwoods (fig. 11.52) or on the terminal leader of redwood saplings. They have been known to remove the outer bark for nest material without exposing or removing the sapwood. Damage within stands is often sporadic and unpredictable. Stands become less attractive and consequently less populated by woodrats after 30 years.

Management options. Given their importance as prey for spotted owls, consult the local agricultural commissioner prior to any use of toxic baits. No fumigants are registered in California for control of woodrats. Snap traps may be effective at single sites, but



Photo: Greg Giusti.

Figure 11.52. Woodrat damage to a clump of redwoods.

they are not generally considered effective in a larger forestry context. Given that woodrats are nocturnal, shooting is not considered an effective control method.

Younger stands are at greatest risk from woodrat damage. If damage is beyond economic thresholds, reexamining silvicultural practices may be the best option.

Mountain beavers

Mountain beavers (*Aplodontia rufa*) (fig. 11.53)—also known as mountain boomers, sewellel beaver, ground bear, and giant mole—are considered the oldest type of rodent in North America. They are found throughout the Cascade, Klamath, and Sierra Nevada ranges and sporadically along the Coast Ranges, often found near water as they need soft, friable soils to construct underground burrows. Mountain beavers feed on thimbleberry, salmonberry, lupines, willows, ferns, and young conifers, caching food in their burrows.

Some populations of mountain beavers are afforded special protections in California. Consult with the local agricultural commissioner prior to initiating any management measures with this species.

Reproduction and life traits. Mountain beavers do not concentrate their urine and thus require large daily intakes of water. Nonmigratory and sedentary, they do not hibernate and are active throughout the year. They will defend their burrows, but territories may overlap and most activity occurs relatively close to the burrow. Mountain beavers breed from December through March, with the peak in February. Litter sizes vary between two and three young, with females not reproductively active until their second year.

Symptoms, signs, and significance of damage. Mountain beavers are known to damage young seedlings. Damage can be heavy and severe in Douglas-fir plantations, where mountain beavers will select lateral and terminal branches on the seedlings, saplings, and pole trees. Lateral and terminal branches have been damaged up to 10 feet. Basal girdling and undermining of tree roots from burrowing can occur in young stands.



Photo: Jacob Kirkland.

Figure 11.53. Mountain beaver.

Management options. Vexar tubes and tree shelters are effective deterrents in field applications. To improve effectiveness of the tubes they must be positioned tightly to the ground to prevent mountain beavers from digging below or climbing over and feeding on the tree. Depending on the size of the seedling being impacted, tubes up to 30 inches may be considered.

Traps and fumigants. Unbaited conibear 110 body-grip traps set in the entrance of the burrow can be used to catch mountain beavers. Consult with the local agricultural commissioner to determine if toxic baits or fumigants are a legal management option. Fumigants can be effective if used properly. Soils must contain some moisture to minimize venting of fumigant gases through soil pores; since mountain beavers do not hibernate, fumigants may prove useful throughout the year if soil conditions are right. Several types of fumigants are available:

- Incendiary devices (smoke bombs, flares) often release sulfur gas, asphyxiating an animal below-ground. Caution must be exercised during dry months when grasses may ignite.
- Carbon monoxide gas has been legal to control fossorial (belowground) pests since 2012. Both commercial and self-designed devices have been developed to deliver carbon monoxide gas to burrows.
- Aluminum phosphide tablets are a restricted materials pesticide requiring a permit from the county agricultural commissioner. A training certificate from the manufacturer or distributor often is required before the permit is issued.

Ungulates (deer, elk, livestock)

A variety of wild and domesticated ungulates are found throughout the forests of California. Most are sedentary and nonmigratory (except for some eastern mule deer populations), and they can have repetitive impacts on forest regeneration efforts. Domestic species include cattle, horses, sheep, and goats, while wild ungulates in a forest setting are restricted to deer and elk. Cattle, elk, and horses are grazers while deer, sheep, and goats tend to be more omnivorous browsers. Deer and elk population densities are set by the carrying capacity of the habitat and are present throughout the year, while livestock densities can be arbitrary and seasonal.

Legal status. Deer and elk are game species with strict harvesting restrictions. Depredation permits can only be authorized by the California Department of Fish and Wildlife. Livestock are private property under the control of the property owner.

Symptoms, signs, and significance of damage.

Ungulates are big animals that can eat up to 3 percent of their body weight in a day. Damage can be from direct feeding to lateral and terminal buds (fig. 11.54), rubbing from antlers or other body parts (cattle), or trampling. Deer can reach terminal branches up to 5 feet, while elk can reach even higher, and horses and goats can remove bark from trunks. Damage can be localized and severe depending on density and duration of the grazing or browsing pressure.

Management options. Vexar tubes and tree shelters are effective deterrents in some field applications. Depending on the size of the seedling being impacted, tubes up to 30 inches may need to be considered. Tubes may be useful for deer and smaller ungulates but are not considered effective for larger animals such as elk, cattle, or horses. Fencing may be needed to exclude larger animals for a period of time until the regeneration effort grows beyond their reach.

Though commercial repellants are available, their utility in forestry operations is limited by the need for constant application. Some products are packaged in small bags or pouches to hang on the tree, but their effectiveness has not been substantiated in the scientific literature.

Livestock can be conditioned to avoid sensitive areas by placing salt blocks, mineral supplements, and water sources away from the area needing protection. Placing “rubbing posts” away from planted areas can condition livestock to seek out alternative sites for scratching and rubbing.



Figure 11.54. Deer feeding can be distinguished from rabbit feeding by the “roughness” of the bite. (A) Deer lack upper incisor teeth so tend to crush vegetation. (B) Rabbits with sharp upper and lower incisors cleanly cut stems at a 45° angle.

Photos: IPM (A), John Ghent, Bugwood.org (B)

Bears

The American black bear (*Ursus americanus*) is widely distributed in forested regions throughout the state and is the only species of bear found in California. Though the name implies a single-color variation, the black bear can be black, brown, or cinnamon in color.

Reproduction and life traits. Black bears are omnivorous. They will readily feed on grasses, forbs, fruit, nuts, and carrion, as well as prey on living animals. They tend to be seasonal specialists feeding on grasses, forbs, and insects during the spring; berries in the summer; and acorns and fish carrion in the fall. They have been known to kill adult deer and livestock. Young are born in winter dens in January and February. Young will stay with the female for at least 1.5 years, with individuals living up to 25 years in the wild.

Legal status. Black bears are game species with strict harvesting restrictions. Depredation permits can only be authorized by the California Department of Fish and Wildlife.

Symptoms, signs, and significance of damage. Bear damage usually occurs during the later spring months prior to the emergence of summer fruits (fig. 11.55). This is a time of year when bears are losing weight,



Figure 11.55. Bear damage.

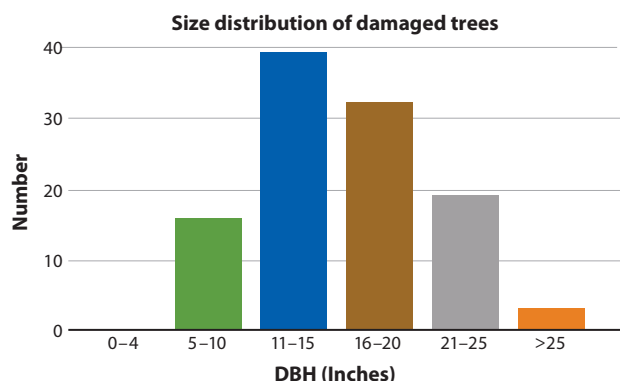


Figure 11.56. The amount of bear damage varies by tree diameter.

and lactating females are under stress caring for their young. Bear feeding removes the bark of coast redwoods (fig. 11.56), Douglas-fir, and Port-Orford-cedar, exposing the cambium, which is scraped with the canine teeth. Damage is often associated with roads, but damaged trees can be found randomly in a stand. Feeding is initiated by increased spring sap flows and is often associated with precommercial thinning activities, which further increases sap flows. Feeding is often initiated by females in search of food to meet their lactating energy demands, thereby exposing her young to the behavior. Trees are often “tested” and not fed upon, only to be revisited later in the season when resin flows have increased. Damage can be localized, sporadic, minor, or severe. Stands experiencing bear feeding damage often share similar characteristics. Cohorts are often precommercially thinned, even-aged stands with trees between 12 and 20 inches diameter at breast height, as well as good road access.

Management options. Long-term transition to alternative silvicultural treatments, such as even-aged to uneven-aged, may make stands less attractive by eliminating the need for precommercial thinning. Though anecdotal evidence suggests that stands above 160 square feet in basal area may be less susceptible to bear feeding, that has not been validated through long-term studies.

Areas targeted for recreational hunting can reduce bear numbers during the authorized hunting season. Though not currently allowed in California, research in Washington State has demonstrated some success using alternative food sources such as sugar-wood pellets during the time of year when bear damage is predicted to occur.

Abiotic damage

Abiotic damage is caused by nonliving, noninfectious agents that physiologically or physically impact a plant. Abiotic damage can result from a broad range of interacting host and environmental conditions, either natural or human-induced, that are often only partially understood. Weather events and climatic conditions such as hail, frost, and drought produce the most common abiotic damage seen in forest plantations. In situations where best management practices are followed, extreme or uncommon conditions are typically needed to produce damage. Extreme is a relative term because it depends on what is extreme for a given site, time of year, tree species, or genetic stock. It may relate to abnormal highs or lows, how quickly conditions change from one to the other, how long adverse conditions persist, or the influence of coincidental factors. Going forward, climate change will be a factor in both abiotic and biotic damage.

Diagnosis of abiotic damage is complex and may require making subjective determinations with respect to changes in the environment and their possible effects. Confirmation of certain abiotic damage (for example, road salt and mineral deficiencies) may require laboratory analysis. An excellent resource for identifying abiotic damage is USDA Forest Service Agricultural Handbook No. 521, [Diseases of Pacific Coast Conifers](#). The possible permutations of abiotic damage mean that not every situation will fit a textbook description. Often the event or condition that produced the damage is not directly observed, and it may be necessary to review records of past events to identify likely causes. Conversely, cause and effect may be relatively simple to deduce, such as with the pattern of wounding that is caused by hail.

An important aspect of diagnosing abiotic damage is recognizing that the damage is not caused by a biotic agent. In general, damage caused by abiotic factors tends to be more uniform, nonspecific, and widespread. For example, damage caused by freezing temperatures can affect multiple tree species in a similar way across an elevational band or geographic feature. Note that symptoms of biotic and abiotic damage can overlap, and secondary organisms can enter damaged tissue. It is useful to learn the signs and symptoms of the most common and significant causes of biotic damage so that these can be looked for. Confirming their absence is a strong case for abiotic damage. When secondary organisms invade damaged trees, their presence is often inconsistent. Sometimes they are present, other times not, or different organisms may be present on different trees.

In many situations, abiotic damage is the result of an unusual event with a low probability of reoccurrence. It may be a learning experience that influences future management decisions, but otherwise cannot be mitigated directly.

Drought

Drought is a reoccurring feature of California's Mediterranean climate that impacts conifers of all types and ages. In addition, weather records show that the state is becoming drier. The extent of damage depends on the severity and length of drought. Impacts can be particularly severe on young trees, which have less well-developed root systems. Damage often is concentrated in drier locations, but is also influenced by host genetics, microsite (for example, local areas of shallow soil), or even planting irregularities. Reduced moisture availability also increases the susceptibility of trees to insects and diseases. The damage and mortality of drought-stressed trees is often attributed to insect pests, but with the youngest trees the role of insects



Photo: Ricky Satomi.

Figure 11.57. Premature shedding of older needles on incense cedar due to drought stress.

may be minimal compared to the direct effects of drought. Stocking control and control of vegetation that competes with young conifers for water is the single most important action that can be taken to improve tree survival.

Drought also suppresses growth. Visible manifestations are reduced height and shoot growth, shorter-than-normal needles, and, if several years of needles are present, the premature loss of older needles (fig. 11.57). The crowns of chronically stressed trees develop a characteristic thin appearance due to poor growth and needle retention. Severe or chronic drought may also lead to shoot and top dieback.

Drought can interact with other factors to produce increased levels of damage. In spring 2003, young incense cedar exhibited dieback and mortality over a large area of Northern California and southern Oregon. The damage was speculated to be the result of both drought and a sudden shift to unusually low temperatures in late October 2002. The classic example of increased damage occurs when drought-stressed conifers are killed by bark beetles such as the western pine beetle, *Ips* species, and fir engravers.



Photo: Donald Owen.

Figure 11.58. Partially healed wounds from hail damage on sugar pine.

Hail

Foliage and smaller diameter stems are directly injured by the impact of hail. Young tissue is particularly susceptible. Damage occurs on many different plant species but can vary significantly by species. Douglas-fir is more susceptible to hail damage than other conifers. Look for scattered spots of tissue bruising or wounding on the upper sides of foliage and branches (fig. 11.58). Damage can be heaviest on one side of the crown and main stem, depending on the direction and intensity of wind-driven hail. Needles may be lost. With heavy damage, spots of injury will coalesce, and shoots and tops may be weakened or killed (fig. 11.59). Crown dieback can affect tree growth for many years after injury. Lighter damage may not immediately be apparent but become more obvious as tissue dies and calluses.

Frost

Damage from frost is most likely to occur in the spring. It occurs when new tissues are exposed to unusually late, below-freezing temperatures. Damage can vary from one tree to the next based on species, how much new growth is exposed, and position on the landscape. Damage often is restricted to cold air sinks, also known as frost pockets. Classic spring frost damage kills most new growth on a young tree (fig. 11.60). Larger trees respond with additional new growth and recover well, while seedlings and small trees are at risk of significant dieback and mortality because of their small size and higher ratio of new-to-old growth. Although less common, damage can also occur in the



Photo: Donald Owen.

Figure 11.60. New shoots and needles of Douglas-fir damaged by spring frost.

fall when the current year's growth has not yet been conditioned to the coming cold season.

Prevention is the best means of avoiding frost damage. When establishing a plantation, it is important to recognize frost pockets and avoid planting trees unlikely to survive there. Douglas-fir planted on the eastern edge of its range in the Cascade Range of Northern California have suffered frost damage in these situations. Utilize planting stock from the appropriate seed zone.

Winter needle and shoot desiccation

This type of injury can be caused by a variety of winter conditions that promote the drying of foliage and sometimes stems, with inadequate uptake of moisture by the roots to replace what is lost. A common form of this damage is referred to as “red belt” because it occurs in a distinct band or belt on the landscape that follows an elevation contour. It occurs when a temperature inversion causes affected trees to be exposed to warm daytime air while the soil is too cold for water uptake. Another situation that can lead to desiccation is a low or nonexistent midwinter snowpack due to drought at elevations where young trees would normally be covered by snow. Foliage is exposed to sun and wind while roots and soil remain cold.

Milder cases of desiccation result in needles browning from the tip downward (fig. 11.61A). Once new growth begins in the spring, older damaged needles



Photo: Donald Owen.

Figure 11.59. Dieback in the crown of sugar pine damaged by hail.



Photos: Donald Owen.

Figure 11.61. Ponderosa pine with winter needle desiccation, commonly referred to as red belt (A); trees with red belt may look dead from a distance (B).

are retained or lost, depending upon the amount of necrosis (browning). If needles dry completely, shoot tips may also be impacted. Mild desiccation is primarily cosmetic. Trees with partially brown, desiccated needles can appear dead (fig. 11.61B), but closer inspection of foliage and shoots should reveal that they are still alive. Such trees “green up” when new growth begins in the spring. However, severe desiccation of young trees can cause dieback and mortality.

Herbicide damage

Best management practices for herbicide use are covered extensively in this manual. Following these practices provides insurance against damage from herbicides, but not a guarantee. Damage may be due to an error made during the herbicide application or perhaps some unrecognized host or environmental condition. Symptoms of herbicide damage vary with the type and amount of herbicide used and include distortion and dieback of shoots, and twisting, stunting, discoloration, desiccation, and loss of needles. Diagnosis is usually based on three conditions—symptoms, no evidence of other causes, and a recent history of herbicide application.

Other abiotic damage

The possible causes of abiotic damage are wide-ranging. Additional causes include solar radiation, soil mineral imbalances, road salt, pollution, fire, excess water, and various types of mechanical damage.

Additional resources

More is being learned about pest organisms and their ecological roles all the time, which in turn influences how land managers respond to the damage they may cause. Invasive pests are significantly impacting certain conifer species and the threat of new invasive pests is ever present. Climate change is also producing new impacts. Consequently, the pests and abiotic factors considered important are expected to change over time. Forest managers will, in some cases, be confronted with damage and pest conditions that differ from experience. An appropriate response to such conditions will depend on accurate diagnoses and the flexibility to adapt to changing environmental conditions.

The California Forest Pest Council offers education on forest pests through its annual meeting, field meetings, and targeted training sessions. The University of California, CAL FIRE, and USDA Forest Service also provide a variety of educational services and assistance from technical experts located throughout the state.

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Web addresses

Pitch Canker Task Force

ufei.calpoly.edu/pitch-canker-task-force

California Oak Mortality Task Force

suddenoakdeath.org

Diseases of Pacific Coast Conifers

govinfo.gov/content/pkg/GOVPUB-A-PURL-gpo29040/pdf/GOVPUB-A-PURL-gpo29040.pdf



Chapter 12

Reforestation of areas burned by large wildfires

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California forests with Mediterranean climates have a long history of frequent fires (Miller and Safford 2017), and the frequency and severity of fires are increasing across the West (Dennison et al. 2014; Stephens et al. 2018). The frequency of fires has increased across all types of land, most dramatically on federal forest lands (Starrs et al. 2018). Fires that exceed 10,000 acres are becoming more common in the West and, in particular, in the forested portion of California (Stevens et al. 2017). These megafires are the result of more than a century of fire suppression, subsequent overstocked forests, drought, insect damage, and a warming climate.

Natural regeneration after fires is usually very poor. A survey of fires on 10 national forests in California found that conifers did not regenerate on 43 percent of all plots within fire perimeters (Welch et al. 2016). Salvage logging after wildfire is a common practice on many managed forest areas, and its effects are often closely related to site-specific characteristics (Leverkus et al. 2018; McIver and Starr 2000). Forest landowners who proceed with salvage logging to recoup value and initiate reforestation face significant challenges to ensure that soil erosion is low, conifers are reforested successfully, desired habitats are maintained, and environmental outcomes are positive. Large fires pose unique challenges for those responsible for subsequent timber salvage and reforestation operations, including timely landscape-level planning that involves complex decisions about logistics and potentially limited labor resources and budgets. This chapter focuses on planning and practices that can help make the reforestation of areas burned by large wildfires a success, with a little less stress.

Planning large scale reforestation

Because the timing and location of reforestation activities are heavily dependent on salvage strategies, planning after a large wildfire requires a cooperative effort with those conducting the timber salvage operation. If postfire salvage requires multiple years or is more than several thousand acres, the reforestation effort will need to be broken up into multiple years. For example, if a fire burns 12,000 acres in August 2017 and salvage operations begin immediately, planting would likely be planned for fall 2018 or spring 2019, to allow time for salvage and site preparation treatments.

Based on landowner objectives and capabilities, replanting areas are often split into equal pieces for managing salvage, site preparation, and replanting operations. A common tactic is to split the burn area into three project sites to be completed over three years. For this scenario, reforesting 4,000 acres at 250 trees per acre would therefore require planting approximately 1 million seedlings per year, with corresponding vegetation management to ensure establishment of the seedlings. This seems to be a common threshold above which operational restrictions and logistics become increasingly more difficult.

It is crucial to complete reforestation within three years of the wildfire to leverage post-fire site preparation benefits and initiate stand development as soon as possible (see chapter 7, “Site preparation”). Delaying reforestation will result in significant future costs and may result in type conversion of the landscape out of forests (see chapter 2, “Investing in reforestation”). Although challenging, reforestation of wildfires greater than 100,000 acres can be achieved by subdividing the project area into regions and reassigning forestry staff from other departments or consultants to act as

individual reforestation teams responsible for each subregion.

The number of acres chosen as an annual reforestation goal is up to the reforestation team and its capacity to carry out the necessary steps for properly establishing the new forest. Some factors that limit success in planting large acreages include lack of a suitable seed source, budget constraints, and limited personnel. It is important to make reasonable goals based on the reforestation team's capacity and salvage schedule. Once a reforestation schedule is determined and seeds are sown in the nursery, the project planting area must be prepared the following spring.

Unitizing the site

Immediately after large fires are controlled, or even while they are still being suppressed, foresters can begin making plans to salvage the damaged timber. Once planning for postfire salvage is complete and the multiyear reforestation effort is launched, the next step is to break the wildfire area into harvest units and map them. Operational salvage units should be based on the logging method most appropriate to various terrains and slopes, as well as site access. While the urgency of beginning the salvage of fire-damaged trees drives early planning efforts, this is also the time for the reforestation team to get involved. Using harvest units as a start, the entire fire area can also be broken down into reforestation units. Complete unitization of the burn area is critical to a systematic and orderly restoration.

Multiple strategies can be used to unitize the reforestation site, based on common principles. Units should be delineated into easily manageable sizes—generally less than 100 acres—which contain similar soils, slope, and timber types. Boundaries with features such as roads, streams, or ridgelines may define the unit. In general, different harvest methods such as helicopter and tractor yarding should not be combined into a single reforestation unit. Timber salvage methods can further aid in determining unit boundaries. Identifying a single logging method for each unit will result in postharvest conditions that more easily accommodate common reforestation techniques.

Postfire satellite imagery products can help with the unitization process, as fire intensity can be variable in all fires, but especially large ones. Rapid assessment of vegetation condition (RAVG) products for fires that burn some federal land can provide information to assist with postfire vegetative management planning; they use satellite images captured before and after a wildfire to identify the changes in vegetation (Miller et al. 2009; Miller and Quayle 2015; Miller and Thode 2007). RAVG imaging is sensitive to vegetation

mortality from the wildfire, and it produces maps with estimates of basal area loss.

In wildfires involving thousands of acres, aerial imagery is invaluable to identify unburned islands, nontimbered areas, and other features not readily mapped with ground-based observation. It also can be used to identify areas that may need follow-up reforestation because of differences in the fire's severity and its impact on salvage needs. In addition, this process can identify unstable areas or those with a high potential for erosion, which may require more intensive vegetation management than more geologically stable areas. A unique identifier should be assigned to each unit for the reforestation effort and beyond. Once the unitization process is complete, the planning phase of the operation can begin.

Scheduling planting activities

The timing of planting depends on the progression of the timber salvage operations and subsequent site preparation activities. The best candidates for replanting are units where timber salvage is complete, because the ground-disturbing harvest activities following salvage scarify the soil, preparing it for planting and often improving site drainage. Slash left on the ground after harvest such as limbs, treetops, and submerchantable trees further stabilizes the soil.

Areas where replanting should be delayed to allow time for revegetation include those with hydrophobic soils that are prone to erosion; that consist primarily of brush, small trees, or young plantations; or which don't have merchantable timber. These areas should be considered for mechanical tilling or subsoiling, since no harvest activities will help mitigate hydrophobic conditions such as increased water repellency, decreased infiltration, and increased surface runoff. When prioritizing units for planting, the ability to apply preplant herbicides should also be considered in plans for mechanical site preparation. If landing piles are disposed of by chipping or burning, it is important to complete these activities prior to planting to avoid damage to seedlings around the landings.

Large projects will require additional labor sources. It is a good idea to become familiar with larger forest labor contractors in the region who have the expertise and personnel to tackle planting large numbers of trees and hand-spraying potentially large acreages. It is also important to include helicopter contractors in this phase of the reforestation planning so that they can plan ahead for the additional workload.

Sourcing seed

Landowners with large projects may face challenges in securing enough seed for reforestation. Outside of seed that they already own and store, the best starting point for private landowners to find suitable seed is to consult with the California Department of Forestry and Fire (CAL FIRE) forester in the area nearest the burn. CAL FIRE's Lewis A. Moran Reforestation Center in Davis, California, maintains the state seed bank, which is available to the public in times of need. The potential to get seed is limited by the seed bank's inventory of seed that is appropriate for the zone, elevation, and species of the reforestation project.

Another possibility for securing seed is to consult with larger landowners in the burn area. Most large timberland owners maintain seed banks to cover their reforestation needs after fires, and they may have surplus to sell. Private seed companies such as Silvaseed Company and Pacific Forest Seeds may have stores of seed for sale and in some cases seedlings grown for the area. Federal land managers also maintain a seed bank in Placerville, California, which may have seed available.

Reforestation professionals should resist the temptation to use readily available but inappropriate seed and should adhere to existing standards for seed that is acceptable for the zone and elevation of local burn areas. If no seed is immediately available, or to prepare for the future, trees within the burned area that are damaged but survived frequently have a "stress crop" of cones that will yield seed for reforestation projects. In many cases the stress crops will not produce adequate quantities of viable seed for the entire reforestation; it is therefore important to verify that the developing cone crop contains enough viable seed of sufficient quality to make its collection worthwhile.

Additionally, reconnaissance of unburned forest stands in the vicinity may yield seed collection opportunities. Contractors are available who specialize in collecting conifer cones. Consult with an area State Forester, Cooperative Extension Forester, or local Registered Professional Forester for information about climbing contractors who collect cones. Another option is to choose seed from similar ecotypes that is available in the adjacent seed zone, within breeding zones (see chapter 5, "Seeds," for more information).

Mechanical site preparation

If mechanical site preparation is an option in the burned area, make arrangements well in advance of the planned reforestation project. This is true not only to ensure contractor availability, but also to take advantage of opportunities to increase infiltration rates and

disturb potentially hydrophobic soil conditions after the fire. This is especially important in the first year following the fire and prior to the first heavy rains. Hydrophobic soils are common in burned areas, particularly where the fire's intensity was extreme. Coarse-textured soils are particularly prone to developing a hydrophobic layer.

Piling or windrowing residual slash for subsequent burning helps to reduce fuel loads and facilitate planting. The potential fire risk to the plantation from fuels remaining after the fire salvage must be carefully balanced with the benefits of having slash on the ground to mitigate soil erosion. Recent experience has demonstrated that seedlings can be planted successfully through slash without significant survival or growth issues.

Other mechanical site preparation methods such as subsoiling, ripping, and tilling can have beneficial effects on the establishment of new forests after fire. Subsoiling, which breaks down slash by crushing and incorporating a portion into the soil, was initially promoted as a mitigation measure for soils compacted in forest regeneration projects, but it also increases the area available for planting by exposing bare soil obscured by logging debris.

Due to microbial activity, slash that comes in contact with soil breaks down much more rapidly than debris that does not contact soil. While allowing slash to decompose hastens the nutrient cycling process, it also results in increased fire hazard until it decomposes. Well-planned and executed contour subsoiling can mitigate hydrophobic conditions on some California sites by increasing the infiltration rate prior to the onset of winter rains and breaking up potential channels that could lead to excessive erosion caused by runoff (James and Krumland 2018). Subsoiling can also improve the efficacy of soil-active herbicides that must be applied to bare ground. For example, the herbicides hexazinone and oxyfluorfen are generally more effective when bare soil is exposed, because they can get tied up in organic material if high levels of slash obscure the soil layer and reduce the application's effectiveness on target soils.

Vegetation management

Regeneration foresters and Pest Control Advisors must anticipate the rapid regrowth of vegetation that occurs after a fire. Burned areas can revegetate rapidly, because fire both scarifies the seeds of serotinous weeds and releases a flush of nitrogen that spurs new plant growth. Taking advantage of a largely intact root system, some brush species and most hardwood trees will resprout in the first year after a fire and grow rapidly,

and herbaceous weeds and brush seedlings will germinate the following spring.

These two types of competing vegetation (herbaceous weeds and brush seedlings) may need to be treated differently and at different times to be successful. Resprouting brush and hardwood plants may not have enough leaf area reestablished for successful treatment with foliar-active herbicides until after a full growing season has passed. With a burn in August 2023, for example, brush and hardwoods would not be ready for foliar treatment until after the 2024 growing season. In some instances, and if using a helicopter to apply herbicides, it may take even more time for the leaf area to grow enough to be treatable with foliar-active herbicides such as imazapyr and glyphosate. On the other hand, in the case of an early-season fire, brush species and resprouting hardwoods may develop enough leaf area to be successfully treated in the same season as the burn.

In general, brush and hardwood species that are easily controlled with foliar-applied herbicides should be treated as soon after the burn as possible, because directed treatments on small, early-stage resprouts require less herbicide and are less expensive than treating larger sprouts. Hand treatment is preferable in this situation because helicopter applications may not provide adequate foliar coverage to control small sprouts.

Brush and herbaceous species that compete with seedlings can be treated in the first growing season after the burn with applications of soil-active herbicides or hand-directed sprays. Some soil-active herbicides such as hexazinone will control resprouting brush and hardwoods to some extent, but generally don't provide enough control for a one-time treatment, especially where there are a lot of hardwoods and resprouts. In most cases, conifer release spray applications will be needed by the third year after replanting. Effective control with herbicide site preparation sprays helps minimize the need for follow-up applications. In remote areas, inadequate road access can prevent ground-based herbicide applications; in these areas, applying herbicides by air or controlling weeds by hand are the only options.

(See chapter 8 for detailed information on the principles of vegetation management.)

Seedling delivery from nursery to roadside

The sheer number of seedlings needed for reforestation after a large wildfire presents many challenges for the reforestation team, including transporting large numbers of seedlings from nurseries to local cold storage facilities, and then to planting sites. Reducing the total

number of seedling pallets that must be transported and stored can improve efficiency, either by reducing the number of trees per acre planted, planting the smallest suitable seedlings, or both.

Reducing the number of trees per acre has a dramatic effect on the total number of trees planted. For example, a 3,000-acre burn planted at 12-by-12-foot spacing (302 trees per acre) requires 906,000 trees. That same area planted at 18-by-18-foot spacing (134 trees per acre) requires 402,000 trees. In addition to reducing the number of pallets that need to be transported and stored, planting fewer trees per acre also significantly reduces other complications and costs encountered in large-acreage reforestation projects, including the amount of seed and nursery growing space needed and the number of planting crews deployed during the short planting-season window.

Planting fewer trees per acre may also reduce the need for precommercial thinning 7 to 10 years after planting, thereby moderating its scope and cost and reducing slash loading across thousands of acres. However, it may not be advisable to plant on very wide spacing with more difficult-to-establish species such as white fir or harsh sites as stocking levels will be quite low if mortality is high.

Because reforestation with ponderosa and Jeffrey pine typically results in very high survival rates when all of the proper reforestation steps are followed, a good option to consider is wider planting spacing of 134 trees per acre (18-by-18 foot spacing) if the desired forest spacing is about 100 trees per acre with ponderosa and/or Jeffrey pine. In areas where the dominant species is Douglas-fir or true fir, higher planting densities are usually necessary to achieve the desired stocking densities.

When the USDA Forest Service wanted lower tree densities (often based on land allocation) on their land, the agency used a cluster, or diamond, planting scheme with wide spacing, in which multiples of trees were planted at each site. For example, planting three seedlings close together in a cluster with 27-foot spacing between groups requires planting only about 180 trees per acre. If the goal is for at least one tree to survive in each group, the stand will soon have spacing similar to the historical spacing of a mature forest. This approach addresses the possibility of mortality and allows multiple species to be planted at each site. It also can reduce the cost of manual release (grubbing a circle around each seedling) in rehabilitating burned sites where herbicide use is restricted as the number of manual release circles per acre is reduced.

Using the smallest suitable size of seedlings can also reduce the number of pallets needed for transport and

TABLE 12.1. Tree seedlings transported per semitrailer load at a California nursery*

Cell size	Trees/box	Boxes/pallet	Trees/pallet	Pallets/semi [†]	Trees/semi
St-4	400	18	7,200	48	345,600
St-5	320	18	5,760	48	276,400
St-6	270	18	4,860	48	233,280
St-8	240	18	4,320	48	207,360

*Cal Forest Nurseries, Etna, CA.

[†]53-foot refrigerated semitrailer.

storage. Small, containerized seedlings or 1-0 bare root are packed at higher numbers per package and require less storage space than similar numbers of larger seedlings. Cell sizes should be at least styro-4 for ponderosa and Jeffrey pine, and no smaller than styro-6 for Douglas-fir, red fir, white fir, incense cedar, and sugar pine (see chapter 6, “Seedlings,” for more information). Table 12.1 shows how many trees per load that a 53-foot, refrigerated semitrailer can haul and the influence of stock type on that number for a commonly used nursery in California.

Refrigerated vans

If space or facilities are not available to store seedlings at the nursery for a project, refrigerated vans can be used to transport seedlings from the nursery to a commercial-size cold storage facility designed and equipped to properly store seedlings and easily handle pallets of seedling boxes.

Refrigerated vans can also store seedlings for short periods of time in order to supply the daily production needs of one or more planting crews when the nursery or cold storage facility is not within a reasonable distance of the project area. Using the smallest stock type appropriate for planting can reduce the number of refrigerated vans that need to be rented and maintained for the duration of planting operations.

Refrigerated vans used for cold storage must be monitored daily to make sure that the refrigeration unit is operating properly as well as inspected to ensure that the correct temperature is maintained; oil and fuel levels (if the refrigeration unit is fuel-powered and not electric) are adequate; and fans, refrigerator coils, and other critical components are operational. It is also important to line up and have on call a mechanic experienced with repairing the refrigerated vans. Daily monitoring of refrigerated vans and ready access to an experienced repair person are critical so that if (or more likely, when) a unit malfunctions it can be repaired within 24 hours.

On large projects where refrigerated vans are used for temporary cold storage to supply daily planting needs, the forester overseeing the project should plan and coordinate with the nursery and monitor the

production and progress of each planting crew supervisor daily, so that each crew has a ready supply of the specific seedling stock types, seed lots, and species that will be planted each day.

Case study of van use. In our example of a 12,000-acre burned-area planting project, a private forest manager planted 4,000 to 6,000 acres per year over a 3-year period, using an average of four 12-to-14-person planting crews and renting three refrigerated vans. One tractor-trailer driver was hired to rotate the refrigerated vans loaded with seedlings from the nursery to a secure location within a relatively short distance of the project area. Two vans were loaded at the nursery with the specific seedling lots needed for the first week of planting and transported to a central, temporary storage location prior to the start of planting.

Every morning each of the four crews loaded the number and lots of seedlings from the van used for each day's planting. The reforestation project manager coordinated with the nursery manager, tractor-trailer driver, and planting inspectors assigned to each crew so that a third van was scheduled for the loading and delivery of seedlings from the nursery to the temporary storage location, and an empty van could be picked up by the tractor-trailer driver. This coordination and scheduling was done to rotate vans such that each planting crew could readily load a sufficient number of seedlings each day for each species, seed lot, and stock type scheduled for planting into each particular area.

By communicating with the planting inspector for each crew daily, the project manager could instruct the nursery to load the vans in a specific order with specific pallets of seedling lots at specific locations within the van. This allowed for seedling boxes to be unloaded just once on the morning of planting and not unloaded and reloaded with the crews rummaging around in the vans looking for the seedling lots (based on species, stock type, and elevation) scheduled for planting each day.

When ordering, the project manager instructed the nursery to load the seedlings that were going to be planted last to be loaded first toward the front of the van so that seedlings scheduled to be planted

first would be at the back of the van and closer to the doors. It is advisable to map pallet locations by seed lot and species within the van when ordering and/or loading to facilitate and improve the efficiency of seedling handling and planting.

Freezing seedlings

Freezing conifer seedlings for long-term storage helps to arrest mold development and is preferable when storing seedlings longer than 3 months. When freezer storage is used, it is important to have an area available to thaw the seedlings prior to the anticipated planting date. If the storage facility is located in an area where ambient air temperatures are very low, thawing may be impossible. In that case, it is advisable to place the refrigerated van at a lower, warmer elevation to facilitate thawing.

Thawing times can vary widely and are dependent on the packaging, stock type, moisture content of the containerized seedling, airflow around containers, and ambient air temperature. Opinions and experience vary about the best way to thaw seedlings for optimal survival. Several researchers reported that while stock is frozen or thawed the air temperature should not be more than 3.6° above or below freezing; this is considered a slow thaw, which can require up to a month or longer for the seedlings to be ready for planting. Many other practitioners report that a quick thaw at ambient temperatures of 50° to 65°F provides satisfactory results and is much more predictable, with thaw durations of a week or less.

Boxes on pallets should be slightly separated during thawing to allow airflow around individual boxes, which helps thaw the boxes more evenly. Spacers can be placed between boxes in the nursery during packing if the plan is to freeze the seedlings at the time of packing; this also facilitates a more rapid freeze. Thawed trees should be planted as soon as possible after thawing.

Seedling delivery from roadside to field and planting

In burns with limited access, the reforestation team may be faced with getting seedlings to planting crews far away from roads. Using wide spacing and smaller nursery stock can help but delivering seedlings to the planting site will still require extra effort. In very steep terrain, tree yarders can facilitate seedling delivery. Tree-logging yarders can deliver boxes of seedlings to sites as far away as 2,000 yards by suspending the boxes from cables, as long as obstacles such as standing timber or rock outcroppings that can deflect the boxes are not numerous. Planting crews can then either bag up seedlings along the tree yarder corridors



Figure 12.1. A utility task vehicle delivers seedlings to a planting crew using a skid trail.

or crew members can be employed as packers to deliver seedlings to more remote portions of the unit that are inaccessible to the yarder. In difficult terrain a combination of yarding and packers can extend the plantable area significantly.

In areas that are less remote, all-terrain vehicles and larger utility task vehicles are good for getting seedlings to planting crews when roads are impassable by pickup truck due to wet weather or snow (fig. 12.1). All-terrain vehicles can also carry seedlings to planting areas that are not accessible by road using skid trails and open ridgelines. Equipment already in the area for salvage operations can be used to open trails or make trails on ridgelines to provide planting access. Working closely with the foresters managing salvage operations can help to ensure the best possible access for planting.

Extreme circumstances, such as in wilderness or roadless areas that were salvaged by helicopter, may be encountered when mechanical access is not possible due to the lack of road access or difficult terrain.



Figure 12.2. A worker packs in trees following the 2008 Moon Fire west of Redding, California.

Delivering seedlings by helicopter may be a possibility, but it is expensive. Another option is to arrange for a big enough planting crew that personnel can transport boxes of seedlings long distances from the nearest road to the planting site (fig. 12.2). Using packers as planters can double the cost of planting, but when there are no other options it is likely the best way to reforest inaccessible terrain. Using a combination of these options can significantly extend the plantable areas of a large wildfire. Finally, in roadless areas where large planting efforts are unfeasible, the Forest Service has started planting “founder stands,” where a small portion of the high-severity burn area is planted as an island, with the hope of establishing a source for natural seeding in the future.

Managing sediment transport within wildfire units

Large wildfires often result in additional sediment discharge into waterways. Stream flows increase sharply after a high-intensity fire because vegetation that normally intercepts precipitation and protects the soil has been burned and more water flows into channels as a result. Springs and wet areas may appear that were not evident before the fire, which also transport sediment. After a wildfire many soils become hydrophobic, repelling water and causing more surface water to flow during the first heavy rains after the burn.

It is important to take action to reduce any additional transport of sediment due to logging and reforestation activities, following state and regional rules. Salvage logging operations can help break up the continuity of hydrophobic soil conditions through scarification, similar to the effect of mechanical site preparation such as tilling. Increased infiltration rates associated with these activities can reduce the rate of sediment transport (James and Krumland 2018). Logging also commonly results in the deposition of a layer of slash that helps stabilize the movement of soil. Planning for land alterations along contours can also prevent sediment delivery into streams.

When applying herbicides, immediately broadcasting them onto hydrophobic soils or soils that are undisturbed by salvage operations is inadvisable after a fire, as off-site movement is possible in the absence of effective infiltration. An alternative is to apply herbicides by hand at low rates per acre directly on the small, emerging foliage of resprouting brush species, which is more susceptible to the herbicides. Applying herbicides on a limited, site-specific basis significantly reduces the chances of off-site movement.

Burns should be evaluated for additional mitigation measures to address the risk of increased erosion

and sediment discharge. A Pest Control Advisor or Registered Professional Forester should evaluate the choice of herbicide to address the potential for creating bare ground on soils prone to erosion. To retain additional vegetative cover, use foliar-contact rather than soil-active herbicides, and species-specific rather than broad-spectrum herbicides, which can reduce potential for sediment transfer.

Burn areas may be revegetated for a period of time to stabilize the soil and minimize movement; it is also critical to leave dead vegetation on-site to provide extra erosion protection. Follow-up tilling can be beneficial but avoid allowing mechanical equipment to clear bare soil. Leaving vegetated buffer strips along stream courses and areas with slides or gullies can also help stabilize burned areas to prevent additional erosion (fig. 12.3). However, the presence of competing vegetation can affect the survival of tree seedlings and their future growth. Any intentional retention of competing vegetation or delays in treatment can significantly increase costs, threaten plantation success, and unintentionally result in an unforested landscape.

Another strategy is to immediately plant seedlings that were grown for another project (which can be delayed until another year) and are suitable for the burned area in the buffers required when herbicides are used. This allows newly designated stream buffer units to be planted in the fall or spring after the fire, when competing vegetation has not yet established roots, helping to facilitate the survival of first-year conifer seedlings. Competing vegetation may require



Figure 12.3. Unsprayed vegetative strip on the edge of an eroded feature.

Photo: Mark Gray, Sierra Pacific Industries.

treatment with a directed foliar herbicide that is not mobile in soil within 4 or 5 feet of widely spaced conifer seedlings. If done properly this treatment can provide sufficient vegetative cover for the buffer zone while allowing for the successful reestablishment of a conifer overstory.

Conclusion

When carefully analyzed, planned, funded, and executed, the reforestation of large burns can successfully regenerate fire-damaged landscapes. When conducted in a timely manner and with a well-coordinated series of treatments, it can help alleviate the long-term effects of wildfire on the affected watershed, restore the previous forest more quickly than if left alone, and minimize the total costs and amount of herbicides necessary for success.

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