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Adapting Integrated Pest Management for Weeds in California Orchards

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Adapting Integrated Pest Management for Weeds in California Orchards

By

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Abstract

Integrated pest management is a framework for helping farmers use knowledge of weed biology and agroecology to create pest management programs that are less reliant on pesticides. It is imperative that weed scientists engage with other pest management and agricultural scientists to create integrated management solutions that are specifically attuned to each cropping system context. Chapter 1 expounds on these arguments. In this vein, this dissertation examines integrated pest management as it can be applied to weed biology and weed management ecology in nut orchard cropping systems in Central California. Chapter 2 focuses on the reproductive biology of field bindweed (*Convolvulus arvensis* L.), a perennial weed species that is pernicious in California cropping systems, especially young orchards. We evaluated time to flowering and biomass in field and potted plant experiments in response to orchard weed management practices that selectively affect aboveground and belowground field bindweed development. We found that management practices that affect field bindweed roots, such as systemic herbicides, can delay flowering reliably by over a week, which can have practical implications for planning repeated weed management actions. Chapters 3 and 4 focus on a series of experiments implementing weed-suppressing cover crops in orchards. We found that multifunctional cover crop mixes emerge more consistently than mixes containing functionally-similar species, and we also found that weed-suppressing cover crops can be successfully managed at a range of management intensities, especially with a timely cover crop planting. Weed scientists have a continued responsibility to develop integrated management programs that advance agroecological sustainability, and these results could increase the efficiency of field bindweed management and boost adoption of multispecies cover crops in orchards.

Contents

A progressive approach for integrated pest management

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Abstract. Integrated pest management (IPM) and integrated weed management (IWM) are one in the same. Weed scientists do a lot of research that is useful for IPM, but a false dichotomy between IPM and IWM impedes progress. The original goals of IPM (i.e. pesticide reduction and expanding agroecological knowledge) can help weed scientists realize progress towards a more resilient agriculture.

Key words. Integrated weed management; IPM; IWM; weed ecology; agroecology

My view. Weed scientists have been trying to situate weed management within the framework of integrated pest management (IPM) for decades (McWhorter and Shaw 1982).

Cover crops have recently been discussed in this space for their potential to unify efforts towards integrated weed management (IWM) research (Young 2020). In actuality, this apparent resurgence of cover crop research reminds us how IWM has merely coexisted with IPM. Cover crops can indeed support continued development of sustainable weed management, but true integration requires more than coexistence. Weed scientists must think beyond single management practices, whether they be herbicides, cover crops, or any new invention, in order to work towards IPM. By unifying behind the original goals of IPM, namely pesticide reduction and incorporation of ecological knowledge into agriculture, weed scientists can create progress for our discipline.

Entomologists first started writing explicitly about "integrated control" in the middle of the 20th Century, calling for consideration of the detrimental effects of broad-spectrum insecticides on biological controls (i.e. natural enemies or beneficial predatory insects) (DeBach 1951). Synthetic pesticides like DDT and 2,4-D were becoming more popular in agriculture following their post-War commercialization and through the advent of the Green Revolution. IPM was necessarily a reaction to a sudden reliance on chemical insect control, and IPM practitioners recognized the complementarity of using biological and chemical controls together (Stern et al. 1959). Concerned entomologists recognized that pesticides could be a useful tool for regulating highly-disturbed agroecosystems, but also that pesticides are inherently disruptive to the ecological systems on which agriculture is built (Smith and Hagen 1959). For intensified cropping systems increasingly dependent on synthetic inputs, IPM was constructed to reduce dependence on pesticides, though not eliminate them entirely.

Other pest management disciplines became included in IPM while it grew in importance. Interest in IPM expanded alongside the Environmental Movement, as ecology and sustainability became increasingly popular in the middle of the 20th Century (Gay 2012). By the early 1970s, a US government report embraced the potential for IPM, including cultural, mechanical, and biological control, to reduce pesticide risk when used against a wide variety of pests, including weeds (Council on Environmental Quality 1972). Around the same time, the National Science Foundation funded the Huffaker Project, which represented a major step towards broadening the scope of IPM, including making it even more integrative of systems-level ecology and interdisciplinary decision-making (Perkins 1982). Furthermore, the namesake of the Huffaker Project, Carl Burton Huffaker, spent parts of his career working on biological control of weeds, such as his research on St. Johnswort (*Hypericum perforatum* L.) in Northern California (Perkins 1982). Today, scientific regulators in the US and Europe continue to include weeds within the definition of IPM (*A national road*… 2018; Barzman et al. 2015).

This historical context illustrates two foundational aspects about IPM that remain important: weed science is definitely included as a part of IPM, and weed scientists have the responsibility to develop weed management programs that are not focused on herbicides. A false distinction between weeds and pests inhibits progress towards the goal of reducing pesticide dependency. For example, entomologists have realized the challenge of the "other IPM," that is integrated pesticide management, resistance management, and pesticide substitution masquerading together as IPM (Ehler 2006). Weed scientists have been facing the same issues for decades, but the lack of a common IPM framework and language has caused us to continue to adhere to the other IPM while entomologists have found relative success. While many weed scientists do understand the underlying inclusion of weeds in IPM, a preponderance of weed science literature refers to IWM. Weed scientists' self-imposed separation of IWM and IPM is harmful to the interdisciplinary cooperation that is critical for the ecological, agronomic, and practical development of IPM.

Weed scientists have further entrenched IWM by refining IPM to apply only to weeds. Frameworks detailing levels of integrated management based on space, time, and practice have been created for IWM (Cardina et al. 1999, Swanton and Weise 1991). Useful though these frameworks may be, they are basically translations, rather than extensions, of existing IPM frameworks. Herbicides continue to represent the logical basis of IWM, even though contemporary IPM models focus more on biologically-intensive management of all kinds of pests (Kogan 1998). The diversified management practices called for in IWM are typically in addition to conventional herbicide programs, making IWM fall behind IPM in terms of pesticide reduction.

There are of course strong reasons for using different practices to manage weeds compared to other types of pests, but these reasons do not preclude weed scientists from using the same ecological approaches and systems thinking required by IPM. In fact, the differences between weeds and pests at higher trophic levels can actually cause the interactions that necessitate concurrent management of all pests (Norris 2005). Certain specific practices do not apply to weeds and other pests in the same way, but IPM gives us the ecological knowledge to understand why one pest management practice can lead to divergent results. Weed scientists do not need to throw out all of IPM just because weed populations sometimes become unmanageable when using economic action thresholds, for example; we can use IPM to choose a relevant practice based on ecological awareness, such as awareness of weeds' higher fecundity and longer generation time compared to other pests.

I agree with a recent paper arguing that cover crops are aligning current trends in weed science with IPM (Young 2020). No fewer than a dozen studies focusing on cover crops have been published in *Weed Science* since 2018, as indexed by Web of Science. This line of research has a long history, however, with studies of weed-suppressing cover crops in the literature for decades (Barnes and Putnam 1983; Teasdale et al. 1991). Cover crops give weed scientists the opportunity to do whole-ecosystem research on a cultural practice that shifts weed management from an exercise in control to a more-delicate balancing act. When weed-suppressing cover crops can potentially provide rodent habitat, vector fungal diseases, and host insect pests, the necessity of a broader IPM approach becomes clear. Agroecosystem-level thinking is further underscored by the many relationships cover crops have with soil health, water and irrigation, agronomic or horticultural logistics, and other factors across the agroecosystem.

Despite the merits of cover crops, it is important to recognize that cover crops in themselves cannot unlock IPM. Replacing herbicides with cover crops as the main tool for weed management would not bring about a new era of IPM; it would serve to reinforce the existing dichotomous frameworks (i.e. deciding whether management programs are more- or less-integrated) that underpin IWM. Weed scientists can realize new progress towards IPM by recommitting not to individual management practices, but to the biology and ecology that has always been central to our discipline. This basic understanding is essential for using IPM to understand how a variety of weed management practices will affect a particular cropping system. Yes, new management practices like cover crops use ecological design that contributes to IPM, but IPM must be more than the arbitrary stacking of new pest management practices (Ehler and Bottrell 2000). IPM requires us to judiciously integrate multiple management practices with one another using biological and ecological principles.

Scientific reductionism and the nature of applied research can slow progress towards integrative discovery, but weed scientists have many opportunities for new and specific lines of study that build IPM. A dearth of information about genetics, population biology, soil seed banks, and ecological interactions for many weed species represents a virtually limitless opportunity for basic research that can serve IPM. Likewise, new and renewed management practices, such as harvest weed seed control, robotic cultivators, or thermal weeders, can be researched as input substitutions to meet pesticide reduction goals. Various IPM frameworks also call for research dealing with weed prevention, biopesticides, precision agriculture, and weed monitoring.

Biological weed management is an original tenet of IPM that also demands renewed interest from weed scientists. As demonstrated by cover crops, consideration of cultural practices and the whole cropping system is an important feature of weed science research that can only flourish under IPM. Cover crops and other forms of biologically-intensive management certainly add more complexity to agricultural management compared to the practices listed in the previous paragraph. This type of complexity, however, is exactly the kind of challenge IPM allows us to embrace. By understanding site-specific ecological factors that make biological pest management possible, weed scientists can move towards the biological integration that is fundamental to IPM.

Beyond new management research, IPM is most exciting in how it supports a reimagining of what weed science represents as a discipline. Despite its organization alongside the development of synthetic herbicides, weed science has never only been about killing plants. Weed science is meant to protect agriculture and other managed ecosystems, but much of the discipline eschews environmental protection in favor of exerting power over plants. IPM offers a framework for us to focus less on controlling weeds and more on understanding them. Pesticide reduction is now more important than ever, considering herbicide resistant weeds, climate change, agricultural extensification, and other factors. But weed management with fewer herbicides requires more insights into how weeds move, change, and interact within their environment. IPM allows weed scientists to make progress towards a future with both fewer weed problems and stronger agroecosystems.

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Ecological management and reproductive biology of field bindweed (*Convolvulus arvensis*) in California orchards

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Abstract. Field bindweed (*Convolvulus arvensis* L.) is a perennial weed that causes problems, including irrigation losses and harvest obstructions, in California orchard systems. Field bindweed has a relatively complex life history among agricultural weeds, creating both persistent bud and seed banks. More understanding of this species' reproductive biology could support development of better integrated management programs for perennial weeds in perennial crops. We created field and potted plant experiments to evaluate the impact of different orchard weed management practices on field bindweed. In the field experiment, we used contact and systemic herbicides as well as mechanical disturbance at several depths. In the potted plant experiment, we compared field bindweed from agricultural and non-agricultural source populations and subjected them to clipping and simulated tillage. Field bindweed flowering was delayed following weed management, particularly management practices like systemic herbicides and tillage that affect belowground tissues. However, weed management did not affect field bindweed biomass or root:shoot biomass ratios after 10 weeks, and effects on reproductive resource allocation remain unclear. We found evidence in the potted plant experiment that field bindweed collected from an annual crop field had slightly higher root:shoot ratios than populations from orchards or non-crop areas. These results underscore the value of using intensive management practices including systemic herbicides to delay field bindweed reproduction but further reinforce the importance of understanding field bindweed phenology when using repeated management. These results also support the possibility of local adaptation, which highlights the need for long term planning and understanding of reproductive selection when developing integrated management programs for field bindweed.

Key words: integrated pest management, perennial cropping systems, local adaptation, phenotypic plasticity

Introduction. Field bindweed (*Convolvulus arvensis* L.) is a perennial weed that can persist in many cultivated and unmanaged landscapes (Boldt et al. 1998). In California, field bindweed survives in both irrigated and dryland environments, and it grows through much of the year in annual and perennial cropping systems as well as non-crop areas like roadsides (Rosenthal 1983). This species causes yield loss, reduces water use efficiency, disrupts irrigation infrastructure, impedes crop harvest, and creates multiple flushes of growth each growing season (Sosnoskie et al. 2020). These factors contribute to ongoing problems in California orchard systems. Field bindweed has a reproductive biology that includes sexual reproduction with large flowers and hard-coated seeds as well as asexual reproduction with an extensive root system, and this biology has helped it thwart many common weed management programs across California orchard systems (Davison 1976, Jayasuriya et al. 2008, Torrey 1958).

Because it is difficult to control, orchard weed managers often use several weed management operations against field bindweed each year, especially repeated application of systemic herbicides like glyphosate in mature orchards (Wright et al. 2011). Repeated applications of contact herbicides like glufosinate, paraquat, or PPO inhibitors are also common in young orchards where crop safety is a larger concern when using systemic herbicides. In fact, repeated herbicide applications are common in a variety of cropping systems (Sosnoskie and Hanson 2016, Stone et al. 2005, Wiese and Rea 1959). Systemic herbicides offer the apparent benefit of translocation to the extensive root system of field bindweed (Westwood et al. 1997b, Wiese and Lavake 1986). However, translocation of some herbicides to field bindweed roots can be limited, and repeated herbicide applications have the potential to select for herbicide resistance (Duncan and Weller 1987, Enloe et al. 1999, Sherrick et al. 1986a, Whitworth and Muzik 1967). Furthermore, field bindweed frequently demonstrates capacity for regrowth following systemic herbicide applications, even when factors such as application timing, herbicide mixtures, or spray adjuvants are optimized (Sherrick et al. 1986b, Westra et al. 1992, Yerkes and Weller 1996). Mechanical management practices that disturb the soil and underground tissues could likewise be more efficacious against field bindweed relative to mechanical practices that only affect aboveground tissues (Buhler et al. 1994, Orloff et al. 2018). These practices, however, frequently allow regrowth from root cuttings, adventitious roots, or perennial buds (Sherwood 1945, Swan and R. J. Chancellor 1976).

The light environment in young orchards compared to shady, mature orchards is more conducive to field bindweed (Bakke and Gaessler 1945, Stahler 1948). However, many young orchard trees are susceptible to injury from the systemic herbicides and intensive mechanical management practices that are commonly used against field bindweed (Shrestha et al. 2012). The compounded challenges of managing field bindweed in young orchards necessitate deeper understanding of how this species persists and can be managed in unique orchard environments. This knowledge could then inform more sustainable integrated pest management strategies with greater efficacy while reducing reliance on glyphosate and other systemic herbicides and increasing the number of management practices that are known to be safe for young trees (Haring 2021).

Integrated pest management relies, in part, on information about pest life cycles and phenology and how they relate to cropping system context. The development of integrated management programs for field bindweed necessitates greater understanding of this species' population ecology, particularly within the context of current cropping system practices and limitations (Davis et al. 2018). Current management programs react to the presence of field bindweed vegetation, but integrated management programs could better account for the specific ways that this species reproduces and create site-specific management that targets the most susceptible life cycle stages (Jurado-Expósito et al. 2005, Timmons and Bruns 1951). Recent advances in soil seed bank management highlight the importance of understanding all kinds of plant propagules and how these propagules differentially contribute to weed populations (Haring and Flessner 2018). Given its relatively complex life history, field bindweed could be a useful study system for understanding perennial weed reproduction and its importance to integrated pest management.

This species reproduces with both sexual and asexual propagules, creating a persistent seed bank as well as perennial roots and buds (Degennaro and Weller 1984, Swan and R. J. Chancellor 1976). Perfect, self-incompatible flowers bear hard, dormant seeds that maintain genetic diversity within the soil seed bank (Mitich 1991, Westwood et al. 1997a, Xiong et al. 2018). Significant resources are also allocated towards prolific root systems, and individual plants can create underground systems that are several meters in diameter (Barr 1940, Frazier 1943). The morphology and biomass of these root systems are influenced by light, cultivation, and other cropping system cultural factors (Bakke et al. 1944, Bakke and Gaessler 1945). However, field bindweed exhibits varying degrees of phenotypic plasticity despite its morphological diversity (Degennaro and Weller 1984, Gianoli 2001, 2004). Integrated management programs could be strengthened by improved knowledge of how this diversity contributes to field bindweed survival in the face of varied management. Despite the importance of reproductive allocation and diversity, direct quantification of field bindweed reproduction remains challenging due to the inaccessibility of root structures and dehiscence of mature seeds (Pierret et al. 2016).

There is a need for research that addresses these challenges to help us answer questions about field bindweed reproduction in ways that contribute to commercially-relevant management. We are particularly interested in how weed management practices in orchards differentially affect aboveground and belowground tissues in order to better understand how each contributes to field bindweed persistence in orchard cropping systems (Iwasa and Roughgarden 1984, Mokany et al. 2006). Additionally, we focus on time to first flowering as a practically important reproductive trait, because it can help determine when to schedule sequential weed management treatments and how species adapt to changing environmental conditions (Ashworth et al. 2016, Fitter and Fitter 2002, Mason et al. 2017). California orchards are unique cropping systems that require dedicated development of integrated management programs, especially given the distinctive biology of field bindweed and the specific challenges of weed management in young orchards.

Our overall aim is to use information about the reproductive biology of field bindweed to support improved ecological management of this species with practices that are feasible in California orchards. The experiments described in this study evaluated field bindweed flowering and biomass production using field and potted plant experiments. Our approach was to determine how a variety of common and prospective weed management practices in young orchards affect field bindweed reproductive resource allocation. In the field experiment, we tested various chemical and mechanical weed management practices to identify effects on field bindweed flowering timing and aboveground biomass production at timings relevant for commercial orchard production. In the potted plant experiment, we evaluated different mechanical disturbance treatments on field bindweed collected from different source populations to describe responses in flowering timing or root:shoot biomass ratios. Together, these experiments were designed to provide insight into how the distinctive reproductive morphology of field bindweed behaves and responds to orchard weed management programs.

Material and Methods. A field plot experiment was designed to evaluate how *in situ* field bindweed alters its reproductive response to various commercial management practices. A potted plant experiment was designed to create a common environment for testing field bindweed from a variety of source environments, as well as to provide opportunity for detailed assessment of root biomass. Together, these complementary experiments allowed us to use a broader array of methods for observing the reproductive response of field bindweed to management.

Field experiment. The field experiment was a small plot study arranged in a randomized complete block design with four repetitions in each replicate. Various management programs were applied to 4.6 by 6.1 m rectangular plots in fallow fields with endemic field bindweed infestations. The whole experiment was replicated three times in time, each with a different experimental timing that coincides with different management periods for California orchard growers. Each of the replicates took place in separate fallow fields at the Plant Sciences Field Facility at UC Davis in Davis, CA (38.539336, -121.782482). These fields consist of Yolo silt loam (Mollic Xerofluvents) and had a history of orchards, agronomic crops, and field bindweed infestation before being fallowed. Field bindweed grows nearly year-round in central California, with a period of senescence in the winter months only; these replicate timings were chosen to mimic some of the primary periods where agricultural weed management practices already occur within that window. The first replicate was performed in the fall of 2020, to coincide with postharvest weed management timing in nut orchards (Roncoroni et al. 2017). The second replicate was performed in early summer 2021, coincidental with weed management that targets summer weed emergence in orchards, especially in young orchards where there may be a greater need to manage small weeds and prevent weed establishment given a relative lack of registered herbicide options. Finally, the third replicate was performed in the mid-summer of 2021, at the timing of preharvest weed management in orchards.

Management programs tested in this experiment involved sequential management steps, as is often necessary for growers dealing with field bindweed. Each of the treatments received discing and cultipacking as the first management step in order to eliminate emerged bindweed vegetation, as well as to create a uniform soil surface for treatment application. This tillage step occurred on August 19, 2020, March 25, 2021, and May 4, 2021 at each of the three replicates, respectively. The fields were subsequently monitored for bindweed reemergence, and mechanical and chemical treatments were applied to the replicates when stem regrowth reached approximately 10-15 cm in length, approximately when sequential weed management would be applied commercially. Treatments were applied on September 15, 2020, April 20, 2021, and June 3, 2021.

There were seven treatments, including one nontreated control, three herbicide treatments, and three mechanical treatments. The three herbicide treatments were broadcast glyphosate, strip-applied glyphosate, and glufosinate. Both herbicides are widely used for field bindweed management in California, but they have contrasting systemic or contact actions. The broadcast glyphosate (Roundup PowerMAX, Bayer CropScience, St. Louis Missouri, USA, 660 g ae L^{-1}) was applied at a rate of 2.8 L ha^{-1} across the entire plot. The strips (Roundup PowerMAX) were applied at a rate of 5.6 L treated ha^{-1} in two 1.15 m-wide strips in the plot, leaving two 1.15 m-wide nontreated strips in the same plot. The glyphosate strips treatment used the same total amount of herbicide as the broadcast treatment, and this treatment was designed to evaluate potential impacts of glyphosate translocation when applied in strips as is common in orchards. The glufosinate treatment used 3.9 L ha^{-1} of Rely 280 (Bayer CropScience, Research Triangle Park, North Carolina USA, 280 g ai L^{-1}). Each of the herbicide treatments was applied using a CO_2 propelled backpack sprayer equipped with a three-nozzle boom and 80015XRVS nozzles (TeeJet Technologies, Glendale Heights, Illinois USA) and calibrated to apply 187 L ha^{-1} spray volume, based on 3.2 km hr^{-1} ground speed and 50.8 cm nozzle spacing. The three mechanical treatments were rototilling, flail mowing, and string trimming. These three treatments were chosen because they affect field bindweed roots and shoots differently, with rototilling representing deeper disturbance compared to string trimming and flail mowing.

Each plot was monitored weekly for 10 weeks following treatment application. The first five plants to emerge in each plot were marked with stakes. In the glyphosate strip plots only, these first-to-emerge plants were in the nontreated strips within each plot. Individual plant subsamples were evaluated throughout the experiment. Flowers were counted on the five marked plants at each weekly evaluation. We used flower counts to determine average time to first flowering in each plot. No flowering was observed in the first replicate, likely since it was relatively late in the 2020 growing season, and we did not include that replicate in flower timing analysis. At the end of the 10-week observation period, we collected the aboveground portion of the marked plants, dried them in a forced air oven, and weighed the dry biomass.

Pot experiment. The potted plant experiment involved propagating field bindweed plants from several source populations into pots and subjecting them to different mechanical disturbance treatments. The plants were propagated vegetatively from annual crop, perennial crop, and non-agricultural home environments. The experiment used a factorial design with three disturbance treatments, including nontreated, clipping, and simulated tillage, and four field bindweed populations. Plants were collected in late 2020 from an almond orchard near Corning, California (39.906623, -122.123060), an almond orchard in the Wolfskill Experimental Orchard near Winters, California (38.504573, -121.980137), an annual crop field in Davis, California (38.539336, -121.782482; the same field as the second replicate of the field experiment), and a vacant lot in Davis, California (38.545821, -121.722322; roughly 4.5 km from the other site in Davis). Several dozen plants cuttings, each including both root and shoot tissue, were collected at each site and transplanted into greenhouse pots. Plant populations were maintained in the greenhouse and re-transplanted twice into new pots over a six-month period. Re-transplanting included shoot trimming to minimize powdery mildew pressure, ensure uniform plant size, and control for any legacy effects from respective environmental conditions at the time of collection.

After growing in the greenhouse, we transplanted plants into 12 L pots on outdoor benches. Each pot was filled with greenhouse soil (equal parts coarse sand, compost, peat moss, and dolomite). Plants were uniformly trimmed to have 10 cm of root and 10 cm of shoot length, and only one plant was transplanted per pot. Pots were watered daily with drip irrigation. We replicated the experiment twice, and there were six repetitions of each population-treatment combination in each replicate. Transplanting occurred on April 29, 2021 for the first replicate and on May 26, 2021 for the second replicate. Plants had 5-10 cm new vegetative growth several weeks after transplanting, and treatments were applied May 20, 2021 and June 22, 2021 in the first and second replicates, respectively. Nontreated plants were left undisturbed, clipped plants had all aboveground tissues removed, and tilled plants had the top 10 cm of soil in each pot stirred with a trowel. The tillage treatment involved a standardized stirring and flipping motion that inverted soils and resulted in the burying, uncovering, and cutting of some plant tissues. However, we had to exclude one repetition of the nontreated-Corning orchard combination in the second replicate, because not enough plant material was available.

Plants were grown for 10 weeks following treatment application. During this time, drip irrigation was continued on a daily schedule, and entire replicates were given supplemental hand watering as needed. Plants were monitored weekly for flowering. Plants were harvested at the end of the 10-week window, which occurred on July 28, 2021 and September 1, 2021 in respective replicates. Aboveground and belowground tissues were collected separately, and root washing occurred at collection. Plant tissues were bagged and placed into a forced air drier before weighing. Dry biomass was used to calculate root:shoot biomass ratios for each plant.

Statistical analysis. All analyses were performed in R 3.0.3 (R Core Team 2020). We took the general approach of selecting the best, ecologically-relevant statistical models with Akaike information criterion (AIC), using ANOVA for global analysis, and finally using Fisher's LSD for multiple comparisons For the field experiment, we tested various logical combinations of ecologically-relevant predictors with the *aictab* function from the *AICcmodavg* package (Mazerolle 2020). For both flowering timing and aboveground biomass, the best model used just treatment and replicate as predictors, with no interactions. Then, we inspected ANOVA assumptions with *qqPlot* from the *car* package (Fox and Weisberg 2019). One sample with extremely high biomass was removed as an outlier from the biomass dataset based on visual inspection of Q-Q plots. We proceeded with using the *Anova* function from the *car* package and the *LSD.test* function from *agricolae* (Mendiburu 2020).

For the greenhouse experiment, we used the same general approach of using AIC to select models, ANOVA to compare predictors, and Fisher's LSD for multiple comparisons. Some modifications were required to accommodate the factorial design and the structure of the dataset. The flowering timing data required a generalized linear model using a Poisson distribution with a log link function. Model comparison with AIC led us to select treatment, population, and replicate as predictors. Relevant multiple comparisons were made with Fisher's LSD using the *glht* functrion from the *multcomp* package (Hothorn et al. 2008). For the root:shoot biomass ratio data, we chose a multiway ANOVA that included treatment, population, replicate, and their interactions. Upon visual inspection of with Q-Q plots, three samples with very high root:shoot ratios were removed. Additionally, we removed 13 samples with indeterminate values (i.e., there was zero shoot biomass). Multiple comparisons were made with *emmeans* (Lenth 2021) and *cld* from *multcomp*. All figures were created with *ggplot2* (Wickham 2016). We chose different kinds of figures for the field and potted plant experiments, due to the relative size and complexity of the potted plant experiment datasets.

Results and discussion. In the field experiment, weed management treatment did not affect field bindweed aboveground biomass after 10 weeks of regrowth (P=0.212; figure 2.1). The second replicate resulted in overall higher field bindweed biomass than the first and third replicates (P<0.001). However, time to flowering was affected by treatment (P=0.062; figure 2.2). Broadcast glyphosate and tillage significantly increased time to flowering by one to two weeks on average compared to other treatments. Conversely, string trimming, glufosinate, glyphosate strips, and mowing resulted in shorter time to flowering, about five weeks on average after treatment application. These four treatments delayed flowering one week compared to nontreated plots, suggesting that field bindweed flowering phenology is less sensitive to follow up treatment compared to the initial weed management treatment.

Time to flowering is a critical trait for agricultural management which affects the ability of field bindweed to contribute to a persistent soil seedbank. Flowering delays of one to two weeks could be relevant for orchard weed management which is frequently constrained by logistical challenges, such as the availability of application equipment or prioritization of irrigation and other pest management operations. Furthermore, flowering timing could contribute to population-level shifts in field bindweed reproduction that affect fitness and lead to more clonal reproduction. These results indicate that disturbance through weed management can have complex effects on field bindweed even when aboveground biomass is unaffected.

Broadcast glyphosate application appears to be a useful management tool for delaying field bindweed regrowth and affecting the phenology of additions to the soil seedbank. However, we assume that sexual reproduction is positively correlated with aboveground biomass, so this study does not support a link between these orchard weed management programs and the magnitude of soil seed bank additions (Degennaro and Weller 1984). Future research should evaluate whether certain weed management practices, namely systemic herbicides, affect the relationship between biomass and seed production or viability. Additionally, future research should evaluate the intensity of longer sequential orchard management programs that are required to eliminate soil seed bank additions. The relative contribution of sexual and asexual reproduction to overall fitness remains an open question, and better general understanding of reproductive resource allocation could help us understand how various management programs might select for different reproductive and life history strategies over time.

In the potted plant experiment, treatment (*P*=0.025), population (*P*<0.001), and replicate (*P*<0.001) were all important predictors of root:shoot biomass ratio (figure 2.3). Additionally, there were significant interactions between treatment and replicate (*P*<0.001) and all three variables (*P*=0.005). In general, differences were subtle and effect sizes were small. However, the clipping treatment resulted in higher root:shoot ratios than the other treatments, which is logical given that shoot tissues had been removed from that treatment 10 weeks before plant tissues were collected. The field bindweed population sourced from an annual crop field generally produced higher root:shoot ratios than other populations, suggesting that this population produces relatively larger root reserves or less aboveground biomass than the other populations from perennial and non-agricultural systems. Orchard managers should be aware of the possibility that field bindweed has the potential to reproduce differently between annual and perennial cropping systems or in the early stages following an environmental transition, such as during orchard establishment. Future research could evaluate the reliability of such differentiations and their potential contributions to field bindweed population change over time or changes in resource allocation that affect regrowth.

Time to flowering in the potted plant experiment was affected by treatment (*P*<0.001) and replicate (*P*<0.001) and not significantly affected by population (*P*=0.299; figure 2.4). In general, clipping and simulated tillage were similar to one another, and both delayed flowering compared to nontreated plants. The potted plants had different flowering phenology compared to the field experiment, with more variation in flowering timing. We attribute some of these differences to the controlled nature of potted plants, growing plants from transplants, and the subsampling design of the field experiment. Despite these differences, weed management disturbance in the potted plant experiment resulted in average flowering delays of one to two weeks, which is similar to the field experiment. Again, we argue that these delays can be practically important for orchard growers making decisions about management timing.

Knowledge of weed reproduction and population ecology is essential for the implementation of integrated pest management programs. Furthermore, improved knowledge of the diverse and prolific reproductive methods of pernicious weeds like field bindweed can help us understand how weedy plants respond to various kinds of agricultural disturbance. These experiments demonstrate that flowering can be effectively delayed through common management practices. Management practices that affect both root and shoot tissues, such as glyphosate and tillage, are especially effective at delaying field bindweed flowering under field conditions. This information could support integrated management of field bindweed that includes better scheduling of repeated management applications based on the development of field bindweed. Current orchard weed management programs in California frequently address field bindweed with repeated applications of glyphosate, and optimization of these applications could have sustainability benefits for agricultural landscapes in California and crop safety benefits in young orchards.

Additionally, we present information that indicates differential reproductive characteristics between field bindweed collected from different home environments, suggesting the potential for an adaptive response to long term agricultural management programs. Weed populations that change in response to repeated management are a critical threat to agricultural productivity. This research reinforces the importance of planning and repeated management for developing integrated pest management programs that address the unique changes that affect orchards that are situated in complex California landscapes. Future research could account for the24hapiro24ve multi-year effects of disturbance on field bindweed reproduction, including consideration of perennial roots and asexual reproduction of established plants in controlled environments like potted plants or in different stages of the orchard life cycle.

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Figure 2.1. Field bindweed aboveground dry biomass in response to several weed management practices, as collected 10 weeks after treatment application in a field experiment. Points represent mean values, and bars represent standard error.

Figure 2.2. Time to first flowering for field bindweed subjected to several weed management practices. Points represent mean values, and bars represent standard error.

Figure 2.3. Field bindweed root:shoot dry biomass ratios as collected 10 weeks after mechanical disturbance. Each point represents the value observed from one potted plant. Each panel contains values from one field bindweed population, and orange circles and purple triangles represent data from different experimental replicates.

Figure 2.4. Time to first flowering for field bindweed subjected to different mechanical disturbances. Each point represents the value observed from one potted plant. Each panel contains values from one field bindweed population, and orange circles and purple triangles represent data from different experimental replicates.

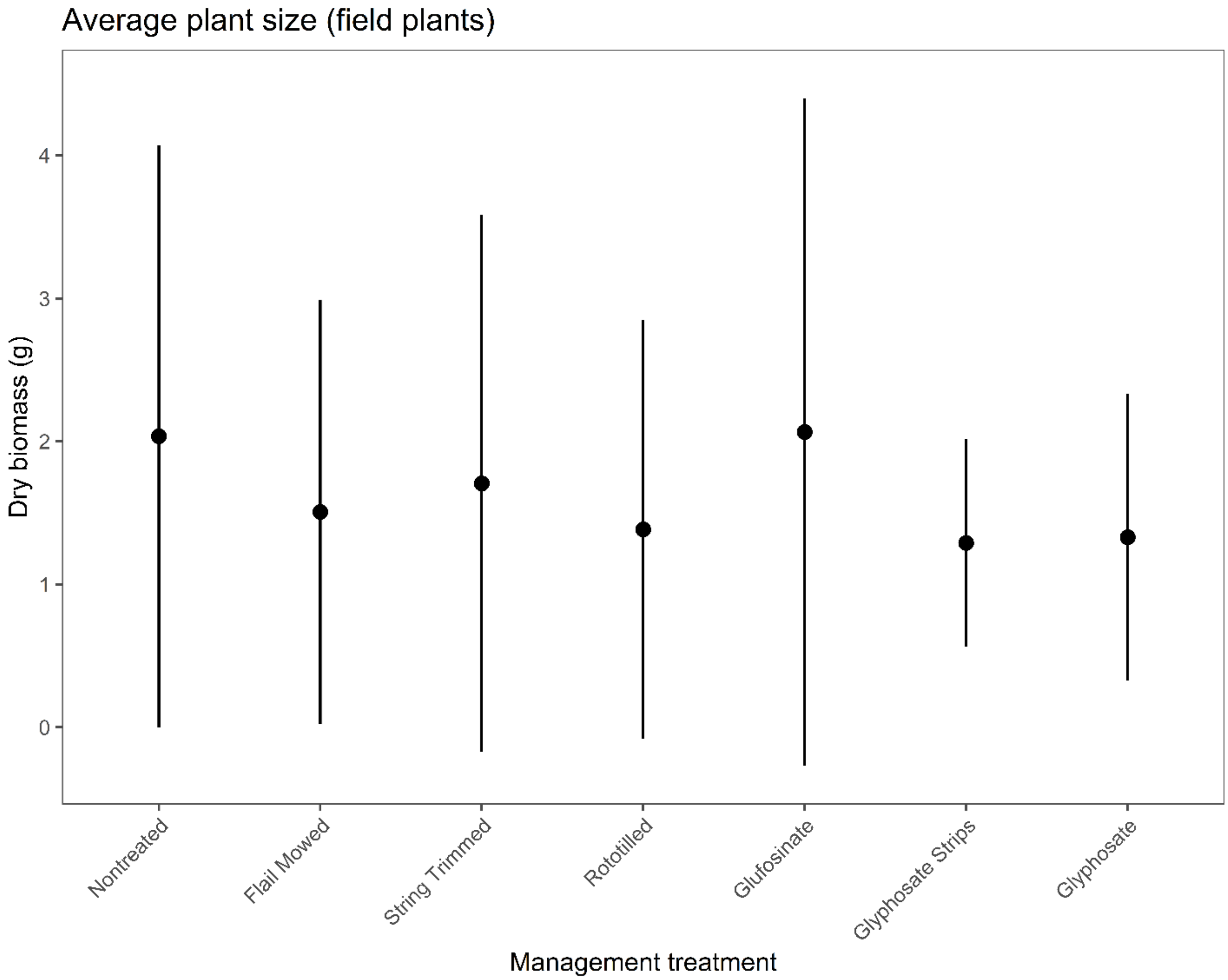
Average plant size (field plants)
Dry biomass (g)
4
3
2
1
0
Nontreated
Flail Mowed
String Trimmed
Rototilled
Glufosinate
Glyphosate Strips
Glyphosate
Management treatment

Figure 2.1

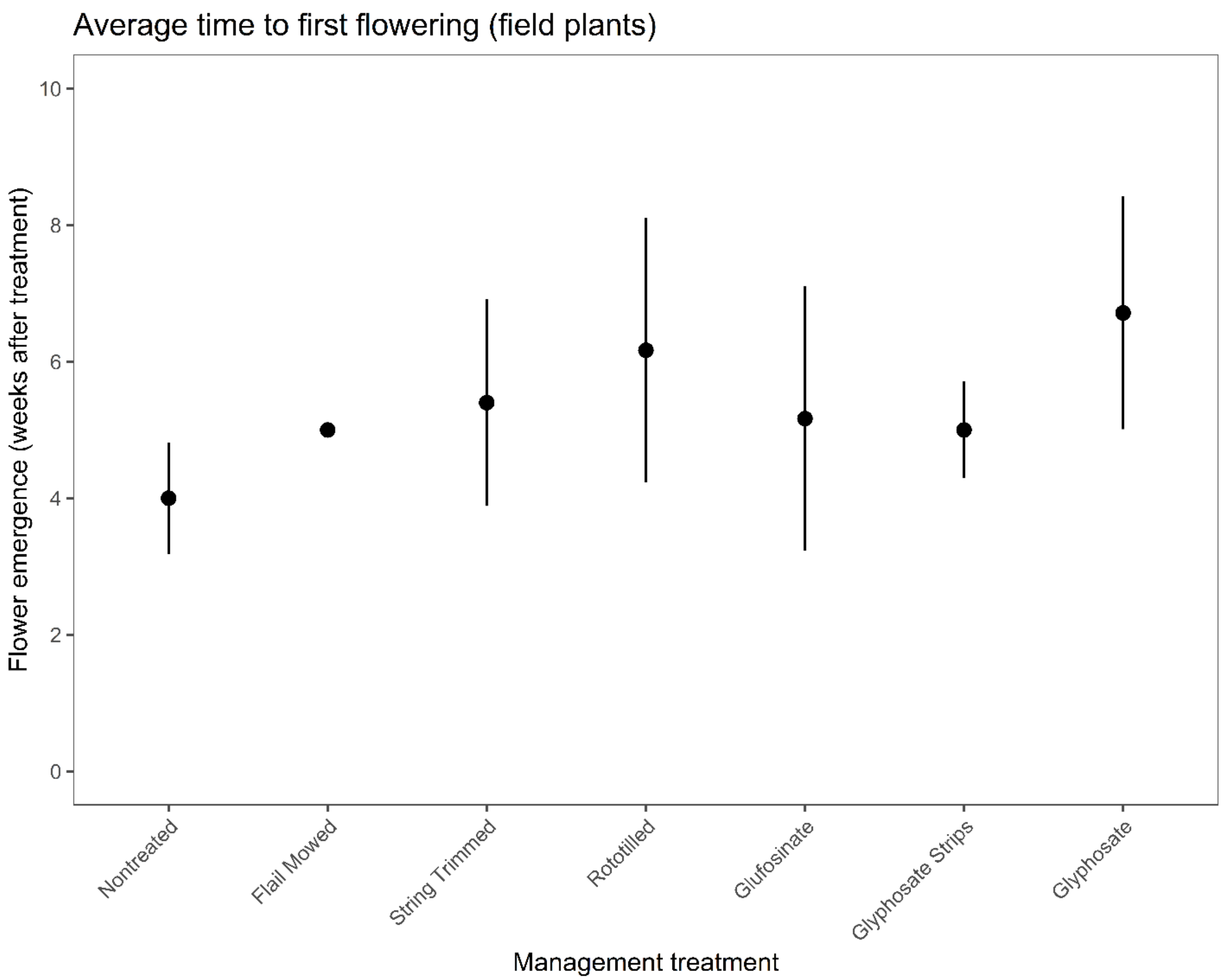
Average time to first flowering (field plants)
Flower emergence (weeks after treatment)
10
8
6
4
2
0
Nontreated
Flail Mowed
String Trimmed
Rototilled
Glufosinate
Glyphosate Strips
Glyphosate
Management treatment

Figure 2.2

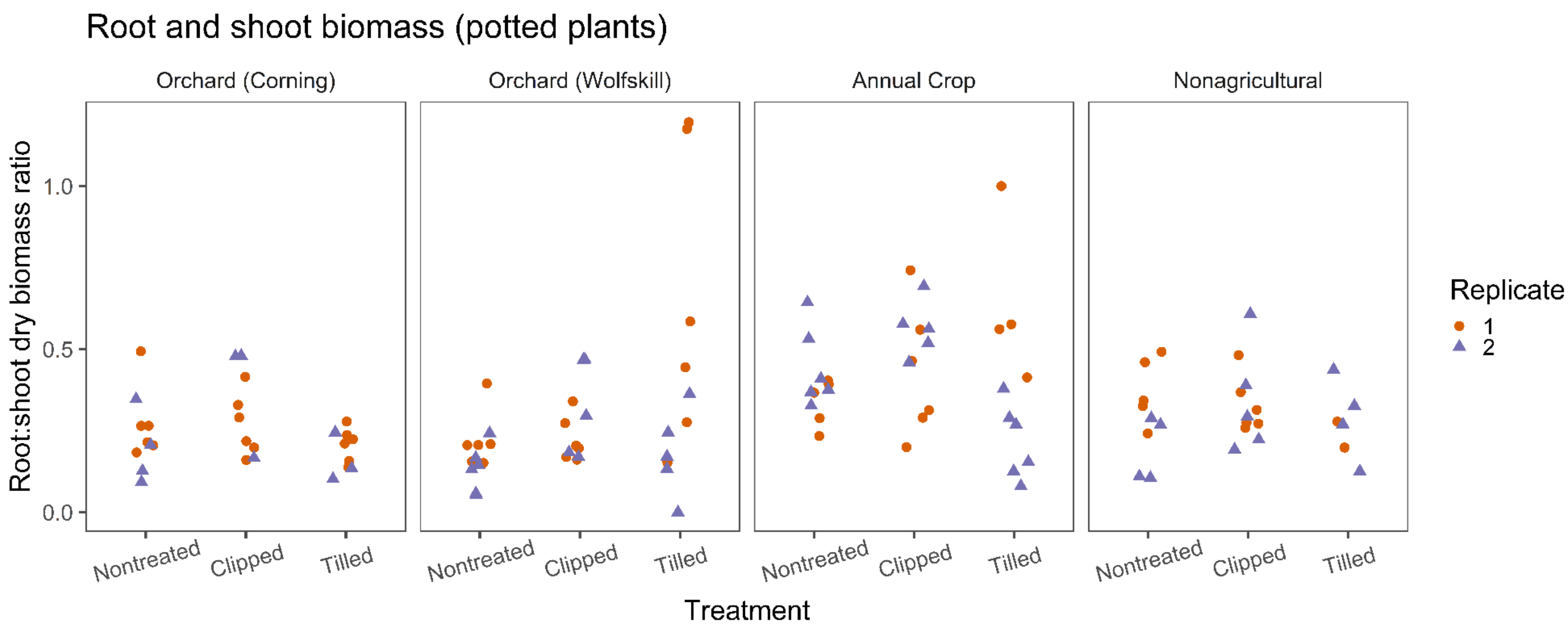
Root and shoot biomass (potted plants)
Orchard (Corning)
Orchard (Wolfskill)
Annual Crop
Nonagricultural
Root:shoot dry biomass ratio
1.0
0.5
0.0
Nontreated
Clipped
Tilled
Treatment
Replicate
1
2

Figure 2.3

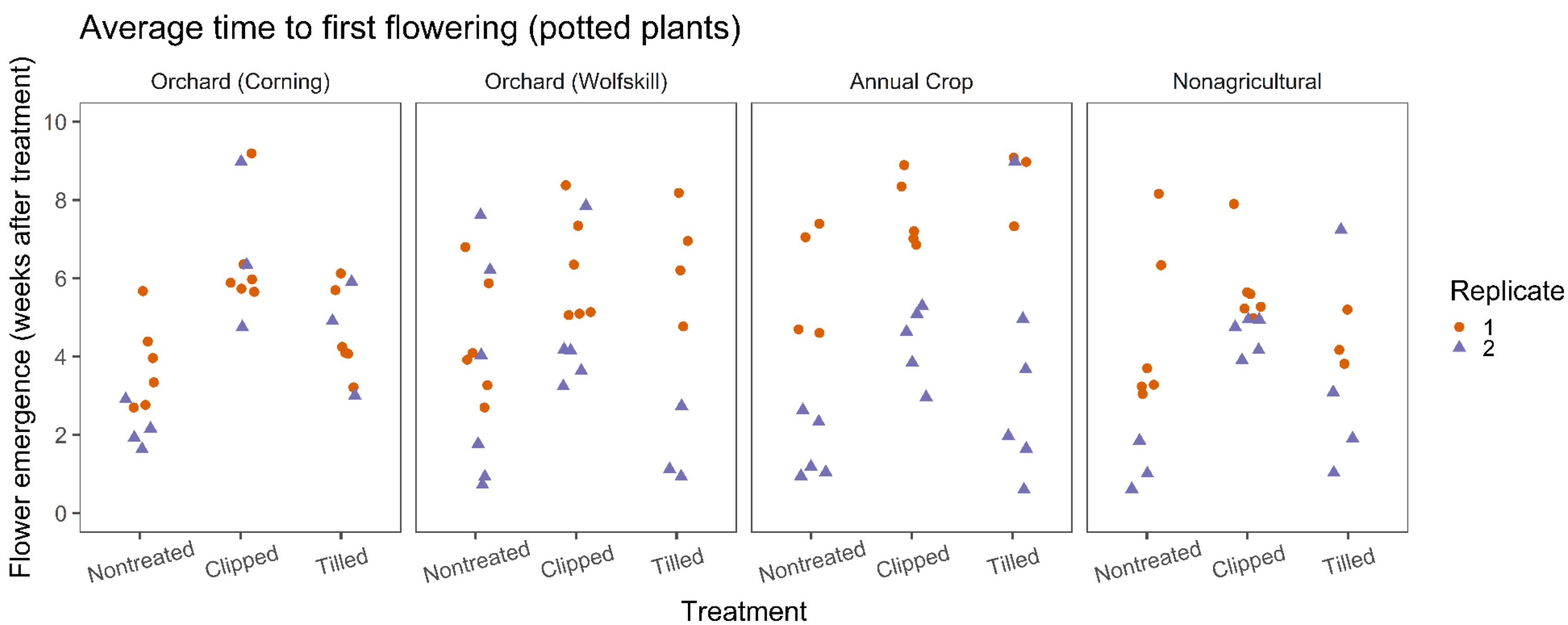
Average time to first flowering (potted plants)
Orchard (Corning)
Orchard (Wolfskill)
Annual Crop
Nonagricultural
Flower emergence (weeks after treatment)
0
2
4
6
8
10
Nontreated
Clipped
Tilled
Treatment
Replicate
1
2

Figure 2.4

Functionally diverse cover crops support ecological weed management in orchard cropping systems

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Abstract.

1. Diverse agriculture management is critical for agroecosystem sustainability, and cover crops can offer varied management that reduces the intensities of directional selection on weed populations and abiotic filters on weed communities. Understanding how cover crops fill open ecological niches, interact with weedy vegetation, and potentially provide useful biodiversity is therefore essential for ecological management of orchard systems.
2. In this study, transect plant surveys were used to evaluate orchard plant communities under two multispecies cover crop programs, a functionally diverse mix and a mix with similar species richness but less functional diversity. Controlled experiments were implemented to test these cover crop programs against standard management practices in three commercial almond orchards across California's Central Valley for two years beginning in 2017.
3. Winter annual orchard cover crops can be effective at reducing bare ground compared to resident vegetation, but this did not consistently affect community composition for low richness weed communities. Cover crop incidence had a negative relationship with weed incidence, while cover crop treatment was not a strong predictor of weed incidence.
4. However, the more-functionally diverse cover crop mix led to increased ground cover stability across site-years, which supports a competitive and abundant cover crop in varied agroecological conditions.
5. *Synthesis and applications.* Cover crops with different levels of functional diversity may have value for vegetation management at scales relevant for commercial orchard systems. Functional diversity supports cover crop establishment, and functional cover crop mixes could be designed to address an assortment of orchard management concerns.

Key words. Agroecology; agroecosystems; integrated pest management; orchards; sustainable agriculture

Introduction. Cover cropping is a management strategy which adds potentially beneficial biodiversity to agroecosystems. Cover crops are non-harvested crop plants that cover soil that would typically be left bare under conventional agricultural management. Depending on specific cover crop management practices (Bergtold et al. 2019), farmers may leverage planned agrobiodiversity to enhance regulating ecosystem services (Tamburini et al. 2020, Beillouin et al. 2021, McClelland et al. 2021), increase cropping system resilience (Reiss and Drinkwater 2018, Renwick et al. 2021), reduce agricultural externalities, and support sustainable intensification (Wittwer et al. 2017). Research has mainly addressed ecological impacts of annual cover crops grown in the fallow period between two annual cash crops (e.g. Teasdale et al. 1991, Brennan et al. 2011, Altieri et al. 2011) but much remains to be known about impacts and potential in perennial systems where cover crops are grown on the ground beneath orchard trees with spatial separation from the main crop. Cover crops have known impacts on abiotic factors such as those related to soil structure or water use (Monteiro and Lopes 2007, Ramos et al. 2010) but more research is needed to understand broader biotic functions of horticultural importance.

Weed suppression is one key indicator that could describe the biotic function of an orchard cover crop. Aside from being practically important for orchard growers, weed suppression can indicate the absence of unfilled ecological niches within the orchard system (Smith et al. 2010). Whereas conventional orchards have significant unused resource pools that lead to the need for intensive vegetation control, cropping systems with diverse ground covers lead to regulation of water, light, nutrients, and safe germination sites so that these resources are less available for weed proliferation (Smith and Gross 2007, Adeux et al. 2019).

An ideal orchard cover crop displaces weed plants with predictable, domesticated species that also provide additional sustainability benefits (Liebman and Davis 2000). Previous studies have demonstrated that cover crops can be useful in the unique environment of irrigated, perennial cropping systems in Mediterranean climates (Bugg et al. 1996, Baumgartner et al. 2008). In these systems, winter annual cover crops have a life cycle coincidental with winter rains as well as the dormant period of deciduous orchard crops. This phenology allows winter annual plants to have significant niche differentiation compared to the orchard crop while having niche overlap with important weedy species.

Exploitative competition between cover crops and orchard weeds may be especially relevant given the long winter cover crop season and the cumulative effects of growing cover crops over multiple years. In contrast, other forms of interference, such as allelopathy or suppression of summer weed germination with cover crop residues (Putnam et al. 1983, Creamer et al. 1996), may be more important in annual cropping systems, where rapid changes in resource availability and fast life histories change the phenology of competition (Pearson et al. 2017). Winter annual cover crops are therefore a practical way to use biodiversity in support of vegetation management in orchard systems, but it remains important to understand potential tradeoffs between ease of management and multifunctionality (Schipanski et al. 2014, Finney and Kaye 2017).

Studies in unmanaged ecosystems highlight the potential role of diverse, multifunctional plant communities in increasing ecological functions and reducing weed invasability through niche differentiation (e.g., through resource partitioning and phenological differences) and variation in developmental biology and phenotypic plasticity (Tilman et al. 1996, Levine and D'Antonio 1999). However these patterns might not be reproducible in highly managed agricultural systems at scales relevant to populations, communities, and fields given increased disturbance and decreased species richness. (Bybee-Finley et al. 2017, Smith et al. 2020).

This study aims to fill a critical knowledge gap in understanding the potential of various multispecies cover crops for integrated pest management goals such as reductions in herbicide use in large-scale, intensified, and highly productive irrigated orchard systems in a unique, Mediterranean climate. We evaluated plant communities under two multi-species cover crop mixes, one that is functionally diverse and one that is functionally uniform, over two seasons in three commercial almond (*Prunis dulcis* (Mill.) D.A. Webb) orchards in the Central Valley of California. Cover crop mixtures were designed to fulfill different ecological goals, and we evaluated their impact on weed population density and species communities across a wide geographical area in central California.

We hypothesize that both functionally uniform and diverse cover crops can effectively provide orchard ground cover that displaces weeds, but that functionally diverse cover crops will emerge and compete for resources more consistently across growing seasons and locations and are therefore better able to impact weed community composition. To evaluate these hypotheses, we examined indicators of cover crop function: 1) elimination of bare ground compared to ground cover provided by weedy resident vegetation, 2) relative incidence of cover crops and weeds, 3) stability of cover crop incidence over space and time, and 4) downstream impacts on weed communities.

Materials and methods.

Experimental design and soil cover treatments. We compared the effects of several ground cover treatments in replicated large-plot experiments in commercial almond orchards in Tehama, Merced, and Kern Counties in California. These locations span nearly 600 km in the Central Valley of California, including a range of environmental variables, especially rainfall. This region produces virtually all of the almonds in the United States (California Department of Food and Agriculture 2020). The experiment used a randomized complete block design with four replications of three or four soil cover treatments at each site, and practices were implemented for two years on the same plots, beginning in the fall of 2017 and ending in the late summer of 2019. Plots were about 25.5 m wide at each site, encompassing four orchard alleys (i.e., alleyways between five tree rows), and the entire length of the orchard management units (195 m at the Tehama site, 385 m at the Merced site, and 320 m at the Kern site).

Two different winter cover crop mixes were planted in orchard alleyways. The “uniform” mix consisted of five functionally similar species that are designed to provide diverse floral resources for honeybees (*Apis mellifera* L.) to support almond tree pollination. This mix is used commercially in California and distributed as ‘PAm Mustard Mix’ by the Project *Apis m.* (Salt Lake City, UT, USA) Seeds For Bees program. The mix was comprised of 35% canola (*Brassica napus* L.), 15% ‘Bracco’ white mustard (S*inapis alba* L.), 15% ‘Nemfix’ yellow mustard (*Brassica juncea* (L.) Czern.), 20% daikon radish (*Raphanus sativus* L.), and 15% common yellow mustard (*Sinapis alba* L.). The uniform mix was planted at 9 kg per planted ha. The “diverse” mix consisted of five species from the grass, brassica, and legume groups that are commonly used together in functionally-diverse cover crop mixes (Altieri et al. 2011). This mix was comprised of 10% ‘Bracco’ white mustard, 10% daikon radish, 30% ‘Merced’ rye (*Secale* *cereale* L.), 20% ‘PK’ berseem clover (*Trifolium alexandrinum* L.), and 30% common vetch (*Vicia sativa*). The diverse mix was planted at 56 kg per planted ha.

Two control treatments were also implemented which reflected mainstream orchard management practices of winter vegetation. The “resident” vegetation treatment involved winter vegetation management with mowing and seasonal herbicide applications which allowed resident vegetation growth. The “bare” treatment involved multiple herbicide applications, as determined by grower cooperators, to eliminate winter vegetation. The Tehama site included only the resident treatment to better reflect standard practices in this region of California which has more abundant winter rainfall. The Merced and Kern sites featured both the resident and bare treatments to better reflect high intensity production systems in these regions.

Sites and horticultural management. The study was designed to use commercially relevant spatial and temporal scales, and orchard management was determined by grower cooperators for agronomic relevance. All orchards were equipped with microsprinkler irrigation, and irrigation schedules were determined based on almond evapotranspiration models in accordance with local weather conditions and recommendations. Conventional irrigation, insecticide, fungicide, and fertilizer treatments and rates were determined by each grower and applied to the tree rows only. Tree rows were maintained with conventional herbicide programs to create vegetation-free zones at the base of trees. Each of the sites was subjected to regular traffic from machinery and farmworkers to complete these orchard management operations throughout the cover crop growing season.

The Tehama County orchard was located in the northern Sacramento Valley (39’56'5”.3"N, 122’07'3”.5"W) on Kimball loam soils (Mollic Palexeralfs). Average precipitation at the site is 645 mm annually. The site was planted in 2016 with almond varieties ‘Nonpareil’ and ‘Monterey’ in alternating rows. Cover crops were drill seeded in a 3.6 m wide swath down the alleyways on November 6, 2017 and November 9, 2018 and mowed for termination on March 30, 2018 and May 25, 2019. The young trees were pruned in February 2018, and every other alley was subsequently mowed to mulch tree prunings. No data described in this paper were collected from those mowed alleys. The whole orchard was mowed on January 29, 2019 to destroy unharvested nuts for navel orangeworm (*Amyelois transitella* Walker) sanitation; data were collected from cover crop regrowth after this mowing event. Frost during almond bloom was a concern at this site, and irrigation was applied in 12-hour long sets to mitigate forecasted frosts in February or March of each year, which is outside of typical almond irrigation timings.

The Merced County orchard, planted in 2008, was located in the northern San Joaquin Valley (37’23”54"N, 120’32”52"W) on Alamo clay soils (Typic Duraquolls). Average precipitation at the site is 325 mm annually. The site had 50% ‘Nonpareil’ and 12.5% each ‘Monterey’, ‘Fritz’, ‘Carmel’, and ‘Wood Colony’ almond varieties, with ‘Nonpareil’ in every other row and the remaining varieties mixed evenly in the alternate rows. Cover crops were direct seeded on November 2, 2017 in a 3.6 m wide swath with a seed drill and mowed for termination on April 9, 2018. In year two, cover crops were broadcast planted on December 21, 2018 with a rotary spreader and mowed on March 19, 2019 for navel orangeworm sanitation following data collection and again on April 12, 2019 for final cover crop termination. The first replicate of the uniform mix was not planted at this site in 2017, and data from that plot was not included in the analysis.

The Kern County orchard, planted in 2006, was located in the southern San Joaquin Valley (35°14’22”N, 118°47’15”W) on primarily Hesperia sandy loam (Xeric Torriorthents). Average precipitation at the site is 180 mm annually. The site had 50% ‘Nonpareil’ and 25% each ‘Monterey’ and ‘Fritz’ almond varieties, with ‘Nonpareil’ in alternate rows and the other two varieties evenly mixed in every other row. A 4.8 m wide swath was planted down the center of each orchard alley. Cover crops were direct seeded on October 30, 2017 and mowed for termination on April 2, 2018. In year two, cover crops were planted on November 1, 2018 and mowed on April 5, 2019. Immediately prior to both planting dates, alleyways across the whole orchard were disked for seedbed preparation and ground leveling. Supplemental irrigation was applied across the orchard in 20-hour long sets throughout the winter of 2017-2018 to support the cover crop a45hapiro45gate frost concerns. At this site, the bare ground cover treatment only involved a deep ripping tillage operation to address soil compaction.

Data collection. Orchard alley plant communities were evaluated with point-intercept transects. Each plot was surveyed with a single 50 m long transect with points observed evenly at each meter along the transect. Each transect was placed beginning 75 m from the end of the second tree row over from the edge of each plot. The transect extended diagonally across a single orchard alley, starting and ending on opposite edges of the planted swath. Plant incidence was observed for the top layer of vegetation, with occurrence of one actively growing plant or bare ground recorded at each point along the transect. Therefore, incidence is a relative measure of how much ground cover is associated with each vegetation type. Plants were identified to species visually, except in the case of the white and yellow mustards in the uniform mix which were identified as one operational taxonomic unit due to morphological similarities. Transects were surveyed on March 29, 2018 and March 22, 2019 at the Tehama site, March 30, 2018 and March 15, 2019 at the Merced site, and March 27, 2018 and March 16, 2019 at the Kern site. These timings coincide with cover crop flowering for most species as well as winter weed flowering for many endemic species in the study area.

Statistical analysis. Analyses were performed in R 4.0.3 (R Core Team 2020). Comparisons of bare ground among treatments were made with ANOVA. ANOVA assumptions were inspected visually with *qqPlot* from the *car* package (Fox and Weisberg 2019), and subsequently the response variable (relative bare ground) was arcsine square root transformed to deal with a heavy tailed distribution. One outlier was identified with the Bonferroni outlier test using *outlierTest*. This outlier value was excluded from further analyses because it was collected in the same plot at the Merced site that had been previously excluded because it had not been planted in 2017 (i.e., no data from this plot from either study year was included). Finally, normality of the transformed, outlier-free model was formally assessed with a Shapiro-Wilk test usi46hapiro*iro.test*. Models with combinations of possible predictor variables (i.e. treatment, year, site, and block (nested within site), modeled as fixed effects due to the number of sites and years in this study) were compared with Aikake information criterion using the *aictab* function from the *AICcmodavg* package (Mazerolle 2020). The best model included treatment, site, and their 2-way interactions as predictors, and neither year nor block were included in the final model. The resulting ANOVA analysis was performed with *Anova* from the *car* package, and contrasts were made with least-squares means using the *emmeans* package (Lenth 2021).

Associations between cover crop and weed incidence were analyzed using linear models. Linear models were created with the *lm* function in base R. Weed incidence was the response variable, and we created models with cover crop incidence and cover crop treatment (i.e., diverse mix and uniform mix), both with and without their interaction terms, as well as a model which only included cover crop incidence. Linear models were compared with the *anova* function from base R. Linear regression including only cover crop incidence as a predictor for weed incidence was statistically similar to linear regression that additionally used cover crop mix (P = 0.914) or cover crop mix and the two-way interaction (P = 0.615) as predictors. Therefore, we considered the most parsimonious model with only cover crop incidence as a predictor of weed incidence.

Cover crop stability was assessed by comparing coefficients of variation for incidence of each cover crop mix as pooled across sites and years in this study. Pooled coefficients of variation were compared with the modified signed-likelihood ratio test as implemented in the *cvequality* package (Marwick and Krishnamoorthy 2019). Weed communities in the different cover crop treatments were analyzed with nonmetric multidimensional scaling (NMDS). NMDS was based on Bray-Curtis dissimilarity and was calculated using the *metaMDS* function in the *vegan* package (Oksanen et al. 2020). Groupings were compared both within and among sites with *anosim* in the same package.

Results. Cover crop treatment ($F_{3,75}$ = 73.86, P < 0.001), site ($F_{2,75}$ = 27.52, P < 0.001), and their interaction ($F_{5,75}$ = 6.96, P < 0.001) had significant impacts on the amount of bare soil observed in orchard alleys (Fig. 3.1). Both the uniform and diverse mix significantly reduced bare soil compared to the standard treatments (P < 0.001 for both bare and resident treatments). The uniform and diverse mixes resulted in similar levels of bare soil (P = 0.279). Across treatments, sites, and years in this study, increased cover crop incidence was negatively associated with reductions in weed incidence (Fig. 3.2; slope = -0.74, R^2 = 0.83, P <0.001). The coefficient of variation for cover crop incidence from the diverse mix was 48.6%, significantly less variation than the 91.5% variation observed in the uniform mix (Fig. 3.3; P = 0.035).

Cover crops influenced weed communities but to different extents depending on the site and year. Throughout the springtime evaluations in this study, we observed five weed species at the Kern site, six weed species at the Merced site, and 22 weed species at the Tehama site. The Kern site primarily included annual bluegrass (*Poa annua* L.) and common chickweed (*Stellaria media* (L.) Vill.), with lesser populations of little mallow (*Malva parviflora* L.), shepherd's purse (*Capsella bursa-pastoris* (L.) Medik.), and Italian ryegrass (*Lolium perenne* L. ssp. *multiflorum* (Lam.) Husnot). The Merced site also had large populations of annual bluegrass and common chickweed, as well as little mallow, whitestem filaree (*Erodium moschatum* (L.) L'Hér), California burclover (*Medicago polymorpha* L.), and wild oat (*Avena fatua* L.). The Tehama site had significant populations of annual bluegrass, common chickweed, shepherd's purse, whitestem filaree, buckhorn plantain (*Plantago lanceolata* L.), chicory (*Cichorium intybus* L.), annual sowthistle (*Sonchus oleraceus* L.), field bindweed (*Convolvulus arvensis* L.), and bermudagrass (*Cynodon dactylon* (L.) Pers.). The remainder of the species at the Tehama site were primarily dicotyledonous, winter annual species, with lesser populations of some grasses and summer annual or perennial dicotyledonous species.

Weed communities clustered by cover crop treatments ($R = 0.091$, $P = 0.004$), though sites also predicted weed communities ($R = 0.569$, $P < 0.001$) and effect sizes were generally small (Fig. 3.4). While no fixed factors significantly explained weed communities in Merced, year was a significant factor in Tehama ($R = 0.919$, $P < 0.001$) and cover crop treatment was a significant grouping factor for weed communities in Kern ($R = 0.316$, $P < 0.001$).

Discussion. Orchard cover crop mixes, as implemented in this study, were effective at establishing, reducing bare soil, and suppressing weeds. However, these effects were highly variable, and there is little evidence that the cover crop mixes we used had fixed impacts on the composition of orchard weed communities. Differences in management and climate at each site-year, especially as related to cover crop planting, spring mowing, and weather conditions during cover crop establishment, likely contributed to this variability. The diverse mix resulted in more consistent ground cover in this study, and ground cover led to greater weed suppression. However, cover crop incidence, not the specific cover crop treatment, was the primary driver for suppression and other effects on weeds in this study.

These results are consistent with previous experimental results of cover crop and weed competition that highlight the importance of cover crop abundance, not diversity, in weed competition (Creamer et al. 1996, Bybee-Finley et al. 2017, MacLaren et al. 2019, Florence et al. 2019, Smith et al. 2020). It is important to note that these studies primarily measured cover crop and weed biomass, while the present study came to a similar conclusion by measuring incidence. Additionally, these studies are in annual cropping systems. Agricultural systems, whether annual or perennial, are designed to support ample plant growth, and this resource-rich environment favors the asymmetric competition that is associated with abundant, fast-growing, cultivated plants.

Maintaining biodiversity is a major challenge for agroecosystems, but this study continues to challenge the importance of functional diversity for achieving agronomic management goals like weedy vegetation management. Agricultural plant communities are not diverse compared to plant communities in non-agricultural systems. The cover crop mixes in this study represented a significant increase in orchard plant diversity, essentially doubling species richness in the mature orchards (Merced and Kern sites). Among treatments, weed species richness was highest in the young orchard (Tehama site), where the orchard floor was relatively unshaded and still populated with many weed species carried over from the previous pasture system. Weed community assembly may be affected by cover crops during the early stages of orchard development, but more research is needed to understand the effects of cover crop competition on filtering weed communities over timescales relevant for orchard production.

Cover crop species in this study were primarily selected for their relevance to almond management goals other than weed suppression. When considering multifunctionality, there are significant tradeoffs between agroecosystem services associated with various cover crop mixes. Managing cover crops for maximum weed suppression, and therefore maximum abundance, may detract from other orchard or cover crop management goals. For example, rye was included in the multifunctional mix in this study and is known to be an important component species for weed suppression (Barnes and Putnam 1983, Akemo et al. 2000), but persistent residues from high-biomass species like rye could negatively affect on-ground almond harvest several months after cover crop termination.

However, weed-suppressing cover crops are also likely to contribute to other ecosystem services. Large and abundant cover crops are more effective in exploitative competition due to asymmetric resource acquisition, such as root competition for soil nutrients (Weiner 1990). The same mechanism that facilitates competition in this example also facilitates improved soil structure and increased soil organic matter. In another example, cover crop functional diversity could enhance competition through niche differentiation, as well as enhance pollination services by increasing floral resource diversity.

Abundant single-species cover crops may be the best for outcompeting weeds, but a multifunctional cover crop mix may be designed to enhance other orchard management goals and protect against environmental uncertainty. Weed suppression may be essentially a prerequisite towards achieving an abundant, competitive, and multifunctional cover crop, but cover crop species and management practices should be selected with consideration for other ecosystem services that may complement orchard production. Balancing multifunctionality against singular management goals like weed management presents opportunities for integration of cover crops into conventional cropping systems. Conventional weed management is chiefly a tool for reducing biodiversity, but cover crops can reduce weed infestation while promoting functional biodiversity.

Uncertainty of outcomes remains a challenge for the practical adoption of cover crops by orchard growers; specific cover crop management practices should be planned alongside specific management goals (De Leijster et al. 2019). Particularly important is uncertainty related to the timing of winter rainfall. In the almond study system, cover crop planting is timed to coincide with the beginning of winter rains, which would reduce demand for supplemental irrigation of the cover crop. Weedy plants also depend on this rainfall for germination, and timely planting of the cover crop can align cover crop emergence with weed emergence. Cover crop mix diversity could be one way to hedge against increasingly uncertain winter rains. In this study, the diverse mix had a level of diversity that led to more stability, even if that stability did not consistently lead to enhanced weed suppression.

Adjustments in cover crop phenology could be an important line of future research. Perennial cropping systems have significant temporal flexibility compared to annual cropping systems, where relatively few options exist for growing a cover crop during the cash crop growing season. Optimization of when a cover crop is planted and terminated in the orchard could improve weed suppression or other ecosystem services. Furthermore, the timing of these management actions could differ across orchard cropping systems, depending on climate or various needs of the main crop. Examples that could facilitate different cover crop management timings compared to those used in the present study could include cropping systems such as citrus, which is harvested during winter months, pistachio, which utilizes off-ground harvest during the fall, or apples, which are frequently grown in climates with colder winters. While this study implemented cover crops on a time scale relevant for adoption in contemporary orchards, further understanding of the cumulative impacts of cover cropping on the decades-long scale of orchard lifespans could further improve temporal arrangements of cover crops.

Author contributions. All authors developed hypotheses, contributed to experimental design, and critically revised the manuscript. SCH led field data collection, data analysis, and manuscript drafting. Stakeholders, including orchard growers and cooperative extension professionals, were included in project design and management, and specific parties are listed in the acknowledgements.

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Conflict of interest. We have no conflicts interest to declare.

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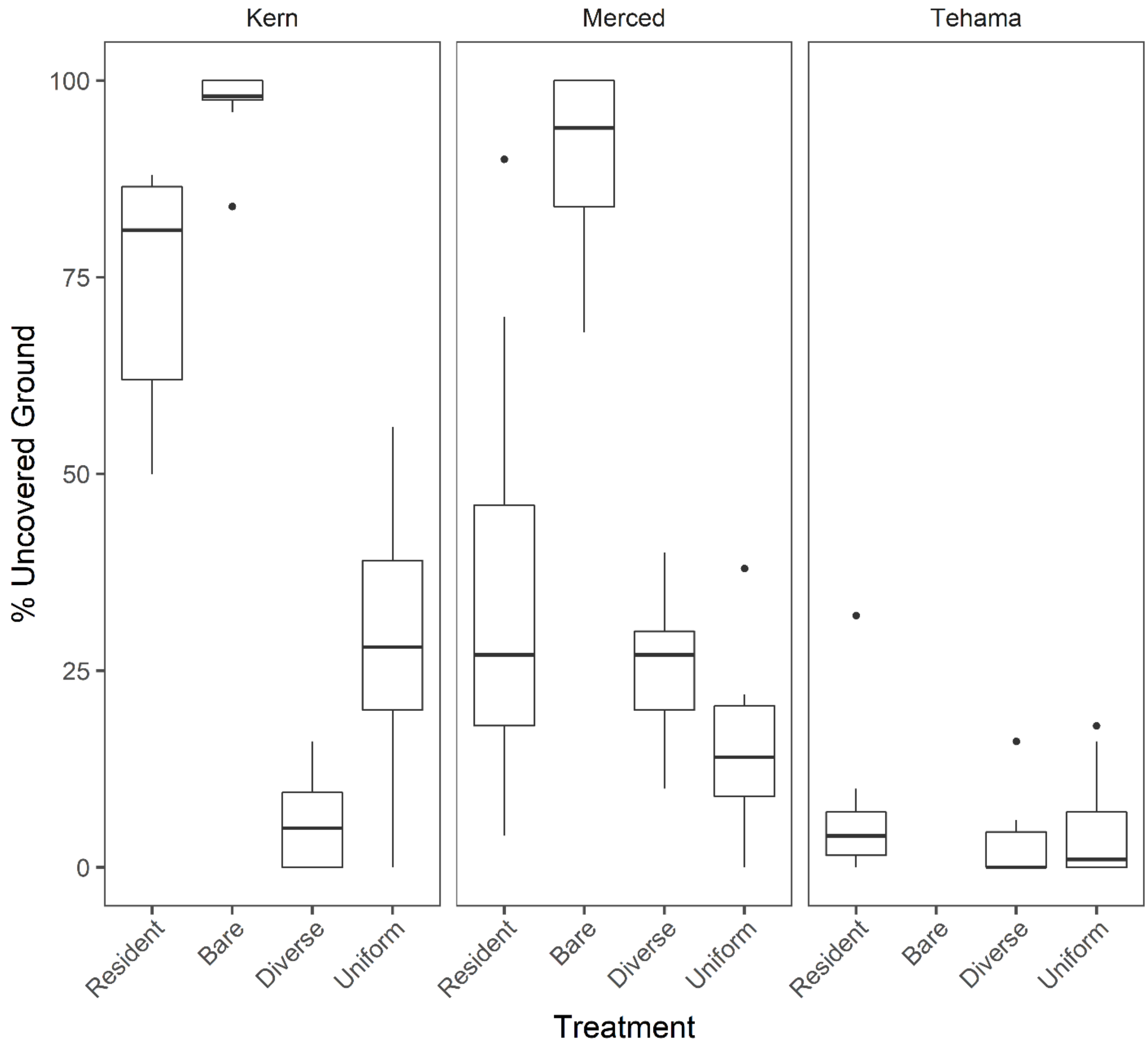
Figure 3.1. Impacts of various cover crop treatments on amount of bare soils in orchard alleyways (2018 and 2019). The center line represents median, hinges represent first and third quartiles, and whiskers represent minimum and maximum values within 150% of the interquartile range. Data analysis was performed on arcsine square root transformed data, but untransformed data are presented here.

Figure 3.2. Relationship between cover crop and weed incidence in orchard alleyways (2018 and 2019). The line displays marginal replacement of each vegetation type relative to the other as determined by a linear model.

Figure 3.3. Stability of cover crop incidence in orchard alleyways (2018 and 2019). Bars show the average coefficient of variation across site-years in this study, with the diverse cover crop mix exhibiting less variation in ground cover compared to the uniform mix ($P = 0.035$).

Figure 3.4. Ordination plots representing weed communities in orchard alleyways (2018 and 2019). Plots were created with nonmetric multidimensional scaling. Stress = 0.036 at the Kern site; stress = 0.119 at the Merced site; stress = 0.150 at the Tehama site.



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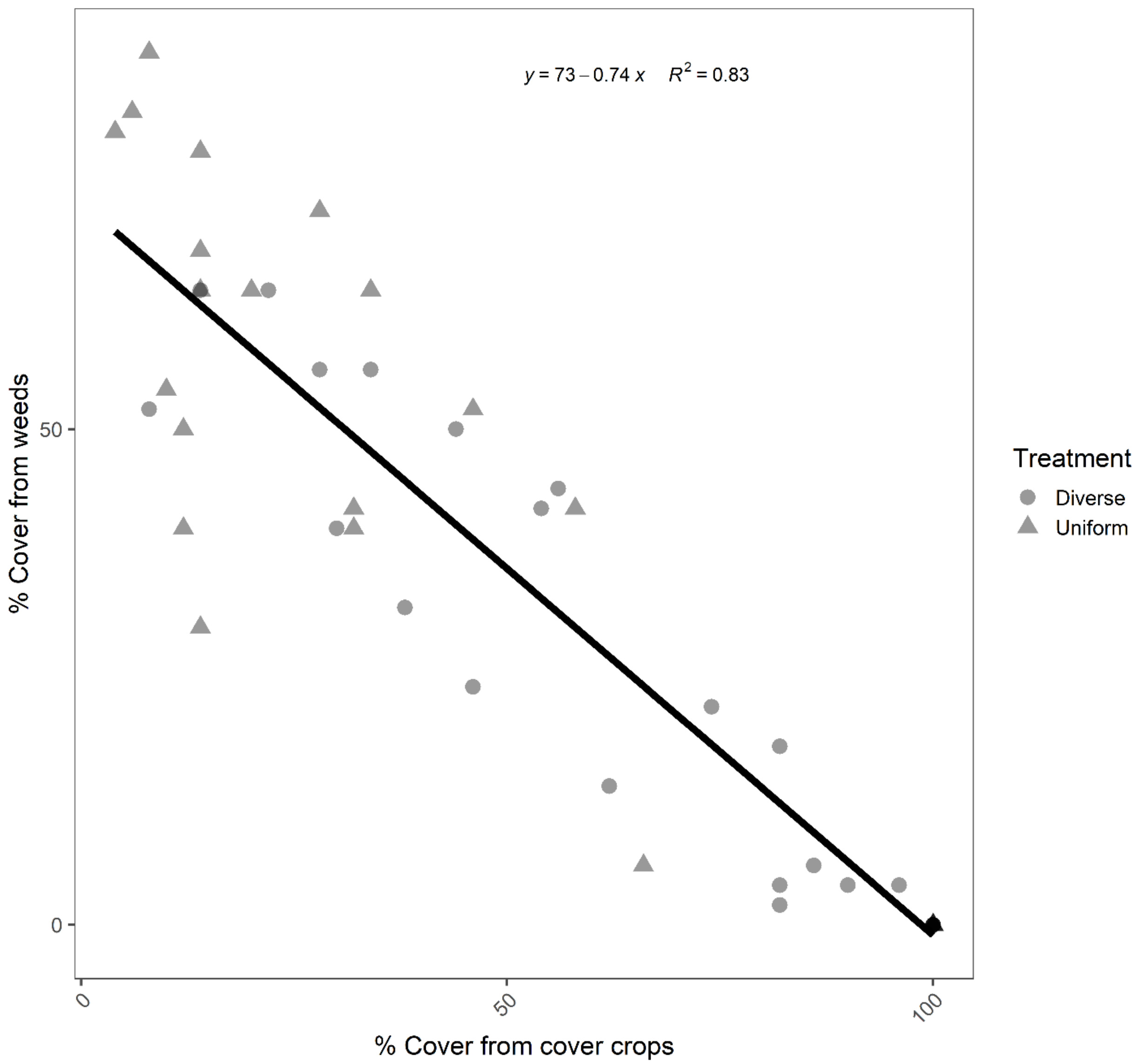

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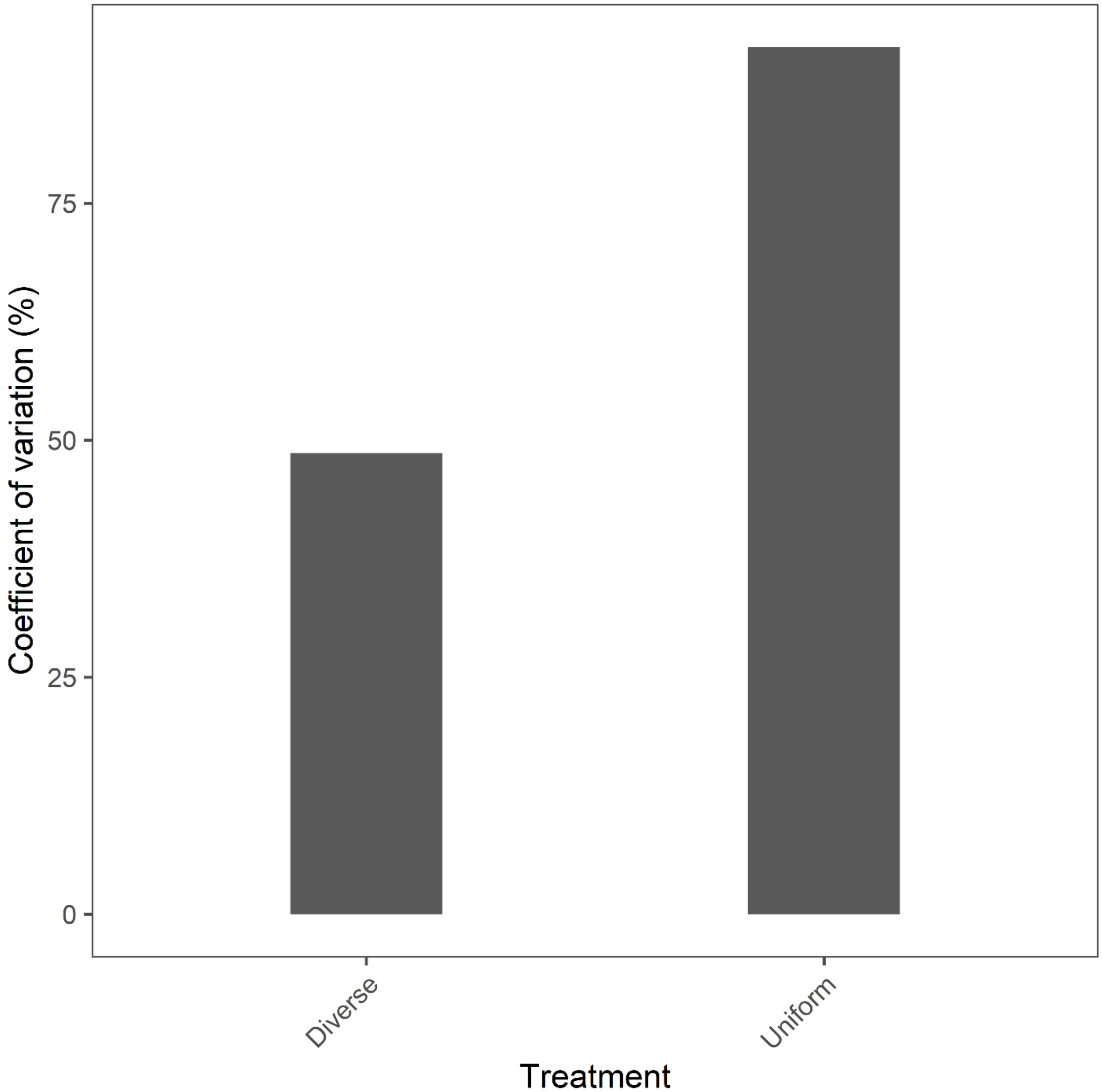

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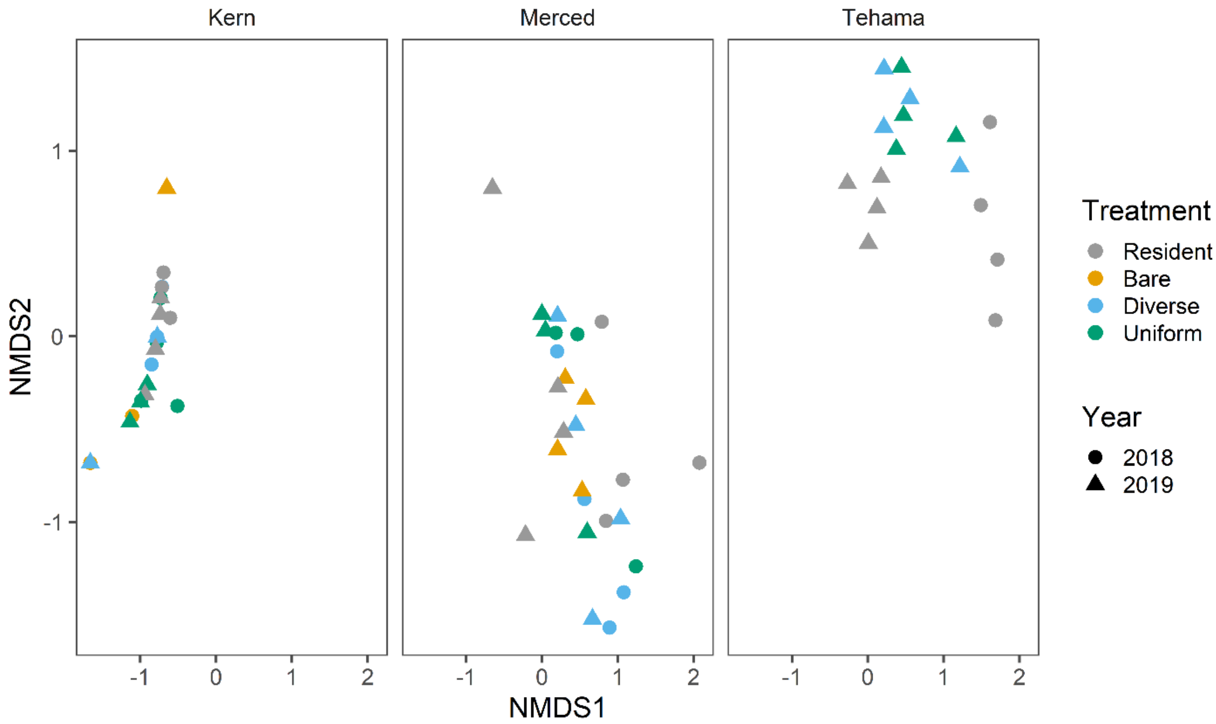

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Agronomic cover crop management supports weed suppression and competition in California orchards

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Abstract. Cover crops enhance the biodiversity of cropping systems and can support a variety of useful ecosystem services including weed suppression. In California orchards, cover crops are typically implemented as annual plants that can replace resident vegetation in orchard alleyways during the rainy winter season. Our research objective was to evaluate cover crop management factors that support a competitive, weed-suppressing cover crop in the unique orchard systems of Central California. We designed two experiments, which included an experiment evaluating cover crop management intensification in walnuts and an experiment evaluating multispecies cover crop mixes and planting date in almonds. These experiments demonstrate that timely cover crop planting is important for producing an abundant cover crop, and a variety of cover crop management programs can produce weed-suppressing cover crops. However, cover crops do not result in weed-free orchards and should be considered within the context of integrated management programs. The apparent flexibility of orchard cover crop management provides opportunity to promote other agroecosystem services, with vegetation management and weed suppression as complementary management goals.

Key words: almonds, walnuts, integrated pest management, ecological weed management, agroecology

Introduction. Sustainable orchard cropping systems require vegetation management programs that produce accessible orchard floors while minimizing management intensity. Orchard systems in California require significant upfront investment that expose orchard growers to heightened risks related to climate change, water scarcity, and land use change compared to more flexible annual cropping systems. Sustainable management systems could reduce risk for orchard growers who manage over 1 million ha of almonds (*Prunus dulcis* (Mill.) D.A. Webb), walnuts (*Juglans regia* L.), stone fruit (*Prunus* spp. L.), and similar orchard crops (Anonymous 2020). Weed management is an important area for orchard sustainability improvements, given that vegetation and vegetation management practices affect many environmental quality parameters across the orchard agroecosystem, including factors such as herbicide use intensity, soil health, water quality, and air contaminants (De Leijster et al. 2019). Rather than seeking vegetation-free orchard floors, growers could potentially cultivate orchard floor vegetation that contributes to ancillary management goals and provides additional ecosystem services (Schipanski et al. 2014).

Cover crops offer flexible management options for creating a functional orchard floor (Brodt et al. 2019). As one cultural management practice within a suite of integrated pest management practices, cover crops can provide a framework for understanding the seasonality and phenology of weed life cycles while also promoting grower acceptance for some level of orchard vegetation (Linares et al. 2008, Ramos et al. 2010). Typically, commercial orchards in California will have a zone of high intensity weed management in a strip centered on the tree row, often 25-50% of the orchard floor, with less intensive weed management in the remainder of the alley between rows (Roncoroni et al. 2017). The high intensity tree strip is maintained to keep weeds from interfering with irrigation infrastructure and minimize non-crop water use in the irrigated area. In crops that are harvested from the orchard floor, which includes many tree nut crops, the alley is generally managed to be weed free ahead of crop harvest in the late summer, where heavy plant residues could impede sweepers and other harvest equipment. Alley management in the winter can vary with grower preferences, but cover crops could easily be implemented in this zone so long as cover crop residues do not affect crop harvest operations. California has mild, rainy winters, which are conducive to cover crop growth. Furthermore, tree nut and stone fruit crops are deciduous, and dormant tree canopies allow ample light to reach the orchard floor throughout the winter, until trees leaf out in mid-February for almonds and later in the spring for other species. Therefore, cover crops in California orchards could have minimal negative impacts on the cash crop if they consist of winter annual plants, since these species have a predictable life cycle that could usually begin with winter rains without supplemental irrigation and ends during hot, dry summers common in the Mediterranean climate of central California.

With this context, winter annual cover crop species could be used to displace winter weeds in orchard alleys. Literature focusing on cover crops and weed management often centers on annual cropping systems, with cover crops growing in the offseason between annual cash crops resulting in temporal separation (Mirsky et al. 2011, 2013, Teasdale et al. 1991). Heavy cover crop residues drive weed control by limiting the emergence of weed seedlings before and during cash crop emergence (Creamer et al. 1996). In contrast, cover crops in orchard systems have spatial separation between cover crops and cash crops, which increases the importance of interference with concurrently growing weeds (Baumgartner et al. 2008). Spatial separation also creates flexibility by reducing restrictions on the cover crop growing season imposed by annual cash crop planting and harvest, and information about the phenology of plant competition could help optimize the management of an abundant, competitive cover crop (Bugg et al. 1996). Finally, California orchards undergo dormant-season management like pruning and orchard sanitation, which could create tradeoffs between these management practices and a winter cover crop. For these reasons, weed-suppressing cover crops require additional research that informs practical management guidelines relevant to orchard systems in this California.

Specific cover crop management recommendations could help growers balance the many functions of cover crops and support various ecosystem services and management goals. Specific management recommendations also support adoption by reducing knowledge barriers of this complex cultural management practice. Would-be adopters of orchard cover crops need to develop a plan that addresses many aspects cover crop establishment and management and acknowledges potential tradeoffs. To address this need, we developed specific questions about cover crop planting date, the phenology of crop-weed competition, and intensified cover crop practices. Research on intensified cover crop management could help us understand how agronomic practices including planting rate, fertilizer or herbicide inputs, cover crop species mixtures, and cover crop termination practices interact with many aspects of agroecosystem function (Finney and Kaye 2017, Romdhane et al. 2019) . Likewise, varied cover crop planting date information helps us understand how cover crop establishment affects cover crop development and when weed competition occur relative to cover crop establishment and the onset of winter rains.

Our objectives were to assess how different aspects of orchard cover crop management affect winter weed management. We evaluated how cover crop management system and planting date impacted cover crop and weed biomass. We also evaluated how cover crop planting date affects cover crop and weed emergence rates. Finally, we evaluated how cover crop management systems differentially affect summer weed emergence through different levels of cover crop residue. Together, these research questions can provide information about to what extent cover crops contribute to overall orchard floor vegetation management and which cover crop management practices have the largest effect on weed suppression.

Materials and methods. We initiated two different experiments to separately examine the effects of intensified cover crop management systems and cover crop planting date in nut orchards. These were small plot experiments in research orchards with commercially relevant cultural practices, including tree spacing, tree strip management, and irrigation. The ‘intensification experiment’ involved a range of cereal rye (*Secale cereale* L.) cover crop management intensities, from minimal management to an intensively-managed forage intercrop, planted in a walnut orchard. The ‘planting date experiment’ involved two different multispecies cover crop mixes each planted at early and late planting dates in an almond orchard. These experiments focused on plant population and community characteristics of orchard floor vegetation in the orchard alleys only.

We used the different orchards as a study system but did not intensively monitor orchard crop performance or yield. We acknowledge that some differences exist in orchard floor light availability between the systems. Namely, almonds maintain a leaf canopy for a greater portion of each year, but the almond orchard in this study was younger with a smaller tree canopy compared to our older walnut orchard. However, the orchard floor environment is generally similar in almond and walnut cropping systems, and each has similar cultural factors including irrigation, alley and strip management, and winter pruning and pest management operations. For cover crops to be a feasible management strategy, they should work in a variety of orchard systems, conditions, and life cycle stages. Therefore, understanding how cover crops influence vegetation management across different orchards is a key aspect of this study. The intensification and planting date experiments were managed independently of one another, but there is a shared treatment to facilitate comparisons between the experiments.

Intensification experiment. The intensification experiment was implemented in an established walnut orchard at the Plant Sciences Field Facility in Davis, CA, USA (38.540343^o N, 121.793977^o W). The orchard was planted in the spring of 2015 with 'Chandler' walnuts. The entire orchard was 0.7 ha in area consisting primarily of Yolo silt loam soils (Mollic Xerofluvents). Orchard management included microsprinkler irrigation and weed-free tree strips maintained with preemergent herbicides.

The experiment was laid out as a randomized complete block design with four repetitions. Experimental plots included the orchard alley between seven pairs of trees, approximately 6 m by 40 m. Cover crop programs were based on cereal rye, since it is known to be a competitive, weed-suppressing species that has desirable termination characteristics (Barnes and Putnam 1983, Teasdale and Mohler 1993). Furthermore, this species thrives under various cultural management conditions and has cultivars that are well-adapted to grow as a winter cover crop in Central California. We used 'Merced' rye, which is a relatively tall cultivar.
The whole experiment was conducted in one orchard over two growing seasons. Cover crops were established in the fall of each year, on November 11, 2019 and November 9, 2020, and terminated in the spring of each study year, on April 24, 2020 and April 9, 2021. Each plot received the same cover crop management program in both years of the experiment. Except for the forage treatment described below, rye was direct-planted with a seed drill at 22.5 kg planted ha^{-1}, and cover crop termination was performed with a flail mower. Planting and termination operations were planned to minimize equipment traffic in the orchard, and only one tractor pass

was made across each orchard alley at each planting and termination date. Flail mowers are practical for cover crop termination in California, since these implements are more common than other cover crop termination tools (e.g., roller-crimpers) and they minimize crop residue ahead of nut harvest.

We had five treatments which represented a range of different cover crop management intensities. The 'sprayed' treatment was used as our nontreated control, and the rye planted in these plots was terminated with a glyphosate application when rye plants reached 5 to 10 cm in height. These burndown applications occurred on January 13, 2020 and January 12, 2021, and included a broadcast application of Roundup WeatherMAX (Bayer Cropscience, St. Louis, MO, USA) at 1.607 L ha^{-1} with a carbon dioxide-propelled backpack sprayer. This treatment mimics a relatively intense commercial management system where orchard alleys are kept weed free. The 'standard' treatment included rye with no other cover crop management until termination. The 'multispecies' treatment included the base planting of rye and several additional cover crop species. The other cover crop species in the mix were c*ommon vetch (Vicia sativa L.)* 4.5 *kg planted* ha^{-1}*, 'PK' berseem clover (Trifolium alexandrinum L.) at* 4.5 *kg planted* ha^{-1}, daikon radish (*Raphanus sativus L.) at 2.25 kg planted* ha^{-1}, and 'Braco' white mustard (S*inapis alba* L.) at 2.25 kg planted ha^{-1}. These seeds were broadcast spread immediately before rye was planted. We used these methods to establish the sprayed and multispecies treatments to minimize logistical challenges and orchard traffic, while also relying on the tractor and seed drill to enhance seed-to-soil contact of our additional cover crop species in the multispecies treatment. The multispecies treatment in this experiment has the same species and approximate planting rates as the multispecies mix in the planting date experiment described below.

The ‘boosted’ treatment included a 45 kg ha^{-1} N topdress with granular urea after rye tillering which were made on February 25, 2020 and February 26, 2021. The ‘forage’ treatment was managed as a rye hay intercrop. This treatment was planted at a rate of 45 kg planted ha^{-1}. At planting, we fertilized with 40 kg ha^{-1} N and 28 kg ha^{-1} P as granular urea and monoammonium phosphate at planting. We also topdressed with 45 kg ha^{-1} N after rye tillering. On the same day as topdressing, we broadcast-applied carfentrazone (Shark EW, FMC Corporation, Philadelphia, PA, USA) at 73 mL ha^{-1} with a backpack sprayer as a postemergent herbicide application for broadleaf weed control. The topdress and herbicide applications were applied on February 25, 2020 and February 26, 2021. The forage treatment was terminated with a swather, and the crop material was subsequently baled and removed.

Immediately before cover crop termination, we destructively sampled cover crop and weed biomass. We collected biomass samples from two 0.25 m^2 quadrat subsamples in each plot. Cover crops and weeds were separated before being dried in forced air drying ovens. Finally, we weighed dry plant biomass. Summer weed emergence was assessed after cover crop termination using point intercept transects. One transect was placed diagonally across the alley in each plot. Transects were 25 m long with 25 points spaced evenly along the transect. Plants were identified visually at each point. These summer weed transects were performed on June 17, 2020 and May 21, 2021, when summer weed emergence and potential cover crop regrowth might be scouted by a grower planning summer weed management.

Planting date experiment. The planting date experiment was implemented in a nonbearing almond orchard at the Wolfskill Experimental Orchard near Winters, CA, USA (38.504788^{o} N, 121.978657^{o} W). The orchard was established in the fall of 2017 with alternating rows of

'Nonpareil' and 'Aldrich' almonds. The entire site was about 1.1 ha in area with primarily Yolo loam soils (Mollic Xerofluvents). Orchard management included microsprinkler irrigation and weed-free tree strips treated with preemergent herbicides.

The experiment was laid out as a randomized complete block design with five repetitions. Experimental plots were roughly 25 m long and 12 m wide, comprising five trees in length and two orchard alleys in width. We had five treatments, including a nontreated control and two multispecies cover crop mixes each planted at two different planting dates. The nontreated control had commercial standard vegetation management practices, which included several glyphosate applications throughout the winter months. We used cover crop mixes in this experiment because of their existing use by California orchard growers (Ingels et al. 1994). Orchard growers frequently choose among cover crop mixes that support a variety of ecosystem services aside from vegetation management, such as pollinator health or improved soil structure, and multispecies cover crops can support some of these multifunctionality goals. Additionally, using different cover crop mixes allowed us to evaluate cover crops with different germination timings and a range of emergence phenologies.

The two cover crop mixes used in this study were a 'multispecies' mix and a 'brassica' mix. The multispecies mix used the same species as the multispecies treatment in the intensification study, and it included a common combination of cover crop functional groups including a small grain, legumes, and mustards (Altieri et al. 2011). The mix consisted of 10% 'Braco' white mustard, 10% daikon radish, 30% 'Merced' rye, 20% 'PK' berseem clover, and 30% common vetch planted at 56 kg planted ha^{-1}. The brassica mix is used commercially in California through the Project Apis m. (Salt Lake City, UT, USA) 'Seeds for Bees' program. It consisted of 35% canola *(Brassica napus L.),* 15% 'Braco' white mustard, 15% 'Nemfix' yellow mustard (*Brassica juncea* (L.) *Czern.*), 20% daikon radish, and 15% common yellow mustard (*Sinapis alba* L.) at 9 kg plant ha^{-1}.

Each of the cover crop mixes was planted at a relatively early planting date and a late planting date. These dates were chosen to represent a timely cover crop planting soon after nut harvest and coincidental with the onset of winter rains as well as a later cover crop planting coincidental with nut pruning, sanitation, and other winter management activities. This experiment was conducted in one orchard over three growing seasons. The early planting date occurred on October 15, 2018, October 24, 2019, and November 9, 2020. The late planting date occurred on January 31, 2019, February 10, 2020, and January 21, 2021. Cover crops were direct-seeded with a conventional grain drill. Ground preparation occurred before each planting date. Before the early planting date, the whole orchard (i.e., all treatments) received light tillage immediately before a glyphosate burndown. Before the late planting date, late planted plots and the nontreated control received an additional glyphosate burndown but no additional soil disturbance. Cover crops were terminated with a flail mower on April 19, 2019, April 27, 2020, and April 22, 2021.

Weed emergence was monitored throughout the cover crop growing season using permanent point intercept transects. Each plot had one transect placed diagonally across one orchard alley. Each transect was 10 m long with 10 points along the transect. Plants were identified at each point along the transect, and monitoring took place weekly while cover crops were growing. This experiment did not have different residue management treatments, so summer weeds were not evaluated. Immediately before cover crop termination, we sampled cover crop and weed biomass using the methodology described above, including two 0.25 m^2 quadrat subsamples in each plot.

Data analysis. Analyses were performed in R 3.0.3 (R Core Team 2020). For biomass data from both experiments, we used ANOVA and performed multiple comparisons with Fisher's LSD. ANOVA was performed by specifying a model with *lm* and entering it into *Anova* from the *car* package (Fox and Weisberg 2019, 2019). The models we used had treatment, replicate, and their interaction as predictors and either weed biomass or cover crop biomass as a response variable. We inspected ANOVA assumptions visually using *plot*. Subsequently, weed biomass from the intensification experiment was analyzed with one outlier removed and a square root transformed response variable due to leptokurtosis. However, unabridged and non-transformed data are displayed in the figures. Finally, we performed Fischer's LSD with *LSD.test* from *agricolae* using a significance level of $P<0.05$ (Mendiburu 2020). Summer weed emergence data were analyzed in the same manner but using cover crop regrowth and summer weed emergence as response variables.

Weekly transect surveys were analyzed with multiple linear regression. We compared the slope of each regression line in to evaluate the relative rates of weed and cover crop emergence after each plant date. Cover crop emergence was represented as the change in ground cover as observed in weekly observations throughout the first ten weeks following the respective planting date of each treatment. There was only one nontreated plot in each repetition, and we evaluated groundcover following both the early and late planting dates in the same nontreated plots. Weed and cover crop emergence were modeled as functions of treatment, weeks after respective planting, and their interaction. These linear models were created using *lm*. We created additional linear models using other possible combinations of predictor variables and compared these various models using *anova*. However, we determined the model described above to be the most parsimonious. Parameter estimates for the slope of each line were compared with Tukey's HSD using *lstrends* from the *emmeans* package (Lenth 2021). All figures were made with *ggplot2* (Wickham 2016).

Results and discussion. In the intensification experiment, cover crop biomass varied with management treatment (P<0.001; figure 4.1). While year was not a significant predictor of cover crop biomass (P=0.551), we detected an interaction between year and treatment (P=0.058). Furthermore, multiple comparison testing led to different conclusions from each year of the intensification experiment. With data pooled across years, the forage and boosted treatments resulted in higher cover crop biomass than multispecies or standard treatments. Within each year, the boosted treatment alone resulted in the highest cover crop biomass in 2020, while the forage treatment did so in 2021. Cover crop treatment (P<0.001) and year (P<0.001) both predicted weed biomass. The interaction term was also important (P=0.035).

In general, the four cover crop programs resulted in less weed biomass compared to the sprayed treatment and similar weed biomass compared to each other. This conclusion was supported in both years of the study, but we observed less weed biomass overall in 2021. Intensified cover crop programs can increase cover crop biomass, but all of the cover crop programs we tested were similarly effective at reducing weed biomass. Less rainfall in 2021 could have contributed to differences between study years, and we attribute some decrease in boosted cover crop biomass to dry conditions after topdress fertilizer application which likely caused a reduction in plant-available nutrients from the applied fertilizer. Some cumulative effect of two years of cover cropping could have also contributed to these results.

In the planting date experiment, cover crop biomass varied with cover crop treatment ($P<0.001$; figure 4.2). Year was not significant ($P=0.356$), but the interaction between treatment and year was ($P<0.001$). In 2019 and 2020, the early planting treatments resulted in higher cover crop biomass than the late planting treatments. Differences between cover crop treatments were greatest in 2020, and the multispecies mix also resulted in greater cover crop biomass compared to the brassica mix in this year. There were no differences in cover crop biomass between treatments in 2021. Year ($P<0.001$), treatment ($P<0.001$), and their interaction ($P<0.001$) all contributed to weed biomass. While we observed a lot of year-to-year variation, the late-planted multispecies treatment was consistently in the lowest statistical group for weed biomass, and the early-planted brassica treatment was consistently in the highest group.

Based on the planting date experiment, early cover planting results in a consistently more abundant cover crop. Winter rainfall is increasingly variable in California, and the late planting date subjects the cover crop to additional uncertainty in rain timing and quantity. This issue was evident in 2020, where the late cover crop planting had to be delayed due to wet conditions in January but subsequently received little rainfall after planting and ultimately produced relatively low biomass. The late planting date sometimes was associated with reduced weed biomass, which we attribute to the extra burndown herbicide treatment ahead of late planting. While an extended cover crop growing season may contribute to cover crop abundance and consistency, it also precludes other weed management practices and therefore effectively extends the weed growing season. Likewise, the multispecies cover crop had more consistent biomass compared to the brassica cover crop across year and planting date, but this was not always reflected in consistent reductions in weed biomass.

The multispecies cover crop mix emerged more quickly than the brassica mix, and this effect was similar following both the early and late planting date (figure 4.3). This effect could be related to certain component species in the multispecies mix that were particularly quick to emerge. In nontreated plots, where cover crops were not planted, weed emergence rates were similar after both early and late planting dates. However, when cover crops were present, weed emergence was generally slower after the late planting date, especially in plots seeded with the brassica mix. Weed emergence rates after the late planting could have been affected by existing weed cover at time of late planting, due to continuous weed germination and a slow-acting burndown herbicide prior to the late planting date. Variations in weed emergence could additionally contribute to reductions in weed biomass from late planted treatments. Overall, the multispecies cover crop had faster emergence than weedy plants, and the brassica cover crop had similar emergence rates with weedy vegetation. However, quicker emergence did not always lead to enhanced weed suppression, which is consistent with previous studies that suggest that biomass, rather than functional diversity, is the most important factor in weed suppression (Smith et al. 2020). While cover crop mixes did not reliably slow weed emergence in this study, their germination uniformity and predictable emergence could make them a useful management tool compared to less predictable weedy vegetation.

Summer weed cover was affected by cover crop treatment in the intensification experiment ($P<0.001$; figure 4.4). The sprayed and forage treatments had similarly increased levels of summer weed coverage compared to the three cover crop treatments that left residues in place, which were similar to one another. These results indicate that cover crop residues suppress summer weed emergence compared to treatments without any cover crop or where cover crop residues have been removed through baling. Cover crop literature in annual cropping systems supports the value of cover crop residue for reducing summer weed emergence (Bybee-Finley et al. 2017, MacLaren et al. 2019). In perennial systems, the spatial separation of the cover crop from the primary crop provides additional options for cover crop termination, including flexibility related to timing, repeated termination actions, and termination equipment. Future research could focus on these under-explored aspects of cover crop management in perennial cropping systems, such as by focusing on high-residue termination methods such as roller-crimpers or delayed cover crop termination in the early summer.

In this study, we observed that cover crops are not consistently effective as a weed control tool compared to weed management programs with repeated herbicide applications, but they continue to demonstrate value as component of an orchard vegetation management program. Such vegetation management programs allow some plant growth on the orchard floor but result in predictable plant cover and favorable orchard floor conditions for nut harvest. Orchard cover crops flourished under a variety of management programs but were most abundant with timely planting and adequate moisture during establishment. We worked in orchards that had not previously been managed with cover cropping, and any effects of cover crops on weeds could compound over the lifecycle of orchard, possibly mediated through processes like depletion of weed seed banks or weed community filtering. Increased understanding of the broader contributions to ecosystem services, such as soil health and agroecosystem resilience, can enhance the benefit of cover crops and make them an attractive component of integrated orchard management systems.

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Figure 4.1. Cover crop and weed biomass across a range of cover crop management intensities. Bars represent the mean value of points. The sprayed treatment was planted with a cover crop but treated with a postemergence herbicide following cover crop emergence and served as a nontreated control. The least signifcant difference for crop biomass was 324.6 g m^{-2} in 2020 and 376.2 g m^{-2} in 2021. The least signficant difference for weed biomass was 357.5 g m^{-2} in 2020 and 52.6 g m^{-2} in 2021.

Figure 4.2. Cover crop and weed biomass associated with two multispecies cover mixes each planted at timely and delayed planting dates. Bars represent the mean value of points. The least significant difference for crop biomass was 521.0 g m^{-2} in 2019, 317.4 g m^{-2} in 2020, and 320.4 g m^{-2} in 2021. The least significant difference for weed biomass was 154.1 g m^{-2} in 2019, 244.3 g m^{-2} in 2020, and 83.9 g m^{-2} in 2021.

Figure 4.3. Rates of cover crop and weed emergence, expressed as changes over time in relative groundcover after respective cover crop planting date. Relative cover is based a range from 0 (no ground coverage) to 10 (complete ground coverage). Regression lines were created with linear regression.

Figure 4.4. Summer weed emergence following cover crop termination across several levels of cover crop management programs. The sprayed treatment was planted with a cover crop but sprayed with a burndown herbicide following cover crop emergence and served as a nontreated control with no cover crop residue. The standard, multispecies, and boosted treatments were all terminated with flail mowing, while the forage treatment had residues removed. Cereal rye was

associated with cover crop regrowth. Cover crop incidence is a range from 0 (no ground coverage) to 100 (complete ground coverage). The least significant difference was 4.5 points of relative cover.

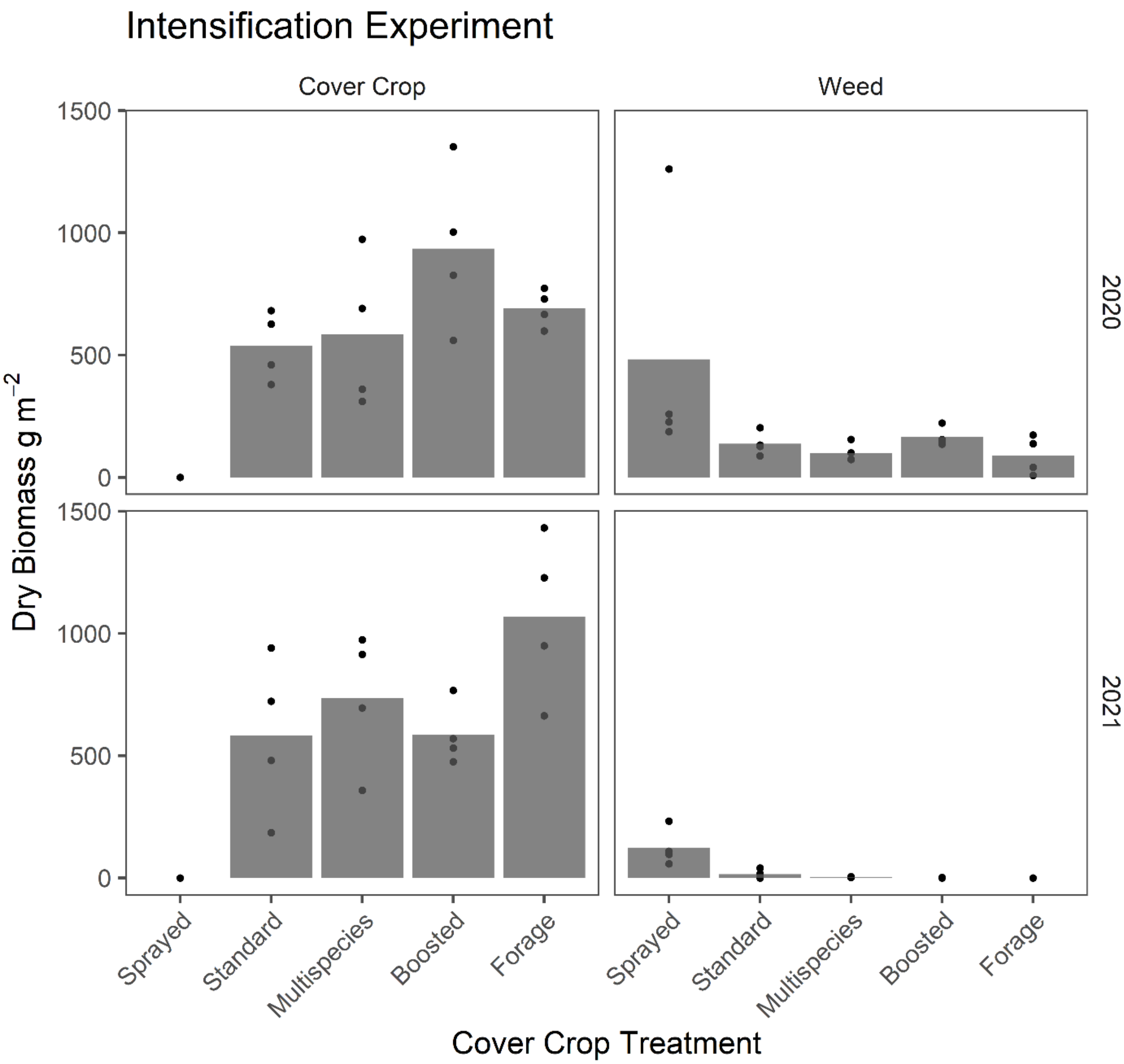
Intensification Experiment
Cover Crop
Weed
2020
2021
Dry Biomass g m−2
0
500
1000
1500
Sprayed
Standard
Multispecies
Boosted
Forage
Cover Crop Treatment

Figure 4.1

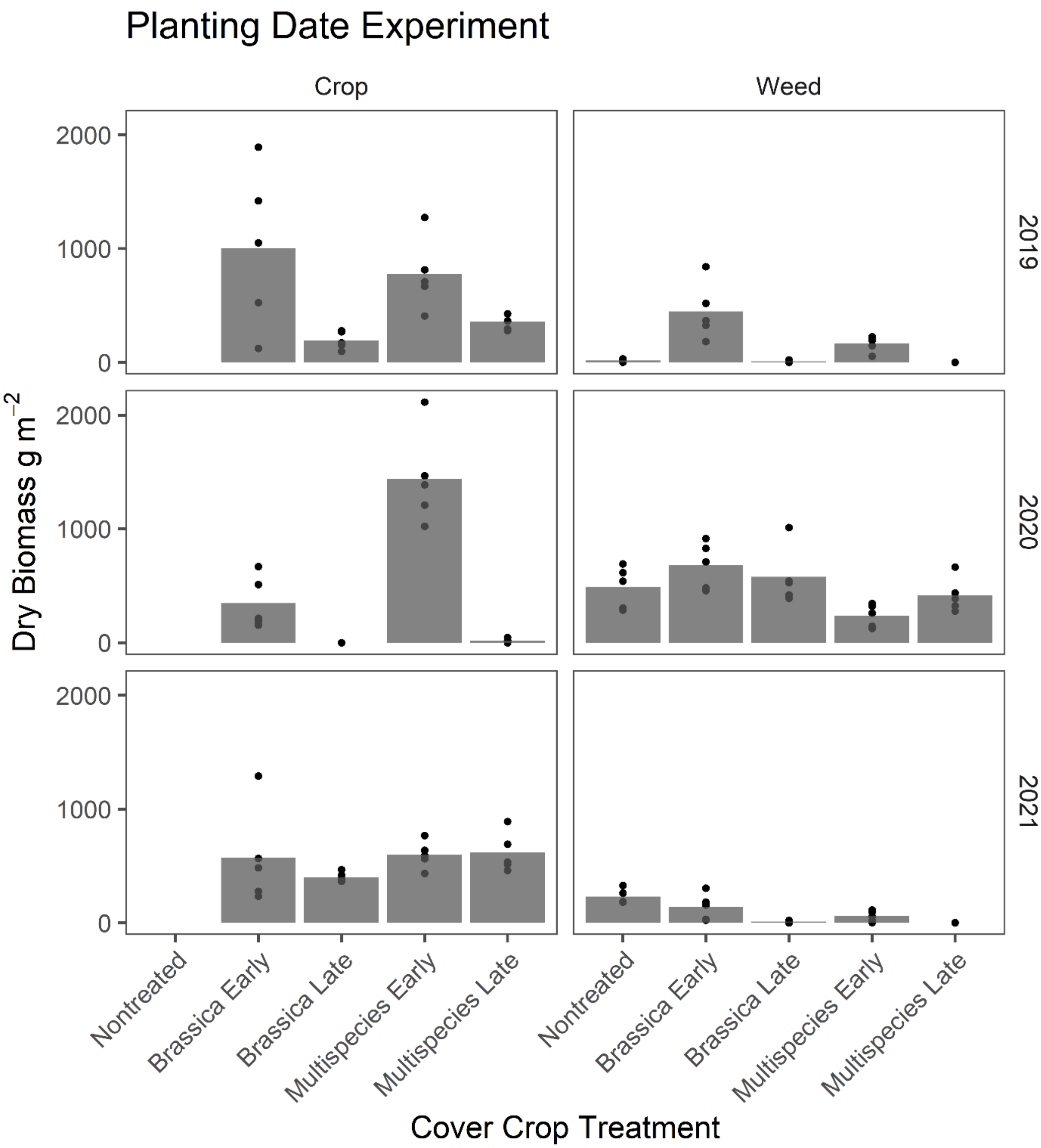
Planting Date Experiment
Crop
Weed
2019
2020
2021
2000
1000
0
Dry Biomass g m^-2
Nontreated
Brassica Early
Brassica Late
Multispecies Early
Multispecies Late
Cover Crop Treatment

Figure 4.2

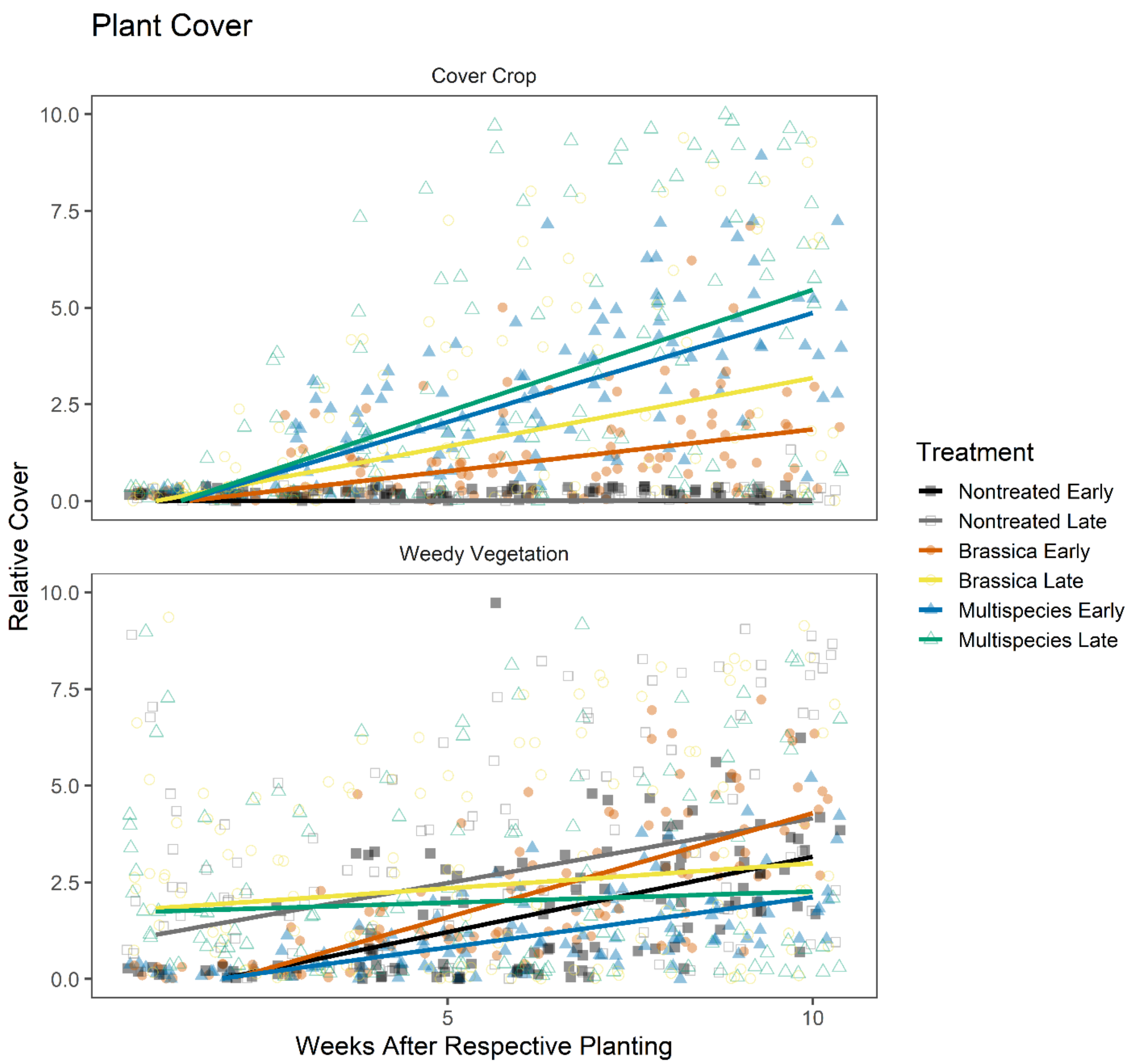
Plant Cover
Cover Crop
Weedy Vegetation
Relative Cover
10.0
7.5
5.0
2.5
0.0
5
10
Weeks After Respective Planting
Treatment
Nontreated Early
Nontreated Late
Brassica Early
Brassica Late
Multispecies Early
Multispecies Late

Figure 4.3

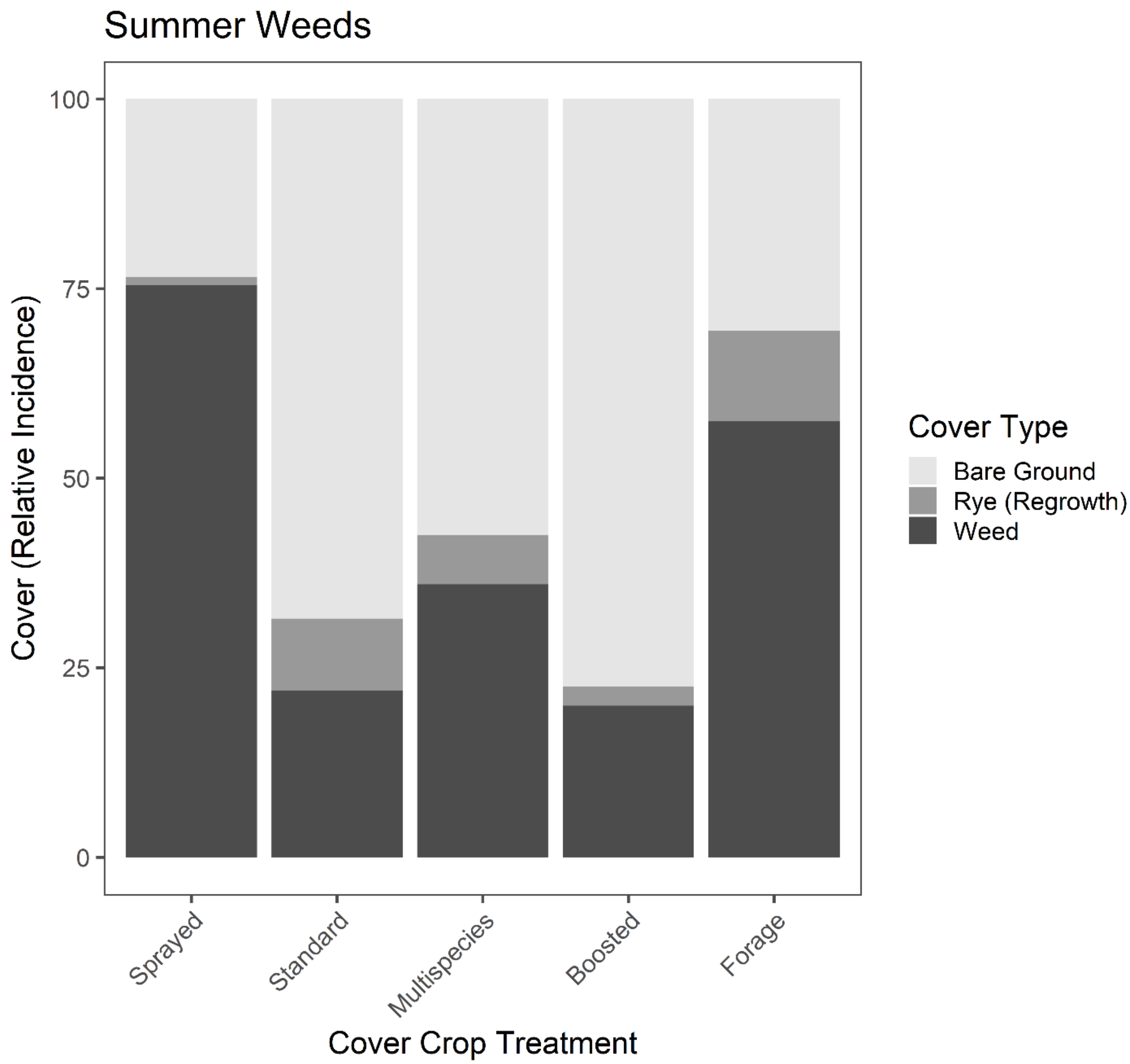
Summer Weeds
100
75
50
25
0
Cover (Relative Incidence)
Sprayed
Standard
Multispecies
Boosted
Forage
Cover Crop Treatment
Cover Type
Bare Ground
Rye (Regrowth)
Weed

Figure 4.4