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Using stakeholder-based fuzzy cognitive mapping to assess benefits of restoration in wildfire-vulnerable forests

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Abstract. Understanding the benefits provided by restoring overstocked forests is crucial to guiding the choice of management actions, policy initiatives, and investments by beneficiaries, i.e., monetizing ecosystem services. Using stakeholder-based fuzzy cognitive mapping, collected through workshops with natural-resource professionals, we mapped the interactions of ecosystem services and the perceived effects of management actions on them. In line with current concerns in the California study area, we found that fire protection was perceived as central (i.e. having a high degree of congruence with other ecosystem services) with improved fire protection providing important secondary effects on other ecosystem services, notably air-quality protection, provision of habitat, and carbon storage. Forest restoration involves multiple fuels-reduction actions, which were perceived as benefiting fire protection, with subsets also offering strong benefits to other ecosystem services. Prescribed burning, defensible-space creation, understory thinning, and replanting showed particularly large differences in effects when accounting for interactions of ecosystem services. Resource managers and other non-manager professionals prioritized similar ecosystem services, with the second group placing more importance on interactions between different ecosystem services. Ecosystem-service valuation that includes interactions offers a salient, credible, and legitimate approach to inform multi-benefit forest management, particularly where partnerships must monetize some of those benefits to finance critical landscape restoration.

Keywords: California, Cognitive mapping, Ecosystem services, Stakeholder perception, Wildfire

Implications for practice

- California's wildfire-vulnerable forests should primarily and urgently be restored to conditions that better regulate wildfire severity, and thus provide greater fire protection and other ecosystem-service benefits. Lower-severity wildfire is a natural and beneficial part of these ecosystems.
- Mechanical thinning of overstocked forests, prescribed burning, and managed wildfire now being carried out to enhance fire protection of the forests are perceived as effective; and have interaction effects on other important ecosystem services.
- Given the complexity of forest ecosystems across the western United States, the investments required, and the management constraints, a range of actions is needed to increase the resilience of forests. Accounting for perceived interactions of ecosystem services can support multi-benefit valuation of restoration investments.

Introduction

Forested ecosystems are increasingly recognized as important providers of multiple benefits, rather than perceived solely as timber-production systems (Sheppard et al. 2020). For productive, wildfire-vulnerable forests in the western United States these benefits are wide ranging and include regulating air quality and natural hazards, providing fresh water, recreation, and others (Deal et al., 2017). Managing forests for multiple benefits can improve ecological resilience (Kessler et al. 1992), facilitate inclusion of marginalized voices in decision making (Farley 2012), and monetize benefits to help pay the costs of management (Engel & Ovando 2019). Making explicit the multiple benefits from forest management beyond maximizing timber production can also help managers achieve an optimal outcome across the multiple ecosystem services that forests can provide (Turkelboom et al. 2018; Hirsch et al. 2011: Sheppard et al. 2020). A multi-benefit approach also recognizes ecosystems as natural capital, whose capacity and capability to deliver benefits that humans get from nature – ecosystem services (Millennium Ecosystem Assessment 2005) – depends on the state of these natural assets (Mace 2019).

While perceived to generate additional economic, ecological, and social outcomes (Lemos & Agrawal 2006; Tallis & Polasky 2009; Kaplan-Hallam & Bennett 2018), forest restoration for multiple benefits requires that managers measure and resolve trade-offs resulting from different actions. California provides a clear example of the complexities of decision making within a multi-benefit forest-restoration framework. Roughly 38 percent of the state's 40 million hectares is forest or woodland vegetation (Dolanc et al., 2016). Many of California's forests are overstocked and face threats of both high-severity wildfire and drought-induced stress that can result in tree mortality (Goulden and Bales, 2019). This is due to a warming climate and fuel buildup resulting from a century of fire suppression and the cessation of indigenous burning (Abatzoglou et al. 2021). California is also experiencing an increase in the extent and severity of wildfires across all forests, making fire protection through a reduction in fuel loads a priority (Goss et al. 2020). In addition, about 50% of the state in public ownership, with forests being a patchwork of public and private land, contributing to heterogeneous expectations for the provision of benefits (Prichard et al. 2021). The way the forest is managed and the expected outcomes on public lands are key to natural-resource management, especially relating to equity and environmental justice. For example, rural communities in and near the forests, as well as other property-rights holders, are at risk from high-severity wildfire; and the general public values the improved air quality, recreation, habitat, and other benefits that deteriorate when wildfire severity increases. The need to restore forests for different benefits and associated beneficiaries is important; and several restoration projects are ongoing in California. However, the pace of this restoration is slow for several reasons, including the high cost of restoration.

Given the high cost of restoring millions of hectares of overstocked and degraded lands, the state is seeking to address the multi-billion-dollar challenge of bringing forests to more-sustainable conditions in part through partnerships between land managers and other beneficiaries (Edelson & Hertslet 2019), leading to payments for forest ecosystem services (Wunder et al. 2018). New governance systems are also emerging where federal land-management agencies are the recipients of direct or indirect payments, providing an important policy tool for resolving government and market failure to account for ecosystem-service losses due to land-management policies and short-term budgeting decisions (Miller et al. 2017). While many ecosystem benefits are non-excludable, market instruments can be developed for others (Cubbage et al. 2007; Farley 2012), but the first step is to understand the benefits from different management actions. It is also important to recognize that ecosystem services are socially co-produced by the actions of humans rather than simply flowing from a natural asset (Depietri & Orenstein, 2019). Restoration actions are thus key to regulating the magnitude of ecosystem-service flows, which can result in direct benefits to different beneficiaries. One way of generating funds to support and sustain restoration is through a multi-benefit approach that can engage beneficiaries as partners in financing restoration. However, the challenge arises when an action affects the value of one benefit with trade-offs across multiple ecosystem services. These trade-offs can also have feedbacks that enhance or diminish the magnitude of the change in the original benefit. Novel methods for quantifying such trade-offs from different restoration actions are needed to inform managers on which actions to take and which beneficiaries to approach for financing restoration.

While the ecosystem-services framework (Carpenter et al. 2009, Haines-Young & Potschin 2016) provides a categorization of the benefits humans get from nature (Millennium Ecosystem Assessment 2005, Diaz et al. 2015), it does not establish measurement methods. This has led applications to vary considerably across academic disciplines, management sectors, and geographical scales (Schröter et al. 2018). Moreover, the literature is also divided on accounting for complexity, as some approaches focus on larger-scale but generalized measurements, while others build on detailed, but context-dependent process-based modeling (Reyers et al. 2013; La Notte et al. 2017). The lack of a consistent methodology is particularly problematic in managing forests for multiple benefits, as trade-offs often transcend traditional management aims, leaving some forest managers without tools to effectively gauge the outcomes of potential restoration actions (Hirsch et al. 2011; Turkelboom et al. 2018). The knowledge and experience of relevant stakeholders has been used to account for complexities involved in restoring forests (e.g., interactions, trade-offs, feedbacks, heterogeneity) while producing a synthesis in a general and scalable format (Drescher et al. 2013). Expert-assessment has been shown to aid in estimating stakeholder-specific or hard-to-measure concepts such as non-material values (Small et al. 2017; Balázsi et al. 2021), producing accurate estimates of physical measurements (van Houtven et al. 2014; Roche & Campagne, 2019).

The broader aim of the research reported here was to assess how a multi-benefit framework can help guide and facilitate investments by beneficiaries in forest restoration involving fuels reduction. Three specific objectives concerning how restoration impacts the multiple benefits of forest management in California guided our research. First was to identify the main interactions between benefits, as perceived by expert stakeholders. Second was to understand the expected outcomes of different management actions, given these interactions. Third was to assess differences in perception between stakeholder groups (forest managers versus non-manager resource professionals).

Methods

We developed data through online workshops with expert stakeholders in order to explore interactions between ecosystem services, as well as how these stakeholders perceive the impact of different management actions given their perceptions of interactions. We used fuzzy cognitive mapping to examine direct and indirect benefits from different management actions as perceived by the stakeholders, to gain insight about trade-offs.

Study area. California's Mediterranean climate, with cool-wet winters followed by warm-dry summers, creates conditions conducive to wildfire; and prior to the large in-migration and displacement of native Americans in the mid to late 1800s, forests depended on lightning-caused and prescribed fire to control both fuel loads and evaporative demand. Recent mapping shows 21% of the state in deciduous, evergreen, or mixed forest (National Landcover Data Set, Figure 1), a number that has declined in recent decades as forests burn and are subject to type conversion (North et al. 2021). The annual area burned, and fire severity, have increased in recent decades due to fuel accumulation and longer fire seasons (Westerling et al., 2006). In California, the U.S. Forest Service estimates that of the 8.1 million hectares it manages, 30-45 percent need immediate restoration (Bales and Conklin, 2020). Recognizing the ecosystem benefits of fire, federal forest managers have managed rather than suppressed some wildland fires, contributing to restoration (Collins et al. 2009). However, broader application of mechanical treatments (e.g., thinning, masticating) and prescribed fire are needed to reduce fuel levels and thus reduce projected fire severity and transition to greater future use of managed wildfire (Stephens et al. 2012).

Data collection. During fall 2020 to spring 2021, we conducted ten stakeholder workshops with natural-resource professionals in California. We recruited participants through an online survey, distributed through snowball sampling within networks and organizations working with natural resources in the state. Snowball sampling is method of chain referral where a base of initial contacts refers others in their network. This method has been observed to increase response rates and improve sample representativity when studying less-well-defined populations (Wright and Stein 2005). Out of 216 survey respondents, 60 volunteered to participate and 32 of these volunteers took part in the workshops. All respondents were currently active natural-resource professionals working in the state, with approximately half of the group being forest managers with responsibility for on-the-ground management and half being researchers or other professionals with a close relationship to the management and use of California's natural resources. These groups are key to implementing the state's multi-benefit forest restoration. Each participant attended one of the ten identical workshops, which were conducted through Zoom and had a duration of 60 minutes. During the first 10 minutes of each workshop participants were introduced to the broader context of ecosystem services associated with natural-resource management in California. Participants were then instructed (10 minutes) in use of the Mental Modeler software (available at www.mentalmodeler.org) and prompted to produced two mental maps (15 minutes each), during which time members of the research team were available to answer questions. The last 10 minutes of each workshop was open discussion.

Mapping exercises. Elicitation methods reported in the literature vary, with participants either given a predetermined set of concepts or allowed to create their own concepts (Hobbs et al. 2002; Gray et al. 2015). A map can be created through collective discussion and collaboration, through aggregation of multiple individual maps, or through researcher coding of qualitative data (Gray et al. 2015). We turned to fuzzy cognitive mapping to aid in making quantitative comparisons, including accounting for indirect effects. The Mental Modeler software generates semi-quantitative concept maps that describe how individuals or groups perceive reality (Gray et al. 2015) and can provide quantitative comparisons (Ozesmi & Uygar 2004). The maps show structural relationships between concepts, making them particularly useful when studying processes involving complex processes and interactions (Jones et al. 2011).

In each of the two tasks respondents were instructed to draw connections between concepts and assign each connection a numeric weight, ranging from -1 to 1, indicating the direction and strength of that connection. The first task involved mapping interactions between ecosystem services. That is, when an ecosystem service changes, regardless of the action causing the change, it affects other ecosystem services. The weights (-1 to 1) reflect these perceived effects. Participants were given a file containing the ecosystem services listed in Table 1, excluding sense of place, and were instructed to indicate the extent to which they saw positive or negative net interactions between them. Sense of place was excluded from the first task to reduce task complexity. For the second task participants were given a file containing both the management actions and ecosystem services listed in Table 1, with instructions to draw directional connections going from management actions to ecosystem services, signifying their perception of the impact of management actions on the measured ecosystem services. The maps were combined to show direct and indirect effects.

Measurements and measures. The ecosystem-service measurements used in this study were derived from the Millennium Ecosystem Assessment (2005) and subsequent literature; and were selected by forestry and water-management experts within the project team for their relevance to forest management in California (USDA Forest Service 2018). While 10 of the 11 services in Table 1 are adapted from the Millennium Ecosystem Assessment, fire protection is an important addition. Fire protection is the capability that both ecosystems and landscapes have in regulating fire through managing attributes that determine fire behavior and effects (Sil et al. 2019). It has been noted by others that ecosystem services for fire regulation are rarely accounted for in the literature, and generally excluded from ecosystem-service classifications (Depietri & Orenstein, 2019; Sil et al., 2019). While wildfires can be destructive disturbances, beneficial wildfire enhances many other provisioning, regulating, and cultural ecosystem services (Pausas & Keeley, 2019). Thus, the ability of forests across California and elsewhere to provide beneficial rather than destructive wildfire protects and enhances the values of multiple services.

We explained ecosystem services to participants in a way that retained as clear a logical connection between management actions and their impacts as possible. While terms used in our survey may differ slightly from those appearing in some references, the services remain the same. For example, air-quality regulation was referred to as "air quality." While we did not explicitly identify ecosystem services over time in our data collection, it was implicit in the mapping exercise. All participants are aware of forest ecosystems changing following disturbance, including restoration.

Analysis. After data collection, the two mental maps created by each participant were aggregated into a single weighted (-1 to 1 scale) adjacency matrix. To explore potential structural differences in perceptions of ecosystem services by the two subgroups, we created three aggregated maps by calculating mean effects for ecosystem-service interactions and management effects (Ozesmi & Uygar 2004), one for managers with responsibility for on-the-ground management, one for non-managers, and one for all participants. The subgroups were only used when analyzing ecosystem-service interactions.

We analyzed the structural makeup of the aggregate maps using simple graph-theory tools, such as examining the number of variables in a map and the number of connections between them. In addition, we calculated network density (number of connections drawn divided by number of possible connections) indegree (the summed weights of connections going into a node), and outdegree (the summed weights going out of a node) and centrality (the absolute sum indegree and outdegree for a node). Since management actions were transmitter nodes by design, nodes were not classified into types (Ozesmi & Uygar 2004). Relative impacts of management changes were calculated using the scenario tool provided in the online mental modeler. After combining the data into a single network, the effects of an increase in management action (+1) were calculated conditional on the underlying network structure, by intensifying the use of each management action while keeping the others constant (using the hyperbolic-tangent setting).

Results

Ecosystem-service interactions. Each of the 32 participants was first asked to assign weighted connections between 10 predetermined ecosystem services (Table 1), resulting in 32 individual maps, each having 10 components and a potential maximum of 90 connections. The group-level averaging of the network data across all respondents had the largest number of connections (83) and the largest density (0.92), while the group map of the 15 participants classified as on-the-ground managers had a slightly lower number of connections and density than did the map for the 17 non-managers (Figure 2).

All nodes had both outgoing and ingoing connections. The averages across all respondents show fire protection perceived as the most central concept in the map, with a centrality score of 2.21 (Table 2). Fire protection also had a comparatively high outdegree rating (1.62) compared to indegree (0.59), perceived as more of a transmitter (affecting other nodes) than receiver node (affected by other nodes). Other central components were water supply and provision of habitat, with centrality scores of 1.88, and soil retention (centrality 1.80). Water supply and soil retention had higher outdegree values, with provision of habitat having a higher indegree than outdegree value. Air quality and recreation were seen mainly as recipients of benefits from other ecosystem services, having indegree values over 1.0, but outdegree weights of 0.37 and 0.14, respectively. Carbon storage and flood protection had moderate amounts of ingoing and outgoing connections, while energy and timber production were perceived as less central to the network.

The non-manager map consistently showed higher indegree, outdegree, and centrality scores for all ecosystem services, suggesting that they perceived ecosystem services as depending more on each other (interconnected) than did managers (Table 2). Managers perceived fire protection to be a more-important receiver node than did non-managers (indegree values of 0.78 versus 0.42), while non-managers assigned fire protection a more-prominent role as a transmitter node than did managers (outdegree of 2.0 versus 1.12). Non-managers saw higher indegree effects for six ecosystem services (water supply, soil retention, carbon storage, flood protection, air quality). They also identified much higher outdegree effects for provision of habitat, soil retention, and flood protection. As in the combined map, both indegree and outdegree values are relatively low for recreation, timber production, and energy production.

A graphical representation of the three aggregated maps only showing effects with absolute effects larger than 0.15 confirms the impact of fire protection on air quality as the most prominent connection in the system, with provision of habitat also important (Figure 2). Across the three aggregated maps, there are also strong connections between carbon storage and air quality, as well as between soil retention and water supply. Non-managers made a strong bi-directional connection between flood protection and soil retention. While timber production had a -0.20 effect on soil retention among non-managers (Figure 2), energy and timber production were largely isolated from the rest of the system. However, aside from non-managers reporting somewhat stronger ecosystem interactions than managers, the two groups displayed structurally similar networks in terms of main ecosystem drivers and directions of effects. Non-managers showed more connections with carbon storage than did managers. All average effects are available in the supplemental material (Table S1).

Perceived effects of management. In the second task we asked participants to assign weighted connections from nine forest-management actions, such as understory thinning and managed wildfire, onto the eleven ecosystem services (Table 1). Responses averaged across all respondents (Table 3) show that of the nine management actions, eight had a positive average impact on ecosystem services, with effects ranging from 0.11 to 0.34 ($p<0.05$). Six of the management actions were perceived as having higher effects on fire protection (defensible-space creation, managed wildfire, overstory thinning, prescribed burning, salvage logging, understory thinning). Five management actions were perceived as having large positive effects on provision of habitat (managed wildfire, meadow restoration, prescribed burning, understory thinning and replanting). Three management actions showed large positive effects on both carbon storage and air quality (meadow restoration, replanting, understory thinning), with prescribed burning and managed wildfire also being important for carbon storage. Understory thinning, meadow restoration, and replanting had the largest effects on recreation.

From the perspective of management actions, overstory thinning and salvage logging were perceived to have large positive impacts on fire protection and timber production ($p<0.05$). thee largest benefits of understory thinning were related to carbon storage and fire protection, with minor impacts on soil retention and water supply, as well as recreation and sense of place ($p<0.05$). Managed wildfire and prescribed burning were both perceived to have positive impacts on fire protection and provision of habitat. The benefits of defensible-space creation were largely understood in terms of fire protection, while meadow restoration and replanting benefited a variety of ecosystem services. Clear cutting was the only management option perceived to have clear negative impacts on ecosystem services, while its only beneficial effect was on timber production ($p<0.05$).

Note that strong positive as well as negative interactions with other ecosystem services were mapped by different participants for energy production and timber production, muting the magnitude of the average interaction reported in Table 3.

Effects of management, including interactions. The maps produced in tasks 1 and 2 were combined to a single map to calculate how interactions between ecosystem services amplify the effects of management (Figure 3). These individual maps were aggregated into a group map showing the average effects reported by all respondents. The Mental Modeler scenario builder was then used to estimate the aggregate effects of each management action, with ecosystem-service interactions accounted for. On average, this process strengthened existing patterns, having a positive impact in all cases except clear cutting, which showed an increased negative impact. The average difference, in absolute terms, between the reported and estimated impacts of management was 0.08 with a standard deviation of 0.48. Prescribed burning had large interaction effects for six ecosystem services, versus five for replanting, three for understory thinning, and two for meadow restoration.

Of the ecosystem services, air quality was perceived as having large secondary effects from five different management activities, versus four for recreation, three for provision of habitat, and two for water supply and flood protection. Secondary impacts of management actions on fire protection were small, with those for provision of habitat, air quality, recreation, and water supply large (Figure 3).

Discussion

Ecosystem-service interactions and management outcomes. Forested watersheds are often managed for complementary services, as well as for potentially conflicting multiple benefits and associated trade-offs such as timber production and habitat; and the interactions of these benefits (ecosystem services) are sometimes not well understood. In our study, the central importance of regulation of fire risk, and particularly the several strong outgoing connections from fire protection to other ecosystem services, suggests that managing for fire protection drives positive secondary effects on multiple other ecosystem services. Most notable of these are regulation of air quality, provision of habitat, and carbon storage. This is not surprising as high severity fire burns much of the above-ground vegetation and reduces many benefits such as air-quality regulation, carbon storage, and habitat for both plant and animal species. Although fire suppression can have short-term benefits, lowering the risk of high-severity wildfire through fuels reduction can enhance the longer-term expected value of multiple ecosystem services. In contrast, fire suppression immediately after an ignition can provide shorter-term benefits. This centrality of fire protection is also in line with recent policies across federal, state, and local agencies to reduce fuels as a way to lower the spread of destructive wildfire, while also continuing to suppress fire to protect built infrastructure (USDA Forest Service 2022; Governor's FMTF 2021).

We found the perceived effects on fire protection to be large across many actions. However, they were not overly sensitive to interaction effects, suggesting that management aimed at achieving other ecosystem services such as meadow restoration or provision of habitat may be less effective at providing fire protection than actions specifically focused on fire protection. Fire protection is a regulating ecosystem service, falling under the increasingly important category of natural-hazard mitigation, or regulation of extreme events (Carpenter et al. 2009; Haines-Young & Potschin 2016). It has been added to the Common International Classification of Ecosystem Services (Haines-Young & Potschin 2018), and more recently defined as "those benefits resulting from specific, co-produced ecosystem features and ecosystem management, that prevent the social-ecological system from experiencing impacts from catastrophic fires." (Depietri & Orenstein, 2019). Modifications to ecosystems change fire-regulating services and increase or decrease vulnerability to human capital and other services, e.g., threats to human lives and health, property damage, loss of habitat, soil erosion, loss of productivity, and ultimately land degradation. In Europe these modifications are driven by rural depopulation and land abandonment, particularly in mountains. Reforestation of agricultural land decreases landscape heterogeneity and increases the amount of contiguous fuel loads available to burn (Sil et al. 2019). While the driving force for these effects in forests of the western United States was historical fire suppression and unsustainable logging practices (Merschel et al. 2014; Pausas & Keeley 2019; Hanan et al. 2021), the outcome of a decreasing fire-protection ecosystem service was the same. There remains a forest "fire deficit" across the western United States attributable to the combined effects of human activities, ecological, and climate changes (Marlon et al. 2012). It has been recommended that in Europe the management and planning of areas affected by farmland abandonment should focus on actions that maintain landscape heterogeneity, important to regulation of wildfires and the capacity for protecting people and their livelihoods (Sil et al. 2019). For California, establishing heterogeneity in a way that protects rural communities given the growing, highly dispersed nature of the wildland-urban interface is challenging, especially when also balancing management actions with goals of maintaining habitat and biodiversity (Radeloff et al. 2018; Kramer et al. 2019).

Water supply was the second most central ecosystem service, with notable impacts on provision of habitat and recreation, while perceived to be affected by soil retention and flood protection. Our findings also mirror those of previous studies, which have found positive relationships between water supply and soil retention, as well as between water supply, soil retention, and recreation and tourism services (Egoh et al. 2008; Raudsepp-Hearne et al. 2010). The "high regulating bundle" of ecosystem services (carbon storage, water, and soil retention) have also been shown to be highly interrelated in places such as China and South Africa (Yang et al. 2019). Soil erosion is a global problem, and lack of soil retention can result in less water retention, thus affecting plant growth and habitat provision. Meadow restoration, understory thinning, and prescribed burning were perceived to be particularly effective in improving water supply, indicating synergy in managing for water supply and fire protection. Replanting was also important when considering interactions. However, it is interesting that three actions with great potential for biomass reduction, and thus water use by the forest – clear cutting, managed wildfire, overstory thinning – were not perceived as having large effects on water supply. These responses may reflect the dual meaning of water supply, which historically has referred to water quality (Gartner et al. 2013), and only recently to water quantity (Roche et al., 2020).

The centrality of provision of habitat is also consistent with public interest in wildlife as a key component of forest health (USDA Forest Service 2009). Habitat loss is also related to biodiversity loss. It has been observed that the feedback between the growth in provisioning services and declines in regulating, maintenance, and cultural services gives the perception of the world as a habitat that is getting better and better for humans, yet threatening humanity's future (Dasgupta 2021). While this may also be the case in the California, actions that enhance fire protection, soil retention, and water supply also provide important secondary effects on provision of habitat. For example, meadow restoration, replanting, managed wildfire, and prescribed burning were perceived as the most-efficient management actions to improve provision of habitat and were enhanced when including interaction effects. Understory thinning also became important for provision of habitat when considering interactions.

Overall, meadow restoration and replanting were the two management actions perceived as having the largest average impact across all ecosystem services The high scores for meadow restoration suggest that participants perceived it as important to the local intensity of restoration despite making up a small part of the landscape in California's mountain forests. Montane meadows have high biodiversity, contribute locally to regulating water and nutrient fluxes, have suffered significant encroachment over the past century; and in the absence of management interventions meadows are projected to decline further in a warming climate (Lubetkin et al. 2017; Maher et al. 2017). Interaction effects also amplified the importance of replanting. In western North America, tree planting can serve as a valuable tool to nudge the trajectory of post-fire landscapes towards more climate-adapted tree species (North et al. 2019; Prichard et al. 2021).

Differences between stakeholder groups. Both managers and non-managers perceived fire protection to generate considerable benefits in terms of other ecosystem services. That is, both groups of study participants were convinced that managing forests for fire protection, through actions such as defensible space, prescribed burning, managed wildfire, overstory thinning, and understory thinning, is likely to have a positive impact on multiple ecosystem services. While managers saw important interaction effects of water-supply gains on fire protection, non-managers did not. Otherwise, non-managers mapped higher interaction effects, particularly for air quality, carbon storage, and flood protection than did managers. These results contribute towards our understanding of the extent that the perception of natural-resource professionals can be a viable proxy of both direct and indirect benefits from ecosystem services (Carpenter et al. 2009; Grêt-Regamey et al. 2013), and suggest that expert knowledge aggregated across a range of resource-management professionals can contribute to analyzing trade-offs in ecosystem services.

Applications for method. Our findings are largely in line with expectations, given previous research (Hobbs et al. 2002; Jones et al. 2011) and the severe California wildfire season of 2020, suggesting that fuzzy cognitive mapping of ecosystem services among natural-resource professionals is a viable method of linking management actions to changing ecosystem services in a multi-benefit framework. In addition, the observed differences between managers and non-managers show the potential of this method to identify knowledge gaps and biases among stakeholder groups. Using fuzzy cognitive mapping to study the aggregate impacts of management, given actor perceptions, is a promising way to understand interactions between ecosystem services; and can contribute to development of management scenarios (Glick et al. 2012; Gray et al. 2015).

The strength and importance of co-benefits offers opportunities for broadening the partnerships aimed at increasing the pace and scale of forest restoration. It is helpful to consider three broad categories of beneficiaries in California and the Western United States: i) the general public, ii) rural communities, and iii) property-rights holders. The general public accrues large primary benefits from wildfire regulation, which in turn benefit air quality, recreation, and other services. For example, smoke from recent large fires in California was transported across the state and beyond, exposing millions to prolonged periods of poor air quality, leading to public-health emergencies and the extended closure of thousands of schools and businesses (Goss et al. 2020). The second category, rural communities located in or `near mountain forests, may often lack resources to make major investments in forest management, but provide local built infrastructure and human resources, and thus help to co-produce forest ecosystem services. These communities may also live in low-cost housing, have lower access to health coverage than do urban areas, and be associated with issues of environmental justice that may motivate broader societal support for maintaining them.

Third, both public and private land and infrastructure have risk costs linked to the risk of wildfire disturbance, and thus can directly benefit when forest-management actions lower risk. An additional property right, water rights, has both local and distant beneficiaries, as water from mountain source-water areas is moved around the state. A reduction in live forest biomass can result in lower water use by the forest, resulting in a greater fraction of precipitation leaving the forest as surface runoff to rivers or subsurface groundwater flow. The result is greater availability of water for hydropower production, for downstream water users, and for ecosystems. The first two directly benefit the holders of the water rights, who sell the water or electricity to downstream users. Recognizing these large benefits, the state's water and hydropower agencies are taking formal steps to lower barriers to engaging with land managers, whose actions directly affect much of the state's water supply (ACWA 2020). Pursuing a program of fire protection for forests at risk of high-severity wildfire, while also monetizing the direct and indirect ecosystem-service benefits of fire protection flowing to property rights holders, offers an important complement to public financing of forest management on public land. The aggregate benefits to partnerships representing these different ecosystem services brings together resources and capacity equal to the challenge at hand, leveraging those available to public land managers.

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Table 1. Concepts and definitions presented to participants

Concept	Definition
Ecosystem services	
Carbon storage	Ability of trees and vegetation to store carbon through sequestration
Water supply	Amount of water in the ecological system available for beneficial uses
Energy production	Total amount of produced energy from all sources, inc. bioenergy and hydropower
Timber production	Amount of produced timber
Recreation	Use of nature for sporting, or recreational activities
Flood attenuation	Capacity to mitigate future floods
Fire protection	Capacity to mitigate future wildfires
Provision of habitat	Protected habitat for plant or animal species
Air quality	Amount of pollution in the air
Soil retention	Erosion control. Ability of vegetation to prevent soil erosion and sedimentation
Sense of place	Your attachment to and the meanings you ascribe to wildlands in California
Management actions	
Understory thinning	Reducing tree and vegetation density. Restoration focused. Not for commercial gain
Overstory thinning	Reducing tree and vegetation density. For commercial gain
Clear cutting	Removing most trees in an area
Salvage logging	Removing trees after disturbance like fire or tree die-off, or before construction
Replanting	Restoring forests by planting new trees
Meadow restoration	Removing trees to create open meadows
Defensible space creation	Removing vegetation and trees around homes and buildings. Reduces wildfire risk
Prescribed burning	Creating fire to achieve management goals
Managed wildfire	Allowing naturally occurring wildfires to burn. Suppressed under defined conditions

Table 2. Network statistics and weighted node degree (node strength) based on reported ecosystem service interactions. Indegree values are sums across rows and outdegree sums down columns in Table S1. Centrality is sum of indegree and outdegree values.

Ecosystem service	All respondents (Connections 83, network density 0.92, N 32)			Managers (Connections 76, network density 0.84, N 15)			Non-managers (Connections 73, network density 0.81, N 17)		
	Indeg	Outdeg	Centrality	Indeg	Outdeg	Centrality	Indeg	Outdeg	Centrality
Fire protection	0.59	1.62	2.21	0.78	1.21	1.99	0.42	2.00	2.42
Water supply	0.79	1.09	1.88	0.66	1.06	1.72	0.91	1.11	2.02
Provision of hab.	1.10	0.78	1.88	1.01	0.31	1.32	1.33	1.19	2.52
Soil retention	0.65	1.15	1.80	0.45	0.89	1.33	0.9	1.39	2.29
Carbon storage	0.73	0.91	1.64	0.66	0.90	1.56	1.06	1.01	2.07
Flood protection	0.79	0.77	1.56	0.59	0.56	1.14	1.03	0.96	1.99
Air quality	1.14	0.37	1.51	0.82	0.38	1.20	1.48	0.37	1.85
Recreation	1.05	0.14	1.20	0.99	0.39	1.38	1.11	0.19	1.30
Timber production	0.30	0.49	0.80	0.24	0.56	0.80	0.43	0.66	1.09
Energy production	0.43	0.25	0.68	0.28	0.22	0.50	0.59	0.38	0.97

Table 3. Perceived benefits of management, averaged over all participants, scaled -1 to 1.

	Ecosystem service (Values ≥0.20 are underlined; values ≥0.30 are underlined and in bold)									
Management action	Air quality	Carbon storage	Energy production	Fire protection	Flood protection	Provision of habitat	Recreation	Soil retention	Timber production	Water supply
Clear cutting	-0.19	-0.34	0.05	0.03	-0.25	-0.19	-0.20	-0.34	**0.40**	-0.23
Defensible space creation	0.09	0.02	0.01	**0.55**	0.00	0.00	0.07	-0.04	0.02	0.00
Managed wildfire	-0.03	0.13	-0.02	**0.41**	0.10	**0.39**	0.00	0.01	-0.02	0.09
Meadow restoration	0.20	**0.32**	0.01	0.15	**0.41**	**0.42**	0.29	0.27	0.00	**0.45**
Overstory thinning	0.04	0.11	0.10	0.28	-0.01	0.07	-0.02	-0.02	**0.34**	0.13
Prescribed burning	0.05	0.19	-0.01	**0.66**	0.13	**0.34**	0.11	0.16	0.15	0.22
Replanting	0.23	**0.50**	0.04	0.11	**0.33**	**0.35**	0.17	**0.39**	0.23	0.18
Salvage logging	-0.02	0.10	0.13	0.23	0.00	-0.03	0.07	-0.04	**0.30**	0.01
Understory thinning	0.17	**0.34**	0.12	**0.46**	0.01	0.21	0.16	-0.02	0.13	0.25

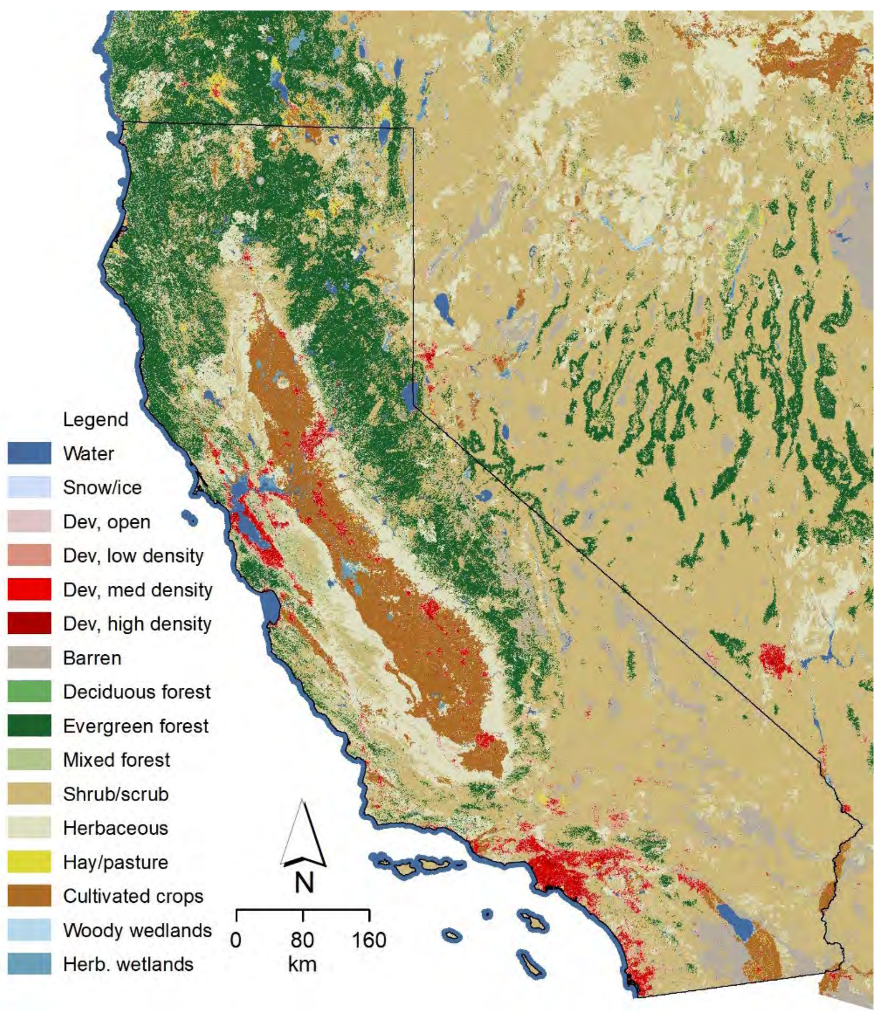

Figure 1. Landcover map of California. Adapted from National Landcover Data Set, 2019. Note that forestland that has burned in recent years may now be classified as shrub. Data from https://www.mrlc.gov/data accessed May 2022.

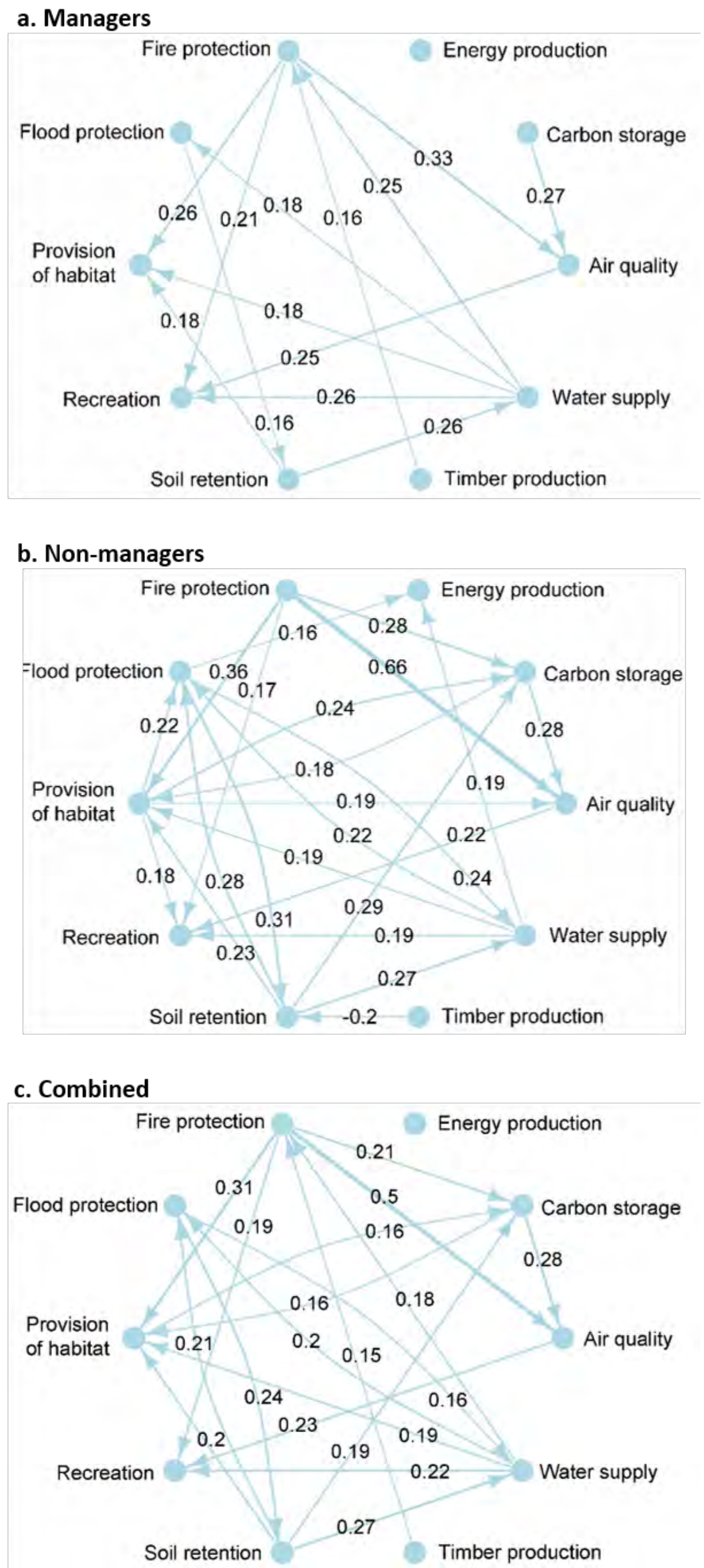

Figure 2. Ecosystem service interactions with values averaged across respondents of 0.15 or higher (scale of -1 to 1**).** Refer to Table S1 for all values.

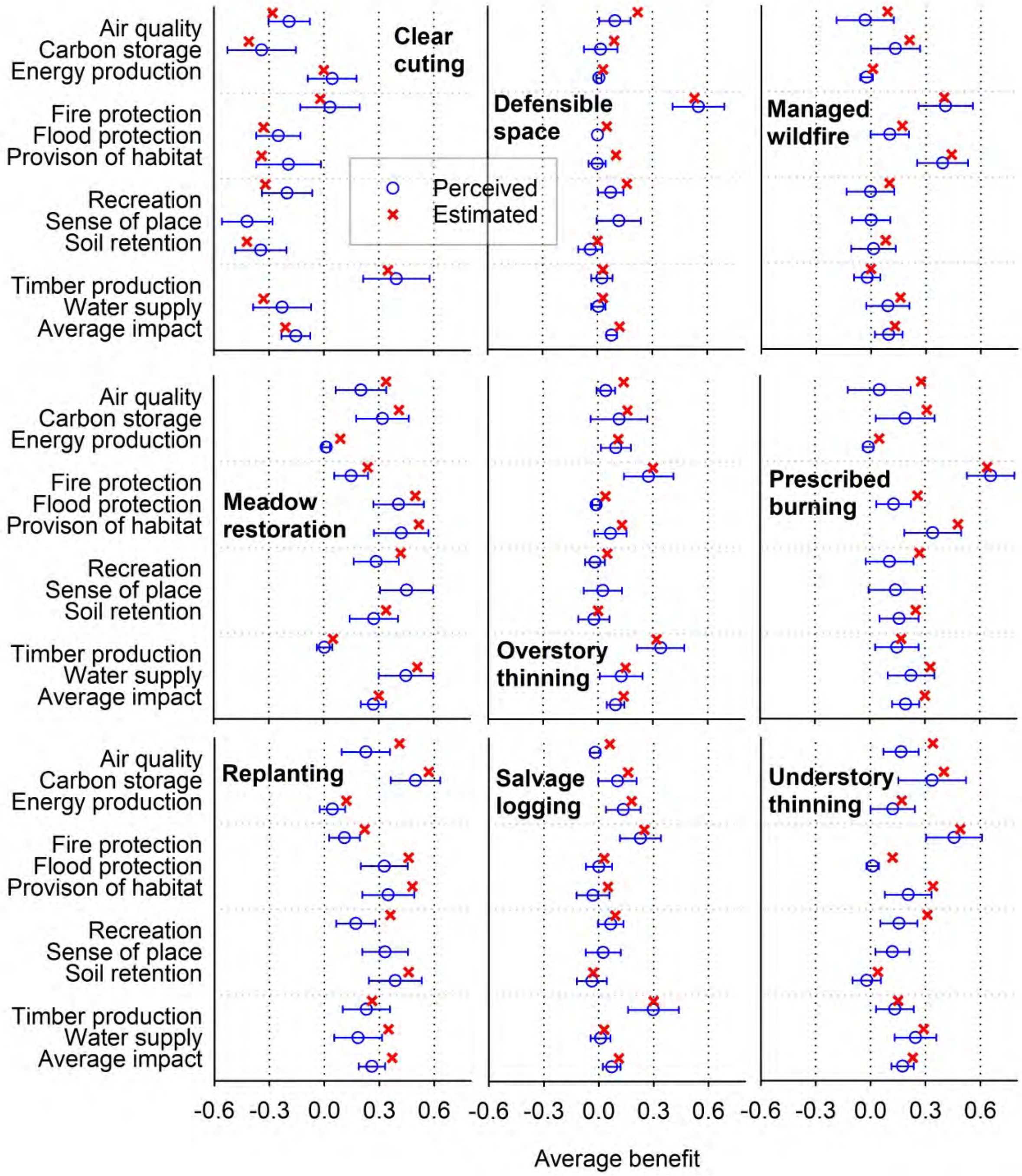

Figure 3. Average perceived and estimated benefit of management, all respondents. Blue circles and error bars are without interactions (perceived), red X is with interactions (estimated). Error bars represent range of responses. Numerical average values and differences between perceived and estimated are in Table S2. Note that Figure S1 has the same data, presented by management action rather than by service.

Supplemental information

Table S1. Ecosystem service interactions, reported effects averaged by respondent group, on a scale of -1 to 1.

Affecting ecosystem service	Affected ecosystem service (Values >0.15 are underlined; values >0.20 are underlined and in bold)									
	Air quality	Carbon storage	Energy production	Fire protection	Flood protection	Provision of habitat	Recreation	Soil retention	Timber production	Water supply
All respondents, n=32										
Air quality	0.00	0.03	0.00	0.03	0.00	0.07	**0.23**	0.00	0.01	0.00
Carbon storage	**0.28**	0.00	0.03	0.06	0.12	0.16	0.06	0.07	0.06	0.10
Energy production	-0.09	0.02	0.00	0.00	0.01	-0.06	0.00	0.00	0.03	0.03
Fire protection	**0.50**	**0.21**	0.05	0.00	0.11	**0.31**	0.19	0.12	0.04	0.09
Flood protection	0.01	0.05	0.10	0.03	0.00	0.09	0.08	**0.24**	0.01	0.16
Provision of habitat	0.11	0.16	-0.01	0.08	0.11	0.00	0.15	0.06	0.01	0.11
Recreation	0.03	0.03	0.01	0.02	0.00	0.02	0.00	-0.01	0.00	-0.01
Soil retention	0.06	0.19	0.02	0.03	**0.21**	**0.20**	0.06	0.00	0.11	**0.27**
Timber production	-0.03	0.01	0.09	0.15	-0.03	0.00	-0.06	-0.10	0.00	0.03
Water supply	0.04	0.03	0.14	0.18	**0.20**	0.19	**0.22**	0.05	0.04	0.00
Managers, n=15										
Air quality	0.00	0.00	0.00	0.05	0.00	0.06	**0.25**	0.00	0.02	0.00
Carbon storage	**0.27**	0.00	-0.02	0.08	0.08	0.13	0.04	0.10	-0.03	0.15
Energy production	-0.05	0.08	0.00	-0.01	0.02	0.03	0.00	0.00	0.00	0.04
Fire protection	**0.33**	0.14	0.02	0.00	0.10	**0.26**	**0.21**	0.09	0.01	0.05
Flood protection	0.02	0.06	0.03	0.07	0.00	0.08	0.07	0.16	0.00	0.07
Provision of habitat	0.01	0.06	0.00	0.02	0.00	0.00	0.12	0.02	0.01	0.07
Recreation	0.09	0.07	0.01	0.05	0.03	0.11	0.00	0.03	0.00	0.00
Soil retention	0.03	0.09	0.00	0.07	0.12	0.18	0.00	0.00	0.13	**0.26**
Timber production	0.00	0.14	0.12	0.16	-0.06	0.00	-0.05	0.01	0.00	0.02
Water supply	0.02	0.03	0.09	**0.25**	0.18	0.18	**0.26**	0.03	0.03	0.00
Non-managers, n=17										
Air quality	0.00	0.06	0.00	0.01	0.00	0.08	**0.22**	0.00	0.00	0.00
Carbon storage	**0.28**	0.00	0.06	0.03	0.15	0.18	0.08	0.04	0.14	0.05
Energy production	-0.13	-0.03	0.00	0.00	0.00	-0.13	0.00	0.00	0.06	0.03
Fire protection	**0.66**	**0.28**	0.07	0.00	0.13	**0.36**	0.17	0.14	0.07	0.12
Flood protection	0.00	0.03	0.16	0.00	0.00	0.10	0.09	**0.31**	0.03	**0.24**
Provision of habitat	0.19	**0.24**	-0.01	0.12	**0.22**	0.00	0.18	0.09	0.00	0.14
Recreation	-0.02	0.00	0.01	0.00	-0.03	-0.05	0.00	-0.05	0.00	-0.03
Soil retention	0.09	**0.29**	0.03	0.00	**0.28**	**0.23**	0.11	0.00	0.09	**0.27**
Timber production	-0.05	-0.10	0.06	0.14	0.00	0.01	-0.07	-0.20	0.00	0.03
Water supply	0.06	0.03	0.19	0.12	**0.22**	0.19	0.19	0.07	0.04	0.00

Table S2. Reported average benefits of management by ecosystem service, on a scale of -1 to 1. Perceived values are the same as Table 3. Estimated values include interaction effects. Both are shown on Figure 3.

	Ecosystem service (Values >0.20 are underlined; values >0.30 are underlined and in bold. Estimated values that are at least 0.10 greater than perceived values are underlined in red)										
Management action	Air quality	Carbon storage	Energy production	Fire protection	Flood protection	Provision of habitat	Recreation	Sense of place	Soil retention	Timber production	Water supply
Perceived											
Clear cutting	-0.19	-0.34	0.05	0.03	-0.25	-0.19	-0.20	-0.42	-0.34	**0.40**	-0.23
Defensible space creation	0.09	0.02	0.01	**0.55**	0.00	0.00	0.07	0.12	-0.04	0.02	0.00
Managed wildfire	-0.03	0.13	-0.02	**0.41**	0.10	**0.39**	0.00	0.00	0.01	-0.02	0.09
Meadow restoration	0.20	**0.32**	0.01	0.15	**0.41**	**0.42**	0.29	**0.45**	0.27	0.00	**0.45**
Overstory thinning	0.04	0.11	0.10	0.28	-0.01	0.07	-0.02	0.03	-0.02	**0.34**	0.13
Prescribed burning	0.05	0.19	-0.01	**0.66**	0.13	**0.34**	0.11	0.14	0.16	0.15	0.22
Replanting	0.23	**0.50**	0.04	0.11	**0.33**	**0.35**	0.17	**0.33**	**0.39**	0.23	0.18
Salvage logging	-0.02	0.10	0.13	0.23	0.00	-0.03	0.07	0.02	-0.04	**0.30**	0.01
Understory thinning	0.17	**0.34**	0.12	**0.46**	0.01	0.21	0.16	0.12	-0.02	0.13	0.25
Estimated											
Clear cutting	-0.28	-0.41	0.00	-0.02	-0.33	-0.34	-0.32	NA	-0.42	0.35	-0.33
Defensible space creation	0.22	0.09	0.03	**0.53**	0.05	0.10	0.16	NA	0.00	0.03	0.03
Managed wildfire	0.09	0.21	0.01	**0.40**	0.17	**0.44**	0.10	NA	0.08	0.00	0.16
Meadow restoration	0.34	**0.41**	0.09	0.24	**0.50**	**0.52**	**0.42**	NA	0.34	0.05	**0.51**
Overstory thinning	0.14	0.16	0.11	**0.30**	0.04	0.13	0.05	NA	0.00	**0.32**	0.15
Prescribed burning	0.28	**0.31**	0.05	**0.64**	0.26	**0.48**	0.27	NA	0.25	0.17	**0.33**
Replanting	**0.41**	**0.57**	0.12	0.22	**0.46**	**0.48**	**0.36**	NA	**0.46**	0.26	**0.35**
Salvage logging	0.06	0.16	0.18	0.25	0.03	0.05	0.09	NA	-0.03	**0.30**	0.03
Understory thinning	**0.34**	**0.40**	0.17	**0.49**	0.12	**0.34**	**0.31**	NA	0.04	0.15	0.29

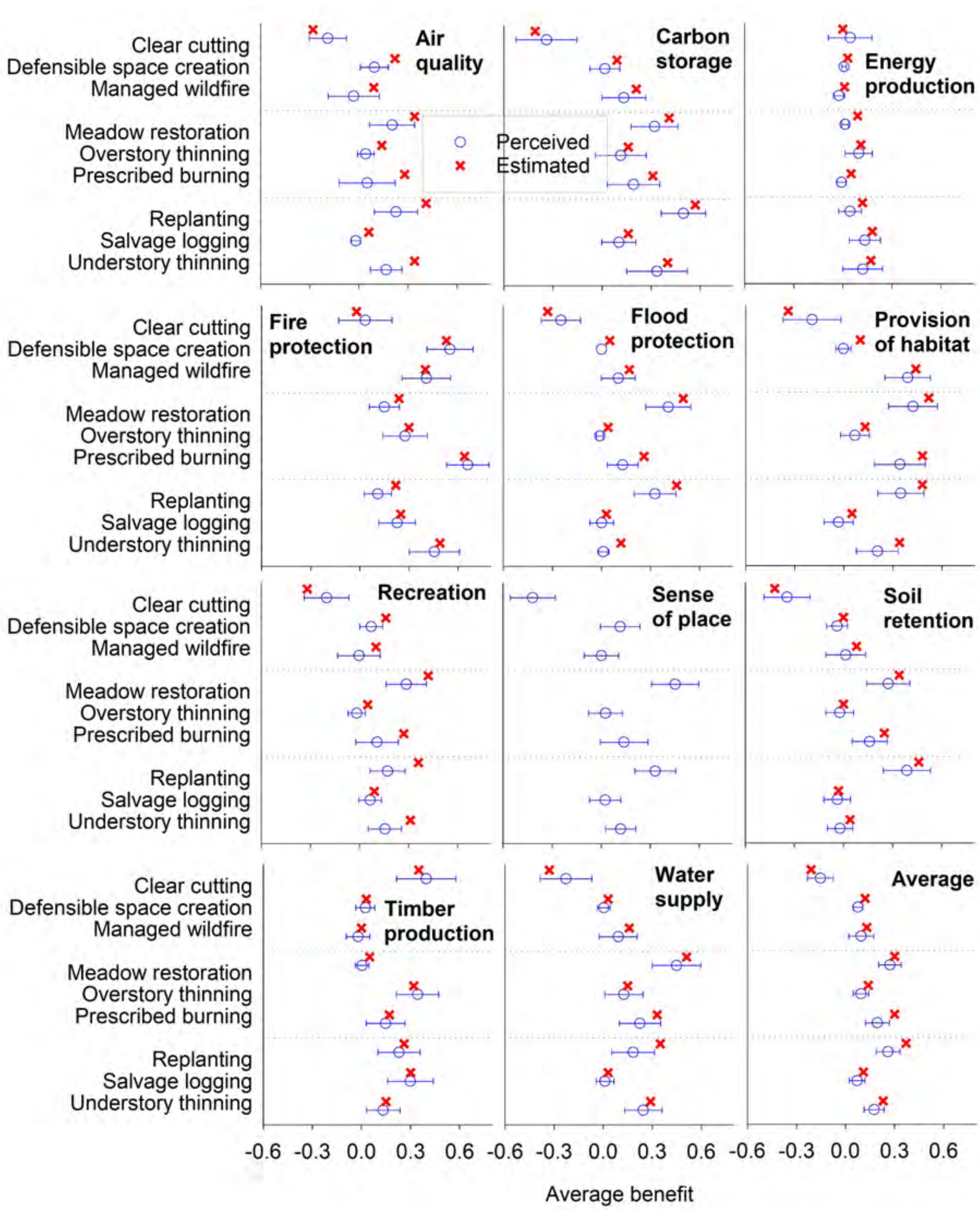

Figure S1. Average perceived and estimated benefit of management, all respondents. Blue circle and error bars are without interactions, red X is with interactions. Note: this is the same data as Figure 3, presented by ecosystem service rather than by management action.