Title

Valuation of forestâmanagement and wildfire disturbance on water and carbon fluxes in mountain headwaters

Authors

Chung, Min Gon
Guo, Han
Nyelele, Charity
et al.

Publication Date
2024-03-28

DOI
10.1002/eco.2642

Peer reviewed

Chung, M.G., Guo, H., Nyelele, C., Egoh, B.N., Goulden, M.L., Keske, C.M., Bales, R.C. (2024) *Ecohydrology*, doi:10.1002/eco.2642.

Valuation of forest-management and wildfire disturbance on water and carbon fluxes in mountain headwaters

Min Gon Chung[1,2]*, Han Guo[1], Charity Nyelele[3,4], Benis N. Egoh[3], Michael L. Goulden[3], Catherine M. Keske[5], Roger C. Bales[1]

[1]Sierra Nevada Research Institute, University of California, Merced, CA, USA. [2]Environmental Data Science Innovation & Inclusion Lab, University of Colorado, Boulder, CO, USA. [3]Department of Earth System Science, University of California, Irvine, CA, USA. [4]Department of Environmental Sciences, University of Virginia, Charlottesville, VA, USA. [5]Department of Management Innovation, Sustainability and Technology, University of California, Merced, CA, USA

* Corresponding author email: mingon.chung@gmail.com

Abstract

Recent drought, wildfires, and rising temperatures in the western U.S. highlight the urgency of increasing resiliency in overstocked forests. However, limited valuation information hinders the broader participation of beneficiaries in forest management. We assessed how historical disturbances in California's central Sierra Nevada affected live biomass, forest water use, and carbon uptake, and estimated marginal values of these changes. On average, low-severity wildfire caused greater declines in forest evapotranspiration (ET), gross primary productivity (GPP), and live biomass than did commercial thinning. Low-severity wildfires represent proxies for prescribed burns and both function as biomass removal to alleviate overstocked conditions. Increases in potential runoff over 15 years post-disturbance were valued at $108 thousand per km^2 for commercial thinning, versus $234 thousand per km^2 for low-severity wildfire, based on historical water prices. Respective declines in GPP were valued at –$305 and –$1317 thousand per km^2, based on an average social cost of carbon. Considering biomass levels created by commercial thinning and low-severity fire as more-sustainable management baselines for overstocked forests, carbon uptake over 15 years post-disturbance can be viewed as a benefit rather than loss. Realizing this benefit upon management re-entry may require sequestering thinned material. High-severity wildfire and clearcutting resulted in greater declines in ET and thus greater potential water benefits, but also substantial declines in GPP and live carbon. These lessons from historical disturbances indicate what benefit ranges from fuels treatments can be expected from more-sustainable management of mixed-conifer forests, and the importance of setting an appropriate baseline.

Keywords: forest management; wildfire; valuation; nature-based solution; runoff; carbon stability; land ownership.

Practitioner points

- Following moderate management or wildfire disturbance, both water use and gross primary productivity in central Sierra Nevada forests increased rapidly, reaching pre-disturbance levels within about 15 years.
- Carbon storage has historically recovered more slowly following disturbance, requiring 20 years or longer to reach pre-disturbance levels.
- Realizing net carbon-storage benefits in overstocked forests may require setting a lower, more-sustainable baseline, together with sequestration of material removed through management actions.

1. Introduction

In the western U.S., recent drought, tree die-offs, wildfires, and rising temperatures have decreased the provision of various ecosystem services by worsening forest health (Anderegg et al., 2020; McDowell et al., 2020; Westerling et al., 2006). Historic wildfire suppression in forests exacerbates these ecosystem-service risks (Abatzoglou and Williams, 2016; Hessburg et al., 2021; McIntyre et al., 2015). The suppression of wildfires for over a century has drastically changed the structure and composition of forest density and species (Moritz et al., 2014; Prichard et al., 2021). These biophysical changes have led to increases in wildfire frequency and severity (Halofsky et al., 2020; Hessburg et al., 2021), which has drastically changed in forest carbon and water cycles (Guo et al., 2023; Guo et al., 2022). For instance, high-severity wildfires can cause long-lasting impairment to the carbon sequestration capacity of forests by transforming biomass into atmospheric carbon, resulting in western U.S. forests increasingly acting as carbon sources (Coffield et al., 2021; Law et al., 2018). In addition, while the high density of fire-suppressed forests influences key water processes such as evapotranspiration with high forest water uses, severe droughts exacerbate decreases in water runoff (Bales et al., 2018; Goulden and Bales, 2019; McKinnon et al., 2021). As a result, rapid increases in wildfire frequency and severity negatively impact the supplies of key ecosystem services to people (e.g., landowners, farmers, and urban residents) such as air quality, tourism, water supplies, and carbon storage (Nyelele et al., 2023; Quesnel Seipp et al., 2023). In this study, ecosystem services are the direct and indirect benefits provided by ecosystems that contribute to human well-being (Adams, 2014; Potschin and Haines-Young, 2011).

These negative impacts of both severe wildfire and historical management highlight the urgency of management actions for lowering forest biomass and fuels towards sustainable levels (Collins et al., 2017; Forest Climate Action Team, 2018; North et al., 2015). Although the rate increased in the 2000s, current levels of investment in restoration treatments are not sufficient to keep pace with management needs in public forest lands (Knight et al., 2022b; Starrs et al., 2018). In addition, private landowners account for approximately one-third of total forest lands in the western U.S. However, many management practices have occurred on lands managed by federal and state agencies (Starrs et al., 2018). For this research, forest management refers to implementing practices for increasing forest resilience to meet specific environmental and economic objectives while reducing risks of high-severity wildfires and other disturbances such as drought-induced mortality (Collins et al., 2017; Hessburg et al., 2021). Examples of management activities include timber harvesting and stewardship treatments involving mechanical thinning and prescribed burning (Forest Climate Action Team, 2018).

Forest management aimed at reducing wildfire severity can produce co-benefits of ecosystem services such as water production (Ma et al., 2020; Roche et al., 2020) and carbon fluxes (Liang et al., 2018) across public and private entities, in addition to their main purpose of reducing risks to infrastructure and benefit flows (Eriksson et al., 2022; Kalies and Yocom Kent, 2016; Stephens et al., 2020). For example, management actions can change the biophysical structure and processes (e.g., evapotranspiration, photosynthesis, and plant respiration) controlling water and carbon fluxes. These changes affect the degree of water production and carbon sequestration that can provide economic benefits (e.g., additional water provision and carbon storage) to agencies and landowners, and monetizing those benefits can represent a financing source for further management (Liang et al., 2018; Mueller et al., 2013). To effectively expand management actions for climate risk reduction, funding sources through stakeholder partnerships need to be diversified. However, there is little valuation information to estimate the degree to which forest-management actions provide these co-benefits to any public and private entities during planning and implementing, particularly in the context of the western U.S. (Guo et al., 2023; Quesnel Seipp et al., 2023). The lack of valuation information can prevent further management actions by excluding important beneficiaries such as water agencies, who may be underrepresented in public-land-management planning.

To fill these information gaps, the objectives of this study are (1) to assess the impacts of historical forest management and wildfire disturbance on water and carbon fluxes across different forest ownerships and (2) to estimate the monetary values of carbon fluxes and water production for historical management as well as low-severity wildfires as a proxy of prescribed burns. To achieve these objectives, we performed a case study in the planning area of the Tahoe-Central Sierra Initiative (TCSI), which was launched in 2004 in the central Sierra Nevada of California, to stimulate large-area forest management in order to enhance forest resilience to climate-related disturbances (Wilson and Manley, 2021). The TCSI area has had diverse management actions in forests, based on an array of innovative planning, investment, and management tools.

This study focuses on carbon sequestration and water production, which increasingly play crucial roles for climate-change mitigation and human welfare. The co-benefits of water production and carbon sequestration are different for each type of land ownership and the corresponding management action. We use spatially explicit modeling to combine Landsat-based data with valuation data.

2. Methods

2.1. Study area. The Tahoe-Central Sierra study area is in the central Sierra Nevada of California (Fig. 1). The area receives 700-1800 mm of annual precipitation, with an elevation range of 600-2200 m and corresponding annual mean temperature of 1.6-18.4 °C (Roche et al., 2020; Wilson and Manley, 2021). The area falls within the Sierran Steppe-Mixed Forest-Coniferous Forest-Alp ecoregion and is made up of 70% conifer species

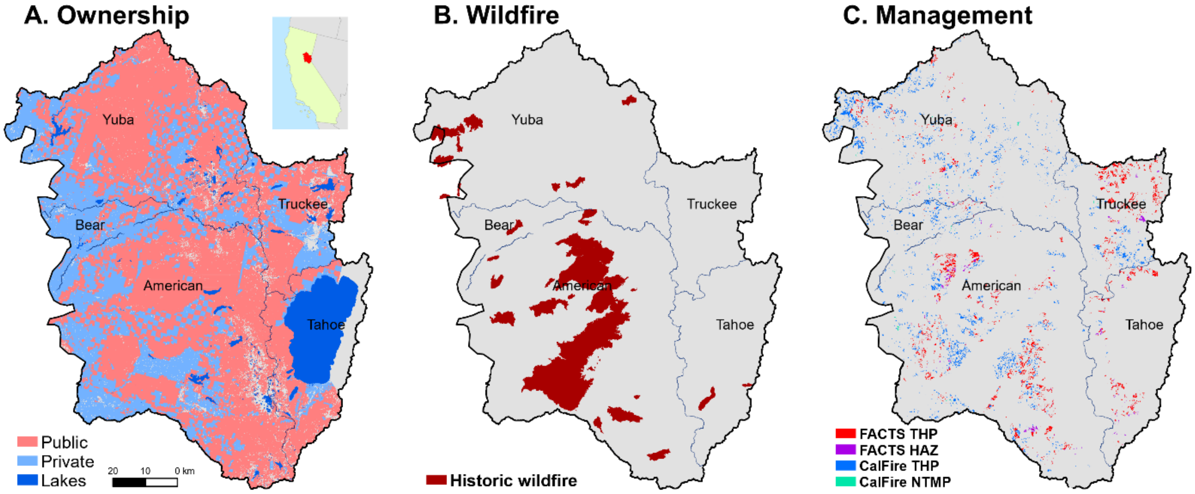

Figure 1. Spatial distribution of (A) forest land ownership in 2017, (B) historical wildfires and (C) management activities during 1999-2020. FACTS indicates the Forest Service Activity Tracking System database from the USFS. THP indicates timber harvests, HAZ indicates hazardous fuel treatment reduction, and NTMP indicates nonindustrial timber management plans. Headwaters of five main river basins are outlined for reference. FACTS and CalFire refer to data sources (see Knight et al. (2022b)).

(Wilson and Manley, 2021). This study area encompasses three main watersheds (i.e., Yuba, American, and Tahoe) with different environmental characteristics. For example, the Yuba watershed has higher precipitation and lower temperature compared to the American watershed (He et al., 2019). Forested watersheds in the Tahoe-Central Sierra region provide water that is crucial to downstream urban residents and farmers, while sequestering carbon at an annual rate equivalent to 3.1 million tons of CO_2 (Wilson and Manley, 2021). However, a combination of unprecedented climate change plus overgrown and unhealthy forests in this region increases risks of high-severity wildfires and drought-related tree die-offs that degrade water security and carbon storage (Roche et al., 2020; Wilson and Manley, 2021). Over the last three decades, this region has recorded 31 large wildfire incidents (>2 km^2, or 500 acre) that covered over 942 km^2 (Fig. 1). For example, the King Fire of 2014 burned over 395 km^2 of natural lands.

The TCSI, which covers approximately 9,800 km^2, was initiated under the Sierra Nevada Watershed Improvement Program in 2004 to reduce the risks of climate-related disturbances. The TCSI partnership includes federal and state agencies as well as nonprofit and private partners, encompassing 5,578 km^2 of public lands and 2,841 km^2 of private lands, excluding open water bodies (Sass et al., 2020). This initiative uses innovative planning, investment, and management tools to enhance the pace and scale of forest management that reduces the risk of severe wildfires while protecting the capacity for water production and carbon sequestration (Wilson and Manley, 2021). In the Tahoe-Central Sierra area, clearcutting on public lands was mainly conducted before 2000, with private clearcutting largely occurring between 2001 and 2003 (Fig. S1). After decreases in the areas of clearcutting and commercial thinning in the TCSI, forest stewardship practices were rapidly expanded after 2015.

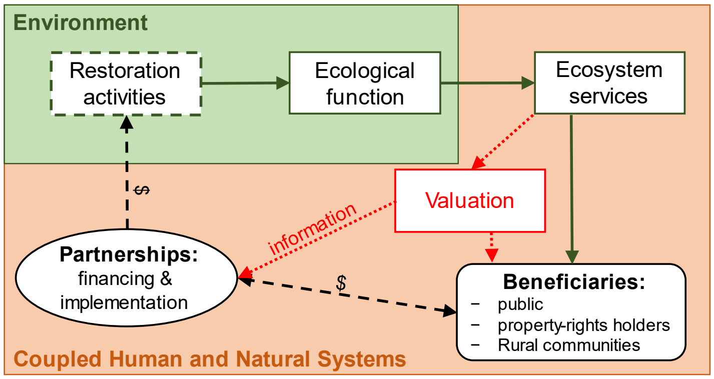

Figure 2. Conceptual framework for ecosystem service valuation with management activities. This framework captures both the impacts of forest management actions on ecosystem-service values and how these values affect beneficiaries and financing mechanisms for forest management. This framework provides a conceptual foundation for valuing multiple ecosystem services associated with diverse management actions, while examining how agencies and landowners fit into the financing and implementation of management activities on their lands.

2.2. Conceptual framework. In this study, we first suggest a conceptual framework for ecosystem-service valuation with forest management (Fig. 2). This framework captures both the impacts of management actions on ecosystem-service values and how these values affect beneficiaries and financing mechanisms for forest management. First, forest management affects the supply of ecosystem services (e.g., water production and carbon sequestration) through changes in biophysical structure and processes in the study area (Díaz et al., 2019; Potschin and Haines-Young, 2011). Such changes in ecosystem-service supplies can both directly and indirectly contribute to human well-being by providing benefits and values. We separated benefits from values in this framework because benefits are defined as gains in welfare from ecosystem services, and there are multiple ways to value the benefits across different times, places, and beneficiaries (Adams, 2014; Potschin and Haines-Young, 2011). For example, water prices in California fluctuate across different water districts, agencies, and drought versus wet seasons.

2.3. Data. To examine the economic impacts of forest management on water production and carbon sequestration, we used data on the spatial distribution of management actions from 1999 to 2020. We focused specifically on clearcutting and commercial thinning as the two representative historical forest-management activities, which account for over 37% of total management activities in the Tahoe-Central Sierra area. Clearcutting and commercial thinning also represent regeneration cutting methods and intermediate cutting methods, respectively. The U.S. Forest Service defines clearcutting as the harvesting of all live trees from an entire stand, with the expectation of managing new stands after harvest (USFS, 2013). Commercial thinning is the intermediate cutting of trees that have economic values for a business purpose, with the expectation of stimulating the yields of merchantable wood materials in a future harvest (USFS, 2013). To enhance the spatial and temporal accuracy of management areas, management-polygon data were obtained from Knight et al. (2022b) that refined the spatial representation and timing of the USFS and CalFire management records by using Landsat-based management pixels with the Continuous Change Detection and Classification algorithm (Knight et al., 2022b). We excluded forest-management polygons that were smaller than 0.04 km^2

(~10 acres) as this threshold minimized missing values. We also obtained gridded disturbance layers at a 30-m resolution, which were used to train the Landsat data on archival disturbance datasets (i.e., fire, harvest, and die-off) based on random-forest algorithms (Goulden et al., 2022).

We also obtained polygon data on 31 historical wildfires that burned across an area larger than 500 acres (~2 km^2) between 1999 and 2020 from the U.S. Forest Service database (USFS, 2017, 2022). Each wildfire reported four burn severities (0-25%, 25-50%, 50-75%, 75-100%) based on changes in forest basal areas using pre- and post-fire satellite imagery.

Forest-ownership data were obtained from the U.S. Forest Service (Sass et al., 2020). The data modeled eight types of land ownership using Forest Inventory and Analysis points from 2012 to 2017 (Sass et al., 2020). The Tahoe-Central Sierra area had only a small portion (<0.01%) of Native American tribal lands, and thus we excluded this land type from our analyses. We divided the seven remaining ownership types into public (federal, state, and local) and private (family, corporate, timber investment management organization and real-estate-investment trust, and other private entities such as conservation organizations and unincorporated associations). Using the forest-ownership data, we divided management and wildfire polygons based on public and private boundaries in ArcGIS 10.3 (ESRI, 2015).

To examine various aspects of changes in carbon and water with forest management, we obtained gridded data on evapotranspiration (ET), runoff, gross primary production (GPP), live carbon, and dead carbon in natural lands from the Natural Climate Solutions Data Atlas, which provides Landsat-based modeling data annually from 1995 to 2021 with a 30-m resolution (Goulden et al., 2022). In the data atlas, annual gridded ET estimates were from a model that used the Normalized Difference Vegetation Index (NDVI), climate data, and empirical ET measurements at California's flux towers (Goulden and Bales, 2019). Based on an annual water balance (precipitation = runoff + ET), runoff yields were the amounts of excess water from precipitation after ET and soil storage occurred at a pixel level (Bales et al., 2018; Roche et al., 2020). In our reported results the absolute values of changes in runoff (precipitation – ET) were not exactly equal to changes in ET because management actions and wildfire occurring in different years were averaged and stacked based on the year of the disturbance. Actual precipitation was from the Parameter-elevation Regressions on Independent Slopes Model (PRISM) data (Oregon State University, 2014). Since runoff occurs when there is less water used by vegetation and soil infiltration than precipitation, runoff yield is equivalent to potential water production (Ma et al., 2020; Roche et al., 2020).

The carbon pool of natural lands in this study consisted of GPP, live carbon, and dead carbon. GPP, that is the above- and below-ground gross amount of carbon dioxide fixed in the process of plant photosynthesis, represents the carbon-sequestration capacity in natural lands (Watson et al., 2000). Live-carbon stocks include total live biomass above and below ground, in addition to net primary productivity. Dead carbon stocks include dead biomass such as standing snags, as well as coarse and fine woody detritus. The available dead-carbon data did not account for biomass removal (e.g., woody-product transport and/or direct emission to the atmosphere) after disturbance, leading to potential overestimations. Therefore, using the percent loss of tree canopy data from the data atlas, we adjusted the amounts of dead carbon by accounting for biomass removal due to disturbance (Figs S2-5). Specifically, we multiplied the percent loss of tree canopy by the amounts of dead carbon to estimate biomass removal due to disturbance. All carbon and water data were based on water years (Oct-Sept). See Goulden et al. (2022) for more information on these carbon and water datasets.

2.4. Data extraction with spatial analyses. Each type of management activity produces ecosystem-service benefits (i.e., water production and carbon sequestration) differently across public and private lands. As such, we used spatially explicit modeling to combine Landsat-based data with historical forest management actions, while comparing managed areas with undisturbed and burned areas.

We excluded forest-management polygons from burned areas when the spatial distribution of management activities overlapped with burned areas. Because each management polygon had different biophysical, geologic, and geographic characteristics, we created undisturbed polygons and compared them with management polygons to control for such differences. We controlled for these differences by subtracting water and carbon attributes in undisturbed polygons from management polygons. Specifically, we created a control polygon that was a 1-km buffer zone around each management polygon, in the same HUC (Hydrologic Unit Code) 12 watershed. Then, historical disturbed pixels were excluded from the buffer zone over the period of 1985-2021.

Using these disturbed and undisturbed polygons, we extracted carbon and water attributes (i.e., ET, runoff, GPP, live carbon, and dead carbon) for both types of polygons. For forest-management actions, there were 2,172 polygons, and wildfires had 31 polygons and buffer zones in TCSI. All management and wildfire polygons covered 1999–2020. We then calculated annual changes in carbon and water attributes that were compared between disturbed and undisturbed areas for 1995-2021. We repeated the same processes for the wildfire-disturbance polygons. To check whether our comparison approach can control for biophysical, geologic, and geographic characteristics across different watersheds, we also performed the same comparisons in the Yuba and American watersheds separately.

As the timing of management activities varied across different projects and management types, we also calculated annual changes in carbon and water attributes in a normalized year. For example, for a commercial thinning performed in 2010, this management polygon had year zero in 2010, -5 in 2005, and +9 in 2019. Finally, in both normalized and actual years, the annual changes of carbon and water attributes were averaged with the weights of management projects' size across management types and land ownerships. All spatial analyses were performed in R 4.1.3 and ArcGIS 10.3 (ESRI, 2015; R Core Team, 2017).

2.5. Carbon and water valuation. Using the data of annual changes in carbon and water attributes, we estimated the economic values of changes in carbon fluxes and water production with forest management. Valuation of annual changes were expressed on a per-square-kilometer basis using the social cost of carbon and market values for carbon and water. In addition, we estimated the economic values of changes in carbon fluxes and water production resulting from low-severity wildfires. Low-severity wildfires can represent prescribed burns, which reduce flammable fuels to mitigate the risk of severe wildfires (Miller et al., 2020).

The social cost of carbon is the monetized value of the marginal damages from one additional metric ton of carbon emissions into the atmosphere with the value discounted over time (National Academies of Sciences and Medicine, 2017). We used the social cost of carbon on the basis of global damages that were estimated from the Interagency Working Group under Executive Order 12866 in the U.S. (Interagency Working Group, 2021; National Academies of Sciences and Medicine, 2017). To capture the range of these estimates, we selected \$50 (3% discount rate) and \$74 per metric ton of CO_2 (2.5% discount rate) in 2018 U.S. dollars (Table S1). Additionally, cap-and-trade programs that aim to reduce the total of carbon emissions with a limited number of emissions allowances play an important role in forming most global carbon prices. California's cap-and-trade program is one of the largest programs in the world, and thus we also used the average value of carbon prices (\$15.05 per metric ton of CO_2) in the program in 2018. These low, mid, and high prices per metric ton of CO_2 were converted to metric tons of C.

For valuing annual marginal water production, we used marginal water prices per unit area that were obtained from local water agencies in the Tahoe-Central Sierra area. The low estimate is \$62 per thousand m^3 (\$50 per acre-foot), the medium estimate is \$247 per thousand m^3 (\$200 per acre-foot), and the high estimate is \$617 per thousand m^3 (\$500 per acre-foot) (Table S1). Low, mid, and high unit prices of water can represent marginal water prices of wet, normal, and dry periods respectively (Guo et al., 2023). All marginal water prices are in 2018 U.S. dollars.

Due to a large variability in carbon and water attributes across individual management projects, we used a bootstrap approach to estimate the economic values of changes in carbon sequestration and water production with forest management. The bootstrapping procedure, a type of Monte Carlo analysis (Hungate et al., 2017), allows us to account for the statistical uncertainty of carbon sequestration and water production across different management projects (i.e., clearcutting and commercial thinning) and land ownerships (i.e., public and private lands). In each of the four groups, we first randomly selected the amounts of marginal changes in carbon sequestration or water production for each of the 21 normalized years (-5 to 15) using the observed marginal changes described above. For example, the sample size of clearcutting in public and private lands of the normalized year 0 was 182 and 697 polygons respectively. The resampling probability of each bootstrapping iteration was based on the size of management projects. Large-sized management projects had high probability during this resampling process. Then, we multiplied this sample with low, mid, and high carbon or water prices. Our bootstrapping algorithm iterated 10,000 times, and then we calculated means and 95% confidence intervals of carbon and water values in each management type and land ownership. All valuation analyses were performed in R 4.1.3 (R Core Team, 2017).

3. Results

Cumulative area evaluated was 2016 km^2 for the 31 wildfires; and for the 2172 management polygons the area was 7417 km^2. Public land accounted for 69% and 72%, respectively, with the balance on private lands. As an example of the data, we show selected attributes for four polygons representing different elevation, precipitation, and tree densities that received commercial thinning in 1997-98 (Fig. 3). Each shows the polygon-average drop in GPP, ET and live biomass following thinning, and a gradual recovery over the following 20-25 years. Figure 3 also shows NPP, which is dominated by trees, with shrub and herbaceous vegetation being much lower. In the following sections we present TCSI-wide results, indexed to the year of disturbance, for GPP, ET and live biomass.

3.1. Changes in ET. Changes in water production became evident in the reduced ET and increased potential runoff the year following a management action (Fig. 4A and B). In the second year post management,

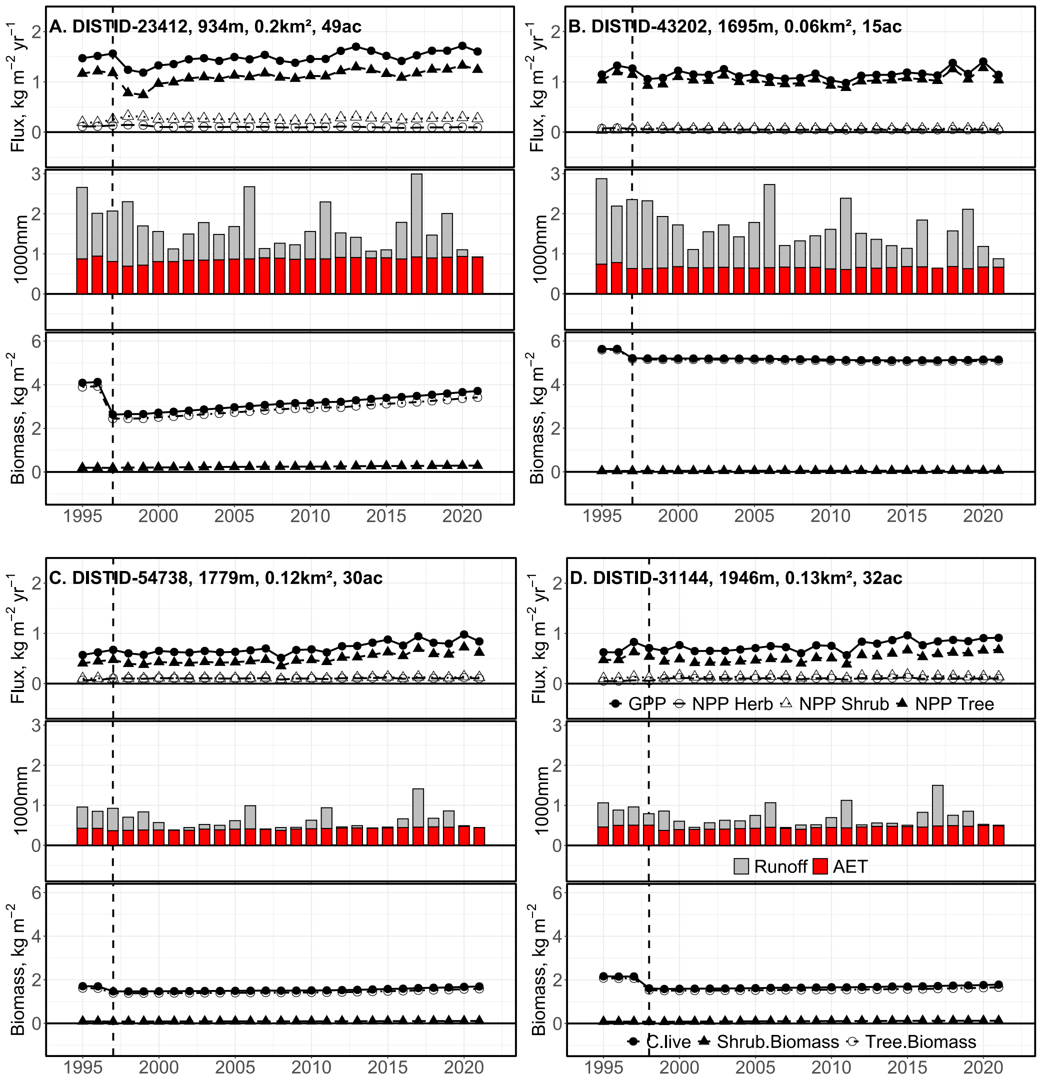

Figure 3. Annual changes in biophysical characteristics (GPP, NPP, live carbon, ET, and runoff) with commercial thinning in public lands. (A) Forested areas with low elevation in the Bear watershed, (B) Forested areas with high elevation in the Yuba watershed, (C) Forested areas in the northern Tahoe of the Truckee watershed, and (D) Forested areas in the southern Tahoe of the Tahoe watershed. Dotted lines indicate the year of a commercial thinning was performed. Annual runoff values are calculated as precipitation minus ET.

clearcutting on public lands produced an average of 7% additional water, than on private lands (373±19 versus 347±8 mm). However, commercial thinning on private lands gave an average gain 63% higher than on public lands (163±38 versus 98±5 mm). Results were similar across the TCSI area. For example, in the second year of post management, public clearcutting in the American versus Yuba watersheds had similar runoff gains (385±30 versus 371±23 mm), as did clearcutting on private lands (344±14 versus 340±9 mm).

Integrated over 15 years, the average gain in potential runoff (precipitation minus ET) from clearcutting averaged 244 mm and was 5% lower for private versus public lands (Table 1). The corresponding average for commercial thinning was 45 mm, 116% higher on private versus public lands. Averaged over 15 years post-disturbance, low-severity burned areas produced 96 mm yr^{-1}, with higher values on private lands (Fig. 4C and D; Table 1). Averaged over 15 years, clearcutting on public lands yielded 254 mm yr^{-1}, 59% higher runoff than did high-severity burned areas (160 mm yr^{-1}). Respective values expressed as reductions of ET were similar (-253 versus -167 mm yr^{-1}). Averages across the TCSI study area were 244 and 188 mm yr^{-1} for clearcutting and high-severity fire.

After the peak runoff gain, clearcut areas across both public and private lands had 6% decreases in runoff per year, with high-severity burned areas decreasing more rapidly, by 9% per year. Some increased runoff with clearcutting persisted at least 15 years after disturbance, with the increase in runoff from commercial thinning

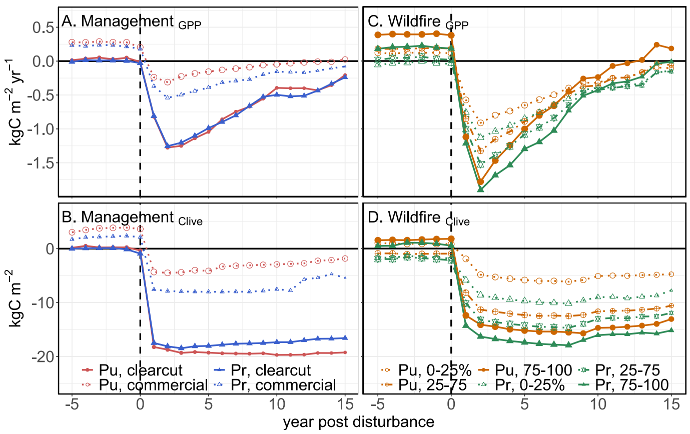

Figure 5. Annual differences in average GPP and live carbon stock between disturbed and undisturbed areas. Year 0 indicates the year of a forest-management action and/or wildfire ignition. The bolded zero x-axis separates differences for undisturbed versus disturbed areas. Positive values indicate that pre- or post-disturbed areas had higher GPP and live carbon than undisturbed areas. Negative values indicate that pre- and post-disturbed areas had lower GPP and live carbon than undisturbed areas. Values are averaged over all polygons in a category. Caption A in the figure shows the offset between undisturbed versus pre-disturbed areas. Pu indicates public lands, and Pr indicates private lands.

returning to the pre-disturbance level after about 15 years (Fig. 4).

Averaged over five years pre-disturbance, the amounts of ET and runoff in clearcut versus undisturbed areas differed by less than 4%. However, commercial-thinning areas in public lands had 5% higher ET and 13% lower runoff than undisturbed areas. Before commercial thinning, private lands had 7% higher ET and 17% lower runoff than did undisturbed areas (Fig. 4). This suggests that commercial thinning in public and private forested areas led to relatively higher ET than those in undisturbed areas (Fig. S6).

3.2. Changes in GPP and carbon stocks. In the second-year post-management, clearcutting reduced GPP on average by about 1.3 kgCm^{-2}yr^{-1} (1.28±0.07 versus 1.26±0.03 kgCm^{-2}yr^{-1} on public and private lands, respectively, Fig. 5A). Consistent with ET reductions, commercial thinning reduced GPP on private lands by 74% more than on public lands (0.54±0.14 versus 0.31±0.02 kgCm^{-2}yr^{-1}). Averaged over 15 years, GPP reductions from clearcutting were around 0.7 kgCm^{-2}yr^{-1}, whereas commercial thinning on private lands had average GPP reductions 2.6 times those on public lands (Table 1).

Table 1. Cumulative values of changes in forest runoff (gain), GPP (loss), and live carbon (loss) with clearcut, commercial thinning, and wildfire

	Average value for public/private lands		
	Runoff, mm	GPP, kgCm^{-2}yr^{-1}	C_{live}, kgCm^{-2}
Clearcut	254/242	0.70/0.72	19.3/17.5
Commercial thin	43/92	0.11/0.28	3.2/7.2
Low severity fire	81/152	0.44/0.59	5.1/9.0
High-severity fire	160/250	0.58/0.83	14.6/16.4

Over 15 years post-disturbance, the average live-carbon loss in clearcut areas was 17.8 kgCm^{-2}, and was 9% lower for private versus public lands (Table 1). The average live-carbon loss for commercial thinning was 3.4 kgCm^{-2}, and was 122% more for private versus public lands (Fig. 5B; Table 1). GPP in managed forests recovered to pre-disturbance levels (12-44% of recovery rate per year) faster than the recovery of live-carbon stocks (-0.2-7% per year) 15 years after management actions (Fig. 5). A longer time-series after disturbance shows that live-carbon stocks slowly recovered to pre-disturbance levels, but not sufficiently 15 years post disturbance; and a full recovery may take 25 years or longer (Fig. 3). Specifically, the recovery rates of live-carbon stocks after disturbance fluctuated across different elevation, precipitation, and tree-biomass conditions.

Averaged over 15 years post-disturbance, public versus private clearcutting reduced dead carbon stocks 4.0 versus 3.4 kgCm^{-2} (Fig. S4). In the case of commercial thinning, there were large differences in dead-carbon storage between public and private lands. After commercial thinning, public lands gained additional dead-carbon stocks (0.6 kgCm^{-2}) while private lands lost dead-carbon stocks (-0.6 kgCm^{-2}).

Averaged over the five years pre-disturbance, the amounts of GPP and live-carbon storage in clearcut versus undisturbed areas differed by less than 3%. However, commercial thinning areas in public lands had 9% higher GPP and 6% greater live carbon storage than undisturbed areas, averaged over five years pre-disturbance. Before commercial thinning, private lands had 9% higher GPP and 7% higher live-carbon storage than undisturbed areas (Fig. 5). Like with ET, this suggests that commercial thinning was in public and private forested areas with relatively higher GPP and carbon storage in undisturbed areas (Fig. S7).

In the second-year post-disturbance, GPP reductions in public and private clearcut areas were 39% and 52% lower than in respective high-severity burned areas. Averaged over 15 years post-disturbance, however, public clearcut areas had 18% greater reduction in GPP compared to high-severity burned areas (Table 1) because GPP recovered more slowly in public-clearcut versus high-severity burned areas (Fig. 5). Private-clearcut areas maintained 15% lower GPP than in high-severity-burned areas over 15 years (Table 1). In addition, clearcut areas in public and private lands had 25% and 6% greater reductions in live carbon compared to high-severity wildfire areas, respectively, over 15 years.

Over 15 years, areas with low-severity wildfires maintained lower GPP and live-carbon losses compared to clearcut areas, with similar differences between public and private lands (Figs 5C and D). Low-severity burned areas had 25% smaller GPP reductions on public versus private lands (Table 1). While maintaining relatively higher GPP, low-severity burned areas in public lands had 43% lower live-carbon losses than those in private lands (Table 1).

3.3. Valuation of carbon fluxes and water production. Using low, mid, and high unit prices, we estimated annual marginal economic values for water and carbon across managed compared to undisturbed areas (Figs 6 and S8). For water, the low, mid, and high represent wet, normal, and dry years. Summed over 15 years post management, clearcut areas produced cumulative water values of \$0.6 million km^{-2} on public lands, about 5% more than on private lands (Table 2 and Fig. 6A). Commercial thinning on private lands produced \$0.2 million km^{-2} of cumulative water value, about double that for public lands (Fig. 7 and S8). TCSI averages across all lands were \$0.6 million km^{-2} for clearcut and \$0.1 million km^{-2} for commercially thinned areas.

The additional water-production values were accompanied by losses in carbon uptake and storage. Over the 15 years after clearcutting, average cumulative carbon sequestration (GPP) declines represent nearly \$2 million km^{-2} (Table 2 and Fig. 6B). Over 15 years, commercial thinning averaged \$0.3 million km^{-2} of the cumulative carbon sequestration declines and was 2.6 times more for private versus public lands (Table 2). Following neither clearcutting nor commercial thinning did carbon losses owing to lower GPP recover over 15 years (Figs 7 and S8).

The value of live-carbon stocks in clearcut and commercially thinned areas recovered very slowly over the post-disturbance 15-year period. In sum, clearcutting on public lands represented a loss with an average value of about \$3.6 million km^{-2}, about 10% greater than on private lands (Table 2 and Fig. 6C). Over the 15 years after commercial thinning, public lands lost carbon stocks valued at an average of about \$0.6 million km^{-2}, versus about double that for private lands.

The changes in values of water and carbon fluxes for low-severity wildfires, a proxy of prescribed burns, were greater than for commercial thinning, but not as high as for clearcutting. Low-severity burned areas annually produced average water benefits of \$0.23 million km^{-2} over 15 years, with 87% more for private versus public lands (Table 2 and Fig. S8). The average values of carbon sequestration (GPP) losses in low-severity burned areas were \$1.2 million km^{-2} and \$1.6 million km^{-2} for public and private lands, respectively. After 15 years, low-severity burned areas recovered their carbon-sequestration losses to near pre-disturbance levels. With low-severity wildfires, public lands lost about \$1.0 million km^{-2} of live carbon stocks, while private lands lost \$1.7 million km^{-2} (Table 2 and Fig. 6C).

Table 2. Cumulative economic values of marginal changes in runoff (gain), GPP (loss), and live carbon (loss) with clearcut, commercial thin, and prescribed burn

	Value, thousand dollars per km^2 (mid, low, high scenarios)		
	Runoff	GPP	Clive
Clearcut, public	618; 155; 1,546	1,948; 586; 2,882	3,569; 1,074; 5,282
Clearcut, private	587; 147; 1,467	1,988; 599; 2,943	3,235; 974; 4,788
Commercial thin, public	103; 26; 258	286; 86; 423	600; 181; 888
Commercial thin, private	218; 55; 545	733; 220; 1,084	1,289; 388; 1,907
Prescribed burn, public	197; 49; 493	1,226; 369; 1,814	951; 286; 1,408
Prescribed burn, private	369; 92; 924	1,647; 496; 2,438	1,670; 503; 2,471

4. Discussion

4.1. Valuing water and carbon impacts. Our study examined and estimated the economic values of historical forest management on two key ecosystem services: water production and carbon storage. For example, in the study area, forest management increased water production over at least 15 years, providing an important co-benefit to historical timber production. Going forward, this same co-benefit will accrue with fuels treatment by mechanical means or prescribed fire (Eriksson et al., 2022).

Our valuation outcomes from past management activities provide information regarding the spatial and temporal changes in both carbon and water values, with or without management actions, for historic or simulated inputs. Because different agencies and landowners may have different management goals (e.g., wildfire-risk reduction, carbon storage, timber production, or watershed protection), the benefits and values of ecosystem-service changes depend on the management objectives.

The consistently higher values for ET, GPP, and carbon-storage declines following commercial thinning on private lands indicate greater biomass removal than for commercial thinning on public lands (Starrs et al., 2018). Going forward, it is instructive to assess the values of changes in water and carbon fluxes and carbon storage with management actions equivalent to historical disturbances. Based on our findings, an average ET decline of 98 mm yr^{-1}, a value averaged over 15-years post disturbance by low-severity wildfire for public and private lands combined, can be used as a proxy for the benefits of management by prescribed or the equivalent mechanical thinning.

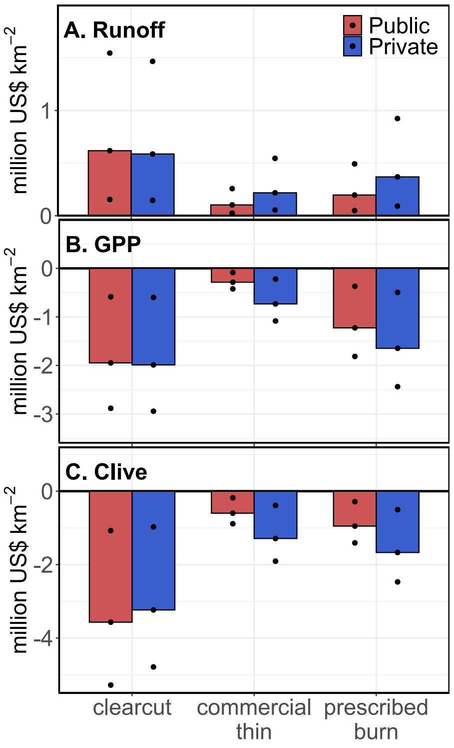

Figure 6. Cumulative economic values of runoff, GPP, and live carbon stock over 15 years post-disturbance. Blue and red bars indicate private and public land ownerships respectively, using mid-unit water and carbon prices. The error bars indicate the ranges of cumulative economic values between low- and high-unit water and carbon prices. All values were in 2018 US dollars.

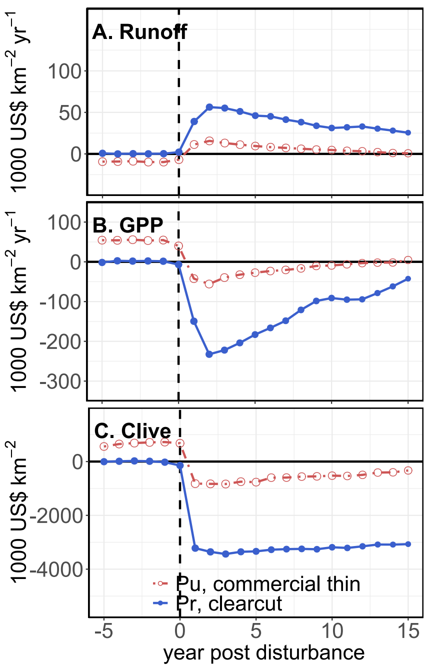

Figure 7. Economic values of marginal changes in runoff, GPP, and live carbon with private clearcutting and public commercial thinning. Year 0 indicates the year of forest management practices. Blue and red lines indicate the mean values of water production and carbon fluxes across each type of management and land ownership, using mid-unit water and carbon prices. In the TCSI area, more clearcutting is on private than public land, and vice versa for commercial thinning. All other types of management and land ownership are shown in Fig. S8. All values are in 2018 US dollars. Pu indicates public lands, and Pr

4.2. Mitigating wildfire and drought risks. To address increasing wildfire risks in high-dense forests under a changing climate, it is crucial to rapidly adopt a range of fuels treatments. The California Forest Carbon Plan suggests that prescribed burns can act as one of the major fuels-treatment options on both public and private lands to meet the goal of treating one million acres of natural lands annually (Forest Climate Action Team, 2018; Knight et al., 2022b; Miller et al., 2020). Our results showed that low-severity wildfires, as a proxy for prescribed burning, provided additional water benefits for at least 15 years and had similar low losses of live carbon-stock losses as did commercially thinned areas. Further, prescribed burning has historically had lower per unit area costs, compared to mechanical thinning (Loeffler et al., 2022). Using our low, mid and high marginal water values, a 98 mm yr^{-1} depth over 1 km^{-2} for 15 years (1.47 million m^3, or 1,192 AF) has respective water values of $59,600, $238,400, and $596,000 km^{-2}. Using a historical mix of 3 wet years, 6 normal (mid) years and 6 dry years in a 15-year period (Guo et al., 2023), this provides an annual value of $238,400 km^{-2} ($965 ac^{-1}) for 15 years. This is in the same range as recent costs for fuels treatment in the area, reported by Guo et al. (2023). Although prescribed burning activity is a cost-effective option to mitigate severe wildfire risks and enhance key ecosystem services, prescribed fire for fuel treatment has not been actively facilitated due to multiple barriers such as negative public perceptions, poor weather conditions, and environmental regulations in California (Miller et al., 2020).

In the western U.S., the combination of long-term droughts with historical wildfire suppression has increased forest water use and decreased water availability for stakeholders, which has rapidly raised water unit prices (Bales et al., 2018; McKinnon et al., 2021; Roche et al., 2020). For example, marginal prices for water during recent drought years have been reported to be over $1,100 ac^{-1}, double the $500 assumed in this analysis (Chediak and Chipman, 2022).

Our results also show that burned areas increased the amount of water production over time, but moderate- and high-severity wildfires in forest lands severely exacerbate damage to the ecological processes of plant photosynthesis, evaporation, and transpiration, with resulting negative effects on both water quantity and quality (Halofsky et al., 2020; Hessburg et al., 2021; Prichard et al., 2021). After wildfires, for example, additional runoff degrades water quality with increased sediment loads and debris (Ice et al., 2004). The degradation of water quality increases water treatment costs for downstream users (Hohner et al., 2019). Additionally, moderate- and high-severity wildfires worsened other types of ecosystem services such as air quality and recreational activities within and beyond burned areas (Quesnel Seipp et al., 2023).

4.3. Balancing co-benefits and management costs. These water co-benefits from forest-management actions come at the cost of losses in carbon sequestration and storage. In the TCSI study area, large reductions of carbon storage on both public and private lands were apparent for at least 15 years after the disturbance by wildfire and management actions. In public and private lands combined, our results show that low-severity wildfires, a proxy of prescribed burns, reduced 0.47 $kgCm^{-2}yr^{-1}$ and 5.96 $kgCm^{-2}$ of GPP and live carbon stocks, respectively, over 15-years post disturbance. Using our mid unit price, the cumulative monetary values of GPP and live carbon losses were approximately \$1.3 million km^{-2} and \$1.1 million km^{-2} for 15 years, respectively.

While prescribed burns and wildfires emit stored carbon into the atmosphere immediately, forest management using mechanical fuels treatments can provide wood products and bioenergy (Marcille et al., 2020). Huge amounts of low-value wood residues that are frequently burned or left to decay after thinning can also provide additional carbon benefits with innovative wood-use technologies, such as zero or low-carbon biofuels and building products (Cabiyo et al., 2021). For example, our results indicate that commercial thinning reduced 3.4 $kgCm^{-2}$ of an average live carbon stocks for public and private lands combined over 15 years. Since such forest biomass can be used for wood products and bioenergy, the amounts of live carbon reduction can be a proxy of largest carbon benefits obtained from commercial thinning. Based on our mid unit price from the social cost of carbon, the largest carbon benefits for commercial thinning can be estimated as \$0.6 million km^{-2}.

We also note that the recovery rates of live carbon stocks from disturbances varied based on biophysical and environmental conditions across the study area. For example, in the western Sierra Nevada watersheds, forested areas at lower elevations had relatively larger biomass recovery rates than those in higher elevations. Further, forested areas in the eastern Sierra Nevada watersheds (east of the Sierra crest) had relatively lower precipitation and thinner biomass than those in the western watersheds. Then, forested areas in the eastern Sierra did not recover as fast as the western forests after disturbance. These results indicate that while averaged results of changes before and after disturbances can be useful, decision makers and local practitioners still need to consider the detailed biophysical information of their specific contexts to plan optimal management actions and maximize the co-benefits.

4.4. Setting sustainable baselines for forest management. To restore overstocked forests towards sustainable levels, current forest management often depends on historical biomass baselines before Euro-American colonization (Knight et al., 2022a). However, in addition to rapid climate changes, the lack of scientific information about historical biomass records may prevent the designation of sustainable baselines for restoration actions (Safford and Stevens, 2013). In this context, our approach and results provide scientific information to set sustainable baselines that balance the reduction of wildfire risks and multiple ecosystem-service benefits together at both local and regional levels. For example, to maintain carbon-storage benefits and stable water production along with wildfire risk reductions in forested areas, decision makers can set a new baseline based on average biomass after the first prescribed burns or mechanical thinning to restore the forest to more-sustainable conditions. Specifically, our results show that low-severity wildfires, a proxy of prescribed burns or the equivalent mechanical thinning, reduced about 0.96 $kgCm^{-2}yr^{-1}$ of GPP in the second year post prescribed burns. Based on the second year post prescribed burns, resetting a biomass baseline for forest management can annually provide \$98,050 of carbon-storage benefits (0.53 $kgCm^{-2}yr^{-1}$, based on mid unit price) in treated forests over the study area for a decade.

4.5. Research limitations. In drawing conclusions, we note a few limitations of the study. First, we did not estimate values for actual water diversion, but for potential water benefits due to forest management. Future research will be needed to extend our valuation approach to examine the impacts of forest management on actual water diversions. Second, it is challenging to select unit prices for water and carbon, although our unit prices were based on the best literature review available. Water prices have continuously changed across different water use types and rainfall periods. For example, in 2021, the Metropolitan Water District of Southern California spent \$625 per acre-foot (\$0.507 per cubic meter) to purchase water from Northern California (Kasler, 2022). In addition, the social cost of carbon in the U.S. has been updated with advanced climate and socioeconomic projections (Interagency Working Group, 2021; Voosen, 2021; Wagner et al., 2021). Third, our valuation outcomes mainly focused on water and carbon fluxes, but forest management can also improve various ecosystem services such as recreational activities and air quality for human welfare. Using the framework of multi-benefits (Fig. 2), our valuation approaches can extend to estimating the economic values of other ecosystem services for decisions about forest land management.

5. Conclusion

This study estimated the economic values of forest management and wildfire disturbances on water and carbon fluxes in California's central Sierra Nevada. We found that both water runoff and GPP recover rapidly, reaching pre-disturbance levels within about 15 years following moderate management or wildfire disturbance. Carbon storage, however, typically requires 20 years or longer to reach pre-disturbance levels. To realize net carbon storage benefits in overstocked forests, we suggest setting a lower, more sustainable baseline and sequestering material removed through management actions.

Despite these limitations, this study provides scientific information about the co-benefits of forest management by estimating monetary values of water production and carbon storage. Our aggregated results, while based on historical dataset, give average values that can help in planning, with results for individual polygons reflecting the range of responses, or heterogeneity. The historical wildfire data are at a larger scale and offer a second dataset to inform planning of fuels treatments. The information of ecosystem-service values can help decision makers identify financing mechanisms to promote public-private partnerships for sustainable forest management among state and federal agencies, non-governmental organizations, and other private entities (e.g., landowners and water agencies). Additionally, our framework and approaches can extend to other large high wildfire-risk landscapes for estimating monetary values of ecosystem-service co-benefits with forest management and for leveraging sustainable climate-risk reduction strategies in productive but stressed mountain forests across the western U.S.

Acknowledgements. This research was supported by the California Climate Investments program through a Strategic Growth Council (CCR20021) contract to the University of California Center for Ecosystem Climate Solutions (CECS) We thank Clarke Knight and John Battles who shared forest treatment data.

References

Abatzoglou, J. T., & Williams, A. P. (2016). Impact of anthropogenic climate change on wildfire across western US forests. *Proceedings of the National Academy of Sciences, 113*(42), 11770-11775. doi:10.1073/pnas.1607171113

Adams, W. M. (2014). The value of valuing nature. *Science, 346*(6209), 549-551. doi:10.1126/science.1255997

Anderegg, W. R. L., Trugman, A. T., Badgley, G., Anderson, C. M., Bartuska, A., Ciais, P., Cullenward, D., Field, C. B., Freeman, J., Goetz, S. J., Hicke, J. A., Huntzinger, D., Jackson, R. B., Nickerson, J., Pacala, S., & Randerson, J. T. (2020). Climate-driven risks to the climate mitigation potential of forests. *Science, 368*(6497), eaaz7005. doi:10.1126/science.aaz7005

Bales, R. C., Goulden, M. L., Hunsaker, C. T., Conklin, M. H., Hartsough, P. C., O'Geen, A. T., Hopmans, J. W., & Safeeq, M. (2018). Mechanisms controlling the impact of multi-year drought on mountain hydrology. *Scientific Reports, 8*(1), 690. doi:10.1038/s41598-017-19007-0

Cabiyo, B., Fried, J. S., Collins, B. M., Stewart, W., Wong, J., & Sanchez, D. L. (2021). Innovative wood use can enable carbon-beneficial forest management in California. *Proceedings of the National Academy of Sciences, 118*(49), e2019073118. doi:10.1073/pnas.2019073118

Chediak, M., & Chipman, K. (2022). Worsening Drought Drives California Water Prices to All-Time High. *Bloomberg*. Retrieved from https://www.bloomberg.com/news/articles/2022-08-02/water-in-california-s-spot-market-is-more-expensive-than-ever-amid-drought

Coffield, S. R., Hemes, K. S., Koven, C. D., Goulden, M. L., & Randerson, J. T. (2021). Climate-Driven Limits to Future Carbon Storage in California's Wildland Ecosystems. *AGU Advances, 2*(3), e2021AV000384. doi:10.1029/2021AV000384

Collins, B. M., Fry, D. L., Lydersen, J. M., Everett, R., & Stephens, S. L. (2017). Impacts of different land management histories on forest change. *Ecological Applications, 27*(8), 2475-2486. doi:10.1002/eap.1622

Díaz, S., Settele, J., Brondízio, E. S., Ngo, H. T., Agard, J., Arneth, A., Balvanera, P., Brauman, K. A., Butchart, S. H. M., Chan, K. M. A., Garibaldi, L. A., Ichii, K., Liu, J., Subramanian, S. M., Midgley, G. F., Miloslavich, P., Molnár, Z., Obura, D., Pfaff, A., Polasky, S., Purvis, A., Razzaque, J., Reyers, B., Chowdhury, R. R., Shin, Y.-J., Visseren-Hamakers, I., Willis, K. J., & Zayas, C. N. (2019). Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science, 366*(6471), eaax3100. doi:10.1126/science.aax3100

Eriksson, M., Safeeq, M., Pathak, T., Egoh, B., & Bales, R. (2022). Using stakeholder-based fuzzy cognitive mapping to assess benefits of restoration in wildfire-vulnerable forests. *Restoration Ecology, n/a*(n/a), e13766. doi:10.1111/rec.13766

ESRI. (2015). ArcGIS Desktop: Release 10.3.1. Redlands, CA: Environmental Systems Research Institution. Retrieved from http://desktop.arcgis.com

Forest Climate Action Team. (2018). California forest carbon plan: Managing our forest landscapes in a changing climate. *Sacramento, CA, 178*.

Goulden, M., Wang, J., Randerson, J., Battles, J., & O'Geen, T. (2022). Natural Climate Solutions Data Atlas. Retrieved from https://cecs.ess.uci.edu/data-atlas/. Retrieved Mar 18, 2023, from Center for Ecosystem Climate Soultions https://cecs.ess.uci.edu/data-atlas/

Goulden, M. L., & Bales, R. C. (2019). California forest die-off linked to multi-year deep soil drying in 2012–2015 drought. *Nature Geoscience, 12*(8), 632-637. doi:10.1038/s41561-019-0388-5

Guo, H., Goulden, M., Chung, M. G., Nyelele, C., Egoh, B., Keske, C., Conklin, M., & Bales, R. (2023). Valuing the benefits of forest restoration on enhancing hydropower and water supply in California's Sierra Nevada. *Science of The Total Environment*, 162836. doi:10.1016/j.scitotenv.2023.162836

Guo, W., Safeeq, M., Liu, H., Wu, X., Cui, G., Ma, Q., Goulden, M. L., Lindeskog, M., & Bales, R. C. (2022). Mechanisms Controlling Carbon Sinks in Semi-Arid Mountain Ecosystems. *Global Biogeochemical Cycles, 36*(3), e2021GB007186. doi:https://doi.org/10.1029/2021GB007186

Halofsky, J. E., Peterson, D. L., & Harvey, B. J. (2020). Changing wildfire, changing forests: the effects of climate change on fire regimes and vegetation in the Pacific Northwest, USA. *Fire Ecology, 16*(1), 4. doi:10.1186/s42408-019-0062-8

He, M., Anderson, M., Schwarz, A., Das, T., Lynn, E., Anderson, J., Munévar, A., Vasquez, J., & Arnold, W. (2019). Potential Changes in Runoff of California's Major Water Supply Watersheds in the 21st Century. *Water, 11*(8), 1651. doi:10.3390/w11081651

Hessburg, P. F., Prichard, S. J., Hagmann, R. K., Povak, N. A., & Lake, F. K. (2021). Wildfire and climate change adaptation of western North American forests: a case for intentional management. *Ecological Applications, 31*(8), e02432. doi:10.1002/eap.2432

Hohner, A. K., Rhoades, C. C., Wilkerson, P., & Rosario-Ortiz, F. L. (2019). Wildfires Alter Forest Watersheds and Threaten Drinking Water Quality. *Accounts of Chemical Research, 52*(5), 1234-1244. doi:10.1021/acs.accounts.8b00670

Hungate, B. A., Barbier, E. B., Ando, A. W., Marks, S. P., Reich, P. B., van Gestel, N., Tilman, D., Knops, J. M. H., Hooper, D. U., Butterfield, B. J., & Cardinale, B. J. (2017). The economic value of grassland species for carbon storage. *Science Advances, 3*(4), e1601880-e1601880. doi:10.1126/sciadv.1601880

Ice, G. G., Neary, D. G., & Adams, P. W. (2004). Effects of Wildfire on Soils and Watershed Processes. *Journal of Forestry, 102*(6), 16-20. doi:10.1093/jof/102.6.16

Interagency Working Group. (2021). Technical support document: social cost of carbon, methane, and nitrous oxide interim estimates under executive order 13990. In: Interagency Working Group on Social Cost of Greenhouse Gases, United States Government.

Kalies, E. L., & Yocom Kent, L. L. (2016). Tamm Review: Are fuel treatments effective at achieving ecological and social objectives? A systematic review. *Forest Ecology and Management, 375*, 84-95. doi:10.1016/j.foreco.2016.05.021

Kasler, D. (2022). As drought continues, Southern California offers millions to buy Sacramento Valley water. *The Sacramento Bee*. Retrieved from https://www.sacbee.com/news/california/water-and-drought/article258220293.html

Knight, C. A., Anderson, L., Bunting, M. J., Champagne, M., Clayburn, R. M., Crawford, J. N., Klimaszewski-Patterson, A., Knapp, E. E., Lake, F. K., Mensing, S. A., Wahl, D., Wanket, J., Watts-Tobin, A., Potts, M. D., & Battles, J. J. (2022a). Land management explains major trends in forest structure and composition over the last millennium in California's Klamath Mountains. *Proceedings of the National Academy of Sciences, 119*(12), e2116264119. doi:10.1073/pnas.2116264119

Knight, C. A., Tompkins, R. E., Wang, J. A., York, R., Goulden, M. L., & Battles, J. J. (2022b). Accurate tracking of forest activity key to multi-jurisdictional management goals: A case study in California. *Journal of Environmental Management, 302*, 114083. doi:10.1016/j.jenvman.2021.114083

Law, B. E., Hudiburg, T. W., Berner, L. T., Kent, J. J., Buotte, P. C., & Harmon, M. E. (2018). Land use strategies to mitigate climate change in carbon dense temperate forests. *Proceedings of the National Academy of Sciences, 115*(14), 3663-3668. doi:10.1073/pnas.1720064115

Liang, S., Hurteau, M. D., & Westerling, A. L. (2018). Large-scale restoration increases carbon stability under projected climate and wildfire regimes. *Frontiers in Ecology and the Environment, 16*(4), 207-212. doi:10.1002/fee.1791

Loeffler, D. R., Anderes, S., Houtman, R. M., Ager, A. A., & Day, M. A. (2022). Forest management activity costs in the continental United States (2012-2018). *Fort Collins, CO: Forest Service Research Data Archive.* doi:10.2737/RDS-2022-0021

Ma, Q., Bales, R. C., Rungee, J., Conklin, M. H., Collins, B. M., & Goulden, M. L. (2020). Wildfire controls on evapotranspiration in California's Sierra Nevada. *Journal of Hydrology, 590*, 125364. doi:10.1016/j.jhydrol.2020.125364

Marcille, K. C., Morgan, T. A., McIver, C. P., & Christensen, G. A. (2020). California's forest products industry and timber harvest, 2016. *Gen. Tech. Rep. PNW-GTR-994. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station. 58 p., 994.*

McDowell, N. G., Allen, C. D., Anderson-Teixeira, K., Aukema, B. H., Bond-Lamberty, B., Chini, L., Clark, J. S., Dietze, M., Grossiord, C., Hanbury-Brown, A., Hurtt, G. C., Jackson, R. B., Johnson, D. J., Kueppers, L., Lichstein, J. W., Ogle, K., Poulter, B., Pugh, T. A. M., Seidl, R., Turner, M. G., Uriarte, M., Walker, A. P., & Xu, C. (2020). Pervasive shifts in forest dynamics in a changing world. *Science, 368*(6494), eaaz9463. doi:10.1126/science.aaz9463

McIntyre, P. J., Thorne, J. H., Dolanc, C. R., Flint, A. L., Flint, L. E., Kelly, M., & Ackerly, D. D. (2015). Twentieth-century shifts in forest structure in California: Denser forests, smaller trees, and increased dominance of oaks. *Proceedings of the National Academy of Sciences, 112*(5), 1458-1463. doi:10.1073/pnas.1410186112

McKinnon, K. A., Poppick, A., & Simpson, I. R. (2021). Hot extremes have become drier in the United States Southwest. *Nature Climate Change, 11*(7), 598-604. doi:10.1038/s41558-021-01076-9

Miller, R. K., Field, C. B., & Mach, K. J. (2020). Barriers and enablers for prescribed burns for wildfire management in California. *Nature Sustainability, 3*(2), 101-109. doi:10.1038/s41893-019-0451-7

Moritz, M. A., Batllori, E., Bradstock, R. A., Gill, A. M., Handmer, J., Hessburg, P. F., Leonard, J., McCaffrey, S., Odion, D. C., Schoennagel, T., & Syphard, A. D. (2014). Learning to coexist with wildfire. *Nature, 515*(7525), 58-66. doi:10.1038/nature13946

Mueller, J. M., Swaffar, W., Nielsen, E. A., Springer, A. E., & Lopez, S. M. (2013). Estimating the value of watershed services following forest restoration. *Water Resources Research, 49*(4), 1773-1781. doi:10.1002/wrcr.20163

National Academies of Sciences, E., & Medicine. (2017). *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide*. Washington, DC: The National Academies Press.

North, M. P., Stephens, S. L., Collins, B. M., Agee, J. K., Aplet, G., Franklin, J. F., & Fulé, P. Z. (2015). Reform forest fire management. *Science, 349*(6254), 1280-1281. doi:10.1126/science.aab2356

Nyelele, C., Keske, C., Chung, M. G., Guo, H., & Egoh, B. N. (2023). Using social media data to estimate recreational travel costs: A case study from California. *Ecological Indicators, 154*, 110638. doi:https://doi.org/10.1016/j.ecolind.2023.110638

Oregon State University. (2014). PRISM Climate Group. Retrieved from https://prism.oregonstate.edu. Retrieved Mar 18, 2022 https://prism.oregonstate.edu

Potschin, M. B., & Haines-Young, R. H. (2011). Ecosystem services:Exploring a geographical perspective. *Progress in Physical Geography: Earth and Environment, 35*(5), 575-594. doi:10.1177/0309133311423172

Prichard, S. J., Hessburg, P. F., Hagmann, R. K., Povak, N. A., Dobrowski, S. Z., Hurteau, M. D., Kane, V. R., Keane, R. E., Kobziar, L. N., Kolden, C. A., North, M., Parks, S. A., Safford, H. D., Stevens, J. T., Yocom, L. L., Churchill, D. J., Gray, R. W., Huffman, D. W., Lake, F. K., & Khatri-Chhetri, P. (2021). Adapting western North American forests to climate change and wildfires: 10 common questions. *Ecological Applications, 31*(8), e02433. doi:10.1002/eap.2433

Quesnel Seipp, K., Maurer, T., Elias, M., Saksa, P., Keske, C., Oleson, K., Egoh, B., Cleveland, R., Nyelele, C., Goncalves, N., Hemes, K., Wyrsch, P., Lewis, D., Chung, M. G., Guo, H., Conklin, M., & Bales, R. (2023). A multi-benefit framework for funding forest management in fire-driven ecosystems across the Western U.S. *Journal of Environmental Management, 344*, 118270. doi:https://doi.org/10.1016/j.jenvman.2023.118270

R Core Team. (2017). R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.R-project.org/

Roche, J. W., Ma, Q., Rungee, J., & Bales, R. C. (2020). Evapotranspiration Mapping for Forest Management in California's Sierra Nevada. *Frontiers in Forests and Global Change, 3*(69). doi:10.3389/ffgc.2020.00069

Safford, H., & Stevens, J. (2013). Natural Range of Variation (NRV) for yellow pine and mixed conifer forests in the bioregional assessment area, including the Sierra Nevada, southern Cascades, and Modoc and Inyo National Forests. *Unpublished report. USDA Forest Service, Pacific Southwest Region, Vallejo, CA.*

Sass, E. M., Butler, B. J., & Markowski-Lindsay, M. A. (2020). Forest ownership in the conterminous United States circa 2017: distribution of eight ownership types-geospatial dataset.

Starrs, C. F., Butsic, V., Stephens, C., & Stewart, W. (2018). The impact of land ownership, firefighting, and reserve status on fire probability in California. *Environmental Research Letters, 13*(3), 034025. doi:10.1088/1748-9326/aaaad1

Stephens, S. L., Westerling, A. L., Hurteau, M. D., Peery, M. Z., Schultz, C. A., & Thompson, S. (2020). Fire and climate change: conserving seasonally dry forests is still possible. *Frontiers in Ecology and the Environment, 18*(6), 354-360. doi:10.1002/fee.2218

USFS. (2013). *Silvicultural Activities: Description and Terminology*. Retrieved from https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5413732.pdf

USFS. (2017). Vegetation Burn Severity - % Change in Basal Area. Retrieved from https://www.fs.usda.gov/detail/r5/landmanagement/gis/?cid=stelprd3804878. Retrieved Mar 18, 2023, from USDA Forest Service, Pacific Southwest Region, Fire and Aviation Mgmt. https://www.fs.usda.gov/detail/r5/landmanagement/gis/?cid=stelprd3804878

USFS. (2022). Rapid Assessment of Vegetation Condition after Wildfire. Retrieved from https://burnseverity.cr.usgs.gov/ravg/data-access. Retrieved Mar 18, 2023, from USDA Forest Service, Geospatial Technology and Applications Center https://burnseverity.cr.usgs.gov/ravg/data-access

Voosen, P. (2021). Trump downplayed the cost of carbon. That's about to change. *Science, 371*(6528), 447-448. doi:10.1126/science.371.6528.447

Wagner, G., Anthoff, D., Cropper, M., Dietz, S., Gillingham, K. T., Groom, B., Kelleher, J. P., Moore, F. C., & Stock, J. H. (2021). Eight priorities for calculating the social cost of carbon. *Nature, 590*(7847), 548-550. doi:10.1038/d41586-021-00441-0

Watson, R. T., Noble, I. R., Bolin, B., Ravindranath, N., Verardo, D. J., & Dokken, D. J. (2000). *Land use, land-use change and forestry: a special report of the Intergovernmental Panel on Climate Change*: Cambridge University Press.

Westerling, A. L., Hidalgo, H. G., Cayan, D. R., & Swetnam, T. W. (2006). Warming and Earlier Spring Increase Western U.S. Forest Wildfire Activity. *Science, 313*(5789), 940-943. doi:10.1126/science.1128834

Wilson, K. N., & Manley, P. N. (2021). Assessment of Current Landscape Conditions: Tahoe-Central Sierra Initiative. *An unpublished report of the Tahoe Central Sierra Initiative*. Retrieved from https://sierranevada.ca.gov/wp-content/uploads/sites/326/2021/10/TCSI-AssessmentOfCurrentConditions.pdf

Supplementary Information

Table S1. Low, mid, and high unit prices of carbon and water.

	Carbon price, $\$/\text{tCO}_2\text{e}$	Water price, $\$/\text{acre-foot}$
low	15.05	50
medium	50	200
high	74	500

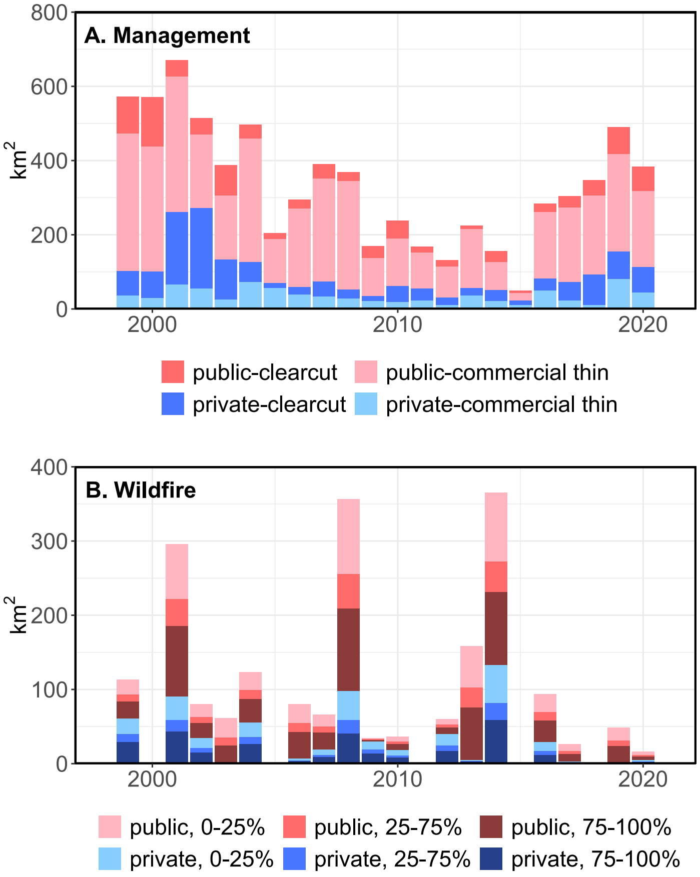

Figure S1. Managed and burned areas (km^2) from 1999 to 2020 in TCSI.

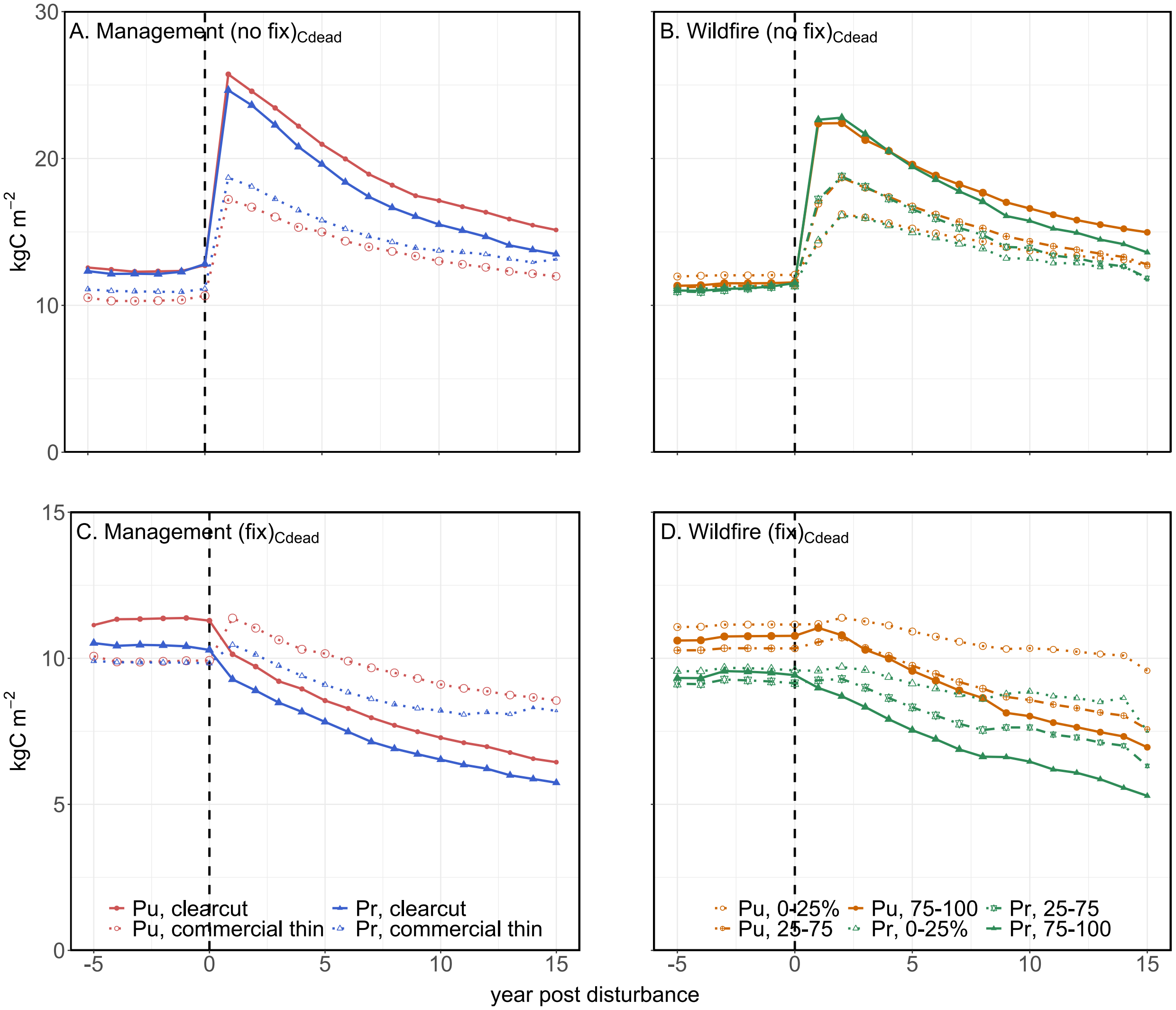

Figure S2. Changes in dead carbon in disturbed areas. Upper figures show the amounts of dead carbon without adjusting biomass processes after disturbances (*no fix*). Bottom figures show the amounts of dead carbon with adjusting biomass processes (*fix*). Pu indicates public lands, and Pr indicates private lands.

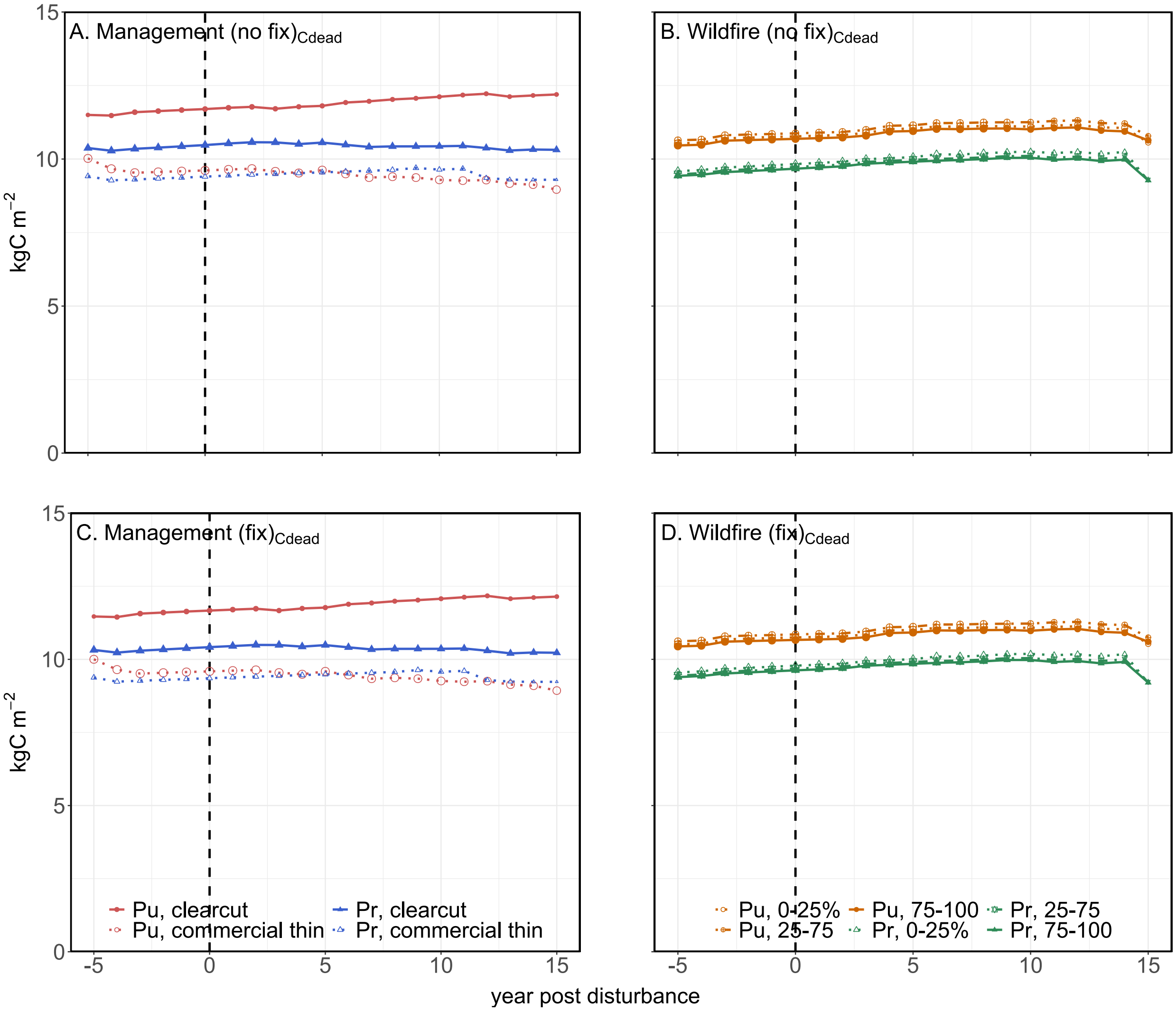

Figure S3. Changes in dead carbon in undisturbed areas. Upper figures show the amounts of dead carbon without adjusting biomass processes after disturbances. Bottom figures show the amounts of dead carbon with adjusting biomass processes. Pu indicates public lands, and Pr indicates private lands.

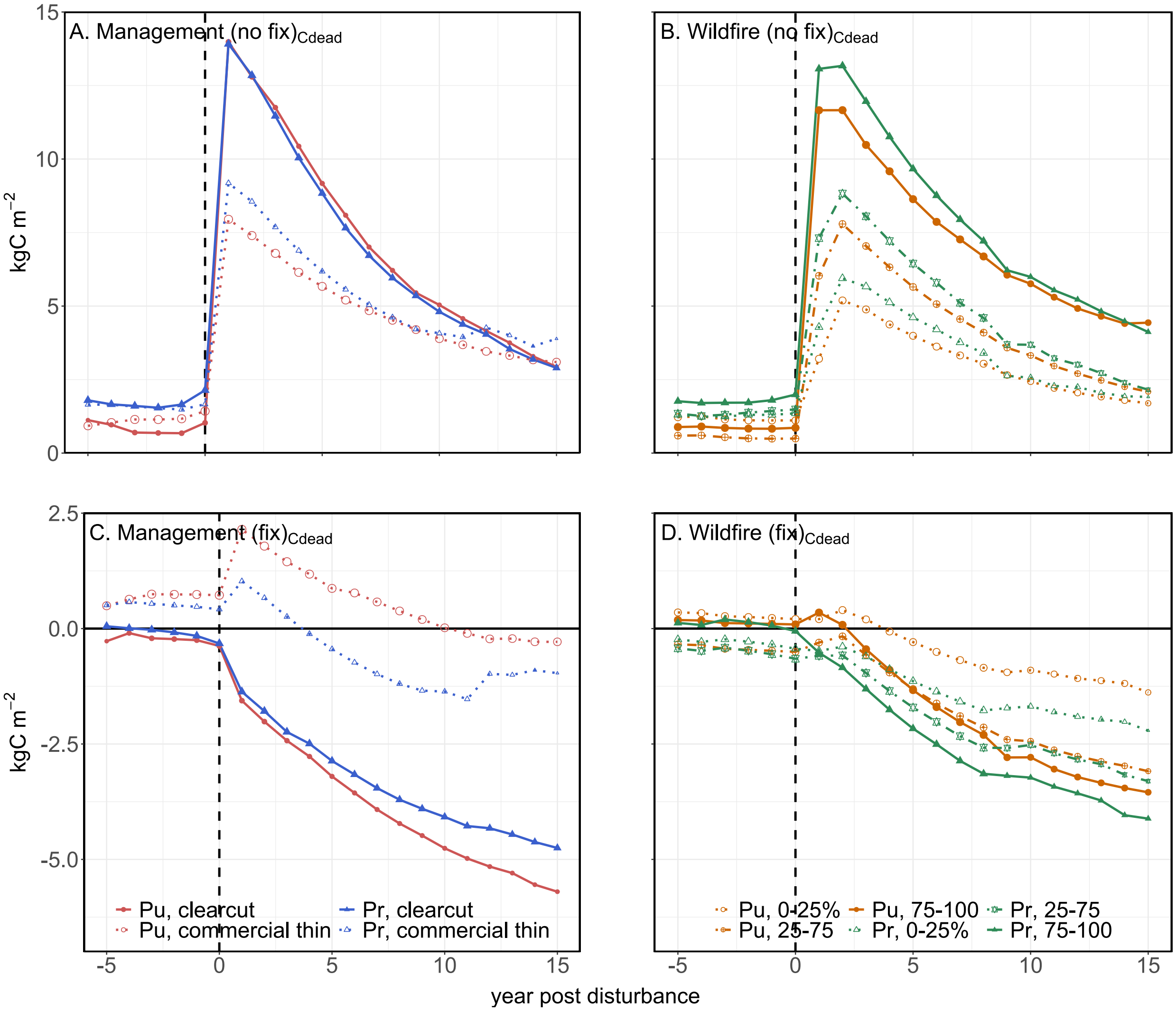

Figure S4. Differences in dead carbon between disturbed and undisturbed areas. Upper figures show the amounts of dead carbon without adjusting biomass processes after disturbances. Bottom figures show the amounts of dead carbon with adjusting biomass processes. Pu indicates public lands, and Pr indicates private lands.

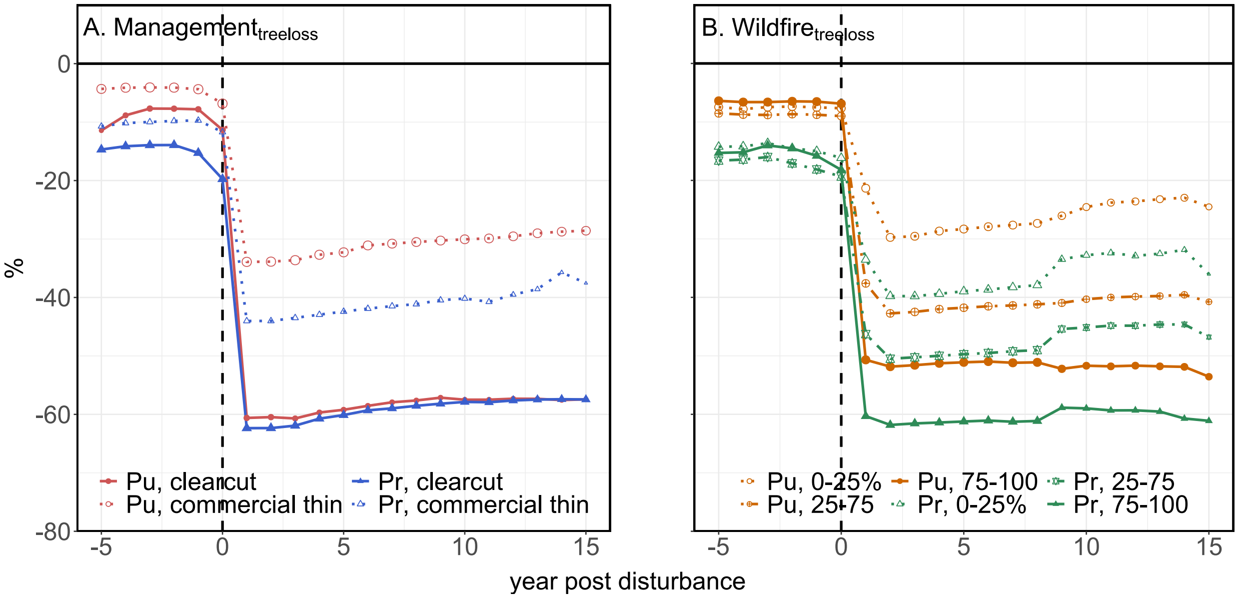

Figure S5. Differences in tree canopy losses (%) between disturbed and undisturbed areas. Pu indicates public lands, and Pr indicates private lands.

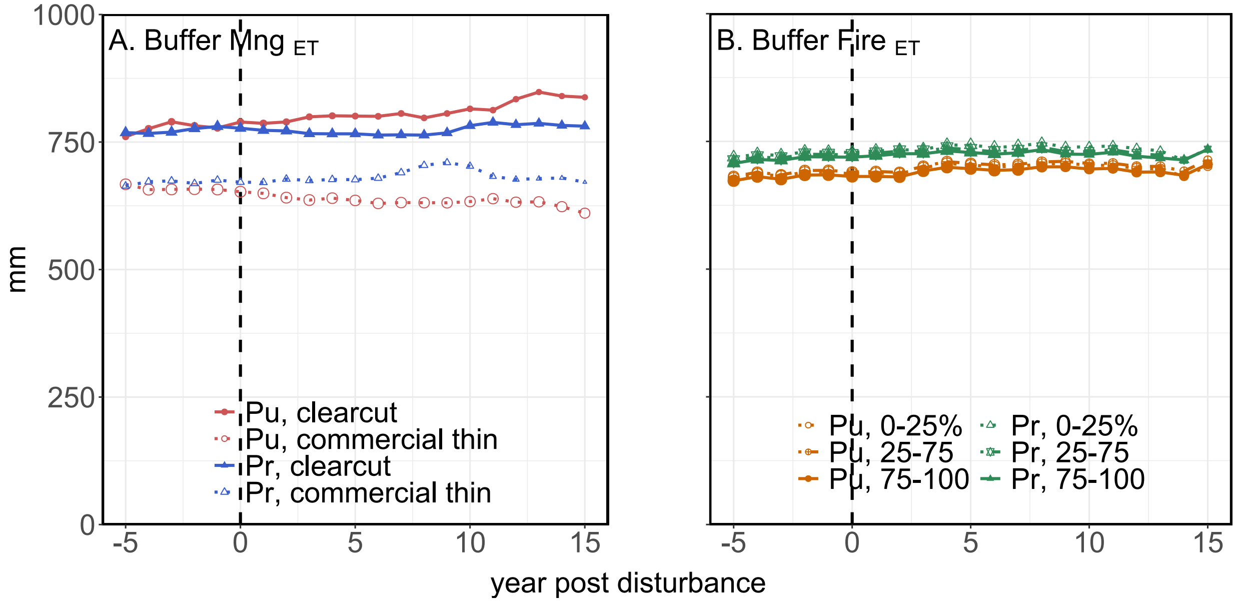

Figure S6. Changes in ET in undisturbed areas. Pu indicates public lands, and Pr indicates private lands.

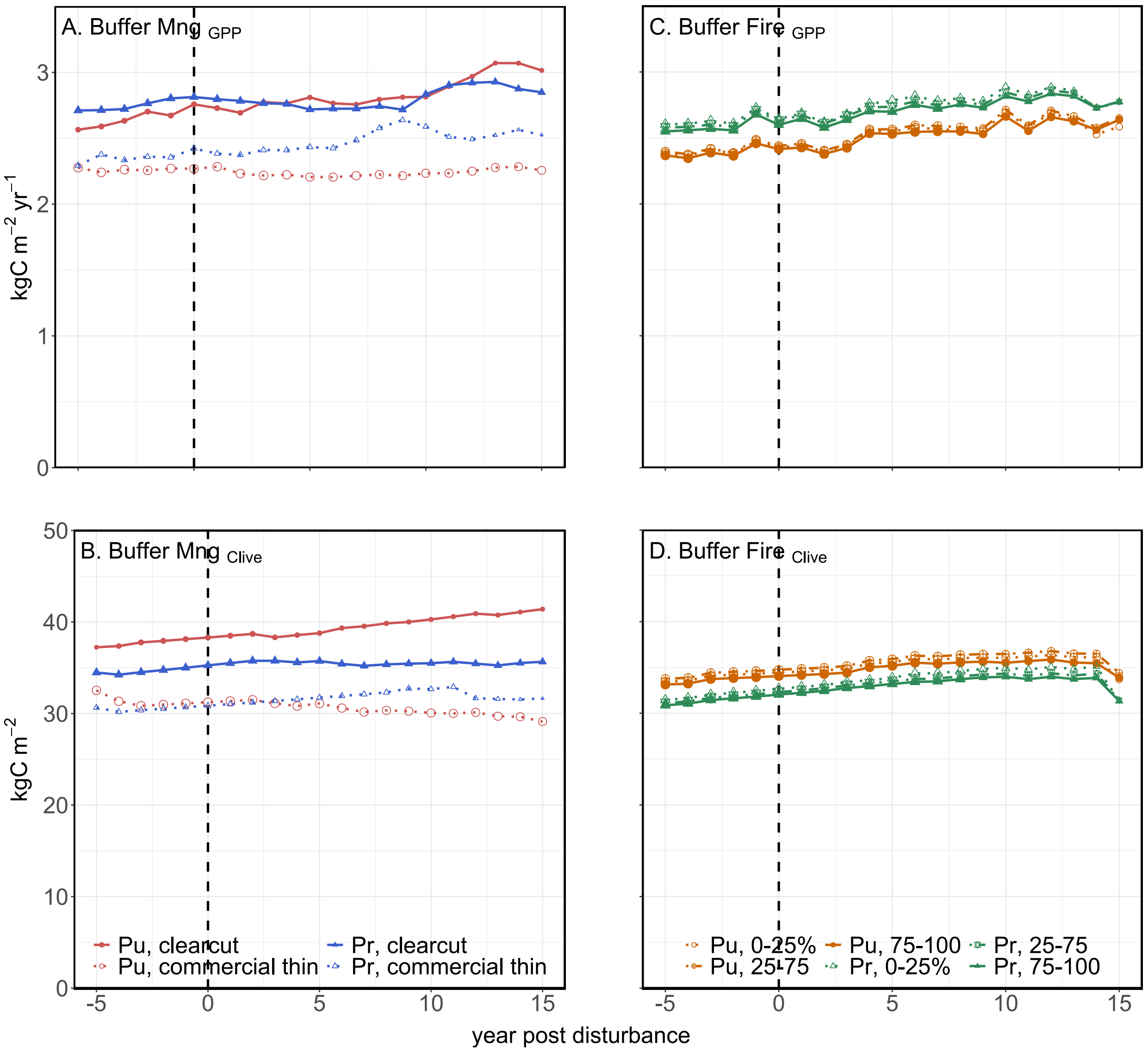

Figure S7. Changes in GPP and live carbon stock in undisturbed areas. Pu indicates public lands, and Pr indicates private lands.

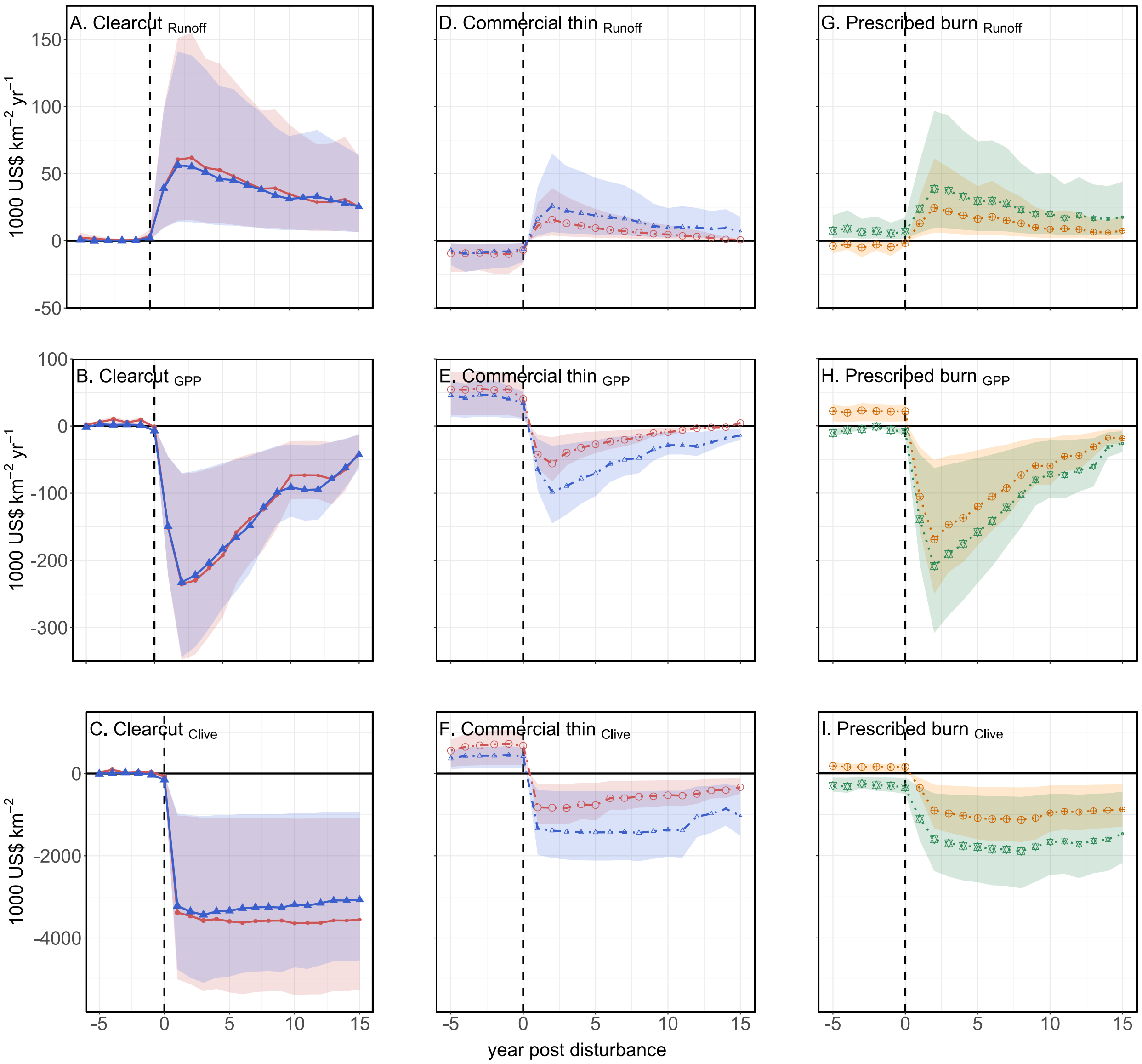

Figure S8. Economic values of marginal changes in runoff, GPP, and carbon stock with forest management practices. Year 0 indicates the year of forest management practices. Blue (*private*) and red (*public*) lines indicate the mean values of water production and carbon fluxes across each type of management and land ownership, using mid-unit water and carbon prices. Green and orange lines indicate the mean values of water production and carbon fluxes for low-severity wildfires as a proxy of prescribed burns. The colored shades indicate the ranges of annual economic values between low- and high-unit water and carbon prices. All values are in 2018 US dollars. Pu indicates public lands, and Pr indicates private lands.