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Valuing the impacts of forest disturbances on ecosystem services: An examination of recreation and climate regulation services in U.S. national forests

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ABSTRACT

The increasing frequency and severity of forest disturbances challenge the sustainable provision of ecosystem services by forests, and this is true even in regions with net forest growth. The combination of ecosystem service losses from forest disturbances that are immediate as well as the slower post-disturbance process of forest regrowth could result in long-lasting social, economic, and environmental costs. Using economic and geospatial analysis, we estimate the value of recreational services losses due to drought and quantify the social cost of carbon emissions due to wildfires and bark beetle damage in three National Forests in the Sierra Nevada region, California (Inyo National Forest, Tahoe National Forest, and Lake Tahoe Basin Management Unit). Our findings indicate that recent droughts resulted in an annual reduction of about \$73 million, \$36 million, and \$15 million for Lake Tahoe Basin Management Unit, Tahoe, and Inyo National Forests, respectively. Tree biomass loss due to wildfires and bark beetle damage generated around 10 Mt CO_2 of total emissions from 2003 and 2012. The estimated cumulative social costs of such emissions were around \$0.8 million for fire and \$2.4 million for bark beetle (using a 3% discount rate for related climate change damage). The social costs almost tripled under extreme climate damage projections. Our analysis could inform adaptation and management strategies to conserve or enhance the health and function of publicly managed forests, and to protect their flow of ecosystem services for present and future generations.

1. Introduction

Healthy forests generate a myriad stream of ecosystem services, such as regulating climate through carbon sequestration, filtering air and water, boosting biodiversity, providing timber and generating a positive effect on human health. Those services enhance human well-being (McMicheal et al., 2005). In turn, disturbances that disrupt the structure and composition of forests and compromise the provision of ecosystem services diminish people's well-being (Führer, 2000). While most disturbances are a natural component of forest ecosystems, their increasing frequency and intensity may alter forests' health too fast for natural adaptation to occur (Trumbore et al., 2015). The slow process of post-disturbance forest recovery or regrowth may result in an almost permanent reduction in the ability of disturbed forests to generate ecosystem services; this reduction may have long-lasting social, economic, and environmental consequences (Dale et al., 2000; Marcos-Martinez et al., 2019).

Climate change is projected to amplify damages to forests caused by disturbances (Seidl et al., 2017). The interplay between forest disturbances and climate change may have cascading effects on ecological and socioeconomic systems across temporal and spatial scales (Huo et al., 2019). In addition, interactions between disturbances themselves can compromise the ability of forests to sustainably generate services for individuals and communities (Allen et al., 2010). For instance, tree pest outbreaks have the potential to alter the probability, extent, or severity of wildfires, and post-fire forest regeneration (Hicke et al., 2012). Similarly, drought in combination with other physiographic parameters, pest types, and time since pest outbreaks, are key determinants of fuel conditions and fire frequency and impact (Andrus et al., 2016; Hicke et al., 2012).

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Additionally, the socioeconomic system influences forest ecosystem responses to stressors (Maes et al., 2016, Marcos-Martinez, et al., 2018). Policy initiatives that positively affect social responses or forest management on public lands that, in turn, enhance ecosystem services can improve human well-being. The economic quantification of forests disturbances effects on human well-being may provide public land managers and stakeholders with critical information that better aligns policy initiatives and budgets with changing social preferences. An understanding of the economic effects may improve the protection of and access to forests ecosystem services at different temporal and spatial scales.

In the United States (U.S.), tree mortality on publicly managed forests caused by disturbances has been increasing since the 1980s (Williams et al., 2016). This increasing mortality has resulted in forest cover loss at rates comparable to global deforestation hotspots (Hansen et al., 2010). Based on remotely sensed data, around 1.42% (~3.6 million hectares) of U.S. forest lands were disturbed each year from 1985 to 2015 (Masek et al., 2013). This estimate, however, does not account for low-intensity disturbances. Using estimates based on land management inventories, Dale et al. (2001) report that insect and pathogen outbreaks alone affected around 20.4 million hectares at an average annual economic cost of $1.5 billion.

Despite the significant annual average cost of disturbances, few studies have investigated this issue in detail (see Dale et al., 2001; Hanewinkel et al., 2013; Holmes et al., 2008 for some examples). To fill this gap, we investigate the following research question: what is the economic impact of forest disturbances on ecosystem services? We address this question by examining two important services provided by national forests in detail using benefit transfer: outdoor recreation and climate regulation services impacted by forest carbon emissions.

Outdoor recreation is one of the most valued ecosystem services from U.S. public lands. Approximately half of all Americans participate in outdoor recreation at least once per year (Outdoor Industry Association, 2018), spending more on this activity than on pharmaceutical products and fuel combined (Outdoor Industry Association, 2017). Outdoor recreation has significant economic benefits for many U.S. rural communities. The Outdoor Industry Association (2017) reports that outdoor recreation nationally generates $887 billion in consumer spending annually while supporting 7.6 million jobs. With respect to federal lands, in 2016, there were around 890 million recreational visits to federal lands resulting in around $49 billion in spending that supported around 826,000 jobs (Cline and Crowley, 2018). Given the importance of outdoor recreation to Americans, we focus on a case study of the effect of forest disturbances on the value of these activities over time (comparing 2015 to 2005) for a range of activities (wildlife and water-based pursuits), and across seasons (warm weather and winter).

Adequate protection of forest carbon stocks is critical for climate change abatement efforts. American public forests and forest products offset around 16% of the annual domestic CO_2 emissions (Durkay and Schultz, 2016). Past forest disturbances, however, have reduced forest carbon stocks to around half of their maximum storage potential (Williams et al., 2016). Biomass regrowth in previously disturbed areas sequestered around 1,600 million metric tons of CO_2 (Mt CO_2) between 1990 and 2016 (Woodall et al., 2015). During this period, wildfires and timber harvests reduced forest carbon stocks in U.S. public forest land by around 791 Mt CO_2. These carbon fluxes have resulted in annual net sequestration of around 30 Mt CO_2 per year on average, contributing to offsetting around 15% of annual U.S. carbon emissions from fossil fuel combustion (Woodall et al., 2015). From 2006 to 2010, the main disturbances creating CO_2 emissions from the continental U.S. were timber harvest (69%), wildfires (10%), land-use change (6%), wind (7%), insect outbreaks (7%), and droughts and other natural disturbances (1%) (Woodall et al., 2015). Since climate change mitigation and adaptation strategies require an accounting of the effects of natural and anthropogenic forest disturbances on carbon stocks and flows, part of our empirical analysis focuses on recent changes in forest emissions and their potential economic costs.

Our study contributes to the literature by providing key evidence of the economic effects of forest disturbances on outdoor recreation and carbon at different spatial and temporal scales. Using the benefit transfer method and geospatial data, we estimate the effects of forest disturbance on outdoor recreation and changes in carbon storage for three national forests located in California's Sierra Nevada region. The findings could be used to inform decision making in national forest management to properly mitigate the losses and maintain the forest health, especially in this critical time of changing global climate.

2. Study area

California has 18 national forests, three of which in the Sierra Nevada provide a wide variety of recreational opportunities. The Inyo National Forest is in the southern Sierra, while Tahoe and Lake Tahoe Basin Management Unit are in the central Sierra (Fig. 1). The Inyo National Forest is home to two ski areas, 100 miles of snowmobile trails, and 25 miles of Nordic ski trails. Inyo National Forest has nine federally designated wilderness areas covering approximately 400,000 hectares (~1 million acres). It is also home to winter sports and popular in the summer for fishing and mountain biking; hiking to the top of Mount Whitney is popular among visitors.

The Tahoe National Forest is situated within a 2-hour drive of Reno, Sacramento, and San Francisco. There are numerous special places that include Donner Camp Picnic Site and Interpretive Trail that is of historical interest. Moreover, in 1978, the North Fork American River was designated as a Wild and Scenic River. It provides recreational opportunities in late fall and spring when other recreation areas of the forest are still covered in snow.

The Lake Tahoe Basin Management Unit has one of the highest peaks in the state and has one of the highest snow packs. The Lake Tahoe Basin Management Unit jointly manages the Desolation Wilderness which covers over 63,900 acres of lakes, subalpine forest, and alpine habitat. The Desolation Wilderness is amongst the most popular in the National Wilderness Preservation System and reservations for the day, and overnight use are required in advance to manage the demand. The Tallac Historic Site is maintained for historical interest and is open late spring through early fall for hiking and sightseeing, with summer-season heritage tours.

Since forest stands at higher elevations are likely to be characterized by high tree density and include old-growth, they are important from a carbon standpoint. Red fir forest is the largest forest type in the higher elevation (1830 to 2286 m.a.s.l.; North, 2014). Other forest types found in the study site region are largely comprised of mixed-conifer, Western Ponderosa Pine, Jeffrey Pine and Lodgepole Pine (North, 2014).

With respect to compounding disturbances in our study area, mild drought conditions were observed in the eastern part of Inyo National Forest in 2005 (Fig. 2a) and in Tahoe National Forests in 2010. The statewide drought observed in 2015 generated significant stress to forest ecosystems with almost all the study area recording high cumulative drought index values (Fig. 2b). In terms of tree mortality, wildfires had a small effect on forest ecosystems in the study area in 2005, 2010 and 2015—high-intensity fires only occurred in some regions of Tahoe National Forest. Bark beetle damage was also low in 2005, occurring mostly in the Lake Tahoe Basin Management Unit (Fig. 2b). In 2010, however, only the eastern section of Inyo National Forest (a region with low forest cover) was not disturbed by bark beetles. Unfortunately, 2010 was the beginning of an ecological catastrophe that resulted in around 163 million death trees by 2019, mostly in the Sierra Nevada National Forest (California Forest Pest Council, 2019).

3. Materials and methods

Our modelling approach in examining both a cultural ecosystem service and a regulating service with global climate change implications

Fig. 1. Study area: Tahoe national forest, lake Tahoe basin management unit, and Inyo national forest.

is based on analysis of visitor surveys and remotely sensed data, benefit transfer estimates of economic valuation of recreational activities, and estimates of global economic impacts of carbon emissions.

3.1. Recreation

Estimation of the economic benefits of outdoor recreation is grounded in economic efficiency criteria which provides a useful framework for evaluating trade-offs for at least three reasons: 1) maximizing net economic benefits can be an important objective when facing scarcity and competing uses, 2) it provides a way to evaluate the opportunity costs of competing objectives, and 3) it provides a measure of the net benefits that both non-local and local visitors receive from recreation (Young and Loomis, 2014). Since entrance fees are not required to participate in outdoor recreation on national forest lands[2], non-market valuation techniques are useful to characterize the economic value of outdoor recreation activities.

If original non-market valuation studies cannot be undertaken due to limited resources or time constraints, benefits transfer method can be used to derive economic values (Johnston et al., 2015; Rosenberger and Loomis, 2001). In estimating the economic effect of forest disturbances on recreation, we apply a benefit transfer function. Johnston et al. (2015) explain that the benefits transfer method can be used to estimate economic values, where benefit transfer is "…defined as the use of research results from pre-existing primary studies at one or more sites or policy contexts (often called study sites) to predict welfare estimates such as willingness to pay (W.T.P.) or related information for other, typically unstudied sites or policy contexts (often called policy sites)."

There are two types of benefit transfer: unit value transfers and benefits function transfer. Unit value transfer uses a single number or set of numbers from previous primary studies to transfer to the new study area. For benefit function transfers, a single pre-estimated function from a single primary study – called a single-site benefit function transfer – can be used, or a set of previously calibrated functions for a meta-analysis – called meta-regression models – can be employed. It is generally accepted that benefit function transfers provide more accurate estimates than unit value transfers (e.g. Kaul et al., 2013). A more detailed description of the benefit transfer method can be found in Johnston et al. (2015) and Rosenberger and Loomis (2001).

For this study, we use recreation values estimated from a benefit function transfer by Rosenberger et al. (2017). We use Rosenberger et al. (2017) as they provide the most up-to-date recreation economic values available, applying a meta-analysis benefit transfer function for estimation. The meta-analysis are based on an exhaustive review of U.S. and Canadian economic studies ranging from 1958 to 2015. The benefit transfer is applied to the per person, per day average value estimates for recreational activities for three national forests (Inyo, Lake Tahoe, Lake Tahoe Basin Management Unit), explained below.[3] Economic value estimates for outdoor recreation activities derived by Rosenberger et al. (2017) are used to estimate the loss of annual economic benefits to recreationists due to forest disturbances.

Additionally, we use the National Visitor Use Monitoring (NVUM) program which the USDA Forest Service employs to track the number of annual visitors to each national forest and the recreational activities they engage in during their visits (English et al., 2002; USDA Forest Service, 2020). The NVUM surveys are quite comprehensive, reporting 28 primary recreation activities such as fishing, hiking, and viewing natural features, and is conducted annually while ensuring that each forest is surveyed every five years. There are 3 years of available NVUM data. The economic estimates for each outdoor recreation activity derived by Rosenberger et al. (2017) uses the most recent updated

[2] As listed in the *Recreation Enhancement Act* (2005), standard amenity fee sites are those that provide designated developed parking, picnic tables, toilet facilities, security, interpretive signs and trash receptacles. Visitors do not have to display a valid recreation pass if they park outside these sites.

[3] For more detail information on this procedure, see Rosenberger et al. (2017).

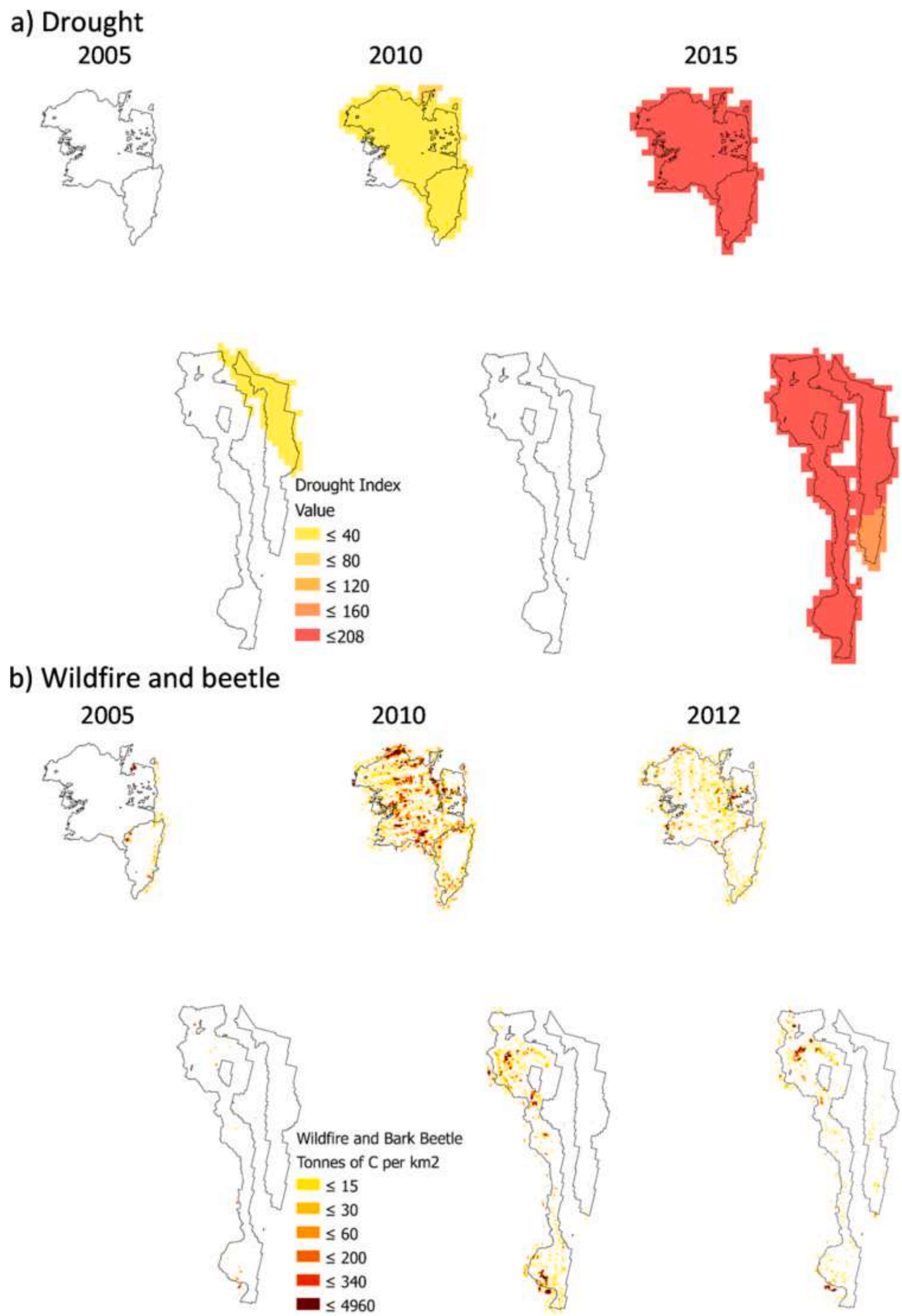

Fig. 2. Spatial distribution and intensity of forest disturbances: Drought, and wildfire and bark beetle tree damage. Note: Wildfire and beetle mortality are only available for the period 2003-2012. The legend in panel b is based on the quantile distribution of the carbon emissions.

Recreation Use Values Database, 2016. NVUM data for our study area were available for the periods 2005, 2010, and 2015 for Tahoe National Forest and Tahoe Basin Management Unit; and for 2006, 2011 and 2016 for Inyo National Forest.

Following Rosenberger et al. (2017), we first estimate total annual visits for each national forest for 28 primary recreational activities using the formula:

$$\text{No. of Visits Per Activity} = \text{NVUM Total Annual Visits} \times \text{Main Activity Percentage} \tag{1}$$

Next, the number of visits per recreational activity is multiplied by conversion coefficients and average economic values (Eq. (2)) to arrive at the aggregate recreation benefit value. The conversion coefficients translate visits into primary activity days. NVUM defines primary days as main activity participation for some portion of a day. For example, a recreationist whose main activity is hiking and engages in that activity for 3 hours a day is one primary activity day of hiking. If it is two individuals, then the primary activity days for hiking will be two. The conversion coefficient is defined as the average number of calendar days per national forest visit and is imputed by Rosenberger et al. (2017) using NVUM survey results. The conversion coefficient is estimated for each main activity and may vary by recreation activity and national forest. The average economic value is estimated for each main activity using a meta-regression model that estimates the average value for each recreation activity (Rosenberger et al., 2017).

$$\begin{aligned} \textit{Aggregate Rec. Benefit Value} = {} & \text{No. of Visits Per Activity} \\ & \times \text{ Conversion Coefficient} \\ & \times \text{ Economic Value} \end{aligned} \tag{2}$$

Climate change and drought appear to affect recreation excursions (Crowley et al., 2020; Hand and Lawson, 2018; Halofsky et al., 2017); winter activities can be negatively affected (Hand and Lawson, 2018) as can water-based activities (Hand and Lawson, 2018; Loomis et al., 2004), but these can have a positive effect on summer activities (Albano et al., 2013; Fisichelli et al., 2015; Hewer and Gough, 2019), thus we investigate how changes in visitation rates are linked to forest disturbances in the study area by using spatiotemporal data of drought, wildfires, and bark beetle damage. As a measure of drought intensity, we use the annual Cumulative Drought Index (CDI), which accounts for the intensity and duration of drought throughout the year (NOAA, USDA, NDMC, 2020). The CDI accounts for the number of weeks a site was classified in one of five drought categories with a maximum value of 208 (NOAA, USDA, NDMC, 2020). Data for 2005, 2010, and 2015 are used to investigates changes in recreational activities. Changes in aesthetic conditions due to tree mortality from wildfires and bark beetle in 2005, 2010 and 2012 are explored using tree mortality data from Berner et al. (2017).

3.2. Climate regulation

Although 60 to 80 percent of total CO_2 emissions are absorbed by land and ocean ecosystem within 200 to 2000 years, the remaining can persist in the atmosphere for thousands of years (Archer et al., 2009). The gradual accumulation of CO_2 emissions in the atmosphere contributes to global warming. Climate change is expected to generate significant net costs to society, reducing crop yields, increasing risks to property and human health. We apply estimates of the global net monetary impact per additional metric ton of CO_2 emitted based on three integrated assessment models (IAMs) of human and ecological systems (Interagency Working Group, 2016). This quantification is called the Social Cost of CO_2 (SC-CO_2) emissions and represents the marginal net cost per additional metric ton of CO_2 emission.

Due to the long life-span of CO_2 emissions in the atmosphere, their social cost is estimated from the year of emission to 2300. Such estimates are then discounted at different rates (2%, 3% and 5%) with higher rates favoring the welfare of current generations. The SC-CO_2 is also estimated for extreme climate change impacts based on upper estimates (95^{th} percentile estimates) of projections generated by the ensemble of IAMs at a 3% discount rate. We use a linear regression model (R^2=0.99) to estimate the annual cost of emissions from disturbance from 2003 to 2012 using SC-CO_2 data reported by the IWG for the period 2010–2100 at five-year intervals. Annual SC-CO_2 estimates from 2003 to 2012 (in 2016 dollars) were multiplied by above-ground forest CO_2 loss due to fire and bark beetle disturbances based on spatially explicit data (1 km resolution) (Berner et al., 2017).

Although timber harvest is the main driver of forest cover and forest carbon stock reductions in the United States, carbon embedded in some wood products could remain stored for decades (Loeffler et al., 2014; Williams et al., 2014). The large range of carbon decay rates across wood product types and final use complicates the estimation of the net carbon flux effect of timber harvesting through the value chain. In addition, selective logging and postharvest reforestation, where it occurs, can set the conditions for gradual recovery of forest carbon stocks. The average residence time for carbon in forest biomass is more than twice that of wood products (Law et al., 2018) and once forests are disturbed, their ability to reach preexisting levels of carbon storage and other ecosystem service provisions could be significantly compromised (Marcos-Martinez et al., 2019). Owing to the complexities associated with estimating net carbon fluxes from timber harvest through the value chain, we focus instead on the analysis of carbon emissions resulting from tree mortality from fires and bark beetles.

4. Results and Discussion

4.1. Recreation

Although in recent decades, drought, wildfires, and bark beetle had reduced the provision of recreational services in the study area, we focus on activities related directly to water or precipitation. Droughts have occurred in California over the study period – both from 2007 to 2009 (California Department of Water Resources, 2010) and from 2011 to 2017 (National Integrated Drought Information System, 2018). These observed patterns of forest disturbances had varying effects on the economic benefits of recreational activities. Fig. 3 illustrates these effects using baseline data from 2005 and 2006. The economic values for each activity is held constant to 2016 values, thus, the reported changes in economic benefits are solely due to changes in visitation. Drought conditions influenced overall visitation patterns for all three national forests. There were positive changes in the economic benefits of warm-weather activities such as viewing natural features, hiking, bicycling, primitive and developed camping, horse riding, and backpacking during the 10-year period; the increase ranges from 9% to about 36%, translating to an annual economic gain of \$6 to \$36 million. The activities with the greatest percentage increases vary across the national forests; in Tahoe, these are viewing natural features (103%) and backing (313%). For Lake Tahoe Basin Management Unit, these activities are horseback riding (2296%), backpacking (222%), and other non-motorized recreational activities (127%), whilst for Inyo bicycling (109%) and hiking/walking (12%) saw the largest gain in value. These increases are partially due to drier conditions, which resulted in recreation sites and trails opening sooner and closing later in the season. Additionally, a higher number of hotter days at lower elevations may have caused people to escape to higher elevations for cooler temperatures.

In contrast, across the three national forests there was a considerable decline in the economic benefits for winter activities (downhill skiing, cross country skiing, snowmobiling), wildlife activities (fishing, viewing wildlife, hunting), and water-based activities (motorized and non-motorized water activities). The decrease in the value of the benefit ranges from 21 percent to 34 percent, corresponding to an annual economic loss of \$15 to \$73 million. The activities that experienced the greatest decrease in value include snowmobiling (-97%) and downhill skiing (-25%) for Tahoe NF; snowmobiling (-100%), cross-country skiing (-97%), and downhill skiing (-17%) for Lake Tahoe Basin Management Unit; and snowmobiling (-100%) and downhill skiing (-37%) for Inyo NF. These drops in value can be attributed to fewer snow days in the region due to drought conditions. Similarly, for wildlife activities, the decrease in benefits ranges from 10 to 48 percent that translates into an annual economic loss of \$0.9 to \$12 million. The most notable decreases are fishing (-52%) and hunting (-20%) for Tahoe NF; viewing wildfire (-20%) for Lake Tahoe Basin Management Unit; and viewing wildfire (-60%) and fishing (-50%) for Inyo NF. This decline is largely attributed to lower year-round water flows necessary for fishing activities. This lower water flow may have also contributed to the decrease in economic benefits from water-based activities which ranged from 21 to 32 percent, equivalent to \$0.7 to \$3 million per year across the three national forests. The largest decrease is non-motorized water (-70%) for Tahoe NF; motorized water activities (-48%) for Lake Tahoe Basin Management Unit; and non-motorized water (-32%) for Inyo NF. See tables 1A and 2A in supplementary materials for complete list of main recreation activities with visitation estimates, percentage changes, and economic values.

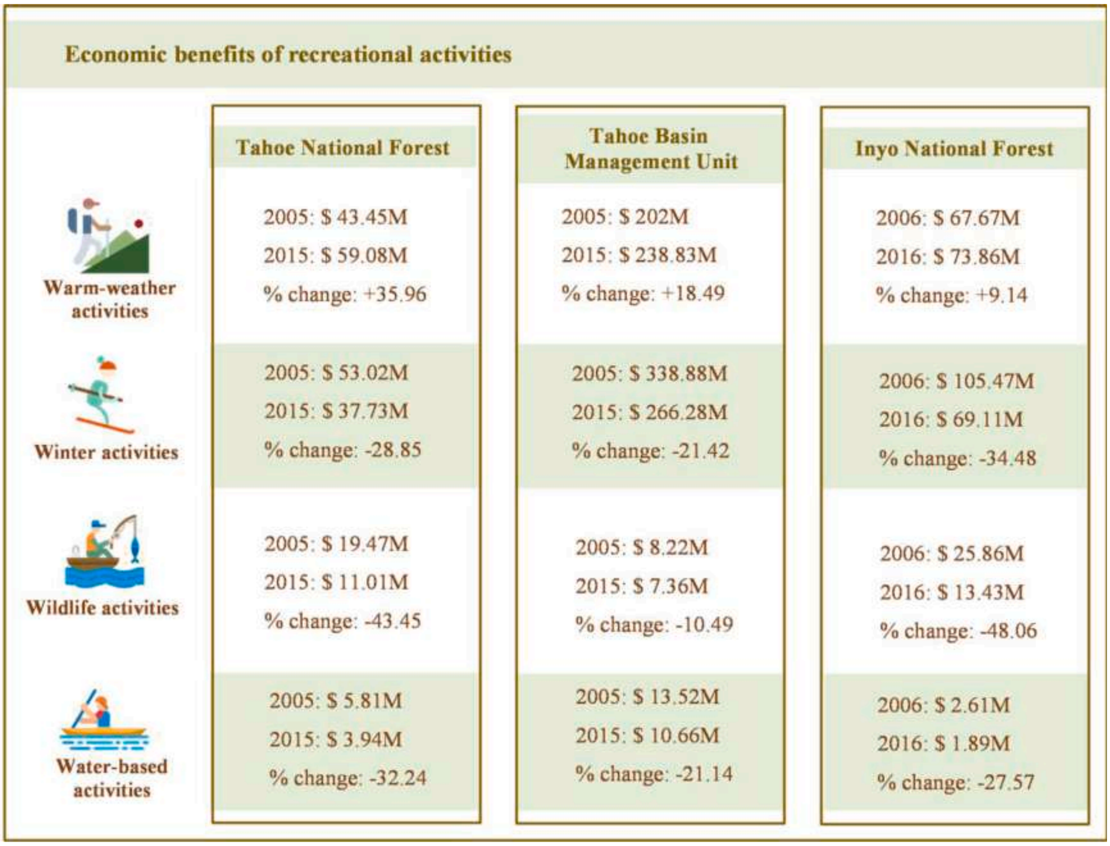

Fig. 3. Changes in economic benefits of recreational activities[11] in Tahoe, Lake Tahoe Basin Management Unit, and Inyo National Forests during a 10-year period.

Table 1
Potential policy responses derived from our analysis based on the Driver-Pressure-State-Impact-Response framework.

Disturbance	Impacts	Specific policy responses	General Policy responses
Drought	Increase in warm-weather recreation activities Decrease in water-based recreational activities	- Shift personnel to better align with anticipated higher demand for warm-weather recreation activities. - Providing necessary information to recreationist e.g. alternative sites as they adapt to impacts of forest disturbances by changing their selection of recreational sites and activities due to such things as changing water levels and snow packs (Hand and Lawson, 2018)	- Monitoring spatiotemporal changes in disturbance regimes and prioritize plans and management areas. - Designing of spatially targeted forest conservation, pest control, or fire prevention and suppression strategies. - Implementing strategies that offset carbon losses from disturbance e.g. managing sawdust timber harvesting, fertilization (Johnson and Curtis, 2001). - Implementing strategies to enhance collaboration and capacity building of related stakeholders to increase social adaptive capacity (Seidl et al., 2016).
Pest Outbreaks	Lower biomass due to tree damage and mortality	Reducing tree stand density and increasing landscape tree species heterogeneity (Fettig, 2012).	
Wildfires	Lower biomass due to tree damage and mortality	Enhancing forest heterogeneity (Long et al., 2014, Pedro et al. 2015).	

4.2. Climate regulation

From 2003 to 2012, CO_2 emissions from tree biomass loss due to bark beetle and wildfire damage accounted for 60%, 70%, and 77% of the emissions observed Inyo National Forest, Tahoe National Forest, and Lake Tahoe Basin Management Unit, respectively (Fig. 4a, b). Tree biomass loss during this period, from the assessed disturbances, resulted in a release of around 10 million tons of CO_2. Carbon dioxide emissions ranged from 3.95 million tons in 2004 to 0.12 million tons in 2005 (Fig. 4c). Although beetle damage was greater, the corresponding tree damage per hectare was significantly lower than wildfire damage. Wildfires were key drivers of CO_2 emissions, particularly during drought years (i.e. 2006-2008). Fig. 4c shows a drastic increase in emissions in 2004, resulting from catastrophic tree die back generated by a large bark beetle outbreak. This is consistent with data indicating that around 1.7 million hectares of forests (4.1 million acres) were affected during that period in California, with tree mortality being most severe in drought-stressed, dense forest stands in the Sierra Nevada National Forests (Smith, 2007). More than $500 million was spent to remove hazardous trees, reduce fuel loads, and restore forests in southern California following this outbreak (Smith, 2007).

The frequency and intensity of wildfire and bark beetle tree damage determined the spatial patterns of the SC-CO_2 emissions (Fig. 5). From 2003 to 2012, on a per hectare basis, the cumulative social cost of forest disturbances associated with CO_2 emissions ranges from $65 to $16,662 per hectare (2016 dollars) – assuming a 3% discount rate for future climate damage (Fig. 5a). Tahoe National Forest had the largest cumulative SC-CO_2 emissions ($2.47 million) amongst the three national forests (Fig. 5b). Inyo National Forest and Lake Tahoe Basin Management Unit had cumulative SC-CO_2 emissions valued at $0.57 and $0.19 million, respectively. The total cumulative SC-CO_2 emissions from 2003 to 2012 was $5.2 million, $3.2 million, and $0.9 million at 2.5%, 3%,

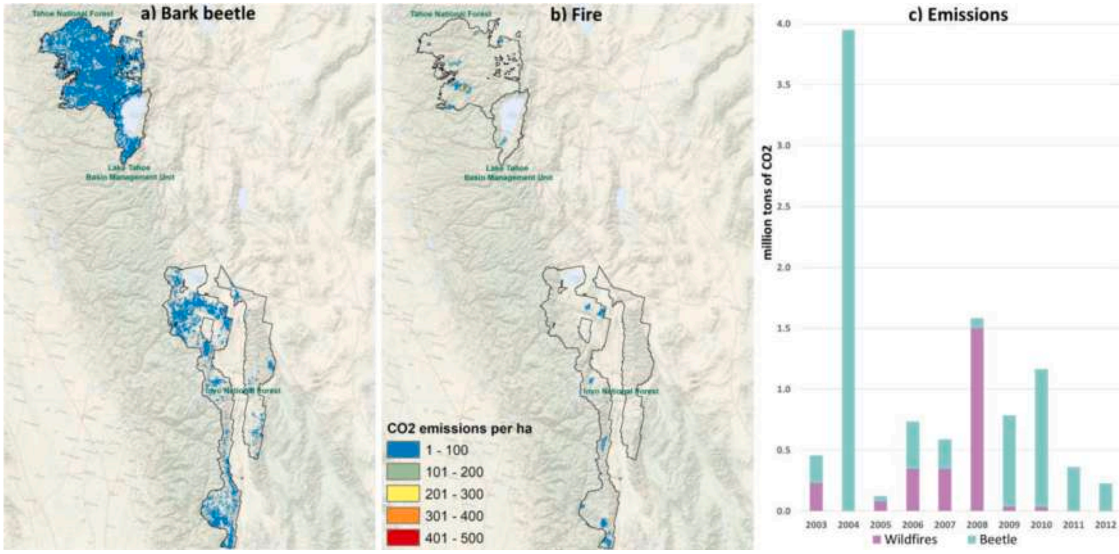

Fig. 4. CO_2 emissions from biomass loss due to bark beetle and wildfires tree mortality (cumulative emissions from 2003 to 2012).
Notes: Cumulative and annual CO2 emissions from above-ground tree biomass loss generated by bark beetle (a), and wildfire (b). These two disturbances and timber harvest constitute the main drivers of change in forest cover loss and forest carbon stock in the U.S.

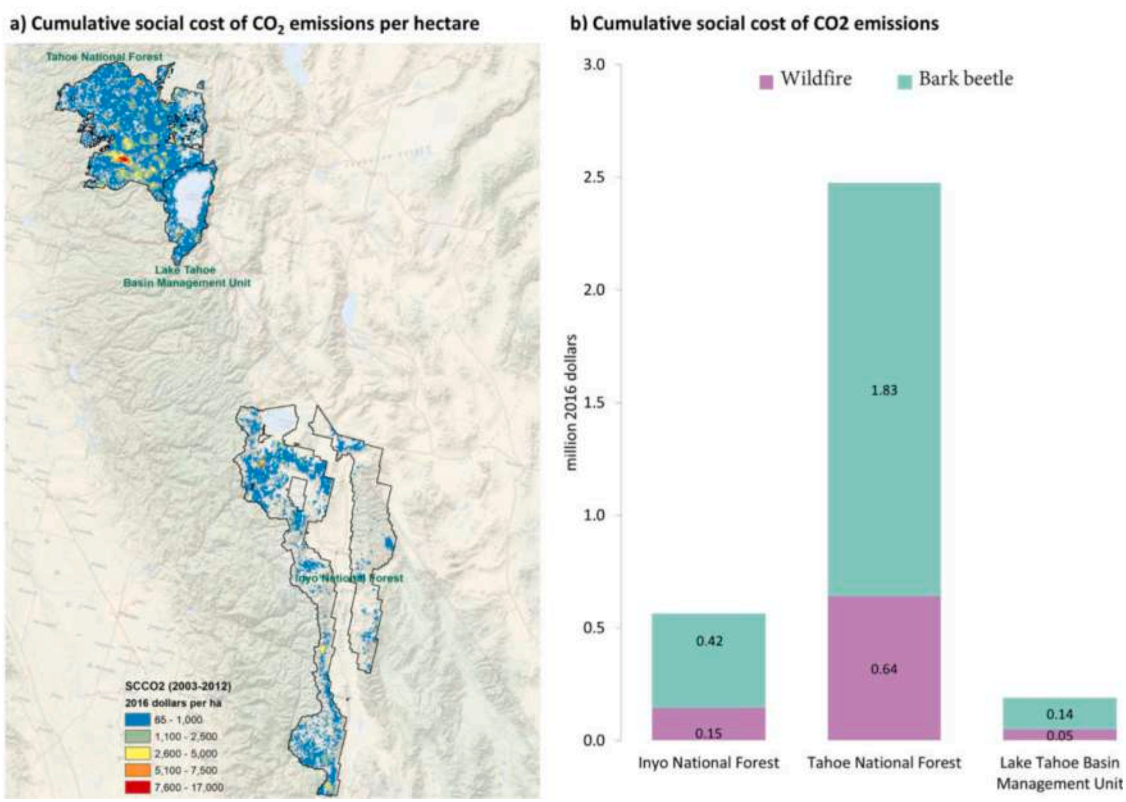

Fig. 5. Cumulative social cost of CO_2 emissions from tree mortality due to bark beetle and wildfire disturbances (2003-2012). Estimates using the global social cost of CO_2 emissions discounted at 3%.

and 5% discount rates, respectively; note how the different discount rates clearly affect the valuation. Accounting for extreme climate impact estimates and using a 3% discount rate the SC-CO_2 emissions from wildfires and bark beetle would reach \$8.9 million.

4.3. Policy implications

As forest disturbances become more frequent and devastating, the

[1] Warm-weather activities include viewing natural features; hiking; bicycling; primitive and developed camping; horse riding; backpacking. Winter activities include downhill skiing; cross country skiing, snowmobiling. Wildlife activities include fishing; viewing wildlife, hunting. Water-based activities include motorized and non-motorized water activities. There are other types of activities that are categorized into others include relaxing; visiting historic sites, nature study, etc. Although they were not listed here in the figure, the data were used to estimate total percentage change in economic benefit above.

sustainable provision of forest ecosystem services is at risk in some regions, raising the possibility of negative welfare effects on individuals and communities. Successful policies will need to account for differences in the resilience of forest ecosystems and human adaptability to dynamic levels of forest services that are likely to result in spatially heterogeneous post-disturbance economic outcomes.

Strategic policies designed to effectively contend with adverse economic consequences of disturbances must rely on rigorous information and insights on how specific forest stressors affect forests' ability to provide multiple ecosystem services. Our case studies of economic impacts of forest disturbances on outdoor recreation and carbon storage may guide land managers in designing policies that maximize limited resources while ensuring the sustainable generation of ecosystem services that enhance human well-being. For example, using our findings in drought years, public land managers could decide to shift personnel to work earlier and later in the season to better align with anticipated higher demand for warm-weather recreation activities such as hiking and camping. The results could also inform the design of spatially targeted forest conservation, pest control, or fire prevention and suppression strategies to minimize adverse impacts on forest health and functions and generate greater benefits to society.

Policies related to the use of these public lands may need to account for changes in recreational patterns to ensure that related infrastructure and resources are resilient over time to support shifting use patterns. For example, recreationists may adapt to impacts of forest disturbances by changing their selection of recreational sites and activities due to such things as changing water levels and snow packs (Hand and Lawson, 2018). Furthermore, public land managers could provide information to recreationists on substitute sites, when the original destination is no longer available for their desired recreation activities.

As reduced tree competition could enhance tree growth and defensive mechanisms, one of the most effective strategies for controlling bark beetle infestation is to reduce tree stand density. In addition, because large contiguous lands with high homogeneity are prone to bark beetle outbreaks, increasing species and landscape heterogeneity could reduce the bark beetle-caused tree mortality (Fettig, 2012). Promoting forest heterogeneity could be carried out through silvicultural practices and proper fire management (Long et al., 2014). Not only do these management strategies improve forest resilience against bark beetle attacks but also other types of disturbances whether acute such as high-intensity wildfires or drought or chronic disturbances such as understory burning or climate effects (North et al., 2014). Strategies that offset carbon losses from disturbance range from managing sawdust timber harvesting, fertilization (Johnson and Curtis, 2001) to species selection (Pedro et al., 2015).

Our study shows that monitoring spatiotemporal changes in disturbance regimes could help to understand the dynamics of underlying ecological processes and prioritize plans that adaptively manage forests and their stressors. This is essential to foster forests resilience to dynamic disturbances. Pathways to forest resilience should account for local ecological and social contexts, that is for structural and species diversity across forest management regions. Such pathways should also include strategies to enhance collaboration and capacity building of related stakeholders to boost not only ecological resilience but also adaptive social capacity in forest regions (Seidl et al., 2016). Social resilience can be strengthened by considering how impactful forest management strategies are in human communities. In turn, the adaptive capacity of communities can help facilitate management to improve resilience (Long et al, 2014).

We summarize policy insights from our findings in Table 1. We adapt the Driver-Pressure-State-Impact-Response (DPSIR) framework (Kristensen, 2004) to report our findings and policy options to support decision makers. The DPSIR framework has been used for more than 30 years to link ecological and socioeconomic drivers resulting in changes in the state of the environment and relevant impacts. This approach is useful for supporting decision making especially in the context of environmental management (Tscherning et al., 2012, Bradley and Yee, 2015).

4.4. Contributions and caveats

Forest disturbances may result in both positive and negative consequences, depending upon the ecosystem service being considered (Thom and Seidl, 2016). As a result, the total valuation of the economic value of disturbances can be expensive, time-consuming, and difficult; indeed, in some cases, such an endeavor may be infeasible. In cases where forest damage is extreme, extensive, or marks a substantial departure from previous natural patterns, the effect on ecosystem services can be severe and wide-ranging. Some of these effects can be readily measured in quantitative terms, but others, particularly those associated with less tangible values such as aesthetics or existence values, are more difficult to quantify. Our analysis may guide the identification of how changes in forest ecosystems affect human well-being and help to quantify these economic values – whether benefits or costs – making trade-offs when prioritizing or balancing which ecosystem services to protect.

Our valuation likely underestimates of the impacts of forest disturbances on outdoor recreation opportunities available on public lands as we focus on valuing changes in recreational benefits due to disturbances rather than the regional economic impact of reduced household expenditure on outdoor recreation. Additionally, we examine visits only to national forests, not all public lands at the federal level and none at the state level. Furthermore, we have only examined use values and do not consider non-use-value such as bequest and existence values; the latter values may be significant in a densely populated state like California. To fully understand the total economic loss in outdoor recreation benefits due to drought, wildfires, and other disturbances, aggregation is needed across all public and private lands that are available for outdoor recreation opportunities and must include nonuse values.

Ideally, comprehensive estimates of the net impacts of changes in forest carbon stocks would include modelling of vegetation and soil carbon dynamics as well as carbon emissions and sequestration in above and below ground biomass. Nevertheless, we intentionally focus on the cost of carbon emissions due to above ground tree biomass loss for a few reasons. First, we want to identify the spatial patterns of forest carbon emissions (and their associated global social cost) due to disturbances. This may help forest managers to identify and target regions that can potentially reduce forest carbon emissions. Second, our spatially-explicit data do not allow the identification of total tree biomass loss, thus preventing us from using analytics such as root-to-shoot ratios when forest disturbances generate a complete loss of above and below ground biomass. Finally, we recognize that in the long run, forest regrowth will offset carbon emissions generated by disturbances, although there is a significant lag between the time of the emissions and their sequestration through biomass regrowth (Marcos-Martinez, et al. 2019). The literature suggests that the omission of below ground and soil carbon impacts in our analysis would not significantly modify our emission estimates. There is evidence of no significant net loss on total carbon in either the topsoil or the whole soil due to prescribed fires and wildfires (see the meta-analysis by Johnson and Curtis, 2001). Under some conditions, fire events could even contribute to increase forest carbon stocks (Jones et al., 2019). Bark beetle outbreaks decrease forest stand densities and above and below ground biomass and increase coarse woody debris and forest floor accumulations (Overby, Hart and Neary, 2003). Hence, the net impact on forest carbon stocks of bark beetle outbreaks would depends on the severity, duration, and frequency of such disturbance.

5. Conclusion

In recent decades, forest disturbances have had a large effect on the health and structure of forest ecosystems in the Sierra Nevada in California. The increasing frequency and intensity of disturbance events in that region threaten the sustainable provision of key ecosystem services. Valuation of these forest stressors may inform management strategies to respond and adapt to changing disturbance regimes. Combining non-market valuation methods with remote sensing forest disturbance data, we monetize the loss of recreational and climate regulation services due to forest disturbances in Tahoe National Forest, Lake Tahoe Basin Management Unit, and Inyo National Forest.

Between 2005 and 2016, drought conditions exacerbated tree mortality, arising from wildfires and bark beetle outbreaks, to reduce the overall economic value of winter, wildlife, and water-based recreational activities. The annual economic loss was substantial. For instance, in 2015, the Lake Tahoe Basin Management Unit and Tahoe National Forests incurred an annual loss of about $73 and $15 million, respectively, for recreation activities relative to pre-drought years, while in 2016 the annual loss for winter activities totaled $36 million on the Inyo National Forest. The annual total loss is greater when aggregating across outdoor recreation categories such as wildlife- and water-based activities. Nevertheless, there were positive annual gains from warm-weather activities valued at $6 million, $15 million, and $36 million for Inyo, Tahoe, and Lake Tahoe Basin Management Unit, respectively.

Forest regrowth on previously disturbed land has resulted in net increases in forest carbon stocks on national forests. This trend is expected to continue, even under climate change, generating valuable social benefits by offsetting CO_2 emissions from other economic activities. Nevertheless, our study suggests that the economic value of emissions from forest disturbances are significant even for forests in low wildfire-risk regions such as the Sierra Nevada in California. The total social cost of carbon emissions from tree biomass loss caused by wildfires and bark beetle was $5.2 million, $3.2 million, and $0.9 million at 2.5%, 3%, and 5% discount rates, respectively. Under extreme climate change projections, the SC-CO_2 emissions would be around $9 million using a 3% discount rate.

As more frequent and severe forest disturbances occur, policymakers, stakeholders, and communities may need to adapt to new conditions and realities that ecosystem service benefits from public forests will change. For example, many of the national forests may continue to experience snowpack losses and an increase in the demand for warm-weather recreation activities. Future research on these issues in other regions globally will improve our understanding of the socio-economic effects of forest disturbances, and thereby can help decision-makers improve critical adaptation and management strategies that will benefit future generations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

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References

Albano, C.M., Angelo, C.L., Strauch, R.L., Thurman, L.L., 2013. Potential effects of warming climate on visitor use in three Alaskan national parks. Park Science 30, 37–44.

Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Vennetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.H.(Ted), Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.-H., Allard, G., Running, S. W., Semerci, A., Cobb, N., 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For. Ecol. Manage. 259, 660–684. https://doi.org/10.1016/j.foreco.2009.09.001.

Andrus, R.A., Veblen, T.T., Harvey, B.J., Hart, S.J., 2016. Fire severity unaffected by spruce beetle outbreak in spruce-fir forests in southwestern Colorado. Ecol. Appl. 26, 700–711. https://doi.org/10.1890/15-1121.

Archer, D., Eby, M., Brovkin, V., Ridgwell, A., Cao, L., Mikolajewicz, U., Caldeira, K., Matsumoto, K., Munhoven, G., Montenegro, A., Tokos, K., 2009. Atmospheric lifetime of fossil fuel carbon dioxide. Annu. Rev. Earth Planet. Sci. 37, 117–134. https://doi.org/10.1146/annurev.earth.031208.100206.

Berner, L.T., Law, B.E., Meddens, A.J.H., Hicke, J.A., 2017. Tree mortality from fires, bark beetles, and timber harvest during a hot and dry decade in the western United States (2003–2012). Environ. Res. Lett. 12 (6), 065005 https://doi.org/10.1088/1748-9326/aa6f94.

Bradley, P., Yee, S., 2015. Using the DPSIR Framework to Develop a Conceptual Model: Technical Support Document. U.S. Environmental Protection Agency, Washington, DC. EPA/600/R-15/154, 2015.

California Department of Water Resources, 2010. California's Drought of 2007-2009. Sacramento: Retrieved from https://water.ca.gov/-/media/DWR-Website/Web-Pages/Water-Basics/Drought/Files/Publications-And-Reports/Californias-Drought-of-200709An-Overview.pdf.

California Forest Pest Council, 2019. 2019 California Forest Pest Conditions. Retrieved from https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fseprd736355.pdf.

Cline, S., Crowley, C., 2018. Economic Contributions of Outdoor Recreation on Federal Lands (2016). Washington, DC: The U.S. Department of Interior, Office of Policy Analysis Retrieved from https://www.doi.gov/sites/doi.gov/files/uploads/recn_econ_brochure_fy_2016_2018-04-04.pdf.

Crowley, N., Doolittle, C., King, J., Mace, R., and Seifer, J., 2020. Drought and outdoor recreation: impacts, adaptation strategies, and information gaps in the intermountain West. https://www.drought.gov/news/new-report-drought-and-outdoor-recreation.

Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., 2000. The interplay between climate change, forests, and disturbances. Sci. Total Environ. 262, 201–204. https://doi.org/10.1016/S0048-9697(00)00522-2.

Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J., Simberloff, D., Swanson, F.J., Stocks, B.J., Wotton, B.M., 2001. Climate change and forest disturbances. Bioscience 51 (9), 723–734.

Durkay, J., Schultz, J., 2016. The role of forests in carbon sequestration and storage. In: National Conference of State Legislatures (NCSL). Retrieved from. https://www.ncsl.org/research/environment-and-natural-resources/the-role-of-forests-in-carbon-sequestration-and-storageaspx#:~:text=The%20U.S.%20Forest%20Service%20reports,%2D%20or%20diesel%2Dfueled%20vehicles.

English, D.B.K., Kocis, S.M., Zarnoch, S.J., Arnold, R.J., 2002. Forest Service National Visitor Use Monitoring process: research method documentation. Gen. U.S. Department of Agriculture, Forest Service, Asheville, NC. Tech. Rep. SRS-GTR-57Southern Research Station. 14 p.

Fettig, C.J., 2012. Chapter 2: Forest health and bark beetles. In: North, M. (Ed.), Managing Sierra Nevada forests. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA, pp. 13–22. Gen. Tech. Rep. PSW-GTR-237.

Fisichelli, N.A., Schuurman, G.W., Monahan, W.B., Ziesler, P.S., 2015. Protected area tourism in a changing climate: Will visitation at US National Parks warm up or overheat? PLoS ONE 10 (6), e0128226.

Führer, E., 2000. Forest functions, ecosystem stability and management. For. Ecol. Manage. 132, 29–38. https://doi.org/10.1016/S0378-1127(00)00377-7.

Halofsky, J.E., Warziniack, T.W., Peterson, D.L., Ho, J.J., 2017. Understanding and managing the effects of climate change on ecosystem services in the rocky mountains. Mountain Res. Develop. 37 (3), 340–352. https://doi.org/10.1659/MRD-JOURNAL-D-16-00087.1.

Hanewinkel, M., Cullmann, D.A., Schelhaas, M.J., Nabuurs, G.J., Zimmermann, N.E., 2013. Climate change may cause severe loss in the economic value of European forest land. Nat. Clim. Chang. 3, 203–207. https://doi.org/10.1038/nclimate1687.

Hand, M.S., Lawson, M., 2018. Effects of climate change on recreation in the northern rockies. In: Halofsky, J.E., Peterson, D.L. (Eds.), Climate Change and Rocky Mountain Ecosystems. Springer, Cham, Switzerland, pp. 169–188.

Hansen, M.C., Stehman, S.V, Potapov, P.V, 2010. Quantification of global gross forest cover loss. Proc. Natl. Acad. Sci. U. S. A. 107, 8650–8655. https://doi.org/10.1073/pnas.0912668107.

Hewer, M.J., Gough, W.A., 2019. Using a multiyear temporal climate-analog approach to assess climate change impacts on park visition. American Meteorological Society 11, 291–305.

Hicke, J.A., Johnson, M.C., Hayes, J.L., Preisler, H.K., 2012. Effects of bark beetle-caused tree mortality on wildfire. For. Ecol. Manage. 271, 81–90. https://doi.org/10.1016/J.FORECO.2012.02.005.

Holmes, T.P., Prestemon, J.P., Abt, K.L., 2008. The Economics of Forest Disturbances: Wildfires, Storms, and Invasive Species. Springer.

Huo, L.-Z., Boschetti, L., Sparks, A., Huo, L.-Z., Boschetti, L., Sparks, A.M., 2019. Object-based classification of forest disturbance types in the conterminous united states. Remote Sens. 11, 477. https://doi.org/10.3390/rs11050477.
Interagency Working Group, 2016. Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866.
Johnson, D.W., Curtis, P.S., 2001. Effects of forest management on soil C and N storage: meta-analysis. In: Forest Ecology and Management, 140, pp. 227–238.
Johnston, R.J., Rolfe, J., Rosenberger, R.S., Brouwer, R., 2015. Benefit Transfer of Environmental and Resource Values: A Guide for Researchers and Practioners. Springer, Dordrecht.
Jones, M.W., Santín, C., van der Werf, G.R., Doerr, S.H., 2019. Global fire emissions buffered by the production of pyrogenic carbon. Nat. Geosci. 12 (9), 742–747.
Kaul, S., Boyle, K.J., Kuminoff, N.V., Parmeter, C.F., Pope, J.C., 2013. What can we learn from benefit transfer errors? Evidence from 20 years of research on convergent validity. J. Environ. Econ. Manag. 66 (1), 90–104.
Kristensen, P., 2004. The DPSIR Framework, workshop on a comprehensive/detailed assessment of the vulnerability of water resources to environmental change in Africa using river basin approach. UNEP Headquarters, Nairobi, Kenya.
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. Proc. Natl. Acad. Sci. U. S. A. 115 (14), 3663–3668. https://doi.org/10.1073/pnas.1720064115.
Loeffler, D., Anderson, N., Stockmann, K., Skog, K., Healey, S., Jones, J.G., Morrison, J., Young, J., 2014. Estimates of Carbon Stored in Harvested Wood Products from United States Forest Service Southern Region, 1911-2012. Missoula, MT.
Loomis, J., Crespi, J., Mendelsohn, R, Neumann, J, 2004. Estimated Effects of Climate Change on Selected Outdoor Recreation Activities in the United States. The Impact of Climate Change on the United States Economy. Cambridge University Press, Cambridge, UK, pp. 289–314.
Long, J.W., Skinner, C., North, M., Hunsaker, C.T., Quinn-Davidson, L., 2014. Chapter 1.2—integrative approaches: promoting socioecological resilience. In: Long, J.W., Quinn-Davidson, L, Skinner, N (Eds.), 2014. Science Synthesis to Support Socioecological Resilience in the Sierra Nevada and Southern Cascade Range. Gen. Tech. Rep. PSW-GTR-247. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA, 712 p. 2 vol.
Maes, J., Liquete, C., Teller, A., Erhard, M., Paracchini, M.L., Barredo, J.I., Grizzetti, B., Cardoso, A., Somma, F., Petersen, J.E., Meiner, A., Gelabert, E.R., Zal, N., Kristensen, P., Bastrup-Birk, A., Biala, K., Piroddi, C., Egoh, B., Degeorges, P., Fiorina, C., Santos-Martín, F., Naruševičius, V., Verboven, J., Pereira, H.M., Bengtsson, J., Gocheva, K., Marta-Pedroso, C., Snäll, T., Estreguil, C., San-Miguel-Ayanz, J., Pérez-Soba, M., Grêt-Regamey, A., Lillebø, A.I., Malak, D.A., Condé, S., Moen, J., Czúcz, B., Drakou, E.G., Zulian, G., Lavalle, C., 2016. An indicator framework for assessing ecosystem services in support of the EU Biodiversity Strategy to 2020. Ecosyst. Serv. https://doi.org/10.1016/j.ecoser.2015.10.023.
Marcos-Martinez, R., Bryan, B.A., Schwabe, K.A., Connor, J.D., Law, E.A., Nolan, M., Sánchez, J.J., 2019. Projected social costs of CO2 emissions from forest losses far exceed the sequestration benefits of forest gains under global change. Ecosyst. Serv. 37, 100935 https://doi.org/10.1016/J.ECOSER.2019.100935.
Marcos-Martinez, R., Bryan, B.A., Schwabe, K.A., Connor, J.D., Law, E.A., 2018. Forest transition in developed agricultural regions needs efficient regulatory policy. Forest Policy Econ. 86, 67–75. https://doi.org/10.1016/j.forpol.2017.10.021.
Masek, J.G., Goward, S.N., Kennedy, R.E., Cohen, W.B., Moisen, G.G., Schleeweis, K., Huang, C., 2013. United states forest disturbance trends observed using landsat time series. Ecosystems 16, 1087–1104. https://doi.org/10.1007/s10021-013-9669-9.
McMicheal, A., Scholes, R., Hefny, M., Pereira, E., Palm, C., Foale, S., 2005. Linking ecosystem services and human well-being. Ecosystem and Human Well-being: multiscale assessments. Millennium Ecosystem Assessment Series, 4. Island Press, Washington, D.C, pp. 43–60.
National Integrated Drought Information System, 2018. California is no stranger to dry conditions, but the drought from 2011-2017 was exceptional. California Drought 2011-2017. Retrieved November 2018, 2018, from. https://www.drought.gov/drought/california-no-stranger-dry-conditions-drought-2011-2017-was-exceptional.
NOAA, USDA, NDMC, 2020. Gridded U.S. Drought Monitor (USDM). National Oceanic and Atmospheric Administration (NOAA), United States Department of Agriculture (USDA) and National Drought Mitigation Center (NDCM). National Integrated Drought Information System. Retrieved from. https://www.drought.gov/data-maps-tools/gridded-us-drought-monitor-usdm.
North, M., 2014. Chapter 2.1-forest ecology. Science synthesis to support socioecological resilience in the Sierra Nevada and Southern Cascade Range. In: Long, J.W., Quinn-Davidson, L., Skinner, C.N (Eds.), Science Synthesis to Support Socioecological Resilience in the Sierra Nevada and southern Cascade Range. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA, pp. 103–126. Gen. Tech. Rep. PSW-GTR-247.
North, M., Collins, B., Keane, J., Long, J., Skinner, C., Zielinski, B., 2014. Chapter 1.3—synopsis of emergent approaches. In: Long, J.W., Quinn-Davidson, L, Skinner, N (Eds.), Science Synthesis to Support Socioecological Resilience in the Sierra Nevada and southern Cascade Range. Gen. Tech. Rep. PSW-GTR-247. U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA, p. 712, 2 vol.
Overby, S.T., Hart, S.C., Neary, D.G., 2003. Impacts of natural disturbance on soil carbon dynamics in forest ecosystems. In: Kimble, J.M., Heath, L.S., Birdsey, R.A., Lal, R. (Eds.), The Potential of US Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect. CRC Press, Boca Raton, FL, pp. 159–172.
Outdoor Industry Association, 2017. The Outdoor Recreation Economy. The Outdoor Foundation, Washington, DC. Retrieved from. https://outdoorindustry.org/oia-participation/.
Outdoor Industry Association, 2018. Outdoor Participation Report 2018. The Outdoor Foundation, Washington, DC. Retrieved from. https://outdoorindustry.org/resource/2018-outdoor-participation-report/.
Pedro, M.S., Rammer, W., Seidl, R., 2015. Tree species diversity mitigates disturbance impacts on the forest carbon cycle. Oecologia 177 (3), 619–630.
Recreation Use Values Database, 2016. College of Forestry. Oregon State University, Corvallis, OR. Available at: http://recvaluation.forestry.oregonstate.edu/.
Rosenberger, R.S., Loomis, J.B., 2001. Benefit Transfer of Outdoor Recreation Use Values: A Technical Document Supporting the Forest Service Strategic Plan (2000 Revision). Rocky Mountain Research Station, Fort Collins, CO. Retrieved from. https://www.fs.usda.gov/treesearch/pubs/4578.
Rosenberger, R.S., White, E.M., Kline, J.D., Cvitanovich, C., 2017. Recreation Economic Values for Estimating Outdoor Recreation Economic Benefits from the National Forest System. Pacific Northwest Research Station, Portland, OR. Retrieved from. https://www.fs.fed.us/pnw/pubs/pnw_gtr957.pdf.
Seidl, R., Spies, T.A., Peterson, D.L., Stephens, S.L., Hicke, J.A., 2016. Searching for resilience: addressing the impacts of changing disturbance regimes on forest ecosystem services. J. Appl. Ecol. 53 (1), 120–129.
Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Reyer, C.P.O., 2017. Forest disturbances under climate change. Nature Climate Change. https://doi.org/10.1038/nclimate3303.
Smith, S., 2007. Bark Beetles and Vegetation Management in California. Forest Health Protection, Region 5, Forest Service. USDA. Retrieved from. https://www.fs.usda.gov/Internet/FSE_DOCUMENTS/fsbdev3_045320.pdf.
Thom, D., Seidl, R., 2016. Natural disturbance impacts on ecosystem services and biodiversity in temperate and boreal forests. Biol. Rev. 91 (3), 760–781. https://doi.org/10.1111/brv.12193.
Tscherning, K., Helming, K., Krippner, B., Sieber, S., Gomez y Paloma, S., 2012. Does research applying the DPSIR framework support decision making? Land Use Policy 29 (1), 102–110. https://doi.org/10.1016/j.landusepol.2011.05.009.
Trumbore, S., Brando, P., Hartmann, H., 2015. Forest health and global change. Science (New York, N.Y.) 349 (6250), 814–818. https://doi.org/10.1126/science.aac6759.
USDA Forest Service, 2020. National visitor use monitoring survey results national summary report. https://www.fs.usda.gov/sites/default/files/2019-National-Visitor-Use-Monitoring-Summary-Report.pdf.
Williams, C.A., Collatz, G.J., Masek, J., Huang, C., Goward, S.N., 2014. Impacts of disturbance history on forest carbon stocks and fluxes: merging satellite disturbance mapping with forest inventory data in a carbon cycle model framework. Remote Sens. Environ. 151, 57–71. https://doi.org/10.1016/J.RSE.2013.10.034.
Williams, C.A., Gu, H., MacLean, R., Masek, J.G., Collatz, G.J., 2016. Disturbance and the carbon balance of U.S. forests: a quantitative review of impacts from harvests, fires, insects, and droughts. Glob. Planet. Change 143, 66–80. https://doi.org/10.1016/j.gloplacha.2016.06.002.
Woodall, C.W., Coulston, J.W., Domke, G.M., Walters, B.F., Wear, D.N., Smith, J.E., Andersen, H.E., Clough, B.J., Cohen, W.B., Griffith, D.M.,Hagen, S.C., 2015. The U.S. forest carbon accounting framework: stocks and stock change, 1990-2016. Gen. Tech. Rep. NRS-154. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 49 p., 154, pp.1-49.
Young, R.A., Loomis, J.B., 2014. Determining the Economic Value Of Water: Concepts and Methods. Resources for the Future, New York, NyRoutledge, p. 337.