CSIRO PUBLISHING

RESEARCH PAPER
https://doi.org/10.1071/WF25060

International Journal of Wildland Fire
International Association of Wildland Fire

Economic efficiency of fuel treatments in western US forests: a methodological framework

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Received: 22 March 2025
Accepted: 6 November 2025
Published: 12 January 2026

Cite this: Hjerpe EE *et al.* (2026) Economic efficiency of fuel treatments in western US forests: a methodological framework. *International Journal of Wildland Fire* **35**, WF25060. doi:10.1071/WF25060

ABSTRACT

Background. Reducing fuels in overly dense, arid forests of the Western US is a prominent fire mitigation strategy. Fuel treatments, including thinning and prescribed burning, are a means of reintroducing fire to fire-dependent forests and alleviating wildfire-related damages to human health, infrastructure and natural resources. **Aims.** To help establish economic efficiency analysis of fuel treatments, we provide a methodological framework illustrating benefit-cost analysis (BCA) and considerations for dealing with valuation complexity. **Methods.** Our framework was developed from research reviews and valuation discussions that occurred at a fall 2024 workshop of social scientists involved in economic research on fuel treatments. We augmented the framework with additional literature reviews and reference example valuations. **Key results.** We detailed 25 unique potential benefits of fuel treatments and multiple costs. Complexity in (BCA) of fuel treatments stems from limited data and reference studies, various beneficiaries and accounting stances, spatial and temporal dispersion of benefits and costs, and aggregating multiple benefits with differing outputs and units. **Conclusions.** Further empirical and simulation-based analyses of the benefits and costs of fuels treatments would support a clearer understanding of the economic trade-offs involved. Such information could highlight opportunities for long-term savings from proactive investments in wildfire resilience.

Keywords: avoided wildfire costs, benefit-cost analysis, economic efficiency, ecosystem services, forests, fuel treatments, wildfire, wildfire resilience.

Introduction

Forests in the American West, particularly arid conifer-dominated forests, are experiencing dramatic fire deficits and widespread changes in ecological structure and function that are leading to uncharacteristically severe wildfires (Hagmann *et al.* 2021; Hessburg *et al.* 2021) and substantial wildfire damages (Thomas *et al.* 2017). While multiple strategies are being developed and implemented to increase wildfire resilience (Moritz *et al.* 2022), a large focus of forest management has coalesced around fuel reductions as a primary means to limit wildfire severity on public and private lands. Fuel treatments in forests – including hand thinning, mechanical thinning and prescribed fire – offer multiple benefits. These include enhancing ecosystem services, improving fire suppression opportunities and reducing wildfire damages (Hjerpe *et al.* 2024). Fuel treatments are generally in line with restoring the structure of frequent-fire forests that are densely overstocked (Stephens *et al.* 2021). While fuel treatments have been implemented on thousands of acres, the pace of treatments is thus far insufficient for landscape-level mitigation of severe wildfires (Woolsey *et al.* 2024).

The biophysical effects of fuel treatments have received extensive research attention. Meta-analyses and large syntheses of empirical and simulation studies have clearly demonstrated that fuel treatments are generally effective at mitigating adverse effects of wildfire (Martinson and Omi 2013; Kalies and Kent 2016; Hunter and Robles 2020; Jain *et al.* 2021; Davis *et al.* 2024). In addition to meta-analyses, case studies have also demonstrated the effectiveness of fuel treatments (e.g. Waltz *et al.* 2014; Lydersen *et al.* 2017; Brodie *et al.* 2024). What has been missing from the research are broad evaluations of the economic efficiency of fuel treatments, or a comparison of benefits to costs, despite some recent forays into this topic (Hunter and Taylor 2022; Simon *et al.* 2022; Hjerpe *et al.* 2024). The lack of rigorous benefit-cost analyses (BCA) stems partly from limited methodological frameworks and economic considerations for evaluating fuel treatment efficiency.

With the prevalence of forested public lands at risk of uncharacteristically severe wildfire, the economic efficiency of fuel treatments is a pressing topical area for land management agencies (Kreitler *et al.* 2019; Crowley *et al.* 2023). And because fuel treatments are also necessary on tribal, state and private lands, there is an overarching need to better understand who will benefit and who will pay for fuel treatments. Homeowners are being financially affected as insurance companies are rethinking and re-estimating their risk and property value estimates to better reflect wildfire risk.[1] Communities in fire-prone areas are actively engaging, and being engaged, in wildfire mitigation strategies and need better information concerning the benefit-cost details of fuel treatments. Communities in fire-prone areas are beginning to tax themselves to help implement fuel treatments via municipal bonds, incorporating partnerships between municipal, state and federal entities (e.g. Flagstaff Watershed Protection Program). Green bond brokerage companies[2] are entering the fuel treatment market (e.g. Blue Forest and Forest Resilience Bonds) in order to leverage funding from potential beneficiaries. Other green bonds are being developed by cities, counties, states, non-governmental organizations and federal agencies to fund the implementation of fuel treatments (Clavet *et al.* 2021). Cost sharing for fuel treatment implementation is a pressing issue in all high fire risk areas, especially those involving at-risk private residents, utility companies and corporations (Meldrum *et al.* 2014; Jones *et al.* 2023).

The rapid expansion of fuel treatment funding mechanisms – especially in private markets – has outpaced evaluations of their long-term economic viability. As is typical in the case of market responses, market-driven approaches tend to prioritize private benefits, often overlooking broader public benefits and long-term ecological costs. This omission can result in an inefficient level of fuel treatments, in which fuel treatments are primarily implemented in areas where private benefits exceed private costs, ignoring other areas where the net benefits to society are greater. Economic research on the social benefits and costs of fuel treatments has not caught up with real world applications. Thus, there is a critical need for greater research in this area to determine if market responses reflect an optimal spatial and temporal mix of fuel treatments.

In this article, we summarize methodological approaches and review literature for conducting BCA of fuel treatments on public and private Western US forests, identify areas of complexity in fuel treatment evaluations, and provide recommendations for addressing complexity and accurately estimating benefits and costs of fuel treatments. We focus on management activities aimed at reducing fuels in forests near communities (the wildland–urban interface, or WUI), typically involving hand thinning, mechanical thinning and prescribed burns implemented prior to wildfire (i.e. presuppression treatments, as we exclude fuel treatments such as back burns that occur during active wildfire). We look primarily at fuel treatments in dry conifer-dominated forests of the West, as these forests are at the highest risk for uncharacteristically severe wildfires, though we provide context for fuel treatments in other US forests, rangelands and grasslands. Our findings and recommendations stem from our review of literature and workshop discussions of economists and other social scientists on this topic held in the fall of 2024 in Fort Collins, Colorado. Additional literature was identified using Google Scholar and Treesearch and searching for key word combinations including 'fuel treatments,' 'fuel reductions,' 'forest restoration,' 'benefits,' 'costs,' 'economics,' 'cost-effectiveness,' and 'avoided wildfire costs.' Snowball techniques were employed to identify multiple studies that were referenced by the initial articles found using Google Scholar.

Approaches to measuring benefits and costs of fuel treatments

Since a wide variety of disciplines are involved in designing methods appropriate for evaluating both ex-ante and ex-post fuel treatments, it is important to define economic terms that will be used in subsequent sections of this paper. Economic efficiency is often measured by conducting BCA, in which immediate and future benefits and costs of fuel treatments are estimated, converted to present value and compared. Fuel treatments are considered economically efficient when their benefits meet or exceed their costs. As more fuel treatments are implemented, they remain economically efficient until the marginal benefit of one additional unit of treatment becomes less than the marginal cost to conduct the treatment, with equilibrium occurring when marginal benefit equals marginal cost.

Measuring the benefits of fuel treatments is not straightforward due to uncertainty in outcomes and baselines, data limitations, complexity in delineating all beneficiaries, and

[1]For example, Zillow house value listings now include a fire risk rating from First Street (Kelleher 2024).
[2]Capital provided by investors (the bond holder) cover the costs of treatments and beneficiaries (the bond issuer) share the cost of reimbursing investors (principal plus interest) over time.

the spatial and temporal dispersion of benefits. Benefits of fuel treatments can be largely allocated to two primary categories: enhanced initial ecosystem services (EIES) that do not depend on subsequent wildfires in the treated site, and avoided wildfire costs (AWC) that do depend on the site encountering wildfire after treatments (Hjerpe *et al.* 2024).

Ecosystem services are the conditions and processes of natural ecosystems and species that help sustain and enhance human life (Daily 1997). These benefits of nature include provisioning goods (e.g. wood for shelter), regulating services (e.g. air purification and carbon sequestration) and cultural services (e.g. recreation or spiritual inspiration). In economics, ecosystem services are valued as the amount a user, household, or entity would be willing to pay for these benefits (Freeman 2003; Brown *et al.* 2007). Who is valuing the ecosystem service, be it a local resident, utility, business, or the public, has important implications for BCA accounting. EIES from fuel treatments, that is, changes in ecosystem services independent of wildfire occurrence, are calculated as follows:

$$\mathrm{ES} = \mathrm{ES}_1 - \mathrm{ES}_0 \tag{1}$$

where ES is a bundle of ecosystem services, ES_0 is the reference level reflecting the pre-treatment quality and quantity of ecosystem services coming from the forested area slated for fuel treatments, and ES_1 represents the new level of ecosystem services after fuel treatments are implemented. Positive changes in ecosystem services resulting from fuel treatments are benefits and deemed to be 'enhanced' ecosystem services. Negative changes to ecosystem services resulting from fuel treatments are costs and result in 'degraded' ecosystem services. Economically measuring changes in the quality and quantity of ecosystem service bundles due to fuel treatments is feasible, and examples of modeling and monetizing changes in ecosystem services have proliferated over the last couple decades (Acharya *et al.* 2019). However, measuring the biophysical changes in ecosystem services due to fuel treatments, which is the starting point for subsequent economic valuation, can be difficult and limited given the large spatial and temporal dispersion of ecosystem services flowing from a particular landscape.

For wildfire costs that may be avoided with fuel treatments, estimations of wildfire damages without treatment must first be considered. The current mathematical approach for limiting damages from wildfire can be summarized as:

$$\min(C + \mathrm{NVC}) \tag{2}$$

where C represents all costs of fire suppression, including the costs of fuel treatments, and NVC represents the net value change to society due to wildfire, or the net fire-related damages (Donovan and Rideout 2003).

An investigation of fuel treatment benefits focuses on the NVC part of the equation, or the NVC associated with wildfire occurrence and severity. Importantly, NVC can be positive or negative, allowing for the calculation of 'good' or 'bad' (positive/negative) wildfire effects. When dealing with uncharacteristically severe wildfires, the majority of effects are adverse, as opposed to wildfires that burn less severely and are more in line with natural fire regimes in arid conifer-dominated forests (which require fuel loads that are within the range of more naturally occurring frequent-fire forests). Thus, most of the NVC coming from modern uncharacteristic wildfires will be negative. For BCA of fuel treatments, any negative NVC (damages) from wildfire that could be lessened or avoided with prior fuel treatments becomes a 'benefit' and avoided or averted wildfire costs.

Measuring the costs of fuel treatments is relatively straightforward, where the primary component is the on-the-ground implementation cost of conducting the fuel treatment. Most analysts consider the direct implementation costs of mechanical thinning or prescribed burning to be the total cost of fuel treatments, though arguments can be made for including planning costs and overhead/administrative costs. Additionally, other costs of fuel treatments could be modeled, such as the expected value of escaped prescribed burns that become damaging uncharacteristic wildfire and result in degraded ecosystem services. Kline (2004) succinctly describes the BCA process for fuel treatments as an aggregation of these annual costs and benefits associated with both the fire and no-fire potential outcomes, weighted by the likelihood of each fire occurring, and discounted over time. That is, benefits and costs need to be aggregated for four sets of outcomes: status quo, status quo with wildfire, fuel treatment with no wildfire and fuel treatment with subsequent wildfire (Kline 2004).

As there can be multiple beneficiaries from fuel treatments on public and private lands, there exist multiple potential funding sources. The multiplicity in potential beneficiaries from fuel treatments also creates various accounting stances when conducting BCA. Treatments on public lands, such as national forests, can provide benefits to a wide range of stakeholders given that all US citizens have an ownership stake in public lands and that treatments on public lands can also affect outcomes on nearby private property. Use and nonuse benefits from fuel treatments on public lands can be realized not only by nearby residents and utilities but also by the public residing far away from the at-risk forest (Loomis and González-Cabán 1996). Likewise, the public also holds use and nonuse values concerning fire risk reduction on private lands. Wildfire spread does not conform to political or legal boundaries and wildfires on public lands often burn into private lands and vice versa, indicating a dispersion of fuel treatment benefits across jurisdictions. For conducting BCA of fuel treatments, care must be taken to adapt accounting stances to the ownership patterns in the chosen study site and to characterize internal and external benefits relevant to the entity incurring the cost of fuel treatments.

Benefits of fuel treatments

When looking at BCA of fuel treatments, it quickly becomes clear there are many more potential benefit categories than cost categories. Fuel treatments provide multiple benefits, which can be broadly categorized into two groups: (1) EIES; (Eqn 1), which accrue soon after treatment, and (2) AWC (Eqn 2), which depend on future wildfire occurrence (Hjerpe *et al.* 2024). In Table 1, we list potential fuel treatment benefit types and provide example values for each. Table 1 identifies 25 unique benefit types, but additional benefits exist. For example, multiple categories of use values could be distinguished beyond those listed. Many, but not all, of the benefit types in Table 1 have been quantified in the literature, and we provide examples of relevant references where they exist.

To incorporate the benefit types identified in Table 1 into a comprehensive BCA requires first converting each into a common monetary metric and then aggregating across categories. The BCA framework requires estimating benefit changes relative to a baseline, and discounting future costs and benefits. The net present of value of individual benefit estimates can be summed to estimate total benefits of a fuel treatment. These totals are then compared to treatment costs to determine benefit–cost ratios. During this 'adding up' process, it is important to avoid double counting of benefits. For example, benefits identified in a hedonic valuation of property values could also already include avoided health or ecosystem service benefits. The BCA framework should formally address uncertainty, although more research is needed to understand how to do this in the context of fuel treatments where wildfire occurrence is highly stochastic. While not all benefit categories will be measurable in every case, the BCA framework allows for partial aggregation of those with available data, with the option to report unquantified benefits qualitatively.

Below we discuss the fuel treatment benefit types and economic methods that can be used to estimate their values. For EIES, primary economic valuation methods include transaction evidence, revealed preferences (e.g. hedonic pricing and travel cost method) and stated preferences (e.g. contingent valuation and choice experiments). For AWC, primary economic valuation methods include replacement costs, cost of illness, statistical valuation of life, revealed preferences and stated preferences.

Enhanced initial ecosystem services from fuel treatments

When fuel treatments are implemented, many ecosystem services can be immediately affected based on the type of treatment and duration of effectiveness. These EIES range from provisioning ecosystem services (e.g. woody biomass and mushrooms), to regulating ecosystem services (e.g. disturbance buffer, changes in carbon balance), to cultural ecosystem services (e.g. use and nonuse values). Two of the most long-studied ecosystem services enhancements stemming from fuel treatments are reduced woody biomass/timber made available for wood processing and greater water availability downstream for wildlife habitat and human uses (e.g. hydropower and irrigation).

Woody biomass availability

In the dry conifer-dominated forests of the American West, fuel treatments such as hand and mechanical thinning generate large volumes of excess biomass. This material must be either removed from the site or burned to reduce fire risk. Unlike traditional timber harvesting, fuel reduction thinning primarily targets ladder fuels and small-diameter trees. Thus, the economics of wood utilization from fuel treatments is much different from the economics of timber production and harvests. Despite this, thinned woody material from fuel treatments offers entrepreneurs opportunities for wood conversion into dimensional lumber, bioenergy, heating pellets, firewood and other products.

The 'benefit' value for thinned woody biomass from fuel treatments is the stumpage value that can be obtained from the sales of reduced fuels. In many places, woody biomass made available from fuel treatments will not have enough stumpage value to fully offset the cost of thinning, if other benefits are ignored (Hjerpe *et al.* 2021). Ultimately, the stumpage value will be dependent on the spatial distribution of regional wood processing infrastructure and markets. Transportation costs, especially for low-value small-diameter material, quickly become cost prohibitive in regions with limited wood product manufacturing capacity. In these areas, woody biomass removal becomes a net cost as opposed to a net benefit.

Water yield

Reducing fuels in overly dense forests can change the water balance on site by reducing total evapotranspiration losses and water interception (Dore *et al.* 2010), allowing for greater runoff and downstream uses. For example, Robles *et al.* (2014) demonstrated that runoff was 20 percent greater in thinned forests of Central Arizona when compared to un-thinned forests. Simonit *et al.* (2015) estimated a potential increase in annual water supply of 8% with a surface water storage value of $104 million for forest thinning in Arizona. Economic valuations of the benefits of increased water yield downstream from fuel treatments have been evaluated with stated preference methods (Mueller *et al.* 2013) and by linking evapotranspiration and hydropower models with marginal pricing for regional water sales (Guo *et al.* 2023). It is important to note that while forest thinning can increase total water yield, it comes with the potential risks of reducing water quality, since rainfall on bare soil can cause soil erosion, changes to aquifer recharge rates and potentially increasing downstream flood risk. Additionally, increases in downstream water yield are place-specific and can be short-

Table 1. Potential unique fuel treatment benefit types.

Benefit type	Example value	Example valuation
Enhanced initial ecosystem services (EIES)		
1. Woody biomass	Stumpage value for access to thinned sawlogs and slash	Skog and Barbour (2006)
2. Water yield	Value of increased water yield downstream from treatment sites	Guo *et al.* (2023)
3. Use values	Increased use values for recreational and subsistence activities in and near the treated forest	Loomis *et al.* (2002)
4. Nonuse values	Increased passive use values such as existence, option and bequest values	Loomis *et al.* (2009)
5. Property values	Increased house and property values in neighborhoods adjacent to fuel treatments	Kim and Wells (2005)
6. Non-timber forest products	Increase in plant collections and harvests, such as mushrooms, after prescribed fire	na
7. Disturbance buffer	Increased resistance to beetle infestations and drought	na
Avoided wildfire costs (AWC) – Direct		
Human health		
8. Fatalities and injuries	Avoided or reduced wildfire-caused fatalities and injuries to firefighters and the public	Huang *et al.* (2013)
9. Air quality (Smoke)	Avoided or reduced health damages from wildfire smoke	Guo *et al.* 2025
10. Well-being	Avoided or reduced mental anguish caused by fire risk worry, evacuations or financial loss due to wildfire	Mason *et al.* (2006)
Built		
11. Structures	Avoided or reduced wildfire damages to houses, commercial buildings and other structures	Evans *et al.* (2022)
12. Infrastructure	Avoided or reduced wildfire damages to utility, transportation and communication infrastructure	Buckley *et al.* (2014)
Ecosystem services		
13. Carbon	Avoided or reduced wildfire-caused CO_2 emissions	Strabo *et al.* (2025)
14. Timber	Avoided or reduced wildfire-caused timber losses	Guo *et al.* (2025)
15. Species	Avoided or reduced wildfire damages to flora and fauna and associated habitat	Jones *et al.* (2022*a*)
16. Recreation	Avoided or reduced wildfire damages to outdoor recreation areas	Wildish *et al.* (2020)
17. Archeological	Avoided or reduced wildfire damages to archeological and cultural sites and artifacts	na
18. Viewshed and esthetics	Avoided or reduced wildfire damages to resident and community esthetics	na
19. Rehabilitation	Avoided or reduced rehabilitation costs due to wildfire such as Burned Area Emergency Response (BAER)	Jones *et al.* (2022*a*)
Suppression		
20. Suppression expenditures	Avoided or reduced wildfire suppression costs in the future	Strabo and Reimer (2024)
Avoided wildfire costs (AWC) – Indirect		
Built		
21. Structures	Avoided or reduced post-wildfire flood damages to houses and buildings	na
22. Infrastructure	Avoided or reduced post-wildfire flood damages to transportation and utility infrastructure	na
23. Water infrastructure	Avoided or reduced post-wildfire flood damages related to clogging and degrading drinking water sources and infrastructure	Jones *et al.* (2017)
Human health		
24. Fatalities and injuries	Avoided or reduced fatalities and injuries from post-wildfire floods, mudslides, etc.	na
25. Well-being	Avoided or reduced worry and averting behavior about post-wildfire flood damages to life and property	na

lived and may convert to decreases in downstream water yield after new vegetation has been established.

Use values

Forests can be heavily used for recreation, including hiking, biking, wildlife viewing, birding, hunting and photography. Forests are also critical places for subsistence hunting and gathering. Opening up overly dense forests, as done by fuel treatments, typically improves esthetics and accessibility, leading to ecosystem service enhancements associated with most types of recreation. For hunting, fuel treatments can help reestablish successional vegetation communities critical to big game (Loomis *et al.* 2002). Because fuel treatments restore more natural forest structure and wildfire regimes, they typically increase native wildlife and game desired by hunters, as well as the potential consumer surplus (i.e. the additional economic benefit beyond what was paid for) of recreationists (Starbuck *et al.* 2006) and subsistence hunters and gatherers. In addition, use values from Indigenous fire stewardship represent a longstanding form of active management that is not currently well integrated into BCA (Pascoe *et al.* 2023; Bennett *et al.* 2024; Long *et al.* 2025). For example, Greenler *et al.* (2024) note the spiritual uses related to cultural burning of meadows and forests. Other researchers have identified cultural, spiritual and place-based obligations from Indigenous fire stewardship in Western fire-prone ecosystems, but do not integrate formal economic valuation techniques (Long *et al.* 2021; Marks-Block *et al.* 2021). We are aware of only one study that has attempted to use non-market valuation to quantify these spiritual and cultural values (Coyne *et al.* 2022).

The type of fuel treatment and time since treatment both appear to affect recreation benefits. For example, White *et al.* (2024) investigated recreation visitation effects due to fuel treatments and found only small, short-term effects. Additionally, light thinning was found to have a slight positive influence on visitation while prescribed fire was associated with a slight negative influence. Sánchez *et al.* (2016) demonstrated likely gains in consumer surplus due to an increase in recreation demand for low intensity wildfires that are mimicked by prescribed fire.

Nonuse values

In some cases, fuel treatments may have effects on societal nonuse values, especially the existence and bequest values that the public holds for intact forests. For example, there may be nonuse values for fuel treatments to protect giant sequoias, redwood forests, or critical habitat of threatened or endangered species (Loomis and González-Cabán 1994).[3] Additionally, regulating ecosystem services can be affected by fuel treatments and spur nonuse values, as in the case of fuel treatments affording greater resistance to beetle infestations and drought tolerance (Bernal *et al.* 2023; Birch *et al.* 2023). Nonmarket valuation techniques are necessary to measure nonuse and other nonmarket values associated with wildfire risk and fuel treatments. Stated preference methods, including contingent valuation methods and choice experiments, are well suited for investigations of nonuse and nonmarket value changes associated with fuel treatments (Loomis and González-Cabán 2010).

Stated preference measures of nonuse values are elicited by asking about the maximum willingness to pay (WTP) a person has for described fuels treatments. Research has shown that the public has significant WTP for fuel treatments that varies by income, education level (Walker *et al.* 2007; Meldrum *et al.* 2024), and race and ethnicity (González-Cabán and Sánchez 2017). However, in some places, WTP for fuel treatments can range from negative to positive (Sánchez *et al.* 2022). Research is limited on explaining why individuals are willing to pay for fuel treatments. Is the primary motivation a reduction in wildfire risk to one's own house and property, as an investment in protecting and insuring the home asset? Is societal WTP for fuel treatments composed of a combination of values, including the traditional nonuse and use values that the public holds for neighboring forests?

Property values

Landowners and homeowners adjacent to fuel treatments may benefit from the reduction in wildfire risk to their properties (Kim and Wells 2005), but in some cases, may suffer costs if forest thinning is aggressive and if living near the forest was one of the amenities they sought. Understanding the spatial range of fuel treatment effectiveness (Vorster *et al.* 2023) can allow for more accurate estimates of how fuel treatments can affect house values through fire risk ratings. Housing markets, however, are not strictly a function of objective amenities and real wildfire risk but rather are a matter of individual preferences and perceived natural disaster risk (Donovan *et al.* 2007).

Fuel treatments involve large-scale land disturbance and smoke that can also manifest as disamenities in adjacent communities. Traditional logging has been shown to substantially reduce neighboring property values (Kim and Johnson 2002). While thinning done for fuels reductions in the US is different from traditional logging, forest disturbance can still negatively affect neighboring property values. Thus, during and soon after fuel treatment implementation, negative effects on adjacent property values can occur, as shown in recent research by Fitch *et al.* (2023). However, it is possible that the reduced wildfire risk will eventually add greater value to properties adjacent to treatments, depending on the relative temporal trends in risk reduction versus other outcomes of the fuel treatments.

[3]In other cases, nonuse values may be reduced due to fuel treatments in specific areas, such as protected areas like Wilderness.

Avoided wildfire costs

Unlike the changes to ecosystem services that can be enhanced (positive) or degraded (negative), AWC can only be positive or zero (non-negative) when considering uncharacteristically severe wildfire. If the treated and restored site does not encounter wildfire during the lifespan of treatment effectiveness, there will be no AWC. Because AWC benefits from fuel treatments are dependent on the site encountering subsequent wildfire and a function of the severity of wildfire, proper inclusion of future wildfire probability and behavior is paramount when estimating AWC. Furthermore, indirect AWC such as decreased or avoided post-wildfire flooding damages are wholly dependent on the treated site encountering subsequent wildfire and subsequent severe rainstorms. Determining the AWC benefits that fuel treatments provide will be unique to every location.

AWC human health

Health-related costs of wildfire are often the largest category of wildfire costs, even larger than suppression costs (Dittrich and McCallum 2020). Measuring the effects of wildfire on fatalities (mortality) and injuries and sickness (morbidity) can require combing through agency incident reports or media accounts of fires. For valuing mortality, economists apply a measure known as the Value of a Statistical Life (VSL) that incorporates societal WTP for reductions in mortality risks. Quantifying the effects of wildfire on residents' health, sometimes hundreds of miles away from wildfire, typically involves epidemiological studies and access to confidential hospital admissions data or surveys of residents immediately after fires. With the growing number and size of fires, especially in WUI areas, studies of wildfire-associated fatalities and injuries are becoming more common (e.g. Moeltner *et al.* 2013; Holder *et al.* 2023).

While we know wildfire smoke can lead to degraded and dangerous air quality, quantified effects on human health are limited and the spatial range of effects is influenced by weather patterns and other factors that are often fire specific (Rittmaster *et al.* 2006). Furthermore, traditional indicators of smoke-induced illnesses tend to be limited to recorded hospital visits, yet we know many respiratory illnesses do not result in a hospital visit and are therefore undocumented. Nonetheless, the literature provides examples of how to conduct such an analysis. Kochi *et al.* (2016) estimated the medical costs associated with non-fatal health effects (i.e. morbidity) of hospital admissions and emergency room visits at $3.4 million from Southern California fires during 2007. They acknowledge these are underestimated, as many people may suffer respiratory symptoms that are not severe enough to go to the emergency room. In addition, it is well known that medical costs significantly understate the loss in well-being (Richardson *et al.* 2013). The cost of in-home averting measures is possible to derive via surveys, but other averting behaviors, such as choosing to travel out of the smoky area and recreate in areas farther away from smoke, are rarely captured in economic investigations of wildfire smoke impacts.

Measuring avoided human health costs from wildfire due to fuel treatments adds additional complexity by taking a step beyond just identifying wildfire damages. While research on the full health damages caused by uncharacteristic wildfire is limited, research on the health effects of prescribed fire and avoided health costs from fuel treatments has, until recently, been nearly non-existent (Dittrich and McCallum 2020; Jones *et al.* 2022*b*). Recent studies are beginning to tackle these complex issues and indicate that prescribed fires typically have much lower particulate matter emissions than wildfires and can therefore be a net benefit for air quality and health (Long *et al.* 2022; Raab *et al.* 2023; Kiely *et al.* 2024; Schollaert *et al.* 2024).

Beyond the immediate health impacts of wildfire, there may also be human health effects from post-wildfire natural disasters such as flooding and mudslides, which can occur for years after a wildfire (Graber *et al.* 2023). Such health impacts are part of the group of indirect AWC, because new natural disasters are subsequently born from the original wildfire. Examples of these indirect health AWC include drowning fatalities (Hjerpe *et al.* 2023) and contamination of drinking water (Smith *et al.* 2011).

AWC structures and infrastructure

Fuel treatments can help limit the number of structures (homes, businesses, schools, etc.) and amount of infrastructure (roads, utilities, etc.) burned by reducing wildfire severity and allowing for fire suppression and protection by firefighters that would often be unavailable without fuel treatments (Bostwick *et al.* 2011; Sánchez *et al.* 2019). While fuel treatments are most effectively used in concert with home hardening, the creation of defensible space, and community awareness (Moritz *et al.* 2022), treatments are an important component of community strategies to reduce lost and damaged structures.

Current methods for generalizing the economic benefits of avoided wildfire structure costs typically are based on modeled scenarios where simulated wildfires are reduced in size (total footprint) and severity (flame length) based on modeled fuel treatment and effectiveness, leading to a decrease in the number of homes fully and partially burned and a correlating decrease in overall losses to house and property values (e.g. Buckley *et al.* 2014). Evans *et al.* (2022) showed that hand and mechanical thinning and prescribed fire can reduce property loss risk in the Lake Tahoe Basin by 45–76%, realizing annual net benefits (minus the cost of fuel treatments) that range from $4 to $8 million a year. Loomis *et al.* (2019*a*) found that fuel treatments, particularly prescribed fire, can reduce property damages and structure losses by making wildfire easier to control and affording greater suppression efforts.

Fuel treatments can reduce damages and costs to maintain energy, transportation and drinking water infrastructures. For example, there was an annual cost saving of

$24 million to Los Angeles County Public Works from reduced debris clean out in areas that experienced low-severity wildfire equivalent to a prescribed burn compared to adjacent watersheds which experienced higher-severity fires (Loomis *et al.* 2003). Infrastructure damaged by wildfire can spur human health effects as well. For example, Proctor *et al.* (2020) found increased levels of volatile organic compounds such as benzene in community drinking water after the Tubbs and Camp Fires in California.

Much like AWC for human health, there are also indirect AWC for structures and infrastructures stemming from post-wildfire flooding or mudslides. Flooded houses, damaged roadways and clogged culverts are all possible in areas that experience post-wildfire flooding. The most-often studied indirect AWC stemming from post-wildfire flooding are damages to drinking water infrastructure (e.g. Jones *et al.* 2017; Gannon *et al.* 2019). Additionally, roads and energy transmission corridors can face some of the most extensive costs of nearby fire over time. Immediately there can be a need to mechanically remove and transport any hazard trees within the corridor. Over time erosion, debris flows and drainage can damage or structurally undermine roads (Cao *et al.* 2021; Ram *et al.* 2025). These risks can extend over large areas inside and beyond fire footprints, leading to very high mitigation costs or several years of risk of major disruption or destabilization (Christiansen *et al.* 2024).

AWC ecosystem services

We group other AWC, including changes to carbon emissions, recreation demand, species habitat, wildfire rehabilitation costs and timber losses, within the category of ecosystem services. As above, the primary economic method for determining AWC for ecosystem services is to model future wildfire damages with and without fuel treatments and assign appropriate values.

Determining carbon emissions that may be averted due to fuel treatments is challenging (Kent *et al.* 2015). Modeling has shown a range of outcomes for carbon emissions that may be avoided with fuel treatments, largely based on whether the treated site encounters wildfire during the treatment's effective lifespan (Hurteau and North 2009). In general, a synthesis of studies focused on carbon storage showed that fuel treatments do not initially store more carbon after wildfire (due to the loss of basal area) but generally result in lower tree mortality and thus lower carbon loss during wildfires as well as lower post-wildfire emissions (Kalies and Kent 2016; Elias *et al.* 2025). Loudermilk *et al.* (2014) simulated hand and mechanical thinning fuel treatments in the Lake Tahoe Basin area, finding initial pulses of carbon losses from the forest due to biomass removal but long-term gains in carbon storage a century out (under current fire regimes). When investigating the economic benefits of avoided carbon emissions from fuel treatments, researchers have modeled carbon flux from fuel treatments and assigned values to them based on the social cost of carbon (Huang *et al.* 2013; Buckley *et al.* 2014; Wildish *et al.* 2020). Given the numerous variables in forest management, wildfires and carbon tradeoffs, caution is recommended when investigating AWC related to carbon emissions.

While there are several articles on the effects of relatively new and old wildfires on recreation demand (Loomis *et al.* 2001; Hesseln *et al.* 2003; Englin *et al.* 2008), there are limited economic valuations of AWC associated with avoided recreation demand losses due to fuel treatments effectively limiting fire severity. Jones *et al.* (2022*a*) estimated lost consumer surplus from decreased recreational demand due to severe wildfire and avoided costs from repairing damaged recreational trail infrastructure. Biodiversity, wildlife habitat and forest type can all be negatively affected by uncharacteristic wildfire, but fuel treatments can reduce post-fire rehabilitation costs (Moghaddas and Craggs 2007) leading to AWC. Likewise, timber losses to wildfire can be avoided or reduced with fuel treatments, resulting in substantial savings (Mason *et al.* 2006; Buckley *et al.* 2014).

AWC wildfire suppression costs

Fuel treatments typically afford greater firefighting effectiveness by decreasing fire severity, which renders fire lines and fuel breaks more effective, and allowing for greater visibility, retardant penetration and access in treated areas during a subsequent wildfire (Moghaddas and Craggs 2007). One of the only empirical analyses of fuel treatments and wildfire suppression costs illustrated that treatments rarely had a significant effect on suppression costs (Loomis *et al.* 2019*a*). These findings were thought to be partially influenced by the fact that fuel treatments can allow for more suppression efforts by making it safer for on-the-ground firefighters to actively engage and can thus lead to greater firefighting costs (Sánchez *et al.* 2019). Yoder and Ervin (2012) used county-level data in the Western US and also found no significant effect of fuel treatments on fire suppression costs. Other modeled estimates have shown potential reduction in suppression costs if fuel treatments can be implemented at a landscape level (Thompson *et al.* 2013; Loomis *et al.* 2019*a*). Leverage effects from treated sites on adjacent untreated sites (Thompson *et al.* 2017) are difficult to model but deserve consideration when estimating avoided suppression costs. More recently, Strabo and Reimer (2024) found that for every dollar spent on fuel treatments, $4–$7 was saved in suppression costs. Fuel treatments and wildfire suppression efforts are both components of overall wildfire mitigation costs, making it challenging to isolate their individual financial impacts (Donovan and Rideout 2003).

Costs of fuel treatments

When accounting for the cost side of the BCA of fuel treatments, most researchers have focused primarily on the direct costs of on-the-ground implementation. Fuel treatments also have indirect costs associated with overhead, planning, road construction/decommissioning, culvert placements, road maintenance and other site preparation not always included in the direct implementation costs. Additionally, fuel treatment costs will be different in every watershed and region because they vary by treatment type (e.g. prescribed fire, hand thinning, mechanical thinning, helicopter thinning), forest type, topography, soil conditions, season, etc. Rummer (2008) recommends caution when extrapolating fuel treatment costs from the literature, primarily due to the various cost types and valuation methods incorporated by researchers.

Regression analysis has been used to assess the factors determining per-acre fuel treatment costs for California (Loomis *et al.* 2019*b*). Key variables were found to be treatment acreage, whether the county is considered metropolitan (and thus, likely has higher wage costs), and treatment type (e.g. pre-commercial thinning, pruning to raise canopy, brush piling, prescribed burning). Similar analysis of fuel treatment costs implemented by the Bureau of Land Management found nonlinear decreases in costs as treatment area increased and increases in real cost over time (Meldrum *et al.* 2025).

An often-confounding factor for assessing the costs of fuel treatments is the interplay between wood utilization and thinning treatments. Depending on the forest type, thinned wood can have standalone value that logging and sawmill companies are willing to purchase, notwithstanding the fact that the focus of fuel treatments is on lesser valuable small diameter and ladder fuels. With various contracting mechanisms for mechanical thinning on federal lands, such as traditional timber sales and more modern stewardship contracts, fuel treatment costs are often documented and reported as net costs after removing stumpage value received. Thus, it is important to separate the full costs of treatments from any stumpage or other such values provided in exchange for thinning services.

Adverse health effects coming from prescribed fire smoke have been noted as a cost of fuel treatments (Afrin and Garcia-Menendez 2021), yet there is a paucity of research on this topic. Development of economic valuations of health costs associated with prescribed fire smoke could be directly incorporated into fuel treatment BCA and indirectly incorporated as a variable for estimating health AWC of fuel treatments (see Jones *et al.* 2022*b*). Other fuel treatment costs include the previously discussed changes to initial ecosystem services that result in adverse (negative) effects as opposed to enhanced (positive) effects. This includes cases where the values of properties adjacent to fuel treatments decrease or when use values are adversely affected by fuel treatments (e.g. short-term closure of recreation areas and trails or disturbance-related displacement of recreation).

A recent synthesis of forest thinning costs in the Western US found a range from \$307/acre (\$758/ha) to \$1737/acre (\$4291/ha) (Chang *et al.* 2023) and a recent review of pile burning costs in the Western US found a range from \$409/acre (\$1010/ha) to \$735/acre (\$1815/ha) (Barker *et al.* 2025). However, some reported fuel treatment costs exceed the ranges provided here. Furthermore, the costs of broadcast prescribed burns are not included in these ranges. As noted in Barker *et al.* (2025) and in recent anecdotal accounts, fuel treatment costs are rapidly increasing. Transaction evidence is the best way to evaluate the costs of fuel treatments, but as noted, it is important to make sure that transaction evidence is just for on-the-ground implementation and not inclusive of stumpage values or services traded for wood.

Finally, when prescribed burns are effective, wildfire risk is reduced and benefits are realized. But a very small portion of prescribed fires escape and initiate uncharacteristic wildfire and its associated damages. In 2022, the Calf Canyon/Hermits Peak Fire became the most destructive and largest wildfire in New Mexico history, burning almost 1000 structures. The origin of the fire came from two separate fuel treatments – an escaped prescribed fire and a re-ignited pile burn. When a prescribed fire escapes and becomes an uncharacteristic wildfire, the fuel treatment can add significant costs as opposed to benefits. Furthermore, as agencies move to drive the escaped prescribed fire risk to zero, the costs of fuel treatments increase due to more suppression needs on site (e.g. engines, firefighters, water, resources). One way to account for escaped prescribed fires in fuel treatment BCA is to model the probability of escape based on historical occurrences (e.g. Li *et al.* 2025), multiply that probability by an average cost determined for an uncharacteristic wildfire and aggregate potential costs based on the number of prescribed fires anticipated for a particular study area. A recent US Forest Service review of their prescribed fire program showed that of the annual 4500 prescribed fires conducted by their agency, only 0.16 percent escaped (USDA Forest Service 2022).

Addressing complexity in BCA of fuel treatments

Economists can take advantage of 'natural experiments' to determine the effectiveness of fuel treatments. When wildfire does occur, we can observe fire behavior and the suppression effort required as the wildfire moves from an area without prior fire to the area with prior fire (Collins *et al.* 2023; Davis *et al.* 2024). Loomis *et al.* (2003) exploited such a series of natural experiments to compare the amount of sediment coming into Los Angeles County debris basins from areas untouched by fire for many years with that from areas where fires had burned 5 years prior and were deemed to now have a vegetation structure that mimics a prescribed fire. Because natural experiments are not often available, economists often rely on modeling the effects of fuel treatments, which requires working with foresters, wildfire specialists and geographic information system (GIS) specialists to model the likely progression of wildfire (e.g. rate of spread and fire intensity) with different fuel treatments.

Sometimes these models can be developed from existing wildfire risk assessment models, such as the West-wide models (Sanborn Map Company 2013) and the State of Colorado wildfire risk assessment models (Colorado State Forest Service 2022).[4]

Additionally, the benefits of a given reduction in wildfire risk may depend on socio-economic variables that influence the specific types of ecosystem services gained or lost due to fuel treatment. Valuing the various types of ecosystem services will likely require a range of data and methods. The various valuation methods and measuring units complicate fuel treatment BCA and the analyst's ability to aggregate multiple benefit types. Further, different locations (e.g. rural versus metropolitan) with different human populations will usually result in different aggregate demand, so that a demand assessment must be conducted even if values per unit of ecosystem service (e.g. visitor day or acre of wetlands) are available in the literature. These complexities can potentially necessitate focusing on ecosystem services with the largest changes and greatest value. Table 2 demonstrates aspects of complexity in valuing benefits and costs of fuel treatments and potential solutions for addressing these aspects.

Recommendations for future planning, data collection, and research

Given the substantial investments that US land management agencies are making in fuel treatments, it would be prudent to have a better understanding of the benefits and costs of treatments. The cost of collecting the requisite data and conducting BCA analyses are likely justified if incorporated into improved fuel treatments planning and prioritization. Looking forward, we make eight recommendations to facilitate broader use of BCA of fuels treatments. These are presented below:

1. One of the most obvious research findings when investigating BCA of fuel treatments is that benefits, and specifically AWC, will typically be greatest in areas that have the highest valued assets at the greatest risk of uncharacteristic wildfire (though vulnerability to wildfire hazards also plays a role). A focus on mapping and prioritizing values-at-risk in regions with high wildfire risk is a great starting point when planning types and locations of fuel treatments (Hjerpe et al. 2024). This prioritization should be an integral part of any wildfire risk reduction planning process at different geographic and jurisdictional scales, including community wildfire protection plans (CWPPs). Rather than relying on a point estimate of wildfire risk, analysts should pair values-at-risk with a distribution of fire behavior outcomes, recognizing that outcomes are likely to differ across wildfire behavior metrics. Broad mapping exercises overlaying wildfire risk models with Census population data can provide initial filtering of areas with the potential for myriad benefits from fuel treatments. Furthermore, a risk-averse approach may be more appropriate than a simple expected value calculation in the context of extreme events (low probability, high consequence) that threaten highly personal and or irreplaceable values, such as homes.
2. More consistent and comprehensive tracking of the damages and costs of uncharacteristic wildfires would support important insights, as information on the costs of wildfire is a prerequisite to determining AWC benefits of fuel treatments. Establishing a wildfire cost database would provide a record of damages that can be updated years after a wildfire. The long-term tracking of wildfire costs is particularly important for wildfires with compounding events like post-wildfire flooding (Hjerpe et al. 2023). Better documentation of wildfire costs would facilitate greater and more consistent approaches to AWC valuations and could lead to metrics and concepts such as the social cost of uncharacteristic wildfire.
3. Gaps in available data indicate the value of more empirical studies and modeled simulations for individual benefit types. Likewise, the literature would be improved by more comprehensive BCA analyses where multiple benefits are investigated and aggregated (e.g. Buckley et al. 2014; Wildish et al. 2020; Jones et al. 2022a). Additional research looking at bundling fuel treatment benefits and the use of integrated modeling can further highlight the multiplicity of returns on forest restoration and fuel treatment investments (Hunter and Taylor 2022; Bryant et al. 2023). These BCA analyses can improve over time as more empirical data becomes available on the full costs of wildfire occurrence. As communities recover from wildfires, documentation of the variety, extent and lifespan of damages increases (Thomas et al. 2017; Buechi et al. 2021).
4. Researchers can improve the translation and communication of findings, especially given the complexity inherent in multi-level modeling and economic theory used in most fuel treatment analyses of benefits and costs. Sensitivity analysis with better visual illustration of the outer bounds and thresholds will be critical for better conveyance of fuel treatment benefits, particularly AWC (e.g. Jones et al. 2022a).
5. As more fuel treatments are implemented, greater empirical comparisons of actual wildfire damages in similar areas with and without fuel treatments and evidence-based research (ex post) would offer more opportunities to assess convergence with modeled simulations.
6. Greater consideration of distributional and equity issues concerning fuel treatments and cost-sharing programs for

[4]Many wildfire hazard and risk assessments can be found at the USGS Wildfire Hazard and Risk Assessment Clearinghouse, available at: https://apps.usgs.gov/wildfire_hazard_and_risk_assessment_clearinghouse/ (accessed 15 March 2025).

Table 2. Complexity in benefit-cost analysis (BCA) of fuel treatments.

Valuation complexity factor	Potential solutions/treatment
Benefit: enhanced initial ecosystem services (EIES)	
1. Ecosystem service flows, and their changing values due to fuel treatments, are spatially and temporally dispersed.	Baseline monitoring; geographic information system (GIS) analyses; benefit transfer
2. Initial ecosystem service changes due to treatments do not always result in 'enhancement' or benefits. When changes to ecosystem services represent a reduction in the quality and quantity of ecosystem services, these adverse effects are realized as costs, not benefits.	Allow for positive or negative changes to initial ecosystems services; negative changes become 'costs'
Benefit: avoided wildfire costs (AWC)	
1. All avoided wildfire costs are predicated on the treated site encountering wildfire during the effective lifespan of the treatment.	Probability of wildfire; Bayesian techniques; sensitivity analysis
2. All avoided wildfire costs are predicated on how effective the fuel treatment is at reducing fire severity. Given the range of wildfire variables, the 'effectiveness' of the fuel treatments is likely to also have a large range. Thus, AWC will often need to be estimated based on modeled fuel treatment effectiveness, and it is assumed that future fire severity is reduced and that this translates into reduced wildfire damages and associated costs.	Clear articulation of assumptions and 'reasonableness' of the assumptions based on the available literature
3. Treatment effectiveness is only 'effective' for a period of time before more maintenance and treatment is needed. Treatment effectiveness is not the same over the lifespan of the treatment (ranging from high effectiveness to zero after the last year of effectiveness).	Understanding treatment effectiveness lifespans and rate of decay
4. Some AWC are predicated on indirect disturbance, such as post-wildfire flooding, that can follow the wildfire and can create additional costs for communities. Thus, estimating indirect AWC assumes the treated site encounters wildfire and subsequent and adjacent severe rainstorms during the lifespan of the treatment.	Fire-climatic-atmospheric-weather models; modeling both wildfire and severe storm probabilities
5. In order to estimate AWC, a first estimate of the costs of hypothetical (or real) wildfire on the treated site without treatment needs to be calculated, (or the estimated net value changes of uncharacteristic wildfire burning the landscape planned for fuel treatment). Then, AWC must be modeled based on the assumed effectiveness of treatments and assumed wildfire costs.	Greater research and cataloging of wildfire damages; develop a wildfire cost database
6. As we cannot conduct controlled experiments with uncharacteristic wildfire, researchers will often need to adapt simulation models developed for assessing fire risk to estimate the effectiveness of fuel treatments or draw conclusions on fuel treatment effectiveness from past fuel treatments in similar areas or 'natural experiments.'	Rely on existing fire risk assessment models; locate past fuel treatments to use as a guide as to what might be expected at the fuel treatment under study; analyze low-severity wildfires that produced outcomes similar to those desired with prescribed fire
Cost: fuel treatment costs	
1. Fuel treatments have a range of costs to implement based on types of forests, proximity to communities, topography and other factors.	Synthesize cost data from records of past fuel treatments, and adjust for inflation, wage levels, availability and cost of other resources needed for the fuel treatment
2. All land management activities come with associated planning costs and associated overhead/administrative costs. Are planning and administrative costs for fuel treatments uniquely different from other land activities and should they be included in the cost-side of the BCA?	Consider the full range of costs; highlight unique indirect costs
3. Some fuel treatments may cause adverse effects or can, in the case of prescribed fire, become a severe out-of-control wildfire.	Embed the probability of escaped prescribed fire in cost accounting

fuel treatments is important (e.g. González-Cabán and Sánchez 2017; Sánchez *et al.* 2022; Meldrum *et al.* 2024). Are fuel treatment benefits accruing disproportionately among varying demographics and income levels? Are the costs of fuel treatments spread relatively evenly across beneficiaries and at-risk communities?

7. There are potential economic implications of reduced wildfire risk resulting from fuel treatments, even if treated areas do not encounter wildfire. For example, although AWC are only realized if treated areas subsequently experience wildfire, the reduction in wildfire risk that immediately follows fuel treatments is valuable on its own with or without subsequent wildfire, especially as related to property values and community well-being. Greater understanding of this benefit can ultimately result in monetary benefits that are currently not included in fuel treatment BCA calculus. Likewise, the communication of this reduced wildfire risk can be an important motivator for further funding of fuel treatments from beneficiaries and the public.
8. Broader incorporation and analyses utilizing existing and updated secondary data would help fill gap topics in the literature. Economists may not be familiar with many of

the recent improvements in organized datasets related to fuel treatments and the coinciding query and analytical tools. These include streamlined databases, such as the Treatment and Wildfire Interagency Geodatabase,[5] that illustrates federal fuel treatments and wildfire information and has query and download options. The Environmental Benefits Mapping and Analysis Program (BenMAP) is publicly available software that calculates illnesses and deaths attributable to air pollution and the corresponding economic value.[6] Dittrich and McCallum (2020) explore options for assessing the costs from wildfire smoke with BenMAP-CE (Community Edition) that would be directly applicable to fuel treatment economic analyses.

BCA has long been required in many federal and state decision-making contexts. For example, Executive Order 12866 requires federal agencies to prepare regulatory impact analyses for major rules and regulations. OMB Circular A-94 outlines principles for conducting BCA, including the treatment of uncertainty, distributional effects and the application of discount rates. Recent efforts, through the Subcommittee on the Frontiers of Benefit-Cost Analysis established under the National Science and Technology Council, have sought to modernize the federal BCA framework by identifying priority areas where methodological advances are needed. These include ecosystem service accounting, incorporating uncertainty from wildfire and extreme weather, and distributional impacts. Our recommendations on conducting BCA for fuel treatment effectiveness build on these efforts to improve the BCA methodology more generally.

Discussion

The evaluation of fuel treatment economic efficiency is quickly evolving, moving from theoretical models to practical applications that influence funding decisions. The rapid development of the wildfire crisis and mitigation strategies makes it imperative that economic research also rapidly responds to the cumulative costs and benefits of fuel treatments. Estimating the benefits of fuel treatments varies in complexity. Changes in EIES values from thinning and prescribed fire are more straightforward to assess, as they occur soon after implementation. In contrast, AWC benefits depend on future wildfire occurrence, requiring an additional layer of modeling or empirical analysis. However, both EIES and AWC benefits, along with fuel treatment costs, are highly site-specific and can vary significantly across landscapes.

Wildfires can also generate negative economic impacts, or regional economic disruptions and changes to supply chains, market output, employment and taxes (Thomas *et al.* 2017). While fuel treatments can mitigate some of these regional economic losses, they are often excluded from BCA due to their distributional nature. For instance, a wildfire may reduce tourism revenue in one area, but visitors may simply redirect their spending to another unaffected region, offsetting overall market losses. Determining avoided or reduced economic impacts due to fuel treatments would involve similar with/without analysis used to measure AWC from fuel treatments. Likewise, implementation of fuel treatments generates positive regional economic impacts (Huber *et al.* 2019; Hjerpe *et al.* 2021) that are not dependent on the treated site encountering wildfire. These positive economic impacts are especially important in rural areas that have lost wood processing infrastructure but are also distributional effects and are not included as economic benefits in BCA.

While this analysis focuses primarily on forested fuel treatments in the Western US, wildfire risk is also increasing in other regions. Warming and drying trends are raising fire hazards in Southeastern US forests (Ingram *et al.* 2013), as the region is experiencing an increasing trend in large wildfires (Donovan *et al.* 2023). Rangeland and grass fires are also becoming more frequent and severe in the Western US (Crist *et al.* 2023) and averted wildfire suppression costs from fuel treatments have been illustrated in these ecosystems (Taylor *et al.* 2013). Prescribed fire in Florida was shown to result in net benefits when modeled with wildfire losses that primarily included burned structures and timber losses (Mercer *et al.* 2008). Fine particulate matter emissions from prescribed fire have been investigated in the Southeastern US (Afrin and Garcia-Menendez 2020). For the most part, proposed methods and modeling complexities discussed in this article are applicable to other types of uncharacteristic wildfire throughout the US, and internationally. Care will need to be taken to adjust regional BCA models for different tree and plant species, aridity, topography, community adjacency and regional values at risk. Furthermore, the term 'uncharacteristic' implies that there is an optimal fire regime (characterized by frequency and severity). But this will vary regionally, and over time as ecosystems are altered due to climate change. The benefit-cost framework is very useful for quantifying and identifying efficient fuel treatment interventions and associated fire outcomes, but how these become reconciled with the ecological community's suggestion (e.g. Prichard *et al.* 2021) to restore Western forests to their historical fire regimes has not been attempted.

The existing benefit-cost literature also generally ignores the potentially beneficial role of wildfires, when occurring within their natural historical regimes, in terms of providing important provisioning, regulating and cultural ecosystem services (Pausas and Keeley 2019). In fact, wildfires are

[5]Treatment and Wildfire Interagency Geodatabase. Available at: https://reshapewildfire.org/about-twig (accessed 15 March 2025).
[6]Environmental Benefits Mapping and Analysis Program - Community Edition (BenMAP-CE). Available at: https://www.epa.gov/benmap (accessed 15 March 2025).

ecologically essential to many fire-adapted forests in the American West. These benefits of wildfires, which can vary both across and within individual large fires, are generally excluded from BCA at present and future economic research should explore how these impacts can be implemented into both EIES and AWC benefits.

The framework and review in this analysis focuses on dry, mixed-conifer forests in the Western US, largely because of the immediate threat posed by rapidly changing wildfire regimes. However, the methodological approach of BCA is broadly applicable to other regions in the US and internationally that are experiencing uncharacteristic wildfire. We recognize that there are conflicting opinions concerning the scale of proactive land management activities, especially for activities like fuel treatments that impose risks and involve cutting trees. The lack of public consensus on the appropriate level of fuel treatments highlights the importance of region-specific data collection and the ability of researchers to tailor analyses to the unique fire regimes, ecological conditions, market structures, discount rates and policy environments found in other contexts.

With wildfire damages escalating, proactive mitigation strategies – such as pre-suppression fuel treatments – are more critical than ever. A clearer understanding of the economic trade-offs involved can help highlight the substantial long-term savings from proactive investments in wildfire resilience. Without a comprehensive understanding of fuel treatment costs and benefits, wildfire management may remain a reactive practice – focused on costly suppression rather than proactive mitigation.

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Data availability. The data that support this study will be shared upon reasonable request to the corresponding author.

Conflicts of Interest. The authors declare that they have no conflicts of interest.

Declaration of funding. This work was funded under United States Department of Agriculture (USDA) Forest Service Domestic Grant 22-DG-11132543-089 authorized under Section 40803I(8) of the Infrastructure Investment and Jobs Act (PL 117-58).

Acknowledgements. Funding for this research came primarily from the USDA Forest Service. The findings and conclusions in this study are those of the author(s) and do not necessarily represent any official USDA or US Government determination or policy. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government. The authors would like to thank the editor and anonymous referees whose comments substantially improved this article. Additionally, we appreciate contributions from James Meldrum and suggestions from Travis Warziniak.

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