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Economic Analysis of Wildfire Impacts to Water Quality: a Review

Matthew Wibbenmeyer,[1,*] Matthew R. Sloggy,[2] and José J. Sánchez[2]

[1]Resources for the Future, Washington, DC, USA
[2]USDA Forest Service, Pacific Southwest Research Station, Riverside, CA, USA
*Corresponding author email: Wibbenmeyer@rff.org

Abstract

As the frequency and severity of large wildfires in the western United States have grown, impacts to private property and air quality have typically attracted the greatest attention; however, wildfires can also substantially affect water resources, altering watershed function and contaminating drinking water supplies. Although there is significant scientific literature describing impacts of wildfires on water resources, the literature on economic dimensions of these impacts is limited. In this article, we identify ways in which economic analyses can contribute to understanding and managing wildfire impacts to water resources and review pertinent literature to characterize important areas of future work. These include estimation of damage costs, measurement of avoidance behavior and costs, mapping risks to infrastructure and the environment, optimization of fuel treatments, and risk mitigation. The areas of research covered in this review will only become more important as the climate changes and wildfires continue to pose a risk to natural resources.

Study Implications: Rising wildfire activity in the western United States increasingly threatens watersheds and water supply infrastructure. Efficiently managing this risk requires understanding both potential impacts and the costs and benefits of potential management responses; however, little economic research exists on wildfire impacts to water quality. This article identifies and reviews relevant literature from four areas where economic analysis can contribute to managing these impacts: (1) identifying potential for adaptation, (2) measuring damage costs, (3) mapping risk, and (4) developing models to optimize damage mitigation strategies.

Keywords: forest disturbance, water resources, risk mapping, forest management, wildfire, water quality, cost-benefit analysis

Over the past several decades, climate change has contributed to large increases in wildfire hazards (Abatzoglou and Williams 2016; Jolly et al. 2015), leading to mounting health risks (Burke et al. 2021) and damage to the built environment (Buechi et al. 2021). Although these impacts typically garner the most attention, effects of fires on water quality have also emerged as a topic of significant concern following recent wildfire-related disruptions to drinking water supplies in the United States (Proctor et al. 2020; Writer and Murphy 2012) and Australia (Walton 2020). In the United States, the drinking water supplies for 83 million people are primarily (>50%) derived from forested lands (Liu et al. 2022). As the frequency of catastrophic wildfires increases, so too does the potential for impacts to critical watersheds (Hohner et al. 2019). Moreover, catastrophic fires that enter urban areas—of which the United States has seen several in recent years (e.g., the 2017 Tubbs Fire, the 2018 Camp Fire, the 2020 East Troublesome Fire)—pose risks to water storage and delivery systems. Optimal management of wildfire impacts to water resources requires both an understanding of potential impacts and an understanding of costs and benefits of management actions. However, although there exists extensive documentation of wildfire impacts on water quality, economic analysis has been infrequently applied to understanding the significance of these impacts and efficient ways of adapting to or mitigating them.

This article aims to provide a review of existing literature related to economic impacts of wildfire on water quality and to identify areas where economic research can contribute to an improved understanding and management of wildfire impacts with respect to water quality. We consider that the primary role for economics in this case relates to the understanding of two overarching categories of costs: direct and indirect economic impacts (i.e., benefits and damage costs that occur due to resource impacts) and adaptation costs (i.e., monetary expenses incurred before or after an event to reduce damage costs).

Economic analyses of wildfire impacts to water quality can contribute both to understanding the extent of impacts and what can optimally be done to minimize those impacts. For example, economic analysis may provide estimates of the economic value of direct impacts or estimate adaptation costs. These costs remain understudied, limiting understanding of the economic significance of wildfire effects on water quality. What's more, economic analysis can estimate the extent to which avoidance and mitigation behavior may offset potential damage.

After providing a brief background on the physical impact wildfires have on water quality,[1] we discuss ways in which

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economic analyses can contribute to understanding the costs and benefits of adaptation behavior, and the extent of potential damage. These sections highlight existing research on these topics, and how economic analysis can further contribute to improved understanding of wildfire impacts to water quality. We also discuss how economic analysis can contribute to minimizing impacts of wildfires on water quality. Such analyses include cost–benefit analyses and optimization models and necessarily rely on accurate estimates of avoidance behavior, adaptation costs, damage costs, and estimates of risk. They also may include spatial descriptions of the variation of risk, which may allow prioritization of mitigation activities over space.

Background

Fire is crucial to the functioning of many ecosystems globally (Scott et al. 2013). Many landscapes depend on fire for plant propagation (Pausas and Lamont 2022) and the general health of habitats (Pausas and Keeley 2019). However, wildfires can also have negative consequences for water resources depending on their timing, frequency, and severity, and their location with respect to infrastructure and human communities. For example, wildfires can alter the timing of streamflow, sediment production, and downstream water chemistry (Hohner et al. 2019). This can have consequences for water treatment, water storage, and ecosystem health for periods ranging in length from a few years to multiple decades (Wagenbrenner et al. 2021). Wildfires that burn in developed areas—which have been increasingly common in recent years (Buechi et al. 2021)—can have distinct effects, including contamination of drinking water supplies with volatile organic compounds such as benzene (Solomon et al. 2021).

By consuming surface biomass (Wu et al. 2021), reducing interception of rain in the canopy (Shakesby and Doerr 2006), and in some cases, by increasing concentration of hydrophobic substances at the surface (Doerr et al. 2006; Savage et al. 1972; Woods et al. 2007), wildfire can increase variability in water flow and increase erosion and sedimentation during high run-off events. Periods of very high sediment concentrations can increase water treatment costs and disrupt water treatment infrastructure, sometimes requiring plants to shut down and interrupting water delivery (Hohner et al. 2019). Heavy run-off following fires can also lead to flooding (Neary et al. 2003) or hazardous overland debris flows (Cannon et al. 2001; Shakesby and Doerr 2006). For example, a large rainstorm following the 2017 Thomas Fire in Ventura and Santa Barbara counties resulted in flash floods and debris flows that killed twenty-three people and destroyed over one hundred homes (Lukashov et al. 2019).

Sediment flows following wildfires can also have substantial impacts on water storage capabilities. Due to increasing wildfire activity, postfire sedimentation is expected to double in more than one-third of watersheds—and to increase in all watersheds—in the western United States over the next several decades (Sankey et al. 2017). Accumulated sediment behind dams can reduce water storage capacity, which in turn reduces the expected benefits and physical lifetime of the reservoir unless costly dredging is used to remove the sediment (Holmes 1988; Moody and Martin 2004; Moore and McCarl 1987; Palmieri et al. 2001; Wisser et al. 2013).

In addition to increasing sedimentation and turbidity, wildfires can affect the concentrations of organic matter, nutrients, trace metals and elements, and other solutes (Swindle et al. 2021). Increases in trace metals and other solutes can result from fires, potentially affecting the taste and smell of water or even posing hazards to health (Finlay et al. 2012). Increased dissolved organic matter in water due to deposited ash and increased erosion (Murphy et al. 2015) can be costly for water treatment plants to remove, especially when runoff and erosion are high, such as during and following storm events, because it can reduce the effectiveness of conventional treatment methods and can interact with chlorine to form hazardous carcinogenic disinfection by-products (Hohner et al. 2019).

These various hydrologic and physical watershed impacts, including effects on water flow, sedimentation, nutrients, dissolved oxygen, pH, and water temperature, can have noticeable impacts on ecosystem function and health (Bixby et al. 2015; Gomez Isaza et al. 2022). Wildfires can consume vegetation that normally regulates stream temperatures (Beakes et al. 2014) and can increase acidity and decrease the ability of the stream to regulate acidity in the future (Bayley et al. 1992), potentially affecting stream ecology, including critical fish habitat (Burton 2005). For instance, Pereira et al. (2021) found that freshwater fish can experience declines in population from decreased pH levels (increase in acidity) from ash in the water following fire. As fires consume organic matter, nutrients (including nitrogen and phosphorous) are released into the environment, supporting the growth of algae, cyanobacteria, and aquatic plants (Bladon et al. 2014; Emelko et al. 2011; Ice et al. 2004; Smith et al. 2011), and potentially contributing to harmful algal blooms (HABs) (Gilbert 2020). Although we are not aware of documented instances of HABs associated with wildfire-induced changes in nutrient levels, changes in nutrient levels are nonetheless thought to change stream ecology and pose a risk of HABs in certain conditions (Ranalli 2004). Increasing frequency and intensity of wildfires has also increased fire retardant use (Cal Fire 2018). Fire retardants are not considered harmful for human health; however, evidence of their effects on stream ecology is mixed. Although evidence indicates fire retardant may increase mortality among some fish species (Puglis et al. 2022), it is unclear whether exposure time is long enough in practice to generate significant negative impacts (Rehmann et al. 2021).

Distinct from their impacts on watershed function, wildfires that burn in developed areas can negatively affect the delivery of clean drinking water through destruction and contamination of infrastructure. Following both the 2017 Tubbs Fire and 2018 Camp Fire, unsafe levels of benzene and other volatile organic compounds were found within local water supplies (Proctor et al. 2020). Furthermore, Proctor et al. (2020) found that benzene contamination persisted in Santa Rosa for 11 months following the Tubb Fire. Although scientific understanding of the precise causes of this contamination is still emerging, possible sources included plastic pipes from water distribution networks or structures, both of which may release volatile organic compounds when burned (Proctor et al. 2020; Schulze et al. 2020). These water quality impacts can delay reconstruction and prevent residents from resettling due to prolonged presence of contaminants in the water delivery system. For instance, Solomon et al. (2021) found that following the 2018 Camp Fire, some homes still had significant contaminant levels 11 months after the fire.

Adaptation

Although there are potentially large costs associated with the impairment of water quality, adaptive behavior on the part of land management agencies, water treatment facilities, individuals, and other stakeholders can reduce or even eliminate these impacts. We define adaptation as the investment in infrastructure, conservation, or other activities or products to reduce the economic burden of wildfire events. Although sometimes costly in and of themselves, adaptive measures can be a net benefit when the amount by which they reduce damage is greater than their cost (Mendelsohn 2000). Adaptation to wildfire-water quality impacts may occur following fires, or in anticipation of fires. When adaptation occurs before fires, we label it as mitigation. After wildfires, damage can be reduced either through actions to improve water quality—which we term remediation—or through actions on the part of individuals that would expose them to health or hazards; we refer to these latter actions as avoidance behavior.

Remediation

In many cases, impairments to drinking water quality can be removed by water treatment facilities before they cause health effects. However, reductions in source water quality can increase water treatment costs. A variety of studies have used "replacement cost" methods to investigate how costs of providing similar quality treated water increase as source water quality declines (e.g., Dearmont et al. 1998; Heberling et al. 2015; see Price and Heberling 2018 for a review). In general, these studies have found that water treatment costs increase in response to decreases in source water quality, but that changes in source water quality cause proportionally smaller changes in costs. Several studies document consequences of wildfires for water treatment systems (e.g., Emelko et al. 2011; Hohner et al. 2019; Writer et al. 2014), and find, for example, that dissolved organic carbon and turbidity in recently burned watersheds may increase during periods of heavy runoff, potentially limiting treatability during these periods. Nevertheless, we are aware of no studies that have specifically estimated the costs of wildfires on water treatment.

Like impacts for source water, costs of wildfire-caused contamination to urban water systems can be estimated using replacement cost methods; however, because instances of this kind of impact remain rare, evidence for these replacement costs is anecdotal. For example, in California, the city of Santa Rosa plans to replace the fire-damaged water system (up to five hundred service lines) at a cost of several million dollars, whereas the estimated cost to replace the water pipes for the city of Paradise is as much as $300 million (Wilson 2019).

Impacts of sedimentation can also be measured using replacement cost methods. For example, White (2001) used data from approximately twenty-three hundred dams in thirty-one countries to estimate that an average of between 0.5% and 1% of global water storage is lost each year due to sedimentation. Given the costs of dredging and sediment removal, replacement costs for this lost storage are approximately $13 billion per year (Palmieri et al. 2001). Also, Loomis et al. (2003) used estimates of the effect of prescribed fires on fire intervals and sediment yield coupled with data on costs of sediment removal to estimate that increasing use of prescribed fires could result in approximately $24 million of annual savings from reduced debris clean-up costs for Los Angeles County Public Works.

Landscape restoration can also be used to reduce damage following fires. For example, in the United States, federal Burned Area Emergency Response (BAER) teams are responsible for plans to reduce post-fire impacts, including impacts to watersheds. When implemented, BAER treatments can reduce watershed damage and the duration of impacts. Calkin et al. (2007) note that BAER teams are required to provide benefit–cost assessments for proposed actions; however, these have generally been based on expert judgment rather than rigorous analysis. Girona-García et al. (2023) review effects of post-fire landscape restoration programs and argue that these programs are worthwhile, although this assessment is likewise not based on rigorous analysis. Therefore, there is a clear need for more work to understand the costs and benefits of these programs.

Avoidance

When institutions are incapable of addressing impacts to water quality, individuals can minimize damage through individual avoidance behavior. For example, purchases of bottled water or water purification systems can be a substitute for poor source water quality. Costly individual avoidance behavior in response to poor water quality is well documented, for example, in increased bottled water sales where drinking water is low or perceived to be low (see e.g., Jakus et al. 2009; Zivin et al. 2011).

Although we are not aware of any studies that have investigated avoidance costs related to water quality impacts from wildfires,[2] there have been a variety of anecdotal reports of avoidance behavior, mostly in response to contamination following urban conflagrations. For example, following contamination of the Paradise, California, water supply as a result of the 2018 Camp Fire, residents were warned not to drink or bathe using the water, and officials estimated that it could take 2 years and up to $300 million to make the town's water supply safe again (Hallema et al. 2019). As a result, residents bought water purification systems or water tanks to fill with potable water brought in from elsewhere. The Camp Fire also affected the trust residents had in their public water system. For instance, Odimayomi et al. (2021) found that 85% of residents sought alternative water sources following the Camp Fire; 47% of surveyed residents invested in home water filtration systems, further increasing costs.

Although such impacts from fires have been rare, and avoidance behavior can remove or reduce the threat of harmful health effects, the costs of such avoidance behavior may nevertheless be substantial for affected households. According to a press report, households spent as much as $6,500 on water tanks, which could cost hundreds of dollars to refill every few weeks (Siegler 2019). Water filtration systems capable of removing benzene may cost thousands of dollars. Additional research is needed to more fully account for total avoidance costs incurred by households following these fires.

Measuring Damage Costs

When adaptation before or after a fire cannot cost-effectively eliminate damage, damage costs may result. Although a deep scientific literature exists documenting the impacts of wildfire on water quality, (see the Background section, or Smith et al. 2011 for a complete review) there is a paucity of research estimating damage costs of these wildfire impacts to water quality. Such estimates are needed in part because in many cases the values of adaptation measures are defined based on the reduction in damage; to understand the value of adaptation measures, we need to understand damage costs.

Damage may include both direct and indirect damage. Direct damage involves direct costs of changes in water quality changes to individuals (e.g., health impacts), whereas indirect costs include "ripple" effects through other systems. For example, decreased visitation to a recreation site due to low water quality may have indirect impacts to the local economy due to decreased revenue from tourism.

Both direct and indirect damage costs associated with wildfire impacts to water quality may be poorly understood in part because they are difficult to measure. Although costs of remediation—for example, increased treatment costs or costly sediment removal—are easily measured by the market, damage costs frequently accrue to ecosystem services that are not typically traded in a market setting, including support for human health, recreation, and existence values associated with biodiversity and ecosystem function (Keeler et al. 2012). Environmental economists make use of a variety of nonmarket valuation methods to measure both the benefits from and losses associated with degradation of ecosystem services. Benefits of a policy change can then be derived by estimating changes in the ecosystem service as a result of the policy change and applying estimated nonmarket values. Similar to direct nonmarket damage, estimation of indirect economic damage is difficult, and often requires understanding both direct impacts and use of general equilibrium sectoral models (e.g., IMPLAN) to understand downstream indirect impacts.

Valuation methods for estimating direct nonmarket damage can be sorted into two categories: revealed preference methods and stated preference methods. Revealed preference methods estimate nonmarket values based on observed behavior, such as home purchases or visits to recreation sites. In the hedonic pricing method (e.g., Leggett and Bockstael 2000; Poor et al. 2007; Walsh and Milon 2016), econometricians estimate the contribution particular home characteristics, including environmental quality, make to home price; in equilibrium, this contribution can be shown to be equal to marginal willingness to pay for the amenity (Rosen 1974). The travel cost model (e.g., Bockstael and Hanneman 1987; Keeler et al. 2012), recognizes that although recreation may be low-cost or free, traveling to recreation sites is costly. Examining how the rate at which visitors travel to a recreation site declines with increasing distance and how this decline differs across sites that vary in environmental quality allows estimation of implicit willingness to pay for recreation sites, and environmental quality at those sites. Stated preference methods estimate nonmarket value based on responses to hypothetical questions. Therefore, they are especially well suited to providing estimates of nonuse values such as existence values, although they are also frequently applied to use values associated with environmental outcomes such as water quality. Two frequently used stated preference methods are contingent valuation (e.g., Chatterjee et al. 2017; Johnson et al. 2000), in which survey respondents are asked to state their willingness to pay for an incremental environmental improvement, and discrete choice experiments (e.g., Brouwer et al. 2010), in which survey respondents are asked to choose their preferred alternatives from a series of hypothetical environmental programs that vary in a series of experimentally varied characteristics.

Although we are aware of few studies that have specifically valued direct nonmarket damage of wildfire effects for water quality,[3] there are numerous examples of studies within the broader ecosystem services literature that have measured the value of ecosystem services—including drinking water, recreation, and ecological function—provided by water resources (for surveys, see van Houtven et al. 2007; Olmstead 2010; Griffiths et al. 2012, and Keiser et al. 2019). Many studies estimating the value of drinking water focus on developing countries or economic history and examine benefits of improvements from low status quo levels of drinking water quality or service reliability (e.g., Berry et al. 2020; Cutler and Miller 2005; Soares 2007). These studies generally find significant health benefits from initial improvements in water quality and substantial welfare effects relative to income. Estimates of the value of ambient water quality frequently rely on preferences revealed in recreation or home purchase decisions, or they use stated preference survey methods to elicit willingness to pay for improvements in water quality. Results of these studies are often difficult to compare because they may assess willingness to pay for disparate water quality improvements at a variety of distinct sites. Nevertheless, comprehensive evaluations of benefits from improvements in ambient water quality in the United States have generally found modest benefits relative to cost, although estimates remain incomplete and uncertain (Carson and Mitchell 1993; Keiser et al. 2019; Lyon and Farrow 1995).

Optimizing Wildfire Hazard and Damage Mitigation

Investments in natural and built infrastructure can reduce the expected impacts of wildfire for water resources by reducing hazard or improving communities' abilities to remediate impacts. Fuel treatments, including fuel breaks, prescribed fires, mechanical thinning, and other mitigation activities, can be used to modify fire behavior, making fires easier to control and in some cases, reducing their impacts on watersheds (Bart et al. 2021; Finney et al. 2007; Reinhardt et al. 2008). Drinking water treatment may vary in its capacity to decontaminate affected source water, whereas water delivery infrastructure may vary in its vulnerability to damage from wildfires. For instance, Lee et al. (2022) found, in the state of California, utilities serving larger populations also tended to be more vulnerable to wildfire damage than those serving smaller populations.

Because investments in natural and built infrastructure are costly and in some cases limited by logistical and political difficulties, they cannot be implemented everywhere they may be needed. Therefore, investments must be prioritized based on project costs, expected benefits (a function of risk and expected effectiveness), and available budgets. Evaluation of optimal mitigation investments must therefore integrate information on risk with data on potential project effectiveness and costs and have criteria for choosing among projects. In the case of investments in infrastructure or fuel treatments, criteria should be designed to prioritize investments that minimize the expected net present value of overall costs (including damage costs, as well as the costs of mitigation and other adaptation measures) over time.

Methods from economics, engineering, and operations research can be used to choose optimal investments in mitigation to reduce wildfire impacts to water resources. Projects may be chosen based on their benefit–cost ratio, to maximize the overall difference between benefits and costs given a flexible budget, or to maximize project benefits given a fixed budget through constrained optimization methods. Optimizing fuel treatment portfolios is challenging as it may involve consideration of a large set of potential projects and locations, the effectiveness of which may vary depending on the timing and method of treatment and the location of treatment relative to another.

Nevertheless, a variety of studies have considered optimal allocation of fuel treatments (see Chung 2015 for a review). Many of these studies use wildfire simulation models (e.g., FlamMap, FSPRO, or FARSITE) to maximize fuel treatment benefits for reducing fire behavior over a planning area and over time (e.g., Ager et al. 2012; Arca et al. 2015; Finney et al. 2007). Less commonly, researchers have linked models of fuel treatment effects to spatial data on values at risk, such as structures, to evaluate potential effectiveness of various treatment strategies for reducing risk (e.g., Stockmann et al. 2010; Wei et al. 2008). Other studies have modeled optimal fuel treatment allocations on simple schematic landscapes to yield general insights regarding optimal allocation of fuel treatments to minimize damage to values at risk (Konoshima et al. 2010; Wei 2012).

However, only a few articles consider implications of fuel treatment allocation decisions for water resources. Although not optimizing over fuel treatment locations, Elliot et al. (2016) examined how targeted fuel treatments affect post-fire sedimentation, and through modeling, demonstrated a decline in sedimentation in treated versus nontreated parcels. Jones et al. (2017) evaluated the return on investment with respect to sediment removal costs across fuel treatment scenarios, finding that, although there is a positive return on investment, marginal benefits begin to decline after between 50% and 80% of the treatments are deployed. Extending optimization to consider a broad array of ecosystem services, Warziniack and Thompson (2013) argued for using an investment portfolio approach to optimize watershed-level fuel treatments.

Finally, the study that most comprehensively models optimal allocation of fuel treatment for watershed benefits is Gannon et al. (2019). Gannon et al. (2019) linked a fire simulation model with models of erosion and sediment transport and develop a model that selects optimal fuel treatment locations to minimize expected sedimentation costs for water supplies. Gannon et al. (2019) found that (1) consideration of water quality impacts changes the optimal distribution of fuel treatments, but that (2) the benefits from the treatments typically do not cover the costs, which suggests a need to consider a range of benefits. Optimization models that rely on the maximization of net benefits require accurate accounting of ecosystem service impact values; otherwise, these methods will misallocate treatments. Further, failure to include certain ecosystem service impacts of fuel treatments may lead to the effects of the fuel treatments being undervalued. Due to the lack of studies that value changes in water quality from wildfire (see Adaptation section) optimization studies may misallocate treatments because of a lack of information on net benefits of water quality. Practitioners commonly face the dilemma of reducing risk dramatically in a few key watersheds or reducing risk to a lesser extent across a broader set of watersheds. Additional work on optimization might yield better models for addressing this important applied question.

Although there is an extensive engineering literature on optimal infrastructure siting and replacement, including in studies of water delivery infrastructure (e.g., water treatment plants, pumps, reservoirs, etc.), very few studies consider effects of wildfire on water infrastructure and infrastructure investment decisions. Gannon et al. (2020) studied water supply disruption risk related to wildfires in systems of water supply reservoirs and diversions in Colorado and found that system redundancy substantially reduced risk. Emelko et al. (2011) studied effects of wildfire on source water quality and implications for treatment, including potential for impacts beyond water treatment infrastructure design thresholds. However, we did not identify any studies that weighed cost of infrastructure upgrades. Further, although it is possible that, in many cases, the costs of replacing potentially vulnerable water delivery infrastructure are prohibitive, we did not find any studies evaluating such investments.

Mapping Risk

An important input into optimal mitigation investment decisions is an understanding of the geographic distribution of fire risks to watersheds. Past research evaluating natural hazards defines hazard as the product of the likelihood an event occurs, exposure as the extent to which valued assets are in harm's way, and vulnerability as the degree to which those assets might be affected if an event were to occur (Field et al. 2012). Measuring and mapping risk to watersheds requires an understanding of each of these factors.

Scientific understanding of wildfire hazard is more advanced than understanding of the exposure or vulnerability of watersheds to fire risk. Over the past several decades, advances in fire behavior modeling have been combined with remotely sensed biophysical datasets (e.g., LANDFIRE) to yield a variety of fire simulation software tools that can be used to model the spread of active wildfires and project fire hazard. For example, given a set of fire ignitions, FSIM[4]—a fire simulation software tool developed by the USDA Forest Service—can be used to predict the probability any point on the landscape will burn and at what intensity. The Forest Service Wildfire Hazard Potential dataset uses outputs from FSIM as well as spatial fire occurrence data to map areas where there is greater likelihood of fires that would be difficult to contain and therefore greater threats to assets at risk. In addition to FSIM, fire modeling systems used in the United States include BehavePlus (Andrews 2007), FARSITE (Finney 1998), FlamMap (Finney 2006), and more (for a review of these models, see Miller and Ager 2012).

Exposure of a watershed to wildfire risk is a function of the uses of the watershed and the value of those uses. For example, the value of watersheds that provide drinking water may depend on the size of the population served by the watershed and the availability of substitute sources of water. Exposure of water systems infrastructure to risk may depend on the number of individuals served and the replacement costs. Most existing measures of exposure of watersheds to wildfire risk focus on evaluating hazard to valued resources. For example, Scott et al. (2012) performed simulations to derive fire metrics for watersheds, including municipal watersheds, in the Beaverhead-Deerlodge National Forest in Montana but admitted that their study was limited by low-resolution input data. Robinne et al. (2016) modeled risk at a global scale, developing a set of global indices that considered both fire activity and available water resources across landscape types, finding that the landscapes with the most exposure are tropical landscapes.

Many studies have examined watershed vulnerability to wildfire damage, and there are a few studies that address the ability of water systems to treat watersheds and mitigate impacts in the case of fires; these studies are reviewed above. However, few studies link constant or spatially varying estimates of watershed vulnerability to measures of exposure to wildfire risk. Two exceptions are Thompson et al. (2013) and Thompson et al. (2016). Thompson et al. (2013) coupled wildfire hazard maps risk with watershed maps and erosion risk to identify high-value, high-risk areas and prioritize treatments. Thompson et al. (2016) examined municipal watersheds in the Rocky Mountain region as well to produce metrics of watershed vulnerability from wildfires.

The literature on measuring and mapping wildfire risk to watersheds is incomplete in several ways. First, many dimensions of water quality (e.g., organic carbon, nutrients, trace metals, etc.) have yet to be integrated into measures of risk. Vulnerability with respect to these constituents may depend on a variety of hydrological characteristics, including watershed size and storage capacity, which determines its ability to buffer and absorb increases in constituent levels without harmful effects. Second, measures of watershed exposure in existing studies have not typically considered potential losses associated with watershed impacts. Accounting for losses requires linking the biophysical vulnerability of the watershed to outcomes and, ideally, to the value of those outcomes for human populations. Third, existing measures or risk do not account for water treatment and other adaptive measures, which may have potential to mitigate loss in the event of impacts to watersheds. Fourth, studies are only beginning to emerge that assess wildfire risk to drinking water infrastructure (e.g., Proctor et al. 2020; Schulze and Fisher 2020). As this science emerges, it can be used together with wildfire hazard data and population data to inform assessments of variation in risk to water systems across communities.

Finally, the spatial distribution of wildfire risk is not static through time. Climate change will affect the distribution of fire risk in numerous ways. For example, climate change will influence the distributions and intensities of droughts (Martin et al. 2020; Williams et al. 2020), distribution of tree species (Hashida and Lewis 2019), and availability of water resources (Duran-Encalada et al. 2017), which will all contribute to different distributions and intensities of wildfire (Abatzoglou and Williams 2016). As these conditions change, the need to produce spatial models of wildfire risk will grow in importance as fires enter areas that previously were not at risk. Failing to account for the way in which climate change will influence watershed risk over time may lead to inefficient allocation of risk-mitigation projects, especially in the case of infrastructure projects, which may have multiyear or multidecadal lifespans.

Conclusion

Although the understanding of wildfire's physical impacts to water quality and associated ecological outcomes is well developed, economic research on this topic is limited. In part, this may because instances of significant damage associated with wildfire impacts to water quality have remained rare, and this damage has been overshadowed by impacts to air quality and physical infrastructure. However, the past several years have seen a number of notable disruptions in water quality after wildfires, including increased treatment costs and sedimentation following fires in Colorado and Alberta (Fountain 2021) and contamination of water delivery systems after urban conflagrations. As large and severe wildfires increase in frequency in certain regions, significant impacts to water quality and associated ecosystem services may become increasingly common. It will correspondingly become increasingly important to understand the extent of these impacts and how best to minimize total costs associated with them, including mitigation, avoidance, remediation, and damage costs.

In this article, we highlighted four areas where economics can contribute to improved management of impacts to water quality by wildfires and reducing overall costs. The final two areas (optimizing mitigation and mapping risk) are especially pertinent to planning and allocating resources to reduce costs. However, optimization and risk mapping studies are not possible without accurate measurements of direct costs. Therefore, more research is needed to understand damage and adaptation costs.

As wildfire activity increases, opportunities for such research may unfortunately increase as well. Studies of damage costs incurred from specific wildfires, or of costs to individuals or institutions to mitigate or avoid damage, will provide insight into the potential magnitude of impacts and benefits from fuel treatments. Such case studies can, through benefit transfer methods (e.g., Johnston et al. 2015), enable researchers or practitioners to estimate potential impacts in other contexts or provide the basis for broader optimization or risk mapping studies. Moreover, a broad portfolio of such studies is needed due to the diversity of impacts wildfires may have across different locations, depending on fire severity, values at risk, and other factors. By beginning to build this body of research as opportunities arise, the research community will be in a better position to help society minimize costs of wildfire impacts to water quality as these impacts increase.

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Endnotes

1 We refer readers to Smith et al. 2011 for a thorough review on several of the physical impacts of wildfires on water quality.

2 A related study, Richardson et al. (2012), examines avoidance behavior related to wildfire smoke.

3 Though it is not specifically concerned with water quality, the nearest example is Mueller & Loomis (2008), which measures the

decline in value homes within post-fire floods zones face, over and above the loss in value that accrues to them from being near a recently burned area.

4 https://www.firelab.org/project/fsim-wildfire-risk-simulation-software

Literature Cited

Abatzoglou, J.T., and A.P. Williams. 2016. "Impact of anthropogenic climate change on wildfire across western US forests." *Proceedings of the National Academy of Science of the USA* 113 (42): 11770–11775.

Ager, A.A., N.M. Vaillant, M.A. Finney, and H.K. Preisler. 2012. "Analyzing wildfire exposure and source–sink relationships on a fire prone forest landscape." *Forest Ecology and Management* 267: 271–283.

Andrews, P.L. 2007. "BehavePlus fire modeling system: past, present, and future." In *Proceedings of 7th Symposium on Fire and Forest Meteorology* (pp. 23–25). Boston MA: American Meteorological Society.

Arca, B., T. Ghisu, and G.A. Trunfio. 2015. "GPU-accelerated multi-objective optimization of fuel treatments for mitigating wildfire hazard." *Journal of Computational Science* 11: 258–268.

Bart, R.R., M. Safeeq, J.W. Wagenbrenner, and C.T. Hunsaker. 2021. "Do fuel treatments decrease forest mortality or increase streamflow? A case study from the Sierra Nevada (USA)." *Ecohydrology* 14 (1): e2254.

Bayley, S.E., D.W. Schindler, B.R. Parker, M.P. Stainton, and K.G. Beaty. 1992. "Effects of forest fire and drought on acidity of a base-poor boreal forest stream: similarities between climatic warming and acidic precipitation." *Biogeochemistry* 17 (3): 191–204.

Beakes, M.P., J.W. Moore, S.A. Hayes, and S.M. Sogard. 2014. "Wildfire and the effects of shifting stream temperature on salmonids." *Ecosphere* 5 (5): art631–art614.

Berry, J., G. Fischer, and R. Guiteras. 2020. "Eliciting and utilizing willingness to pay: Evidence from field trials in Northern Ghana." *Journal of Political Economy* 128 (4): 1436–1473.

Bixby, R.J., S.D. Cooper, R.E. Gresswell, L.E. Brown, C.N. Dahm, and K.A. Dwire. 2015. "Fire effects on aquatic ecosystems: an assessment of the current state of the science." *Freshwater Science* 34 (4): 1340–1350.

Bladon, K.D., Emelko, M.B., Silins, U., and Stone, M. 2014. *Wildfire and the future of water supply*. *Environmental Science & Technology* 48 (16): 8936–8943.

Bockstael, N.E., W.M. Hanemann, and C.L. Kling. 1987. "Estimating the value of water quality improvements in a recreational demand framework." *Water Resources Research* 23 (5): 951–960.

Brouwer, R., J.Martin-Ortega, , and J. Berbel. 2010. "Spatial preference heterogeneity: a choice experiment." *Land Economics* 86 (3): 552–568.

Buechi, H., P. Weber, S. Heard, D. Cameron, and A.J. Plantinga. 2021. "Long-term trends in wildfire damages in California." *International Journal of Wildland Fire* 30 (10): 757–762.

Burke, M., A. Driscoll, S. Heft-Neal, , J. Xue, J. Burney, and M. Wara. 2021. "The changing risk and burden of wildfire in the United States." *Proceedings of the National Academy of Sciences of the USA* 118 (2): e2011048118.

Burton, T.A. 2005. "Fish and stream habitat risks from uncharacteristic wildfire: observations from 17 years of fire-related disturbances on the Boise National Forest, Idaho." *Forest Ecology and Management*, 211(1-2): 140–149.

Cal Fire. 2018. Wildland Fire Retardant FAQ. https://www.fire.ca.gov .

Calkin, D.E., Hyde, K.D., Robichaud, P.R., Jones, J.G., Ashmun, L.E., and Loeffler, D. 2007. *Assessing post-fire values-at-risk with a new calculation tool*. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Cannon, S.H. 2001. "Debris-flow generation from recently burned watersheds." *Environmental & Engineering Geoscience* 7 (4): 321–341.

Carson, R.T., and R.C. Mitchell. 1993. "The value of clean water: the public's willingness to pay for boatable, fishable, and swimmable quality water." *Water Resources Research* 29 (7): 2445–2454.

Chatterjee, C., R. Triplett, C.K. Johnson, and P. Ahmed. 2017. "Willingness to pay for safe drinking water: A contingent valuation study in Jacksonville, FL." *Journal of Environmental Management* 203: 413–421.

Chung, W. 2015. "Optimizing fuel treatments to reduce wildland fire risk." *Current Forestry Reports* 1 (1): 44–51.

Cutler, D., and G. Miller. 2005. "The role of public health improvements in health advances: the twentieth-century United States." *Demography* 42 (1): 1–22.

Dearmont, D., B.A. McCarl, and D.A. Tolman. 1998. "Costs of water treatment due to diminished water quality: a case study in Texas." *Water Resources Research* 34 (4): 849–853.

Doerr, S.H., R.A. Shakesby, W.H. Blake, C.J. Chafer, G.S. Humphreys, and P.J. Wallbrink. 2006. "Effects of differing wildfire severities on soil wettability and implications for hydrological response." *Journal of Hydrology* 319 (1-4): 295–311.

Duran-Encalada, J.A., A. Paucar-Caceres, , E.R. Bandala, and G.H. Wright. 2017. "The impact of global climate change on water quantity and quality: A system dynamics approach to the US–Mexican transborder region." *European Journal of Operational Research* 256 (2): 567–581.

Elliot, W.J., M.E. Miller, and N. Enstice. 2016. "Targeting forest management through fire and erosion modelling." *International Journal of Wildland Fire* 25 (8): 876–887.

Emelko, M.B., U. Silins, K.D. Bladon, and M. Stone. 2011. "Implications of land disturbance on drinking water treatability in a changing climate: Demonstrating the need for "source water supply and protection" strategies." *Water Research* 45 (2): 461–472.

Field, C.B., Barros, V., Stocker, T.F., and Dahe, Q., eds. 2012. *Managing the risks of extreme events and disasters to advance climate change adaptation: special report of the intergovernmental panel on climate change*. Cambridge University Press. Cambridge, UK.

Finlay, S.E., A. Moffat, R. Gazzard, D. Baker, and V. Murray. 2012. "Health impacts of wildfires." *PLoS Currents* 4: e4f959951cce2c..

Finney, M.A. 1998. *FARSITE, Fire Area Simulator--model development and evaluation (No. 4)*. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Finney, M.A. 2006. An overview of FlamMap fire modeling capabilities. In *Fuels management—how to measure success: conference proceedings* (Vol. 28, p. 30). USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO.

Finney, M.A., R.C. Seli, C.W. McHugh, A.A. Ager, B. Bahro, and J.K. Agee. 2007. "Simulation of long-term landscape-level fuel treatment effects on large wildfires." *International Journal of Wildland Fire* 16 (6): 712–727.

Fountain, Henry. 2021. "Wildfires Threaten Urban Water Supplies, Long After the Flames Are Out." *The New York Times*, June 24.

Gannon, B.M., Wei, Y., MacDonald, L.H., Kampf, S.K., Jones, K.W., Cannon, J.B.,...Thompson, M.P. 2019. "Prioritising fuels reduction for water supply protection." *International Journal of Wildland Fire* 28 (10): 785–803.

Gannon, B.M., Y. Wei, M.P. Thompson, J.H. Scott, and K.C. Short. 2020. "System Analysis of Wildfire-Water Supply Risk in Colorado, USA with Monte Carlo Wildfire and Rainfall Simulation." *Risk Analysis* 42 (2): 406–424.

Gilbert, P.M. 2020. "Harmful algae at the complex nexus of eutrophication and climate change." *Harmful Algae* 91: 101583.

Girona-García, A., C. Cretella, C. Fernández, , P.R. Robichaud, D.C. Vieira, and J.J. Keizer. 2023. "How much does it cost to mitigate soil erosion after wildfires?" *Journal of Environmental Management* 334: 117478.

Gomez Isaza, D.F., R.L. Cramp, and C.E. Franklin. 2022. "Fire and rain: A systematic review of the impacts of wildfire and associated runoff on aquatic fauna." *Global Change Biology* 28 (8): 2578–2595.

Griffiths, C., Klemick, H., Massey, M., Moore, C., Newbold, S., Simpson, D.,...Wheeler, W. 2012. "US Environmental Protection Agency valuation of surface water quality improvements." *Review of Environmental Economics and Policy* 6 (1): 130–146.

Hallema, D.W., A.M. Kinoshita, D.A. Martin, F.N. Robinne, M. Galleguillos, S.G. McNulty, and P.F. Moore. 2019. "Fire, forests and city water supplies." *Unasylva* 251 (1): 58–66.

Hashida, Y., and D.J. Lewis. 2019. "The intersection between climate adaptation, mitigation, and natural resources: An empirical analysis of forest management." *Journal of the Association of Environmental and Resource Economists* 6 (5): 893–926.

Heberling, M.T., Nietch, C.T., Thurston, H.W., Elovitz, M., Birkenhauer, K.H., Panguluri, S.,...Neyer, T. 2015. "Comparing drinking water treatment costs to source water protection costs using time series analysis." *Water Resources Research* 51 (11): 8741–8756.

Hohner, A.K., C.C. Rhoades, P. Wilkerson, and F.L. Rosario-Ortiz, . 2019. "Wildfires alter forest watersheds and threaten drinking water quality." *Accounts of Chemical Research* 52 (5): 1234–1244.

Holmes, T.P. 1988. "The offsite impact of soil erosion on the water treatment industry." *Land Economics* 64 (4): 356–366.

Ice, G.G., D.G. Neary, and P.W. Adams. 2004. "Effects of wildfire on soils and watershed processes." *Journal of Forestry* 102 (6): 16–20.

Jakus, P.M., W.D. Shaw, T.N. Nguyen, and M. Walker. 2009. "Risk perceptions of arsenic in tap water and consumption of bottled water." *Water Resources Research* 45 (5): W05405.

Johnson, F.R., M.R. Banzhaf, and W.H. Desvousges. 2000. "Willingness to pay for improved respiratory and cardiovascular health: a multiple-format, stated-preference approach." *Health Economics* 9 (4): 295–317.

Johnston, R.J., J. Rolfe, R.S. Rosenberger, and R. Brouwer, eds. (2015). "Introduction to Benefit Transfer Methods." In *Benefit Transfer of Environmental and Resource Values*. The Economics of Non-Market Goods and Resources, Vol. 14. Springer, Dordrecht.

Jolly, W.M., M.A. Cochrane, P.H. Freeborn, Z.A. Holden, T.J. Brown, G.J. Williamson, and D.M. Bowman. 2015. "Climate-induced variations in global wildfire danger from 1979 to 2013." *Nature Communications* 6 (1): 1–11.

Jones, K.W., Cannon, J.B., Saavedra, F.A., Kampf, S.K., Addington, R.N., Cheng, A.S.,...Wolk, B. 2017. "Return on investment from fuel treatments to reduce severe wildfire and erosion in a watershed investment program in Colorado." *Journal of Environmental Management* 198: 66–77.

Keeler, B.L., S. Polasky, K.A. Brauman, K.A. Johnson, J.C. Finlay, A. O'Neill, K. Kovacs, et al. 2012. "Linking water quality and well-being for improved assessment and valuation of ecosystem services." *Proceedings of the National Academy of Sciences of the USA* 109 (45): 18619–18624.

Keiser, D.A., C.L. Kling, and J.S. Shapiro. 2019. "The low but uncertain measured benefits of US water quality policy." *Proceedings of the National Academy of Sciences of the USA* 116 (12): 5262–5269.

Konoshima, M., H.J. Albers, C.A. Montgomery, and J.L. Arthur. 2010. "Optimal spatial patterns of fuel management and timber harvest with fire risk." *Canadian Journal of Forest Research* 40 (1): 95–108.

Lee, J., M. Nemati, and J.J. Sánchez. 2022. "Assessing the vulnerability of California water utilities to wildfires." *Water Resources Management* 36: 4183–4199.

Leggett, C.G., and N.E. Bockstael. 2000. "Evidence of the effects of water quality on residential land prices." *Journal of Environmental Economics and Management* 39 (2): 121–144.

Liu, N., P.V. Caldwell, C.F. Miniat, G. Sun, K. Duan, and C.P. Carlson. 2022. Quantifying the role of National Forest System and other forested lands in providing surface drinking water supply for the conterminous United States. *Gen. Tech. Rep. WO-100. Washington, DC: USDA Forest Service, Washington Office*.

Loomis, J., P. Wohlgemuth, A. González-Cabán, and D. English. 2003. "Economic benefits of reducing fire-related sediment in southwestern fire-prone ecosystems." *Water Resources Research* 39 (9): 1260.

Lukashov, S.G., Lancaster, J.T., Oakley, N.S., and Swanson, B.J. 2019. Post-fire debris flows of 9 January 2018, Thomas Fire, southern California: Initiation areas, precipitation and impacts. 7th International Conference on Debris-Flow Hazards Mitigation. Association of Environmental and Engineering Geologists; special publication 28.

Lyon, R.M., and S. Farrow. 1995. "An economic analysis of Clean Water Act issues." *Water Resources Research* 31 (1): 213–223.

Martin, J.T., Pederson, G.T., Woodhouse, C.A., Cook, E.R., McCabe, G.J., Anchukaitis, K.J.,...King, J. 2020. "Increased drought severity tracks warming in the United States' largest river basin." *Proceedings of the National Academy of Sciences of the USA* 117 (21): 11328–11336.

Mendelsohn, R. 2000. "Efficient adaptation to climate change." *Climatic Change* 45 (3): 583–600.

Miller, C., and A.A. Ager. 2012. "A review of recent advances in risk analysis for wildfire management." *International Journal of Wildland Fire* 22 (1): 1–14.

Moody, J.A., and Martin, D.A. 2004. Wildfire impacts on reservoir sedimentation in the western United States. In *Proceedings of the Ninth International Symposium on River Sedimentation* (pp. 1095–1102). China: Tsinghua University Press.

Moore, W.B., and B.A. McCarl. 1987. "Off-site costs of soil erosion: a case study in the Willamette Valley." *Western Journal of Agricultural Economics* 12 (1): 42–49.

Mueller, J.M., and J.B. Loomis. 2008. "Spatial Dependence in Hedonic Property Models: Do Different Corrections for Spatial Dependance Result in Economically Significant Differences in Estimated Implicit Prices?" *Journal of Agricultural & Resource Economics* 32 (3): 212–231.

Murphy, S.F., J.H. Writer, R.B. McCleskey, and D.A. Martin. 2015. "The role of precipitation type, intensity, and spatial distribution in source water quality after wildfire." *Environmental Research Letters* 10 (8): 084007.

Neary, D.G., Gottfried, G.J., and Ffolliott, P.F. (2003). Post-wildfire watershed flood responses. In Proceedings of the 2nd International Fire Ecology Conference. 16–20. Springer, Orlando, FL.

Odimayomi, T.O., Proctor, C.R., Wang, Q.E., Sabbaghi, A., Peterson, K.S., Yu, D.J.,...Whelton, A.J. 2021. "Water safety attitudes, risk perception, experiences, and education for households impacted by the 2018 Camp Fire, California." *Natural Hazards* 108 (1): 947–975.

Olmstead, S.M. 2010. "The economics of water quality." *Review of Environmental Economics and Policy* 4 (1): 44–62.

Palmieri, A., F. Shah, and A. Dinar. 2001. "Economics of reservoir sedimentation and sustainable management of dams." *Journal of Environmental Management* 61 (2): 149–163.

Pausas, J.G., and J.E. Keeley. 2019. "Wildfires as an ecosystem service." *Frontiers in Ecology and the Environment* 17 (5): 289–295.

Pausas, J.G., and B.B. Lamont. 2022. "Fire-released seed dormancy-a global synthesis." *Biological Reviews* 97 (4): 1612–1639.

Pereira, P., I. Bogunovic, W. Zhao, and D. Barcelo. 2021. "Short term effect of wildfires and prescribed fires on ecosystem services." *Current Opinion in Environmental Science & Health* 22: 100266.

Poor, P.J., K.L. Pessagno, and R.W. Paul. 2007. "Exploring the hedonic value of ambient water quality: a local watershed-based study." *Ecological Economics* 60 (4): 797–806.

Price, J.I., and M.T. Heberling. 2018. "The effects of source water quality on drinking water treatment costs: a review and synthesis of empirical literature." *Ecological Economics* 151: 195–209.

Proctor, C.R., J. Lee, D. Yu, A.D. Shah, and A.J. Whelton. 2020. "Wildfire caused widespread drinking water distribution network contamination." *AWWA Water Science* 2 (4): e1183.

Puglis, H.J., M. Iacchetta, and C.M. Mackey. 2022. "Toxicity of Wildland Fire-Fighting Chemicals in Pulsed Exposures to Rainbow Trout and Fathead Minnows." *Environmental Toxicology and Chemistry* 41 (7): 1711–1720.

Ranalli, A.J. 2004. "*A summary of the scientific literature on the effects of fire on the concentration of nutrients in surface waters*." Reston VA: Geological Survey.

Rehmann, C.R., P.R. Jackson, and H.J. Puglis. 2021. "Predicting the spatiotemporal exposure of aquatic species to intrusions of fire retardant in streams with limited data." *Science of the Total Environment* 782: 146879.

Reinhardt, E.D., R.E. Keane, D.E. Calkin, and J.D. Cohen. 2008. "Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States." *Forest Ecology and Management* 256 (12): 1997–2006.

Richardson, L.A., P.A. Champ, and J.B. Loomis. 2012. "The hidden cost of wildfires: Economic valuation of health effects of wildfire smoke exposure in Southern California." *Journal of Forest Economics* 18 (1): 14–35.

Robinne, F.N., C. Miller, M.A. Parisien, M.B. Emelko, K.D. Bladon, U. Silins, and M. Flannigan, . 2016. "A global index for mapping the exposure of water resources to wildfire." *Forests* 7 (1): 22.

Rosen, S. 1974. "Hedonic prices and implicit markets: product differentiation in pure competition." *Journal of Political Economy* 82 (1): 34–55.

Sankey, J.B., Kreitler, J., Hawbaker, T.J., McVay, J.L., Miller, M.E., Mueller, E.R.,...Sankey, T.T. 2017. "Climate, wildfire, and erosion ensemble foretells more sediment in western USA watersheds." *Geophysical Research Letters* 44 (17): 8884–8892.

Savage, S.M., J. Osborn, J. Letey, and C. Heton. 1972. "Substances contributing to fire induced water repellency in soils." *Proceedings-Soil Science Society of America* 36: 674–678.

Schulze, S.S., and E.C. Fischer. 2020. "Prediction of water distribution system contamination based on wildfire burn severity in wildland urban interface communities." *ACS ES&T Water* 1 (2): 291–299.

Schulze, S.S., E.C. Fischer, S. Hamideh, and H. Mahmoud. 2020. "Wildfire impacts on schools and hospitals following the 2018 California Camp Fire." *Natural Hazards* 104 (1): 901–925.

Scott, A.C., Bowman, D.M., Bond, W.J., Pyne, S.J., and Alexander, M.E. 2013. *Fire on Earth: An introduction*. John Wiley & Sons.

Scott, J., D. Helmbrecht, M.P. Thompson, D.E. Calkin, and K. Marcille. 2012. "Probabilistic assessment of wildfire hazard and municipal watershed exposure." *Natural Hazards* 64: 707–728.

Siegler, K. 2019. Paradise, Calif., Water is Contaminated but Residents Are Moving Back Anyway. April 16. NPR. https://www.npr.org/2019/04/16/713430751/paradise-calif-water-is-contaminated-but-residents-are-moving-back-anyway.

Shakesby, R.A., and S.H. Doerr. 2006. "Wildfire as a hydrological and geomorphological agent." *Earth-Science Reviews* 74 (3-4): 269–307.

Smith, H.G., G.J. Sheridan, P.N. Lane, P. Nyman, and S. Haydon. 2011. "Wildfire effects on water quality in forest catchments: A review with implications for water supply." *Journal of Hydrology* 396 (1-2): 170–192.

Soares, R.R. 2007. "Health and the evolution of welfare across Brazilian municipalities." *Journal of Development Economics* 84 (2): 590–608.

Solomon, G.M., S. Hurley, C. Carpenter, T.M. Young, P. English, and P. Reynolds. 2021. "Fire and Water: Assessing Drinking Water Contamination after a Major Wildfire." *ACS ES&T Water* 1 (8): 1878–1886.

Stockmann, K.D., K.D. Hyde, J.G. Jones, D.R. Loeffler, and R.P. Silverstein. 2010. "Integrating fuel treatment into ecosystem management: a proposed project planning process." *International Journal of Wildland Fire* 19 (6): 725–736.

Swindle, C., P.Shankin-Clarke, , M. Meyerhof, J. Carlson, and J. Melack. 2021. "Effects of Wildfires and Ash Leaching on Stream Chemistry in the Santa Ynez Mountains of Southern California." *Water* 13 (17): 2402.

Thompson, M.P., J.W. Gilbertson-Day, and J.H. Scott. 2016. "Integrating pixel-and polygon-based approaches to wildfire risk assessment: Application to a high-value watershed on the Pike and San Isabel National Forests, Colorado, USA." *Environmental Modeling & Assessment* 21(1): 1–15.

Thompson, M.P., J. Scott, P.G. Langowski, J.W. Gilbertson-Day, J.R. Haas, and E.M. Bowne. 2013. "Assessing watershed-wildfire risks on national forest system lands in the rocky mountain region of the United States." *Water* 5 (3): 945–971.

Van Houtven, G., J. Powers, and S.K. Pattanayak. 2007. "Valuing water quality improvements in the United States using meta-analysis: Is the glass half-full or half-empty for national policy analysis?" *Resource and Energy Economics* 29 (3): 206–228.

Wagenbrenner, J.W., B.A. Ebel, K.D. Bladon, and A.M. Kinoshita. 2021. "Post-wildfire hydrologic recovery in Mediterranean climates: A systematic review and case study to identify current knowledge and opportunities." *Journal of Hydrology* 602: 126772.

Walsh, P.J., and J.W. Milon. 2016. "Nutrient standards, water quality indicators, and economic benefits from water quality regulations." *Environmental and Resource Economics* 64 (4): 643–661.

Walton, B. 2020. Western wildfires damage, contaminate drinking water systems. Circle of Blue. https://www.circleofblue.org/2020/wef/western-wildfires-damage-contaminate-drinking-water-systems/ .

Warziniack, T., and Thompson, M. 2013. "Wildfire risk and optimal investments in watershed protection." *Western Economics Forum* 12 (1837-2016-151808): 19–28.

Wei, Y. 2012. "Optimize landscape fuel treatment locations to create control opportunities for future fires." *Canadian Journal of Forest Research* 42 (6): 1002–1014.

Wei, Y., D. Rideout, and A. Kirsch. 2008. "An optimization model for locating fuel treatments across a landscape to reduce expected fire losses." *Canadian Journal of Forest Research* 38 (4): 868–877.

White, W.R. 2001. *Evacuation of Sediments from Reservoirs,* London: Thomas Telford.

Williams, A.P., Cook, E.R., Smerdon, J.E., Cook, B.I., Abatzoglou, J.T., Bolles, K.,...Livneh, B. 2020. "Large contribution from anthropogenic warming to an emerging North American megadrought." *Science* 368 (6488): 314–318.

Wilson, E.K. 2019. "Benzene found in the water supply of fire-ravaged Paradise, California." *Chemical and Engineering News*. April 30. https://cen.acs.org/environment/water/Benzene-found-water-supply-fire/97/web/2019/04.

Wisser, D., S. Frolking, S. Hagen, and M.F. Bierkens. 2013. "Beyond peak reservoir storage? A global estimate of declining water storage capacity in large reservoirs." *Water Resources Research* 49 (9): 5732–5739.

Woods, S.W., A. Birkas, and R. Ahl. 2007. "Spatial variability of soil hydrophobicity after wildfires in Montana and Colorado." *Geomorphology* 86 (3-4): 465–479.

Writer, J.H., A. Hohner, J. Oropeza, A. Schmidt, K.M. Cawley, and F.L. Rosario-Ortiz. 2014. "Water treatment implications after the High Park wildfire, Colorado." *Journal-American Water Works Association* 106 (4): E189–E199.

Writer, J.H., and Murphy, S.F. 2012. *Wildfire Effects on Source-Water Quality: Lessons from Fourmile Canyon Fire, Colorado, and Implications for Drinking-water Treatment* (Vol. 3095). US Department of the Interior, US Geological Survey, Washington, DC .

Wu, J., J.E. Baartman, and J.P. Nunes. 2021. "Comparing the impacts of wildfire and meteorological variability on hydrological and erosion responses in a Mediterranean catchment." *Land Degradation & Development* 32 (2): 640–653.

Zivin, J.G., M. Neidell, and W. Schlenker. 2011. "Water quality violations and avoidance behavior: Evidence from bottled water consumption." *American Economic Review* 101 (3): 448–453.