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Prescribed Fire Effects on Water Quality and Freshwater Ecosystems in Moist- Temperate Eastern North America

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ABSTRACT: Forests of the eastern United States provide numerous ecosystem services, including water filtration. Forest management activities of eastern forests often include prescribed fire to accomplish a variety of management objectives such as invasive species control, wildlife habitat improvement, ecosystem restoration, and hazardous fuel reduction. Despite widespread use of prescribed fire in this region and the need to maintain adequate water quality from forests impacted by this practice, there is a paucity of knowledge on prescribed fire's impacts on water quality. This article summarizes and consolidates known impacts of prescribed fire on chemical, physical, and biological properties related to water quality and freshwater ecosystems in moist-temperate eastern North America, including impacts on drinking water treatability. Based upon this synthesis, it appears that most prescribed fires in eastern forests are low intensity and low severity and cause minimal changes to forest soil properties, leading to minimal adverse impacts that might exacerbate soil erosion and adversely affect surface waters. In some cases, prescribed fire has been shown to enhance water quality in the region. Technological advancements in monitoring fire behavior have the potential to advance our knowledge regarding the effects of prescribed fire on water quality in the eastern forest region, particularly for fires of mixed or moderate severity and fires occurring in complex terrain.

Index terms: fire intensity, fire severity, fuel consumption, mesophication, water treatment, water yield

INTRODUCTION

Forests occupy approximately 31% (4 billion hectares) of Earth's land surface (Bladon et al. 2014). Filtration of water is one of the most important ecosystem services these forests provide (Brooks et al. 2013). Nearly two-thirds of municipalities in the United States and approximately one-third of the world's largest cities obtain the majority of their consumable water from forested watersheds (Bladon et al. 2014). Globally, natural filtration services have been estimated to save approximately 4.1 trillion dollars annually in water treatment costs (Bladon et al. 2014). Increasingly, forest management practices and natural disturbances are monitored for potential impacts on forests and any subsequent impacts on water quality (Brooks et al. 2013).

The extreme wildfire events that occurred in the western United States in 2017 and the southern United States in 2016 (National Interagency Fire Center 2018) provide clear and dramatic examples of the tremendous hazards of wildfires to forest resources, human property, and lives. Wildfires have the potential to cause problems in watersheds due to the widespread consumption of soil organic matter (Neary et al. 2009; Pereira et al. 2012; Bladon et al. 2014; Bixby et al. 2015), which exposes mineral soils to erosive precipitation following fire (Brooks et al. 2013). Wildfires may also cause stem mortality, destabilize roots (Callaham et al. 2012), and favor the spread and growth of invasive species (Martin and

Hamman 2016).

Long-term fire exclusion has resulted in hazardous fuel accumulation in many forests throughout the United States (Keifer et al. 2006). Therefore, forest managers commonly need feasible fuel reduction strategies. In some situations, prescribed fire is a viable tool for reducing hazardous fuel loads (Waldrop and Goodrick 2012). Additionally, prescribed fire may be used to improve wildlife habitat, reduce undesired species competition, combat invasive species, enhance specific environmental attributes, and prepare a stand for future forest management (Brender and Cooper 1968; Whelan 1997; Stanturf et al. 2002; Fairchild and Trettin 2006; Waldrop and Goodrick 2012). In 2017, over 2 million hectares were managed with prescribed fire in the eastern United States. The area burned by prescribed fire in this region has grown steadily in recent years (Figure 1; Melvin 2015).

The scientific literature documents high risk posed by wildfires to water quality and the viability of prescribed fire as a tool for minimizing wildfire occurrence and impact. Despite the common and widespread implementation of prescribed fire as a land management tool in the eastern United States, little research has been conducted to understand the potential impacts of prescribed fire on water quality and freshwater ecosystems (Lafayette et al. 2012). In this review we compile evidence and summarize known effects of prescribed

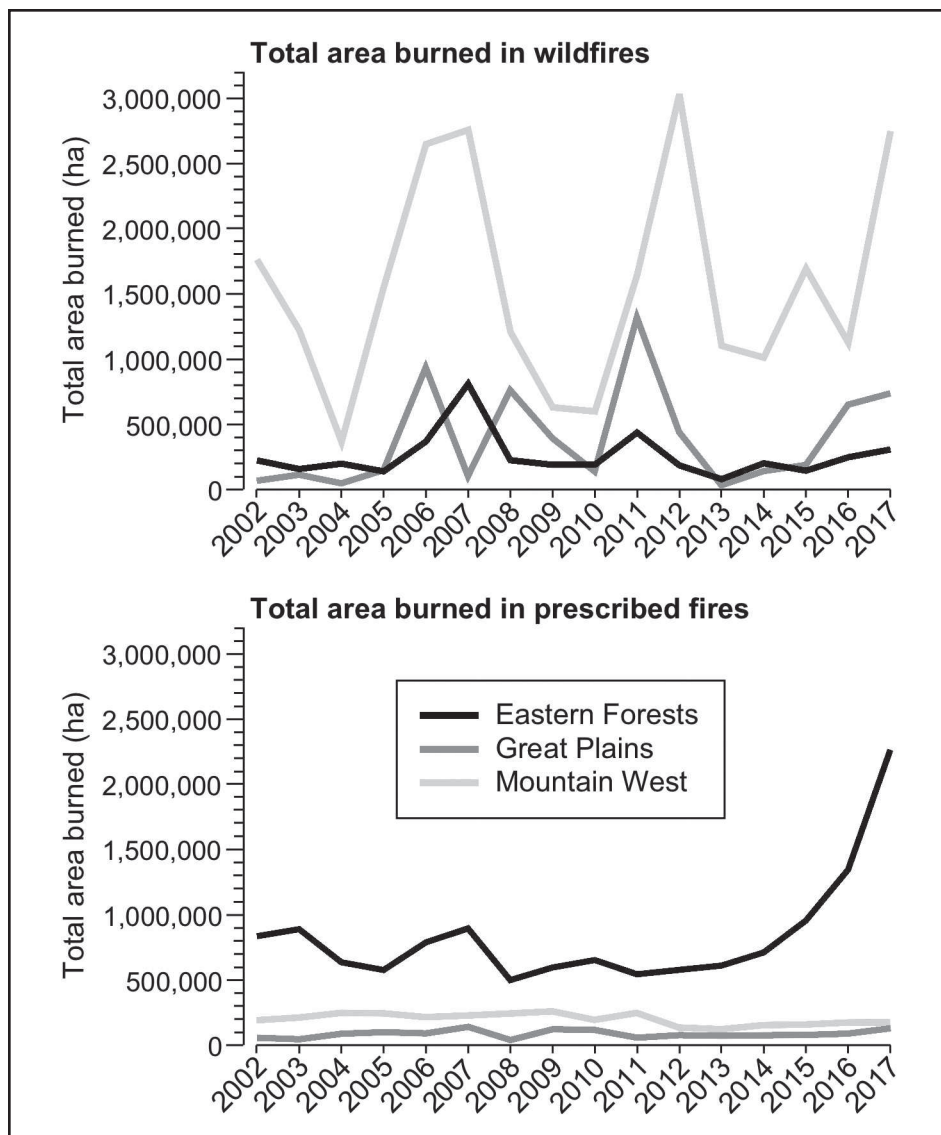


Figure 1. Trends in area burned in wildfires and prescribed fires by ecoregions in the continental United States. Data are from National Interagency Fire Center (2018); ecoregions from US Environmental Protection Agency (2016). Eastern Forests are 30 states representing Level I ecoregions eastern Temperate Forests, Northern Forests, and Tropical Wet Forests (AL, AR, CT, DE, FL, GA, KY, LA, MA, MD, ME, MI, MN, MO, MS, NC, NH, NJ, NY, OH, PA, RI, SC, TN, VA, VT, WI, WV); Great Plains are 7 states representing Level I ecoregion Great Plains (IA, KS, ND, NE, OK, SD, TX); Mountain West is 11 states representing Level I ecoregions Northwestern Forested Mountains, Marine West Coast Forest, Mediterranean California, Temperate Sierras, Southern Semi-arid Highlands, and North American Deserts (AZ, CA, CO, ID, MT, NM, NV, OR, UT, WA, WY).

fire on water resources in the eastern United States, identify urgent research needs, and explore implications for policy and land stewardship practice.

How do Prescribed Fires Differ from Wildfires?

Prescribed fires differ from wildfires in many ways. The primary differences often center on the distinction between *fire*

intensity and *fire severity*. While the two may correlate, they often do not.

Fire intensity refers to the total energetic output of a fire (Keeley 2009). A fire of high intensity may or may not be high in severity and vice versa, depending on local factors such as the type of vegetation burned—whether dominated by fire-tolerant or fire-sensitive species, concomitant fire behavior, and moisture levels in soil

organic matter.

Fire severity refers to the ecosystem effects of fire, for example the degree to which forest soil organic resources are consumed and vegetation is killed in a given fire event (Whelan 1997; Keeley 2009). Fire severity is the result of the interaction between fire intensity and the burned environment. When intact and decomposed plant litter in the soil (known variously as soil organic horizons, duff, and litter) is fully consumed, mineral soil is exposed to heating and subsequent precipitation (Callahan et al. 2012). Following high-severity fires, crusting of mineral soil can occur as the result of heating; this condition is known as hydrophobicity (Brooks et al. 2013). Hydrophobic soils reduce infiltration and increase runoff volume and energy, which can accelerate soil erosion, particularly following large precipitation events (Brooks et al. 2013). Fire-induced vegetative mortality may also contribute to increased soil erosion due to reduced canopy interception and reduced litter production. High fire severity typically results in either immediate or delayed plant mortality (Goforth and Minnich 2008). Large quantities of soil may be dislodged and displaced as a result of root death, further exacerbating soil erosion (Fairchild and Trettin 2006). Eroded soil materials may be trapped on site, but removal of soil organic layers favors their transport to streams. Deposition of eroded material in streams, known as sedimentation, may cause myriad problems ranging from increased water temperatures to a variety of mineralization outcomes affecting overall water quality, treatability, and aquatic life (Van Lear and Danielovich 1988; Minshall 2003; Grace et al. 2006; Malison and Baxter 2010; Clapcott et al. 2012).

Four combinations of fire severity and fire intensity are possible if the ranges of fire severity and fire intensity are divided into simple categories of “low” and “high” (Figure 2). Within this simplistic construct, wildfires can exhibit behavior that falls into low and high intensity and severity while prescribed fires are typically (but not always) low in both intensity and severity. In general, wildfires consume more organic matter, induce more vegetative mortality,

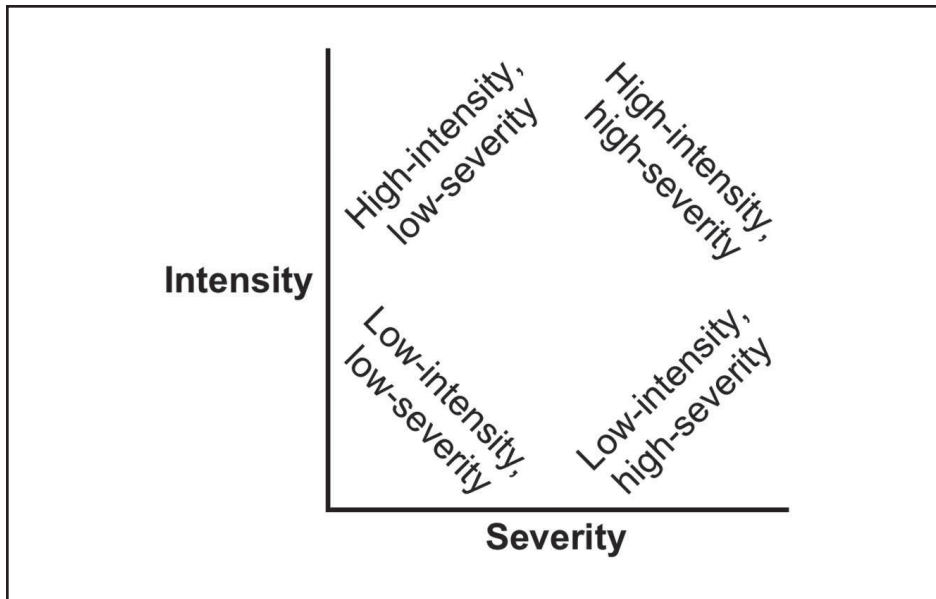


Figure 2. Simplified classification of fires by intensity and severity.

expose more mineral soil, and thus lead to more-severe water resource impacts (Robinne et al. 2018) when compared to prescribed fires. Prescribed fires typically consume little or no soil organic matter, induce little overstory mortality, expose little mineral soil, and thus have been assumed to be of minor water resource concern (Boerner et al. 2005; Fairchild and Trettin 2006). Prescribed fires are implemented under a prescription or plan that emphasizes safety of life and property, thus they are most often low in intensity and severity. For safety concerns and to achieve specific goals and objectives, prescribed fires are carefully planned to occur under specific conditions of wind, temperature, humidity, and ground moisture that minimize the risk of escape. The likelihood and magnitude of water impacts are also assumed to be low for many prescribed fire scenarios in eastern forests because they disproportionately occur on relatively flat terrain, including the Atlantic and Gulf coastal plains and Midwestern tallgrass prairies, where gentle topography favors slower and lower-volume surface drainage into streams.

The simplistic, four-cell scenario of fire intensity and severity defined above limits fire intensity and severity to two categories: low and high. These categories do not fully encompass the heterogeneity of intensity and severity across the landscape in a given

fire event (Keeley 2009) and do not address the effects of fires of moderate intensity or severity. In some cases, prescriptions require moderate, rather than low, fire intensity and severity to achieve specific management objectives. They might include enhancement or restoration of fire-adapted species, reduction of shrubland vegetation to reduce public safety risks (J. Stowe, pers. comm.), or site preparation burns. Moderate- to high-intensity site preparation burns are often implemented following a timber harvest to create a more conducive environment for seed germination.

Given This Context, What Do We Know about Prescribed Fire and Water Resources in the Eastern United States?

Others have compiled and synthesized evidence of the effects of fire on water resources in the eastern United States, including Fulton and West (2002), Elliott and Vose (2006), and Lafayette et al. (2012). We have summarized their findings in a model linking water impacts to fire behavior (Figure 3). Our review highlights more recent research not included in those syntheses, briefly summarized in Table 1.

Chemical Properties

Alterations to water acidity or alkalinity

have important water chemistry effects (Brooks et al. 2013). Changes in soil pH can directly affect the presence of biota (Ågren et al. 2010), soil chemical transformations and losses, and the water solubility of chemicals and nutrients (Beyers et al. 2005). In a laboratory experiment, Battle and Golladay (2003) examined how burned longleaf pine (*Pinus palustris* Mill.) litter, wiregrass (*Aristida beyrichiana* Trin. & Rupr.), and soil organic matter (SOM) affected water chemistry in Georgia wetlands. The authors found that pH increased in wetlands following fire due to the consumption and translocation of SOM during the fire. SOM consumption was also a major driving force behind significant increases in nutrients, such as dissolved organic carbon (DOC), soluble reactive phosphorus (SRP), and ammonium (NH_4^+).

Other water chemistry factors investigated in relation to fire include potentially harmful metals such as mercury. Mercury naturally occurs in aquatic life and bioaccumulates throughout the food web, but high concentrations of mercury can cause infertility in wildlife, among other health effects (Hopkins et al. 2013). Similarly, high mercury concentrations in humans can lead to poor fetal development and death (Liu et al. 2012). Riggs et al. (2017) found that although yellow perch (*Perca flavescens* [Mitchill, 1814]) mercury levels increased after a low-severity prescribed fire and moderate-severity wildfire in a Minnesota watershed, mercury levels also increased in an adjacent, unburned watershed. The authors found no link between low- and moderate-severity fires and mercury accumulation in the perch.

Increases in nutrient concentrations, such as nitrogen and phosphorus, can lead to harmful algal blooms. These blooms may adversely affect aquatic life through a reduction of dissolved oxygen due to bacterial decomposition of dead algae, which can cause fish die-offs, and through shading, which can reduce aquatic plant biomass and diversity (Anderson et al. 2008; Brooks et al. 2016; Konopacky 2017). Increases in sediment can also adversely affect water quality. Bedload sediments can fill spaces between gravel and rocks where fish and other aquatic biota lay eggs and forage for

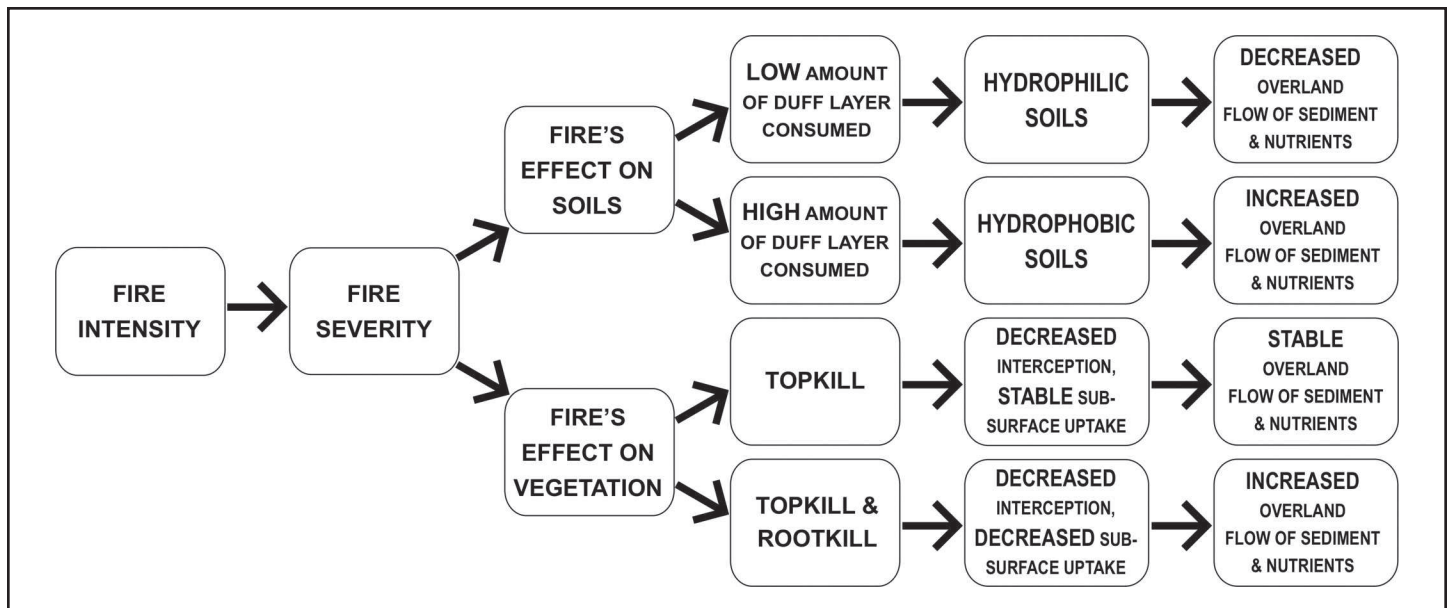


Figure 3. Flow chart depicting fire's effect on water quality, based on Keeley (2009). Each succeeding box is a function of the preceding box.

food. Suspended sediment can increase turbidity and thereby decrease the amount of light available for aquatic vegetation (DeBano et al. 1998; Brooks et al. 2013). The majority of research concerning the effects of prescribed fire on nutrient and sediment loads was conducted between 20 and 40 y ago and is synthesized in Lafayette et al. (2012). Because the majority of prescribed fires in the eastern United States are low-intensity, low-severity surface fires, the effects on sediment and nutrient transport into water bodies were either not significant or were of low magnitude and returned to baseline or control levels within 1–3 y post-fire (see also Wendel and Smith 1986; Shumway et al. 2001; Guyette and Spetich 2003; Smith and Sutherland 2006).

Post-harvest, high-intensity, site preparation burns to reduce logging slash, reduce competing vegetation, and prepare the seedbed for regeneration (Waldrop and Goodrick 2012) have produced mixed results in terms of water quality impacts. Van Lear and Danielovich (1988) conducted high-intensity site preparation burns following a timber harvest in western South Carolina. As a result of this practice, they found that soil nutrients increased. Vegetative regeneration also increased during the following growing season. Emerging vegetation assimilated the available nutrients, thereby offsetting potential

effects (accelerated nutrient mineralization following a disturbance creating a pulse of available nutrients) and minimizing nutrient input into local streams. Knoepp and Swank (1993) conducted a high-intensity site preparation burn in western North Carolina following a clearcut and found that available nitrogen in soil and water temporarily increased, but the increases were within the historically sampled range without fire. Similar short-term pulses were found by Kolka (2012), and again those pulses were within the range of samples collected prior to burning. Both high- and low-severity site preparation burns were conducted in a mixed hardwood–pine forest in upland South Carolina by Robichaud and Waldrop (1994). Sediment yields were approximately 40 times greater in high-severity burn plots than in low-severity burn plots.

Water Treatability

Drinking water demand, especially in the more densely populated coastal areas of the eastern United States, has increased significantly in recent years (Milesi et al. 2003; Bladon et al. 2014). Watershed disturbances, such as wildfires, can amplify the challenge of meeting rising demands for clean water by altering source water quality and quantity. Such disturbances can subsequently increase costs and chemical

usage at water treatment facilities (Emelko et al. 2011; Smith et al. 2011). Wildfires can increase surface runoff, which results in increased erosion, elevating sediment (Moody et al. 2008; Emelko et al. 2011), ions, and metals in streams (Crouch et al. 2006). Increased sediments, turbidity, and metals, such as iron and manganese, increase chemical treatment needs and can produce a larger volume of sludge at water treatment facilities (Moody and Martin 2009; Bladon et al. 2014). The impacts on source water quality from a severe wildfire can last from a few years to decades, whereas impacts from low-intensity prescribed fires are seldom pronounced or long-lasting. A watershed-scale study at the Santee Experimental Forest in South Carolina compared flow and nutrients at paired first-order watersheds (one burned and one control). Although prescribed burning initially increased the water yield by 72%, outflow differences disappeared after 2 y (Amatya et al. 2007). Furthermore, no significant differences in nutrient levels were observed between the two watersheds after 2 y.

Severe wildfires can alter the quantity and chemical composition of terrestrial dissolved organic matter (DOM; Wang et al. 2016; Tsai et al. 2017). DOM plays a significant role in the transport of pollutants and in water treatment processes,

Table 1. Summary of prescribed fire effects on chemical, physical, and biological properties in freshwater ecosystems of moist-temperate North America. Effects on water treatability also include some results from wildfires in semi-arid parts of the continent.

Property	Measured variables	Fire type	Study duration	Result Positive/Negative/Neutral	Citation
Chemical	Sediment yields, infiltration, runoff	Low-intensity, low-severity surface fire and high-intensity, high-severity surface fire	1 year	Neutral and Negative High-intensity and -severity burns produced 40× more sediment yields (negative impact) than low-severity burns (neutral impact).	Robichaud and Waldrop 1994
	Sediment yields, infiltration, runoff	Low-intensity, low-severity prescribed fire and high-intensity, high-severity wildfire	36 years	Neutral and Negative Insignificant impacts following low-severity, low-intensity fires. Negative impacts following high-severity, high-intensity fires.	Kolka 2012
	Sediment yields, infiltration, runoff	Low-intensity, low-severity prescribed fire	1–3 years	Neutral Insignificant, temporary increases in nutrients and sediments, which returned to baseline levels within 3 years.	Lafayette et al. 2012
	pH, alkalinity, dissolved organic carbon (DOC), NH ₄ ⁺ , soluble reactive phosphorus (SRP), dissolved inorganic carbon (DIC)	Low-intensity, low-severity prescribed fire	1 year	Neutral/Negative Burned soil: increased levels of pH, alkalinity, DOC, NH ₄ ⁺ , SRP. Burned pine needles and wiregrass: decreased levels of DOC, DIC. Burned wiregrass: increased levels of NH ₄ ⁺ , SRP.	Battle and Golladay 2003
	NH ₄ ⁺ , NO ₃ ⁻	High-intensity, high-severity surface fire	1.5 years	Neutral Increased NH ₄ ⁺ , no change in NO ₃ ⁻ , Increased NH ₄ ⁺ but within historical range without fire.	Knoepp and Swank 1993
	P, K, Mg, Ca, sediment loads	High-intensity, high-severity surface fire	1 year	Neutral Sediment and nutrient loads not significantly increased. Increased shrub vegetation following fire took up nutrients onsite.	Van Lear and Danielovich 1988
	Mercury (Hg) levels in yellow perch (<i>Perca flavescens</i>)	Low-intensity, low-severity surface fire and high-intensity, high-severity surface fire	100 years	Neutral Hg levels higher in perch in water adjacent to burned and unburned watersheds.	Riggs et al. 2017

Table 1. (Cont'd)

Property	Measured variables	Fire type	Study duration	Result Positive/Negative/Neutral	Citation
Physical	Evapotranspiration	Semi-annual burning before 1842 and light semi-annual burning from 1842 to 1900	80 years	Positive Historical burning regime led to dominance by ring-porous species, which used less water and led to increases in water yields.	Elliott et al. 2017
	Water yield	Low-intensity, low-severity prescribed fire (during drought)	14 years	Neutral Decreased water yield could not be attributed to fire alone.	Hallema et al. 2017
	Water yield	Multiple disturbances, including insect outbreaks; high-intensity, high-severity wildfire; low-intensity, low-severity prescribed fire; storm damage	9 years	Neutral No distinction made between disturbance type. Positive correlation between water yield and vegetation percent cover.	Buma and Livneh, 2017
	Water yield	Low-intensity, low-severity surface fires	40 years	Positive Increased water yield up to 2 years post-fire.	Amatya et al. 2007
	Dissolved oxygen	Unspecified intensity and severity; 81–91% of macrophyte vegetation consumed	2 years	Positive Increased dissolved oxygen.	Hagerthy et al. 2014
	Biological	Genetic diversity, effective population sizes of <i>Hyla femoralis</i> .	Low-intensity, low-severity surface fire and high-intensity, high-severity surface fire	4 months	Positive Biologically significant increases in genetic diversity and population sizes in ponds with high frequencies and intensities of burning.
Small fish and decapod crustacean responses		Unspecified intensity and severity; 81–91% of macrophyte vegetation consumed	2 years	Positive Alterations in C:N:P ratios led to increased abundance of crayfish, small fish, and shrimp.	Hagerthey et al. 2014
Relative abundance/diversity of fish and periphyton		Low-intensity, low-severity surface fire and high-intensity, high-severity surface fire	2 months	Positive Increased nutrients and light led to increased periphyton and fish populations for 3–4 weeks post-burn.	Venne et al. 2016

Table 1. (Cont'd)

Property	Measured variables	Fire type	Study duration	Result Positive/Negative/Neutral	Citation
Water treatability	Aromaticity DBP formation	Low-intensity, low-severity prescribed fire	Pre- and post-fire sampling	Positive Significant reduction in C-DBP formation potential.	Tsai et al. 2015
	Aromaticity DBP formation	High-intensity, high-severity wildfire (white ash)	Wildfire (sampled after the fire)	Negative Significant increase in aromaticity and D-DBP formation.	Wang et al. 2015
	Aromaticity DBP formation	Low-intensity, low-severity wildfire	Wildfire (sampled after the fire)	Positive No significant change in aromaticity. Significant reduction in C-DBP formation potential.	Wang et al. 2015
	Aromaticity DBP formation DBPS	Low-intensity, low-severity prescribed fire	Laboratory study	Mixed Effect Significant reduction in D-DBP formation potential. Significant increase in N-DBP formation potential.	Majidzadeh et al. 2015

especially coagulant dosing (Smith et al. 2011; Chow et al. 2013; Majidzadeh et al. 2017). At water treatment facilities, DOM reacts with chlorine or other oxidants forming carcinogenic disinfection byproducts (DBPs), such as chloroform (Sharifi et al. 2013; Writer et al. 2014; Wang et al. 2015). DBP ingestion or inhalation can have negative impacts on human health, including bladder cancer, rectal cancer, and adverse birth outcomes (Chow et al. 2009, 2011; Liu et al. 2012). The Environmental Protection Agency (EPA) regulates maximum contamination levels for two major classes of DBPs: trihalomethanes (THMs: 80 $\mu\text{g L}^{-1}$) and haloacetic acids (HAAs: 60 $\mu\text{g L}^{-1}$). Recent studies have documented that unregulated nitrogenous (N-) DBPs, such as haloacetonitriles (HANs) and *N*-nitrosodimethylamine (NDMA), can have even more genotoxic effects than regulated carbonaceous (C-) DBPs, THMs, and HAAs (Plewa et al. 2002; Zeng et al. 2016).

A severe wildfire can result in a significant increase in DOM concentration, especially during storm events, for years after the disturbance (Emelko et al. 2011). Besides DOM concentration, increases in DOM aromaticity (polycondensed aromatic structures such as polycyclic aromatic hydrocarbons, indicated by specific UV absorbance at 254 nm) and the abundance of hydrophobic compounds have also been observed after wildfire (Wang et al. 2015). Increases in DOM aromaticity can increase DOM reactivity in the formation of nitrogenous DBPs (Tsai et al. 2015; Wang et al. 2015). Increases in DOM aromaticity after wildfire may be due to white ash formation during intense wildfires (>510 °C) whereas black ash, typical of low-intensity prescribed fires (200–500 °C), can decrease DOM aromaticity (Wang et al. 2015). In contrast to wildfire, formation of white ash in low-intensity (including prescribed) fires is often very limited; thus, changes in DOM export and DBP formation can be minimal. Numerous laboratory and field studies have shown a significant reduction of C-DBP formation potential following prescribed fire (Tsai et al. 2015; Wang et al. 2015). However, Majidzadeh et al. (2015) showed in a laboratory study that post-fire DOM, even after a low-intensity fire, can favor formation of N-DBPs. Fur-

ther studies are necessary to quantify the formation of N-DBPs at field scales after prescribed burns.

Physical Properties

Water yield and dissolved oxygen content are two commonly monitored physical components of freshwater streams (Brooks et al. 2013). Studies of prescribed fire effects on water yield in the eastern United States are limited. Elliott et al. (2017) explored 80 y of water flow and vegetation records at Coweeta Hydrologic Laboratory and found that historically, due in part to prescribed fire, ring-porous species (oaks and hickories) were dominant and consequently water yields were higher than present-day conditions in which fire exclusion has caused a shift in species composition to dominance by diffuse-porous species such as red maple (*Acer rubrum* L.) and yellow-poplar (*Liriodendron tulipifera* L.). Hallema et al. (2017) studied the effects of repeated prescribed fire on water yield in a South Carolina watershed. They found water yield decreased by 39%; however, there was no experimental control and the decrease was more likely attributable to a decrease in precipitation during the sample period than burning. Buma and Livneh (2017) examined the influences of different disturbances such as insect outbreak, timber harvesting, and fire (both wildfire and prescribed fire) on water yield. The authors suggested that prescribed fire can alter streamflow in Georgia and at other sites across the country; however, they failed to separate effects attributable to different disturbances. Hagerthey et al. (2014) found that prescribed fire in the Florida Everglades increased dissolved oxygen and led to higher diversity of aquatic flora and fauna, thereby facilitating a more complex food web.

Biological Properties

Biological components are often considered the most comprehensive and sensitive indicators of water quality (Plotiknoff and Wiseman 2001; Clapcott et al. 2012; Woznicki et al. 2015). The Index of Biotic Integrity (IBI), which is used to determine the presence and quantity of certain benthic

macroinvertebrates, is the primary model used to quantify biological diversity and the health of a waterbody (Brooks et al. 2013). Although no studies in the eastern United States were identified that directly related prescribed fire to IBI, some studies have examined prescribed fire timing and frequency effects on the presence of particular biota. Venne et al. (2016) found that prescribed fire treatments in the Florida Everglades led to short-term increases of periphyton, which in turn increased fish populations. Hagerthey et al. (2014) determined that prescribed fire and the application of herbicides have the potential to assist in eutrophic wetland rehabilitation. Both studies attributed temporary changes in nutrient composition and increased light as the driving forces that enhanced habitat for periphyton. Robertson et al. (2017) concluded that frequent prescribed burning did not limit the genetic diversity or restrain the connectivity between breeding ponds of the endemic pine woods tree frog (*Hyla femoralis* Bosc, 1800) in Florida.

Research Gaps

Counter to the simplified fire intensity and severity matrix in Figure 2, real-world prescribed fires in the East are complex phenomena (Loudermilk et al. 2017; Yedinak et al. 2018). The ecological effects of fire are dictated by numerous factors whose combination is unique to each individual fire, varying greatly from one ecosystem to another and often among patches within a single fire (Whelan 1997), and depend heavily on the season and weather conditions pre-, during, and post-fire. As topography, fuel arrangement and composition, and weather interact in a specific location on a given day, fire effects are variable across the landscape (Coates et al. 2018). Not all eastern prescribed fires are ignited in flat terrain; they are increasingly being used in the southern Appalachian Mountains (Yaussy and Waldrop 2010), the Ozarks (Knapp et al. 2017), and other steep sites.

Climate change and projections of extended growing seasons offer potential for increased fuel loads, increased incidence and severity of pests and disease, and more frequent, longer, and more severe droughts (Dale et al. 2001). Therefore, the

need for fuel reduction, including the use of prescribed fire, is expected to increase. Furthermore, increasing human population increases the need for fuels management as more people move into fire-prone areas. Nowacki and Abrams (2008) concluded that up to a century of fire exclusion in parts of the East has initiated a positive feedback cycle whereby microenvironmental conditions have become cooler, damper, and more shaded and fuel beds less flammable. This process, referred to as mesophication, improves conditions for shade-tolerant, mesophytic species and degrades them for shade-intolerant, fire-adapted species, including oaks and pines. One line of evidence for this process on the landscape is the widespread decline of oak regeneration and the gradual replacement of oak forests with types lacking a historical antecedent; for instance, the switch in upland forests to dominance by red maple or yellow-poplar (Van Lear 2000). Some stands affected by long-term fire exclusion have proven resistant to restoration (Van Lear 2000; Kreye et al. 2018) and appear to have altered decomposition rates, which affect soil nutrients (Alexander and Arthur 2014). Prescribed fire in the dormant season alone does not necessarily enhance oak regeneration sufficiently for oaks to outcompete red maple, yellow-poplar, and other mesophytic, fire-intolerant species that are replacing historically oak-dominated forests in many parts of the East (Oakman 2018). These challenges to prescribed fire implementation, difficulties in effectively predicting fire behavior, and a limited understanding of fire effects on water quality and quantity are significant research gaps. Improved understanding of burning in stands with altered fuels and flora is needed to support stewardship decision-making.

Evidence from Coweeta Hydrologic Laboratory and other locations is consistent with the mesophication hypothesis, confirming that long-term fire exclusion shifts forest species dynamics to more mesophytic, fire-intolerant species (Elliott and Vose 2011; Ryan et al. 2013; Elliott et al. 2017). These species channel more water into evapotranspiration, resulting in less groundwater and surface water yield at the watershed scale (Caldwell et al. 2016). Increased use of prescribed fire

appears to lead to greater water yields in watersheds in the historic range of oak–hickory forests, such as at Price Mountain near Blacksburg, Virginia (Silver et al. 2013), in south-central Illinois (Singh et al. 2017), and in coastal pine–hardwood forests of the southeastern Coastal Plain on the Santee Experimental Forest, South Carolina (Amatya et al. 2006, 2007).

The water quality results on the Santee Experimental Forest complement the findings on water yield. After 40 y of comparison between burned and unburned watersheds, water quality has been either unaffected or temporarily enhanced immediately post-fire by repeated prescribed fires (Richter 1982; Amatya et al. 2007). These results may be related to the low intensity and low severity of prescribed surface fires at Santee and in many fire-maintained forests of the eastern United States. Evidence suggests that fires with this prescription minimally alter forest floor chemistry, leaving behind a mixture of slightly burned or partially charred material post-fire that minimizes water quality effects even if post-fire erosion occurs (Coates et al. 2017). This provides a stark contrast to studies suggesting substantial yields of polycyclic aromatic hydrocarbons (PAHs), which are known carcinogens (Abdel-Shafy and Mansour 2016), following wildfires (Olivella et al. 2005). Similar studies in large watersheds are needed to understand the unique dynamics of many landscapes of the eastern United States where forested areas provide substantial quantities of water treated for human use and consumption.

Currently, prediction of prescribed fire's ecological effects at specific sites in the eastern United States is constrained by incomplete information regarding the nuances of fire behavior as affected by local fuel conditions and terrain (Loudermilk et al. 2017). Enhanced technology is needed to parse the subtleties of fire dynamics, such as levels of intensity and severity, by improving our ability to evaluate them in the field accurately and at a fine spatial scale to hone predictive models based on combinations of key site factors (Bova and Dickinson 2008). With increasingly greater areas being included in fire prescription plans, better understanding of fire

effects will become ever more critical. An expanded understanding of prescribed fire will provide managers and scientists with more and better opportunities to predict and then test the effects of specific practices and their outcomes. This will further enhance prescribed fire professionals' abilities to protect watersheds and freshwater ecosystem integrity.

CONCLUSIONS

Research conducted to date suggests that prescribed fires in the eastern United States have minimal detrimental effects on the chemical, physical, and biological properties of surface waters. In several cases, it appears that prescribed fire may alter forest floor chemistry and overstory composition in ways that may improve both water quality and yield in forested watersheds. Because most prescribed fires are implemented under prescriptions that leave riparian buffer zones unburned, overall effects on water are typically either negligible, slightly adverse but short-lived, or slightly beneficial. In almost every instance, prescribed fire effects on water are inconsequential compared to the effects of wildfires. Indeed, prescribed fires are often implemented to reduce fuels and decrease the probability of an uncontrolled wildfire.

Our review indicates considerable need for additional research regarding the impacts of prescribed fire on water quality in the eastern United States, especially for sites and circumstances where moderate-severity fire will be applied to complex terrain. Additionally, managers need information regarding the use of more intense and severe prescribed burns to achieve certain management objectives. Novel fire effects might occur in many situations where forest stands are burned after long periods of fire exclusion, including high levels of duff consumption, immediate and delayed mortality, and undesired changes in species composition or stand density. New methods and models that define heat release in the conductive, convective, and radiative phases are being developed to better define fire behavior and subsequent fire effects resulting from deliberate burning on the landscape (Yedinak et al. 2018). Such methods could enhance our

ability to measure fire intensity and severity and predict fire effects, which should lead to improved prescriptions designed to produce specific short- and long-term fire effects and minimize adverse impacts. Given our great dependence upon forests, shrublands, and grasslands for a broad array of ecosystem services, the potential impacts on water resources of all facets of land stewardship, including prescribed fire, warrant greater scrutiny.

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rich in species and ecological communities of greatest conservation need in the mid-Atlantic region.

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