Cumulative Watershed Effects of Fuel Management in the Eastern United States

CHAPTER 12.

Effects of Fire and Fuels Management on Water Quality in Eastern North America

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Introduction

Fuels management, especially prescribed fire, can have direct impacts on aquatic resources through deposition of ash to surface waters. On the terrestrial side, fuels management leads to changes in vegetative structure and potentially soil properties that affect ecosystem cycling of water and inorganic and organic constituents. Because surface water systems (streams, lakes and wetlands) are tightly linked to terrestrial systems, these changes in the terrestrial system can also impact surface waters.

Notable reviews of fire effects on water have been conducted at the North American scale (Tiedemann and others 1979, Neary and others 2004), however, these reviews have been mainly focused on the western U.S. and Canada where research has historically been the most prolific (see Stednick 2006 for a Western Synthesis). Still, a number of studies have assessed the influence of fuels management or wildfire on various water quality parameters across Eastern North America (table 1). Because fuels management is an important component to pine management in the Southeast, more research has been conducted in the Southeast than the Midwest, Northeast, and Eastern Canada.

Prescribed fire and mechanical approaches to fuels management (such as precommercial thinning) are used quite extensively in certain parts of the Eastern United States. Although some research has been conducted on the effects of fire on water quality (both prescribed fire and wildfire), little has been conducted on the effects of mechanical treatments. Other fuels management approaches such as herbicide and other chemical applications and biological treatments such as grazing are also practiced in the East, but again little relevant research has been conducted to assess impacts to surface waters.

Although wildfires tend to burn more extensive areas, burn hotter, and consume more fuel than prescribed fires, the effects on surface waters can be analogous to prescribed fire. Many prescribed fires, especially in the South, are intended for site preparation rather than fuels reduction. In this chapter, we review responses of surface water quality to all prescribed fire—independent of intent—and wildfire.

Fire Effects on Hydrology

Either because of increased flows resulting from lower interception and transpiration or because of soil hydrophobicity, the potential exists for higher surface and subsurface runoff following fire. Increased surface runoff and higher instream flows increases the

Table 1. Effects of fire (prescribed fire or wildfire) on hydrology and water chemistry in Eastern North America: cations, anions, total suspended sediment (TSS), nitrate (NO_3), sulfate (SO_4^{2-}), nitrogen (N), total nitrogen (TN), phosphorus (P), total phosphorus (TP), potassium (K), mercury (Hg), calcium (Ca), chlorine (Cl) dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), acid neutralizing capacity (ANC), and acidity or basicity (pH)

Location	Fuels altering event	Aquatic system	Parameters	Findings	Reference
Tennessee, Georgia	Prescribed fire	Streams	Cations, anions, TSS, pH	No differences found following fire	Elliot and Vose 2005
Western North Carolina	Prescribed fire	Streams	NO_3	Streams with autumn burns showed increases in NO_3, with increases persisting for <1 year; streams with spring burns showed no increase	Vose and others 2005
Northwestern Ontario	Wildfire	Streams	Bedload	Bedload increased 20 fold following fire, with recovery in 5 to 6 years	Beaty 1994
Western North Carolina	Prescribed fire	Streams	NO_3	Elevated in one burned stream for 6 months	Knoepp and Swank 1993
Northwestern Ontario	Wildfire	Streams	N and P species	Fluxes of most N species and fractions increased and remained elevated up to 9 years following fire; effects on P flux were short term	Bayley and others 1992a
Northwestern Ontario	Wildfire	Streams	Cations, anions, DIC ANC, pH	Increases in concentrations and fluxes of anions and cations with an overall increase in stream acidity and decrease in pH 2 years following fire	Bayley and others 1992b
Western South Carolina	Prescribed fire	Streams	Sediments, nutrients, cations	No differences found following fire	Van Lear and others 1985
Western South Carolina	Prescribed fire	Streams	Nutrients, cations	No differences found following fire	Douglass and Van Lear 1983

continued

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Location	Fuels altering event	Aquatic system	Parameters	Findings	Reference
Eastern South Carolina	Prescribed fire	Streams	Cations, anions	No differences found following fire	Richter and others 1982
Western South Carolina	Wildfire	Streams	Nutrients, cations, TSS	Only difference was elevated NO_3 in the first year	Neary and Currier 1982
Northwestern Ontario	Wildfire	Streams	N, P, K	Increases in concentrations and fluxes of N, P, and K at least 3 years following fire	Schindler and others 1980
Minnesota	Wildfire	Surface runoff, streams/lakes	Cations, N, P, pH condition	Differences in fluxes for 2 years following fire, no differences in concentrations	McColl and Grigal 1977
Minnesota	Wildfire	Surface runoff, streams/lakes	P	Increases in P fluxes in surface runoff 1 year following fire, no other differences	McColl and Grigal 1975
Western South Carolina	Prescribed fire	Surface runoff	Sediments	Increase in sediment 40-fold for low-severity and high-severity burns for 1 year	Robichaud and Waldrop 1994
Louisiana	Prescribed fire	Surface runoff	Sediments	Small short-term effects on interrill erosion following biennial fires	Dobrowolski and others 1992
Western South Carolina, Piedmont Georgia	Prescribed fire	Surface runoff	Sediments	Low sediment production from low-severity burns; high production from high-severity burns	Van Lear and Kapeluck 1989
Western South Carolina	Prescribed fire	Surface runoff	Sediments	No differences found between burned and unburned clearcut plots	Van Lear and Danielovich 1988

continued

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Location	Fuels altering event	Aquatic system	Parameters	Findings	Reference
Wisconsin	Prescribed fire	Surface runoff	Sediments	No differences found following fire	Knighton 1977
South Carolina	Prescribed fire	Surface runoff	Nutrients, cations	Few differences, "no firm conclusions" following fire	Lewis 1974
Quebec	Wildfire	Lakes	Nutrients, cations anions, DOC, ANC	Increases in concentrations of NO_3, TP, Ca, K, SO_4^{2-}, and Cl 1 year following fire; most still above reference after 3 years	Carignan and others 2000
Quebec	Wildfire	Lakes	Hg (in fish), TP, TN, Ca, SO_4^{2-}, DOC pH, ANC, Chlorophyll-a	TP, TN concentrations higher in burned lakes, Hg in fish, Ca, and DOC no different	Garcia and Carignan 2000
Quebec	Wildfire	Lakes	Nutrients, cations, anions, DOC	Increases in K, TN, TP, Mg, NO_3, and SO_4^{2-} export rates following fire; rates highest 1 year following fire but still above reference after 3 years	Lamontagne and others 2000
Minnesota	Wildfire	Lakes	Cations, anions, ANC, pH, condition, Chlorophyll-a	Small increases in Ca and K 1 year following fire	Tarapchak and Wright 1986
Minnesota	Wildfire	Lakes	Cations, P	Increases in P and K but "minimal impacts" following fire	Wright 1976
Southwestern Georgia	Prescribed fire	Wetlands	Nutrients, DOC, DIC, ANC, pH	Increases in pH, alkalinity, DIC, DOC, and NH_4 1 month following fire	Battle and Golladay 2003

potential for higher sediment production following fire. Flows are expected to increase, depending on the fire's severity and the extent in the watershed (Baker 1988, Gresswell 1999), but little about effects on water yield or sediment production, especially in the East.

Water Yield

Van Lear and others (1985) reported no increases in streamflow following low-intensity prescribed fire in South Carolina, but increases in runoff were reported for other prescribed fire studies in South Carolina (Robichaud and Waldrop 1994), Louisiana (Ursic 1970), Georgia (Battle and Golliday 2003); Battle and Golliday (2003) reported higher water levels in wetlands; and several wildfire studies reported higher water levels of lakes in Minnesota (McColl and Grigal 1975, Wright 1976). The Minnesota study estimated a 60 percent increase in water yield following wildfire (Wright 1976), and a study in Ontario indicated similar increases of 60 to 80 percent (Schindler and others 1980) with levels that remained above normal for up to 5 years following fire.

Studies on hydrophobic soils are not common in the Eastern United States, although they have been assessed in Wisconsin (Richardson and Hole 1978), in the Upper Peninsula of Michigan (Reeder and Jurgensen 1979), and on the Georgia Piedmont (Shahlaee and others 1991). In the Michigan study, the authors concluded that water repellency following fire was not an important long-term management issue (Reeder and Jurgensen 1979) although studies in Georgia indicated slight hydrophobicity following prescribed fire.

In general, low-intensity prescribed fires appear to produce to little or no additional increases in flows. However, as prescribed fires intensify and consume more forest floor and vegetation layers, possibly including the canopy, effects would be comparable to wildfires or forest harvesting (Baker 1988).

Sediment Production

As noted above, little work has been done in the East on the effects of fire on sediment production or total suspended sediment. From the few studies that do exist, prescribed fire—or wildfire as reported by Neary and Currier (1982)—in the East does not appear to alter infiltration or percolation rates or lead to significant increases in surface runoff; and, hence, will not lead to higher sediment transport or more suspended sediments in surface waters (Elliot and Vose 2005, Knighton 1977, Swift and others 1993, Van Lear and Danielovich 1988, Van Lear and others 1985). Studies in Louisiana that have prescribed burned on a biennial basis for 20 years indicate short-term increases in sediment produced through interrill erosion on irrigated runoff plots (Dobrowolski and others 1992). The caveat is that all of these studies are results from prescribed burns, which tend to be less destructive to upper soil layers, forest floor, and vegetation than wildfires. Studies of a wildfire in Ontario indicate that bedload sediment production increased 20-fold with those increases persisting for 5 to 6 years (Beaty 1994). A high severity prescribed fire (similar in impact to a wildfire) in South Carolina led to 40-fold increase in sediment production compared a low severity prescribed fire (Robichaud and Waldrop 1994). Similarly, a high severity prescribed fire on the Georgia Piedmont led to high losses of sediment the first year following fire (Van Lear and Kapeluck 1989). Other studies in the West indicate that fire, especially severe fires, can have dramatic impacts on sediment production (Gresswell 1999).

Fire Effects on Water Chemistry

A number of studies in the Eastern United States have assessed the effect of fire on nitrogen, phosphorus, and cation concentrations in surface waters. Fewer have assessed the effect of fire on nutrient fluxes.

Nitrogen

Total nitrogen, organic nitrogen, nitrate and ammonium have been measured on a number of studies to assess the effects of fire on nitrogen cycling and fluxes to surface waters. In stream systems, studies in western South Carolina found no change in either nitrate or ammonium concentration or flux following prescribed burning (Douglass and Van Lear 1983). In other South Carolina prescribed fire studies, Lewis (1974) also found no difference in surface runoff nitrate between burned and control areas and Richter and others (1982) found no change in volume-weighted concentrations of total nitrogen, nitrate, and ammonium. Similarly, Elliot and Vose (2005) found no differences in stream nitrate and ammonium concentrations in southeastern Tennessee and northern Georgia. However, in another western South Carolina study, Neary and Currier (1982) found elevated nitrate (300 percent), but similar ammonium concentrations in streams the first year following wildfire. Vose and others (2005) found that following prescribed burning conducted in the autumn, two streams had increases in nitrate concentrations with increases persisting for <1 year, compared to no increases for two streams with spring burns. Similarly, Knoepp and Swank (1993) found that stream nitrate increased about 300 percent for some six months following prescribed burning in western North Carolina. After a wildfire in Minnesota, McColl and Grigal (1977) found no differences in surface-runoff total nitrogen or nitrate, but they did see increases in fluxes (about 150 to 200 percent) of both in the first 2 years. In northwestern Ontario, Bayley and others (1992a) found increases in nitrate (about 300 to 800 percent), ammonium (about 150 to 200 percent), suspended nitrogen (about 150 to 200 percent), total dissolved nitrogen (about 150 to 200 percent) and total nitrogen concentrations (about 150 to 200 percent) after two wildfires in the same watershed (6 years apart); after the second fire levels remained elevated for 9 years. Fluxes followed similar patterns (Bayley and others 1992a). In southwestern Quebec, Lamontagne and others (2000) estimated that watershed export rates to lakes of total nitrogen and nitrate were elevated the first year following wildfire and were still elevated 3 years later.

Nitrogen concentrations in northern Minnesota lakes gave no indication of elevated fluxes following prescribed fire (Tarapchak and Wright 1986, Wright 1976). In southwestern Quebec, Carignan and others (2000) found total organic nitrogen and ammonium concentrations doubled, and nitrate concentrations were up to 6000 percent higher in lakes present in watersheds with wildfire compared to lakes in watersheds that were unburned. The increases persisted for up to 3 years. Studies in depressional wetlands in southwestern Georgia indicate increases in ammonium but not for nitrate the first 2 years following prescribed fire (Battle and Golladay 2003).

The solubility of nitrogen species and volatilization of nitrogen from consumed plants and soils during fire could explain why nitrogen species generally do not respond or respond only shortly after fire. Although considerable nitrogen is lost to volatilization during fire (McRae and others 2001), the ash left behind is also concentrated in nitrogen—which quickly succumbs to nitrification processes and becomes available to leaching through forest soils (Knighton 1977). Overall, the preponderance of data suggests little influence of fire on nitrogen; and where differences exist, they usually do not persist more than 1 to 3 years, unless on shallow soils like those found on the Boreal Shield (Bayley and others 1992a).

Phosphorus

Phosphorus is generally the limiting nutrient in surface waters, and excess phosphorus can lead to eutrophication of lakes, wetlands, and streams (Smith 2003). Following a disturbance such as fire, the largest fraction of phosphorus entering surface waters is typically associated with upland sediment sources (Prepas and others 2003). Total phosphorus is typically measured on unfiltered samples and comprises dissolved phosphorus and phosphorus suspended in sediment. Soluble reactive phosphorus, generally considered to be the same measure as ortho-phosphorus, is the inorganic phosphorus that passes through a filter, usually 0.45 µm. Soluble reactive phosphorus and ortho-phosphorus are considered the active form of phosphorus available for uptake.

Total phosphorus, ortho-phosphorus and soluble reactive phosphorus have been measured in streams, lakes, and wetlands following fire in the Eastern United States Because phosphorus is generally bound to particulates, similar results exist for the transport of total phosphorus and phosphorus suspended in sediment. Numerous studies have found no stream response of phosphorus to prescribed fire—or wildfire as reported by Neary and Currier (1982)—including those in southeastern Tennessee and northern Georgia (Elliot and Vose 2005), western South Carolina (Douglass and Van Lear 1983, Van Lear and others 1985), and eastern South Carolina (Richter and others 1982). Lewis (1974) also found no increases in phosphorus in surface runoff following prescribed fire in South Carolina. McColl and Grigal (1975) found no increases in stream phosphorus following wildfire in Minnesota, but they did see a 300-percent increase in phosphorus in surface runoff the first year following fire. Total, suspended, and dissolved phosphorus concentrations and fluxes in streams increased 140 to 320 percent the first 2 years following wildfire in northwestern Ontario (Schindler and others 1980), but these increases did not persist even after a second wildfire in the same area (Bayley and others 1992a).

Although phosphorus concentration did not differ on burned watersheds in northern Minnesota lakes when compared to a lake in an unburned watershed (McColl and Grigal 1975, Tarapchak and Wright 1986), estimated fluxes to burned lakes increased by 93 percent the first year following fire (Wright 1976). In Quebec, lakes in burned watersheds had 200 to 300-percent higher total phosphorus concentrations and 150 to 200-percent higher flux rates than lakes that were in unburned watersheds, with increases persisting for at least 3 years (Carignan and others 2000, Lamontagne and others 2000). Studies in depressional wetlands in southwestern Georgia indicate no differences in soluble reactive phosphorus concentration the first 2 years following prescribed fire (Battle and Golladay 2003).

Similar to nitrogen, phosphorus does not appear to be a major water quality concern following fire (prescribed or wildfire) in the East, unless located on shallow soils such as those found on the Boreal Shield. Even where shallow soils exist, the bulk of the data suggests that impacts are relatively short term.

Cations

Because cations (calcium, magnesium, sodium, and potassium) are concentrated in ash, the potential exists for these nutrients to be transported via surface runoff or easily leached through soils following fire. Studies in the South indicate no differences in surface runoff or stream cation concentration following fire (Douglass and Van Lear 1983, Elliot and Vose 2005, Lewis 1974, Neary and Currier 1982, Richter and others 1982, Van Lear and others 1985). Wildfires in northern Minnesota, Ontario, and Quebec indicate short-term increases in cation concentrations and fluxes.

In northern Minnesota, lake concentrations of calcium and potassium increased following wildfire (Tarapchak and Wright 1986). For the same fire, Wright (1976) showed ≤265 percent increase for potassium in runoff; for the first 2 years, McColl and Grigial (1977) showed increased calcium, magnesium, and potassium in surface runoff but increases in streams were limited to potassium. Similarly, potassium fluxes in streams following wildfire in northwestern Ontario were 140 to 290 percent higher than those prior to fire (Schindler and others 1980), with calcium (190 percent), magnesium (190 percent) and sodium (170 percent) increasing as well (Bayley and others 1992b). In Quebec, potassium concentrations increased ≤600 percent in lakes on burned watersheds, compared to 200 to 400 percent for calcium and magnesium (Carignan and others 2000); levels stayed elevated for 3 years following wildfire. In the same set of watersheds, exports rates estimated for potassium (300 to 700 percent), calcium (200 to 300 percent) and magnesium (200 to 300 percent) were higher in burned watersheds than unburned watersheds the first 3 years following wildfire, steadily decreasing with time (Lamontagne and others 2000).

Similar to the effects on nitrogen and phosphorus, prescribed fires do not appear to have a dramatic influence on the concentration and transport of cations in the South. However, for wildfires in the North, some cation concentrations and fluxes (especially potassium) increase in streams and lakes following fire and those increases can persist for 3 years or more.

Carbon

Interest in effects on ecosystem carbon has increased over the past 15 to 20 years because of the implications for climate change. Fires have been shown to be large sources of carbon dioxide (Amiro and others 2001); for example vegetation is about 50 percent carbon, leaf litter about 50 percent, surface mineral soils about 1 to 8 percent, and organic soils about 20 to 95 percent. Little work has been done to assess the effects of fire on the concentration or transport of water-soluble carbon, otherwise known as dissolved organic carbon. Dissolved organic carbon is operationally defined as the carbon that passes through a filter, usually 0.45 or 0.7 µm, and is considered mobile in water. Research in Quebec showed no effect of wildfire on lake dissolved organic carbon concentrations (Carignan and others 2000) or export rates to those lakes (Lamontagne and others 2000) following fire. Similarly, Battle and Golladay (2003) found no difference in dissolved organic carbon the first month following prescribed fire in Georgia wetlands in 2000, but did find significantly higher dissolved organic carbon following prescribed fires conducted in 2001. They suggest that field conditions are very important in determining fire's effect on the generation of dissolved organic carbon (Battle and Golladay 2003). No other studies from Eastern North America were found that assessed the effect of fire on dissolved organic carbon transport. The paucity of data makes generalizations difficult, but based on these few studies, fire does not appear to dramatically affect dissolved organic carbon concentration or transport.

Mercury

Mercury is of great concern in the environment because it biomagnifies up the food chain in aquatic ecosystems (U.S. Environmental Protection Agency, Office of Research and Development 2002). Although we are beginning to understand the cycling of total mercury and methylmercury (bioaccumulative form) in forested watersheds (Hintelmann and others 2002, Kolka and others 2001), little work has been done understanding the role of fire in mercury cycling. Nearly 100 percent of mercury stored in plant-derived fuels is emitted into the atmosphere, 85 percent of which is elemental mercury and 15 percent particulate mercury (Friedli and others 2003). Newly released elemental mercury enters the global cycle whereas particulate mercury has the potential to be redeposited locally during the fire event. Soils are also sources of mercury during fires. Studies indicate that upper soil layers experience significant decreases in mercury following fire (Amirbahman and others 2004, Dicosty and others 2006). Zooplankton and northern pike (*Esox lucius*) in lakes on burned Quebec watersheds showed no significant difference in mercury concentrations compared to lakes in undisturbed watersheds, although average fish concentrations were about 160 percent higher in burned lakes (Garcia and Carnignan 1999, Garcia and Carnignan 2000). Although somewhat outside the geographic scope of this chapter, a Canadian study of a wildfire in Alberta found elevated methylmercury in lake and stream water following fire (Kelly and others 2006). Although this study suggests that the dynamics that increase nutrients and affect on the food chain are complex, Kelly and others (2006) did find higher mercury (500 percent) in rainbow trout (*Oncorhynchus mykiss*) in burned watersheds than in unburned watersheds. In an Alberta study, few differences were found in aquatic biota when comparing lakes in burned watersheds to ones in unburned watersheds, with even short-term (three month) decreases in mercury content of aquatic biota following fire (Allen and others 2005). Based on what little data we have, fire does not appear to affect mercury cycling and bioaccumulation in the aquatic food chain but further investigation is needed.

Other Water Constituents

Some of the studies discussed above have measured other various ions such as sulfate, chloride, dissolved inorganic carbon, acidity or basicity (pH), alkalinity, conductivity, and chlorophyll-a. Richter and others (1982) found no differences in sulfate, chloride or alkalinity concentrations following prescribed fire in South Carolina. Similarly, no differences were found in acidity or sulfate concentrations in northern Georgia and southeastern Tennessee following prescribed fire (Elliot and Vose 2005). After a month, water in depressional wetlands in burned watersheds had higher pH (indicating less acidity) and alkalinity (ability to neutralize acids) that those in unburned Georgia watersheds (Battle and Golladay 2003). Studies in northern Minnesota indicate little to no differences in lake pH, alkalinity, and conductance following wildfire but did see an apparent decrease in chlorophyll-a (Tarapchak and Wright 1986). Studies in Ontario indicate decreases in stream pH and concomitant increases in concentrations and fluxes of sulfate and chloride, leading to lower alkalinity for 2 years following wildfire (Bayley and others 1992b). Research on lakes in Quebec indicated no difference in lake alkalinity but considerably higher sulfate, chloride, and chlorophyll-a concentrations persisting 3 years after wildfire (Carignan and others 2000). Not surprisingly, export rates from drainage areas for these lakes were also high for sulfate and chloride (Lamontagne and others 2000).

Effects of Mechanical, Chemical, and Biological Treatments

Although mechanical, chemical, and biological fuels treatment are non uncommon in Eastern North America, we found no studies that have specifically addressed the effects of these treatments on water quality. However, numerous studies and a number of reviews have examined mechanical, chemical, and biological approaches for vegetation management.

Certainly mechanical fuels treatment is similar to other types of vegetation management or site preparation practices. A number of papers that evaluate water-quality responses to vegetation management or site preparation are available for those planning mechanical approaches to fuels treatment (Binkley and Brown 1993, Dissmeyer 2000, Grace 2005, Shepard 1994, Thornton and others 2000).

Chemical treatments, predominantly herbicides for the purposes of this chapter, are typically used to control competing vegetation. Chemical approaches to fuels management would likely have similarly impacts on water quality as those used for vegetation management. Several papers that review water-quality responses to chemical application are available for those planning chemical approaches to fuels management (Dissmeyer 2000, Larson and others 1997, Micheal and Neary 1993, Neary and others 1993).

Few studies have assessed biological approaches to forest vegetation management, especially in Eastern North America. The most common biological controls for plants are predation by insects or fungi or grazing by domesticated ungulates such as cows (*Bos taurus*) or goats (*Capra* app.). Although considerable research has been conducted on the biological control of invasive plant species, Markin and Gardner (1993) indicate that only a small portion focused in forest systems for the purpose of vegetation management, and none were found that assessed biological control in the context of water quality. Numerous studies have assessed or summarized grazing impacts on water quality (Patric and Helvey 1986) but again, none in the context of fuels or vegetation management in forest systems.

Conclusions

In general, prescribed fire and other fuels management approaches appear to have little impact on water quality in Eastern North America. When soils are deep and fire severity is low, few water quality changes have been observed, and those that have been reported are generally short lived (less than a year). The most dramatic impacts have occurred where soils are shallow and fires are severe; in these situations, some water quality parameters remained elevated for 3 or more years.

Certainly, more research on the effects of fire and other approaches to fuels management (mechanical, chemical, and biological) on surface water quality in Eastern North America is needed. Although considerable work has been accomplished on various forest types in the South, little has been done in the rest of Eastern North America, even in places where prescribed fire is being used as a tool for fuels management—such as red (*P. resinosa*) and jack pine (*P. banksiana*) management in the Lakes States. Also, considering the growing importance of carbon, carbon cycling, and the importance of carbon in aquatic food chains, more could be done to assess the influence of fire on dissolved organic carbon. Finally, mercury is the number one contaminant in surface waters (with more Environmental Protection Agency advisories than any other substance), and we know little about how fire affects mercury transport and accumulation in the food chain.

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