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.

A number of studies have assessed the influence of fuels management on various water quality parameters across Eastern North America (Table 1). Certainly, the research in the East is considerably less prolific than that from the West (see Stednick, 2006 for a Western Synthesis). 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 (e.g. pre-commercial thinning) to fuels management are used quite extensively in certain parts of the East. Although some research has been conducted on the effects of fire on water quality (both prescribed fire and wildfire), little research has been conducted on the effects of mechanical treatments on water quality. Other fuels management approaches such as chemical (e.g. herbicide applications) and biological treatments (e.g. grazing) are also utilized in the East, but again little relevant research has been conducted to assess impacts to surface waters.

FIRE

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. Even within the category of prescribed fire, many prescribed fires, especially in the South, are intended for site preparation as opposed to fuels reduction. All prescribed fire, independent of intent, and wildfire effects on surface water quality will be reviewed.

Fire Effects on Water Yield and Sediment Production

Either because of increased flows resulting from lower interception and transpiration or because of soil hydrophobicity following fire, the potential exists for higher surface and subsurface runoff. With increased surface runoff and higher instream flows following fire, the potential for higher sediment production exists. Flows are expected to increase following fire, depending on the severity of the fire and the extent in the watershed (Baker, 1988; Gresswell, 1999) however, little research has been conducted in the East addressing fire effects on water yield or sediment production.

Water Yield

Studies in South Carolina indicated no increases in streamflow following low-intensity prescribed fire (Van Lear et al., 1985), but other studies in South Carolina (Robichaud and Waldrop, 1994) and studies in Louisiana (Ursic, 1970), Georgia (Battle and Golliday, 2003), Minnesota (McColl and Grigal, 1975; Wright, 1976) and Ontario (Schindler et al., 1980) indicate increases in runoff (Ursic, 1970; Schindler et al., 1980), wetland stage (Battle and Golliday, 2003) and lake stage (McColl and Grigal, 1975; Wright, 1976) following prescribed fire (Louisiana and Georgia) or wildfire (Minnesota and Ontario). The study in Minnesota estimated a 60% increase in water yield following wildfire (Wright, 1976) while the study in Ontario indicated similar increases of 60-80% (Schindler et al., 1980) and remained above normal for up to five years following fire.

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

In general it appears that low-intensity prescribed fires lead to little or no additional increases in flows but 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 (TSS). From the few studies that do exist, it appears that prescribed fire (or wildfire in the case of Neary and Currier, 1982) in the East doesn't alter infiltration or percolation rates, doesn't lead to significant increases in surface runoff and, hence, does not lead to higher sediment transport or greater TSS in surface waters (Knighton, 1977; Van Lear et al., 1985; Van Lear and Danielovich, 1988; Swift et al., 1993; Elliot and Vose, 2005). 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 et al., 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 20X with those increases persisting for 5-6 years (Beaty, 1994). A high severity prescribed fire (similar in impact to a wildfire) in South Carolina led to 40X the sediment production than 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 (see Gresswell, 1999 for review).

Fire Effects on Nutrients

A number of studies in the East 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 (Douglas and Van Lear, 1983). In other South Carolina studies, Lewis (1974) also found no difference in surface runoff nitrate between burned and control areas and Richter et al. (1982) found no change in volume weighted concentrations of total N, nitrate and ammonium following prescribed fires. Similarly, Elliot and Vose (2005) found no differences in stream nitrate and ammonium concentrations following prescribed fires in southeastern Tennessee and northern Georgia. However, in another western South Carolina study, Neary and Currier (1982) found elevated nitrate (3X) but similar ammonium concentrations in streams the first year following wildfire. Vose et al. (2005) found that two streams with prescribed burning conducted in the fall had increases in nitrate concentrations with increases persisting for <1 year, while two streams with spring burns showed no increases. Similarly, Knoepp and Swank (1993) indicated about a 3X increase in stream nitrate for about 6 months following prescribed burning in western North Carolina. McColl and Grigal (1977) found no differences in surface runoff total nitrogen or nitrate but did see increases in fluxes (~1.5-2X) of both the first two years following wildfire in Minnesota. Bayley et al. (1992a) found that nitrate (~3-8X), ammonium (~1.5-2X), suspended nitrogen (~1.5-2X), total dissolved nitrogen (~1.5-2X) and total nitrogen concentrations (~1.5-2X) increased following two wildfires in the same watershed (6 years apart) and following the second fire remained elevated nine years after fire in northwestern Ontario. Fluxes in this study followed similar patterns (Bayley et al., 1992a). Lamontagne et al. (2000) estimated that watershed export rates to lakes of total nitrogen and nitrate were elevated the first year following wildfire and were still elevated three years later in southwestern Quebec.

Nitrogen concentrations in northern Minnesota lakes gave no indication of elevated fluxes following prescribed fire (Wright, 1976; Tarapchak and Wright, 1986). In southwestern Quebec, Carignan et al. (2000) found total organic nitrogen increases of 2X, nitrate concentrations up to 60X higher, and ammonium concentrations of 2X higher in lakes present in watersheds with wildfire compared to lakes in watersheds that were unburned. The increases persisted for up to three years. Studies in depressional wetlands in southwestern Georgia indicate increases in ammonium but not for nitrate the first two years following prescribed fire (Battle and Golladay, 2003).

The solubility of nitrogen species and volatilization of nitrogen from both the 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 et al., 2001), the ash left behind is also concentrated in nitrogen which is quickly subject to nitrification processes and available to leaching through forest soils (Knighton, 1975). Overall, the preponderance of the data suggests little influence of fire on nitrogen and where differences exist, they usually do not persist more than 1-3 years unless on shallow soils like those found on the Boreal Shield (Bayley et al., 1992a).

<u>Phosphorus</u>

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

Total phosphorus, ortho-phosphorus and SRP have been measured in streams, lakes and wetlands following fire in the East. Because phosphorus is generally bound to particulates, similar results exist for the transport of total phosphorus as that of sediment. Numerous studies have found no stream response of phosphorus to prescribed fire (or wildfire, 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 et al., 1985), and eastern South Carolina (Richter et al., 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 did see a 3X increase in phosphorus in surface runoff the first year following fire. Total, suspended and dissolved phosphorus concentrations and fluxes in streams did increase 1.4-3.2X the first two years following wildfire in northwestern Ontario (Schindler et al., 1980), but these increases did not persist even after a second wildfire in the same area (Bayley et al., 1992a).

Although lake phosphorus concentration in northern Minnesota didn't differ in lakes in burned watersheds 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% the first year following fire (Wright, 1976). In Quebec, lakes in burned watersheds had 2-3X higher total phosphorus concentrations and 1.5-2X higher flux rates to the lakes than lakes that were in unburned watersheds, with the increases persisting for at least three years (Carignan et al., 2000; Lamontagne et al., 2000). Studies in depressional wetlands in southwestern Georgia indicate no differences in SRP concentration the first two 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.

<u>Cations</u>

Cations (calcium, magnesium, sodium and potassium) are concentrated in ash (Raison et al., 1985), therefore the potential exists for these nutrients to be transported via surface runoff or easily leached through soils following fire. Studies in the Southeastern U.S. indicate no differences in surface runoff or stream cation concentration following fire (Elliot and Vose, 2005; Van Lear et al., 1985; Richter et al., 1982; Douglas and Van Lear, 1983; Neary and Currier, 1982; Lewis, 1974). 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 up to a 265% increase for potassium in runoff following fire while McColl and Grigial (1977) showed increases in calcium, magnesium and potassium in surface runoff the first two years following fire but only found increases in stream concentrations of potassium. Similarly, potassium fluxes in streams following wildfire in northwestern Ontario were 1.4-2.9X than those prior to fire (Schindler et al., 1980) with calcium (1.9X), magnesium (1.9X) and sodium (1.7X) increasing as well (Bayley et al., 1992b). In Quebec, potassium concentrations increased up to 6X in lakes embedded in burned watersheds while calcium and magnesium concentrations increased 2-4X (Carignan et al., 2000) and stayed elevated for at least the first three years following wildfire. In the same set of watersheds exports rates estimated for potassium (3X-7X), calcium (2X-3X) and magnesium (2X-3X) where higher in burned watersheds than unburned watersheds the first three years following wildfire, steadily decreasing with time (Lamontagne et al., 2000).

Similar as nitrogen and phosphorus, it does not appear that prescribed fires dramatically influence concentrations and transport of cations in the Southeastern US. 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 three years or more.

Fire Effects on Carbon

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

Fire Effects on Mercury

Mercury is of great concern in the environment because it biomagnifies up the food chain in aquatic ecosystems (EPA, 2002). Although we are beginning to understand the cycling of total-mercury and methyl-mercury (bioaccumulative form) in forested watersheds (e.g. Hintelmann et al., 2002; Kolka et al., 2001), little work has been done understanding the role of fire in mercury cycling. Nearly 100% of mercury stored in plant-derived fuels is emitted to the atmosphere with 85% of that emitted as elemental mercury and particulate mercury accounting for the remainder

(Friedli et al., 2003). Newly released elemental mercury enters the global cycle whereas the remaining 15% that is emitted as particulate mercury has the potential to be re-deposited locally during a fire event. Soils are also sources of mercury during fires. Studies indicate that upper soil layers experience significant decreases in mercury following fire (e.g. Dicosty et al., 2006; Amirbahman et al., 2004). While mercury is a contaminant of major concern, few have assessed aquatic mercury dynamics following fire. In Quebec, lakes in burned watersheds showed no significant difference in zooplankton or northern pike (*Esox lucius*) mercury concentrations when compared to lakes in undisturbed watersheds, although mean fish concentrations were about 1.6X higher in burned lakes (Garcia and Carnignan, 2000; Garcia and Carnignan, 1999). While slightly outside the geographic scope of this review, a study of a wildfire in Alberta, Canada did find elevated methyl mercury in lake water and stream water following fire (Kelly et al., 2006). Although this study indicates there are complex dynamics related to nutrient increases following fire, and that effect on the food chain, Kelly et al. (2006) did find higher mercury (5X) in rainbow trout (*Oncorhynchus mykiss*) in burned watersheds than in unburned watersheds. In a different study in Alberta, 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 et al., 2005). Based on what little data we have, it does appear that fire could have effects on mercury cycling and bioaccumulation in the aquatic food web but further investigation is needed.

Fire Effects on Other Water Constituents

Some of the studies discussed above have measured other various ions such as sulfate, chloride, dissolved inorganic carbon (DIC), pH, alkalinity, conductivity and chlorophyll-a. Richter et al.

(1982) found no differences in sulfate, chloride or alkalinity concentrations following prescribed fire in South Carolina. Similarly, no differences were found in pH or sulfate concentrations in northern Georgia and southeastern Tennessee following prescribed fire (Elliot and Vose, 2005). After one month, water in depressional wetlands in burned watersheds had higher pH and alkalinity that those in unburned watersheds in Georgia (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 acid-neutralizing capacity for two years following wildfire (Bayley et al., 1992b). Research on lakes in Quebec indicated no difference in lake alkalinity but considerably higher sulfate, chloride, chlorophyll-a concentrations persisting three years after wildfire (Carignan et al., 2000). Not surprisingly, export rates from drainage areas for these lakes in Quebec were also high for sulfate and chloride (Lamontagne et al., 2000).

MECHANICAL, CHEMICAL & BIOLOGICAL FUELS TREATMENT

Although mechanical, chemical and biological fuels treatment are used in Eastern North America, a through the review of the literature indicates that no studies have specifically addressed mechanical, chemical or biological fuel treatment effects on water quality. However, numerous studies have examined mechanical, chemical and biological approaches for vegetation management and a number of reviews have been conducted on these topics.

Certainly mechanical fuels treatment is similar to other types of vegetation management or site preparation techniques. A number of papers have assessed and reviewed the effect of vegetation management or site preparation on water quality and should be consulted if planning on mechanical approaches to fuels treatment (e.g. Grace, 2005; Dissmeyer, 2000; Thornton et al., 2000; Shepard, 1994; Binkley and Brown, 1993).

Chemical treatments, herbicides in this case, 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 have reviewed the effect of chemical application on water quality and should be referred to if using chemical approaches to fuels management (e.g. Dissmeyer, 2000; Larson et al., 1997; Micheal and Neary, 1993; Neary et al., 1993).

Few studies have assessed biological approaches to forest vegetation management, especially in Eastern North America. The cost common biological controls are either through insect or fungi predation on plants or by grazing by domesticated ungulates such as cows or goats. Although considerable research has been conducted on the biological control of weeds, Markin and Gardner (1993) indicate that little research has been conducted in forest systems for the purpose of vegetation management and no studies were found that assessed biological control in the context of water quality. Numerous studies have assessed or summarized grazing impacts on water quality (e.g. Patric and Helvey, 1986) but again, none in the context of fuels or vegetation management in forest systems.

CONCLUSION

In general, it appears that prescribed fire or other fuels management approaches have little impact on water quality in Eastern North America. When soils are deep and the fire severity is low, few water quality changes have been observed, and those that have been reported are generally short-lived (<1 year). The most dramatic impacts have occurred where soils are shallow and fires are severe with some water quality parameters remaining elevated for 3 or more years.

Certainly more research on the general topic of the effects of fire and other approaches to fuels management (mechanical, chemical and biological) on surface water quality in Eastern North America are needed. Although considerable work has been accomplished on various forest types in the Southeast, little has been done in the rest of Eastern North America, even in places, where prescribed fire is being used a tool for fuels management (e.g. red and jack pine management in the Lakes States). Also, considering the growing importance of carbon, carbon cycling, and its importance in aquatic food webs, little has been done assessing the influence of fire on dissolved organic carbon. Finally, mercury is the number one contaminant in surface waters (i.e. more EPA advisories for mercury than any other substance), and we know little about how fire affects mercury transport and accumulation in the food chain.

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Table 1. Studies that have assessed the effect of fire (prescribed fire or wildfire) on water quality in Eastern North America.

Study	Location	Fuels Mgm't	Aquatic System	Parameters	Findings
Elliot and Vose, 2005	Tennessee, Georgia	Prescribed Fire	Streams	Cations, Anions, TSS, pH	No differences found following fire
Vose et al., 2005	W. North Carolina	Prescribed Fire	Streams	NO_3	2 streams with fall burn showed increases in NO_3^- with increases persisting for <1 year, 2 streams with spring burns showed no increase
Beaty, 1994	NW Ontario	Wildfire	Streams	Bedload	Bedload increased 20X following fire recovery in 5-6 years
Knoepp and Swank, 1993	W. North Carolina	Prescribed Fire	Streams	NO_3	Elevated in one burned stream for 6 months
Bayley et al., 1992a	NW Ontario	Wildfire	Streams	N and P species	Fluxes of most N species and fractions increased and remained elevated up to 9 years following fire. Only short-term effects on P flux
Bayley et al., 1992b	NW 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 two years following fire.

Van Lear et al., 1985	W. South Carolina	Prescribed Fire	Streams	Sediment, Nutrients, Cations	No differences found following fire
Douglas and Van Lear, 1983	W. South Carolina	Prescribed Fire	Streams	Nutrients, Cations	No differences found following fire
Richter et al., 1982	E. South Carolina	Prescribed Fire	Streams	Cations, Anions	No differences found following fire
Neary and Currier, 1982	W. South Carolina	Wildfire	Streams	Nutrients, Cations, TSS	Only difference was elevated NO_3 in the first year
Schindler et al., 1980	NW Ontario	Wildfire	Streams	N, P, K	Increases in concentrations and fluxes of N, P and K at at least 3 years following fire
McColl and Grigal, 1977	Minnesota	Wildfire	Surface Runoff Streams/Lakes	Cations N, P, pH cond.	Differences in fluxes for 2 years following fire, no differences in concentrations
McColl and Grigal, 1975	Minnesota	Wildfire	Surface Runoff Streams/Lakes	P	Increases in P flux in surface runoff 1st year following fire, no other differences
Robichaud and Waldrop, 1994	W. South Carolina	Prescribed Fire	Surface Runoff	Sediment	40X increase in sediment production when comparing low severity and high severity burns for 1 year
Dobrowolski et al.,	Louisiana	Prescribed Fire	Surface Runoff	Sediment	Small short-term effects on

1992					interrill erosion following biennial fires
Van Lear and Kapeluck, 1989	W. South Carolina, Georgia Piedmont	Prescribed Fire	Surface Runoff	Sediment	Low sediment production from low severity burns but high production from high severity burns
Van Lear and Danielovich, 1988	W. South Carolina	Prescribed Fire	Surface Runoff	Sediment	No differences found between burned and unburned clearcut plots
Knighton, 1977	Wisconsin	Prescribed Fire	Surface Runoff	Sediment	No differences found following fire
Lewis, 1974	South Carolina	Prescribed Fire	Surface Runoff	Nutrients, Cations	Few differences, "no firm conclusions" following prescribed fire
Carignan et al., 2000	Quebec	Wildfire	Lakes	Nutrients, Cations, Anions DOC, Alk.	Increases in concentrations of NO_3, TP, Ca, K, SO_4, and Cl first year following fire but most were still above reference after 3 years
Garcia and Carignan, 2000	Quebec	Wildfire	Lakes	Hg in fish, TP, TN, Ca SO_4, DOC pH, Alk., Chl a	TP, TN concentrations higher in burned lakes, Hg in fish, Ca, and DOC no different
Lamontagne et al., 2000	Quebec	Wildfire	Lakes	Nutrients, Cations,	Increases in K, TN, TP, Mg, NO_3, and SO_4 export rates

				Anions DOC	following fire, rates highest first year following fire but were still above reference after 3 years
Tarapchak and and Wright, 1986	Minnesota	Wildfire	Lakes	Cations, Anions, Alk, pH, Cond., Chl-a	Small increases in Ca and K 1st year following fire
Wright, 1976	Minnesota	Wildfire	Lakes	Cations, P	Increases in P and K but "minimal impacts" following wildfire.
Battle and Golladay, 2003	SW Georgia	Prescribed Fire	Wetlands	Nutrients, DOC, DIC Alk., pH	Increases in pH, alkalinity, DIC, DOC, and NH_4 one month following fire