FIRE EFFECTS ON WATER QUALITY: A SYNTHESIS OF RESPONSE REGULATING FACTORS AMONG CONTRASTING ECOSYSTEMS

Katherine J. Elliott and James M. Vose

Coweeta Hydrologic Laboratory, Southern Research Station, USDA Forest Service, 3160 Coweeta Lab Rd, Otto, NC 28763

Abstract –The key components of watershed processes are inputs in precipitation, interactions of vegetation, soil and water including evapotranspiration (water yield), overland flow (erosion), and storage and filtering (nutrients), and outputs in streamflow. Fire effects occur at the vegetation-soil interface and can result in altering overland flow and infiltration rate of water. Fire can affect infiltration rates by collapsing soil structure and reducing soil porosity, contributing ash and charcoal residues which can clog soil pores, and raindrop splash can compact soil and further contribute to loss of soil porosity. An extreme example is the development of hydrophobic soils as observed in the western U.S. following severe wildfire. Watershed responses to fire depend on intensity and severity. Many factors influence fire severity including the quality and quantity of fuels, soil properties, topography, climate, and weather. The most important factors influencing the response to fire are vegetation mortality and the loss of the forest floor which are directly proportional to fire severity. Vegetation mortality reduces nutrient and water uptake, soil stability with root death, and the litter source for forest floor replenishment. The forest floor litter and humus (duff) layers provide soil cover, act as a sponge, and enhance infiltration. Large storm events immediately after a fire can accelerate surface runoff and compact soil.

INTRODUCTION

Wildland fire has the potential to significantly impact hydrologic processes such as surface runoff, sediment yield, and sediment and nutrient transport to streams. The magnitude and duration of watershed responses to fire depends on the interactions among burn severity, post-fire precipitation regime, topography, soil characteristics, and vegetative recovery rate. The typical impact of fire is an immediate change in vegetative cover, forest floor surface, physical properties of the soil, followed by mid- and long-term changes in biological pools and nutrient cycling processes. Vegetation and litter protect the soil against the forces of erosion by maintaining high infiltration rates and low levels of overland flow (Covert and others 2005). Vegetative cover and forest floor are the primary drivers of sediment responses to fire. Large reductions of vegetative cover, particularly the ground vegetation and forest floor, leave the soil prone to raindrop impact and reduce rainfall infiltration and storage so that erosive overland flow tends to occur more readily (Shakesby and Doerr 2006). Nutrient responses are also impacted by changes in vegetation and forest floor, as well as changes in biological processes that regulate cycling processes.

The magnitude and duration of hydrologic and water quality responses vary greatly across ecosystem types in the continental U.S. As such, it has been difficult to generalize response or apply knowledge derived from one region of the U.S. to any other. Over the past several years, a growing body of research has provided hydrology/water quality response data across a range of ecosystems, fire types, soils, and climate regimes. In this paper, we synthesize current knowledge on factors regulating water quality in contrasting ecosystems.

Defining Fire Severity

Fire severity depends on the interaction between fire intensity (rate at which thermal energy is produced) and duration (length of time burning occurs at a particular point) and describes the magnitude of the disturbance and reflects the degree of change in ecosystem processes (Neary and others 2005). Fire severity is a qualitative measure of the effects of fire on site and soil resources; it can occur along a spectrum from high to low or can be described as a patchwork, mosaic, matrix or mixed-severity event. Debano and others (1998) describe a light severity burn as one that burns only surface fuels, leaves the soil covered with partially charred organic material, and little to no duff consumption (fermentation (Oe) + humus (Oa) layers). A moderate-severity burn results from a large proportion of the organic material burned away from the surface of the soil and the remaining fuel is deeply charred. A high-severity burn results from all of the organic material burned away from the soil surface, organic material below the surface is consumed or charred. Fire severity has been assessed by numerous methods such as degree of destruction of aboveground live and dead biomass (Neary and others 2005), amount of forest floor consumed, particularly the duff layer, or heat penetration into the mineral soil (Swift and others 1993).

Precipitation Regime

After fire, rainfall intensity and duration can influence the amount of sediment delivered to a stream channel. The detachment of soil particles by rainsplash or overland flow and their transfer downslope are sensitive to modifications in land surface properties caused by fire (Johansen and others 2001, Sakesby and Doerr 2006). In low rainfall ecosystems, surface runoff and erosion may not be observed if there is a long period of post-fire recovery before the first rainfall event. Even in ecosystems with low mean annual rainfall, a high-intensity rainstorm immediately after wildland fire can create runoff that alters the topography of the hillslope, which subsequently impacts stream channels. Rainstorm events need to have enough energy to transport sediment. Swift and others (1993) determined that rainfall events of >50 mm hr^{-1} were required to transport material after a fell-and-burn prescribed fire in the southern Appalachians. Sediment yields are typically higher in the first year after burning, especially when the burned watershed has been exposed to high-intensity rainfall events immediately after the fire has exposed the soil surface. Some of the largest increases in surface runoff have been observed where short-duration, high intensity convective rainstorms occur. For example, after the 1996 Buffalo Creek Fire in Colorado, two short-duration, high-intensity rainstorms (~90 mm hr^{-1}) removed ash from the hillslopes, rilled the hillslope surfaces, channelized subtle drainages, which led to a headward extension of the channel network, and deposited sediment in stream channels (Moody and Kinner 2006). Kunze and Stednick (2006) found that rainfall intensity explained more than 80% of the variability in sediment yields. After the 2000 Bobcat Fire in Colorado, a single storm with 30 min rainfall intensity of 42 mm hr^{-1} resulted in 370 kg ha^{-1} and 950 kg ha^{-1} sediment yields, on treated (erosion-control with contour log felling, grass seeding, and mulching) and untreated watersheds, respectively (Kunze and Stednick 2006).

Vegetation Recovery

Post-fire soil erosion amounts vary not only with rainfall but also with burn severity, topography, soil characteristics and amount of vegetative recovery. Under moderate to severe fire severity that removes vegetation and forest floor cover, transpiration, interception and surface storage capacity for rain are temporarily reduced. Conversely, any fire-induced alterations to storage capacity and water repellency will decline as vegetation and ground litter recover. Ground cover protects the soil from raindrop impact and offers resistance to overland flow. Vegetation recovery rates are strongly affected by fire size and severity, post-fire erosion events and vary by climate and geographic area. Rapid vegetation establishment has been regarded as the most cost-effective method to promote water infiltration and reduce hillslope erosion (Robichaud 2005). In the western U.S., land management agencies have spent tens of millions of dollars on post-fire emergency watershed stabilization measures to minimize flood runoff, onsite erosion, offsite sedimentation, mud and debris flows, and other hydrologic damage to natural habitats (Robichaud 2005). Post-fire hillslope rehabilitation treatments include seeding for vegetative re-growth, ground covers or mulches, and barrier and trenches that physically hold runoff and sediment. In the eastern U.S., such costly and dramatic post-fire rehabilitation efforts are typically not required. Even after severe fire, recovery rates of southern Appalachian watersheds are much faster than western forests due to rapid vegetative re-growth (Clinton and Vose 2000, Elliott and others 1999).

Low severity burning, such as prescribed fires, can promote a herbaceous flora (Elliott and others 1999, Gilliam 1988, Hutchinson and others 2005) increase plant available nutrients (Elliott and others 2004), and thin-from-below over-crowded forests. While large, severe fires can cause changes in successional rates, alter species composition, generate volatilization of nutrients and ash entrainment in smoke columns, produce rapid or decreased soil mineralization rates, and result in subsequent nutrient losses through accelerated erosion (Neary and others 1999).

Surface Runoff and Erosion

Wildland fires are often landscape-scale disturbances that can alter the hydrologic and erosion responses of catchments. Erosion can occur when ground cover is reduced or consumed, and subsequently infiltration rates are reduced, i.e., water repellency is high. Fire-induced or enhanced soil water repellency (hydrophobicity) is commonly viewed as a key contributor to the substantial increases in hillslope runoff and erosion observed following severe wildfire (Debano and others 2005, Doerr and others 2006, Huffman and others 2001,), particularly in the western U.S. Soils do not all exhibit the same degree of water repellency; a water-repellent soil is classified as one on which a drop of water will not spontaneously penetrate. Water drop penetration time (WDPT) has been used extensively to characterize soil water repellency (Letey 2001). Several factors associated with fire, such as removal of surface litter and higher raindrop impact, would produce higher runoff and erosion from burned compared with unburned catchments, independent of water repellency. High runoff and erosion occurs from the combined effects of canopy

destruction and water repellency induced by fire (Letey 2001), typically higher water repellency results from high severity fires (Lewis and others 2006).

Sediment yields, in the first year after fire, range from very low in flat terrain without major rainfall events, to extreme in steep terrain affected by high-intensity thunderstorms. In the first post-fire year, sediment yield can vary from 0.01 to more than 110 Mg ha^{-1} $year^{-1}$ (Robichaud and others 2000). High-intensity rainstorms after wildfire can create runoff that alters the topography of the hillslope, which subsequently impacts stream channels. In the coastal plain region of the Southeastern U.S., surface runoff and erosion from forested land would be minimal because the terrain is flat. On steep mountain slopes, Hendricks and Johnson (1944) found that sediment yield ranged from 71 Mg ha^{-1} $year^{-1}$ on 43% slopes, 202 Mg ha^{-1} $year^{-1}$ on 66% slopes, and 370 Mg ha^{-1} $year^{-1}$ on 78% slopes after a wildfire in mixed conifer forests of Arizona. After the 1998 North 25 Fire in north-central Washington, Robichaud and others (2006) reported a first year mean erosion rate of 16 mg ha^{-1} yr^{-1} (Table 1), and this decreased significantly in the second year to 0.66 Mg ha^{-1} yr^{-1}. Mean canopy cover (percent cover provided by live plants) was 18% the first year and 53% the second year after the wildfire. Total precipitation was below average during the four-year period of their study (Robichaud and others 2006), and most erosion occurred during short duration, moderate intensity summer rainfall events. In the southern Appalachian mountain region, terrain is steep and rainstorms events with enough energy to transport sediment (≥50 mm hr^{-1}) have been recorded (Swift and others 1993), but vegetative recovery is rapid minimizing hillslope erosion.

Table 1. Sediment losses the first year after prescribed (Rx) fire and wildfires.

Location	Community	Severity/activity	1st year sediment loss (Mg ha^{-1})	Reference
North Carolina, Mountains	Pine/hardwoods	Low severity, fell-and-burn	0.087	Swift and others 1993
South Carolina, Piedmont	Pine/hardwoods	Low severity, Rx site preparation burn	0.137	Robichaud and Waldrop 1994
		High severity, Rx site preparation burn	5.748	
South Carolina, Piedmont	Loblolly pine	Control	0.027	Van Lear and others 1985
		Low severity, Rx understory burn	0.042	
		Moderate severity, Cut + Rx burn	0.151	
Arkansas, Foothills	Shortleaf pine	Control	0.036	Miller and others 1988
		High severity, slash cut + Rx site preparation burn	0.237	
East Texas, Foothills	Loblolly pine	Clearcut + Herbicide + Rx site preparation burn	0.885	Field and others 2005
		Clearcut + Mechanical tillage + Rx site preparation burn	1.273	
Colorado Front Range	Mixed conifer	Low to moderate severity, Rx fire	0.20 to 0.05	Benavides-Solorio and MacDonald 2005
		High severity, wildfire	2.0 to 10.0	
Colorado Front Range	Mixed conifer	Unburned hillslopes	0.30	Moody and Martin 2001
		High severity, wildfire	6.20	Wagenbrenner and others 2006
North-central Washington	Subalpine fir	High severity, wildfire	16.0	Robichaud and others 2006

In the western U.S., erosion rates increase by several orders of magnitude from areas burned at high severity because of the loss of protective ground cover and increase in surface runoff (Benavides-Solorio and MacDonald 2001, 2002, Robichaud and others 2000). In the Colorado Front Range, highest mean sediment rates were 80 – 100 Mg ha^{-1} from plots burned at high severity in recent wildfires (Benavides-Solorio and MacDonald 2005). The percentage of bare soil explained most of the variability in sediment yields (Benavides-Solorio and MacDonald 2001). Johansen and others (2001) found that post-fire sediment yield increased non-linearly as percent bare soil increased. Specifically, sediment yields increased little when percent bare soil varied from 0 up to 60%, then yield increased exponentially above 60% bare soil. Ground cover effects appeared to be more important in explaining hydrologic response than either surface roughness or slope (Johansen and others 2001). Hence, maintaining vegetation cover or a cover of forest floor organic layers on the soil surface is the best means of preventing excessive soil erosion rates (Debano and others 1998, Neary and Ffolliott 2005, Wagenbrenner and others 2006).

In the southeastern U.S., several authors have reported little to no soil erosion after light- to moderate-intensity fires (Neary and Currier 1982, Shahlee and others 1991, Van Lear and Danielovich 1988, Van Lear and Waldrop 1986, Swift and others 1993). For example, Douglas and Van Lear (1983) found no significant differences in runoff or soil export between burned and unburned watersheds in the Piedmont of South Carolina. Swift and others (1993) reported only minor and localized movements of burned plant fragments and soil after a fell-and-burn treatment in xeric pine-hardwood stands in the southern Appalachian Mountains of North Carolina. In their study, soil erosion was minimal primarily because the forest floor remained largely intact; i.e., duff consumption ranged from 30 to 67 percent (Swift and others 1993). Overall, these fires were classified as high intensity and low to moderate severity. Severity was moderate on portions of the burn where topography increased the fire intensity, causing greater proportions of forest floor consumption in small patches (Swift and others 1993). Effects were severe in a few spots where ribbons of soil were exposed after partially decomposed logs in contact with forest floor ignited and smoldered until consumed. After the burns, the bare soil exposure ranged from 7 to 14%. Where soil was exposed, the material was trapped within a short distance by residual forest floor and wood debris; thus, only two of eight sediment traps collected transported material resulting in < 0.10 Mg ha^{-1} sediment lost (assuming a bulk density of 1.2 Mg ha^{-1} and 40% charcoal by volume) the first year after the fires (Table 1). Sediment deposited at the lower margins of the study areas was transported by only three rainfall events that had enough force (> 50 mm hr^{-1}) to move sediment. Thereafter, no further sediment was lost because subsequent rainfall events were not of sufficient magnitude to transport material. In their study, the residual forest floor was resistant to erosion over the range of burn intensities and sediment was prevented from leaving the site by unburned brush and undisturbed forest floor at the lower margins of the burned areas (Swift and others 1993).

In the Piedmont region of South Carolina, Robichaud and Waldrop (1994) calculated sediment yields for low- and high severity site preparation burns in pine/hardwoods. For low severity fire (7% bare soil), sediments yields were 13.6 kg ha^{-1} mm^{-1} during simulated intense, rainfall (100 mm hr^{-1} rain event lasting 30 min) with a total annual sediment loss of 0.137 Mg ha^{-1} year^{-1} under natural rainfall events; and for high severity fire (63% bare soil), sediment yields were up to 27.7 kg ha^{-1} mm^{-1} during simulated intense, rainfall with a total loss of 5.75 Mg ha^{-1} year^{-1} under natural rainfall events (Table 1). In loblolly pine forests in South Carolina, Van Lear and others (1985) reported 0.042 Mg ha^{-1} yr^{-1} and 0.151 Mg ha^{-1} yr^{-1} sediment loss from understory burn and burn + cut sites, respectively (Table 1). Field and others (2005) estimated annual soil losses of 1.273 and 0.885 Mg ha^{-1} year^{-1} from mechanical tillage and prescribed fire, respectively.

Stream Suspended Sediment

Severe wildfires can cause damage to plant cover and, thus, increase streamflow velocity, sediment delivery to streams, and stream water temperatures, as contrasted to low severity, cool-burning prescribed fires, which have less severe consequences (Reardon and others 2005). If surface erosion via overland flow reaches stream channels, then stream sediment concentrations increase proportional to the sediment delivered. Excess sediment is the principal pollutant of stream water associated with forest management (Phillips and others 2000) and is considered the primary threat to the integrity of aquatic resources (Henley and others 2000). After fire, excess sediment delivery to streams typically occurs after a measurable storm event. Watersheds severely denuded by fire are vulnerable to accelerated rates of soil erosion. While many fires increase sediment transport, wildfire often produces more sediment than prescribed fire (Debano and others 1998). Generally, prescribed fires, by their design, are not intended to consume extensive layers of forest floor litter. Without sediment transport via overland flow or surface runoff, input of sediment to streams would be minimal following prescribed fire or wildfire. If the forest floor

remains intact and little to no bare soil is exposed, there is no mechanism for long-distance transport of sediment to streams (Vose and others 1999), regardless of rainfall event.

In the western U.S., suspended sediment concentrations in streamflow can increase to very high levels following severe fire. For example, Hauer and Spencer (1998) found that stream sediment concentrations increased from 3.0 mg L^{-1} before fire to 32.0 mg L^{-1} after and Fredriksen (1971) recorded an increase from 2.0 mg L^{-1} before disturbance to 150 mg L^{-1} following clearcut + slash burn. In contrast, fire in the southeast and southern Appalachians typically does not create conditions that result in sediment delivery to streams (Table 2). Forested streams in the southern Appalachians with high TSS during storm events are usually influenced by roads or land-use conversion (Table 2).

Table 2. Total suspended solid (TSS) concentration in headwater streams with varying disturbance types and severity.

Location	Community	Severity/activity	TSS (mg L^{-1})	References
North Carolina, Mountains	Mesic hardwoods	Low severity, prescribed fire	1-11	Vose, unpublished
East Tennessee and North Georgia, Mountains	Pine/hardwoods	Low severity, prescribed fire	1-6	Elliott and Vose 2005
South Georgia, Coastal Plain	Mixed oak-pine	Military training using tracted vehicles, <7% catchment area disturbed (low severity)	4 (baseflow) 57-300 (stormflow)	Houser and others 2006
		>7% catchment area disturbed (high severity)	10 (baseflow) 847-1881 (stormflow)	
North Georgia, Mountains	Mixed hardwoods	Roads, land-use conversion	1-10 (baseflow) >100 (stormflow)	Riedel and others 2003
W. Oregon	Douglas-fir	Clearcut, slash burn	150	Fredriksen 1971
Montana	Mixed conifer	Wildfire	32	Hauer and Spencer 1998

For prescribed fires in southern Appalachian pine-hardwoods, Elliott and Vose (2005) found no significant differences in total suspended solids (TSS) concentrations between burn and control streams over a 10-month post-burn sampling period (Table 2). Several factors were attributed to the explanation of their results; a small rain event did occur the first day after the burn treatments, but this event brought less than 15 mm of rainfall, the low intensity-low severity, prescribed fire consumed less than 20% of the forest floor mass, and the burns were in the spring when vegetative re-growth occurs. With other disturbance types and intensities, other researchers have found more distinct and larger increases in sediment concentrations in highly disturbed streams (Houser and others 2006, Webster and others. 1990) than undisturbed streams during storm events (Table 2). For example, Houser and others (2006) investigated a range of disturbance intensities for typical low-gradient, Southeastern Coastal Plain streams to illustrate the impact of upland soil and vegetation disturbance on stream sediments. In catchments with a disturbance intensity of <7%, the mean maximum change in TSS ranged from 57 to 300 mg L^{-1} during storm events. In catchments with a disturbance intensity of >7%, mean maximum change in TSS ranged from 847 to 1881 mg L^{-1} during storm events (Table 2).

Stream Nitrogen

The potential for increased NO_3^--N in streamflow after burning is attributed mainly to accelerated mineralization and nitrification (DeBano and others 1998, Knoepp and Swank 1993, Vitousek and Melillo 1979) and reduced plant uptake (Vitousek and Melillo 1979). Several studies on effects of prescribed fire on streamwater quality (Bêche and others 2005, Clinton and others 2003, Douglas and Van Lear 1983, Elliott and Vose 2005, Field and others 2005, Richter and others 1982, Vose and others 1999), have found little to no detectable changes in streamwater chemistry after burning. For the few cases where a measurable increase in NO_3^--N was detected, timing of wildland fire influenced NO_3^--N delivery to streams. In the spring, less NO_3^--N will be transported to streams when vegetation uptake and microbial immobilization are typically high, compared to burns in the fall when vegetation is dormant.

For example, Clinton and others (2003) compared stream NO_3^--N responses from watersheds burned in the fall and those burned in the spring. The two sites that showed a stream NO_3^--N response were burned in the fall, whereas the sites that were burned in the spring showed no response (Table 3).

Table 3. Stream nitrate-nitrogen (NO_3^--N) responses following prescribed fire (Rx) and wildfire in the southeastern U.S.

Site location	Treatment	Community	Fire severity	Season	NO_3^--N response (mg L^{-1})	Duration	References
Jacobs Branch, NC	Fell and burn, Rx	Mid-elevation; Pine/hardwood	High intensity, moderate severity	Fall	0.065	30 weeks	Knoepp & Swank 1993
Wine Spring, NC	Restoration, Rx	High elevation; Pine/hardwood	Moderate intensity, low severity	Spring	0	None	Vose and others 1999
Joyce Kilmer, NC	Wildfire	High elevation; old-growth hardwoods	Low intensity, low severity	Fall	0.100	6 weeks	Clinton and others 2003
Hickory Branch, NC	Restoration, Rx	Mid elevation; Pine/hardwood	Moderate intensity, low severity	Spring	0.004	2 weeks	Clinton and others 2003
Conasauga, TN & GA	Understory, Rx	Low elevation; Pine/hardwoods	Low-to-moderate intensity, low severity	Spring	0	None	Elliott & Vose 2005
Robin Branch, NC	Understory, Rx	High elevation; Mesic, mixed oak	Low intensity, low severity	Spring	0	None	Vose and others 2005
Roach Mill, GA							
Uwarrie, NC	Understory, Rx	Piedmont; pine/hardwoods	Moderate intensity, moderate intensity	Spring	0	None	Vose and others 2005
Croatan, NC	Understory, Rx	Coastal Plain; longleaf pine	Low to moderate intensity, low severity	Winter	0	None	Vose and others 2005

Vose and others (2005) compared the effects of low severity prescribed fire in Piedmont and southern Appalachian mountain streams (Table 3). In streamwater, measured NO_3^--N was extremely low (<0.1 mg NO_3^--N L^{-1}) before and after burning. Both sites were burned in early spring and fires were confined to the understory and forest floor. There was generally no overstory mortality to prevent the rapid vegetation N uptake and immobilization of soil nutrients typical of the spring growth flush. Fires were of low enough intensity to prevent significant overland flow and movement of nutrients off-site via physical changes in hydrologic processes. Vose and others (2005) also used a nutrient cycling model to simulated stream NO_3^--N response under three fire scenarios: moderate-severity prescribed fire, high-severity prescribed fire, and high- severity wildfire. Only under the wildfire scenario was there a significant increase in stream NO_3^--N concentrations. Vose and others (2005) attributed this simulated increase to reduced nitrogen uptake since the wildfire simulation included 100% overstory mortality. Under their wildfire scenario, streamwater NO_3^--N concentrations only reached 0.20 mg L^{-1} even with these extreme fire effects. Unlike low to moderate-severity prescribed fires, large-severe wildfires often result in dramatic increases in stream solutes, which may last for years after the fire (Earl and Blinn 2003, Minshall and others 2001, Spencer and others 2003). For example, Hauer and Spencer (1998) observed stream NO_3^--N concentrations from 0.12 to 0.30 mg L^{-1} in impacted streams after a wildfire in the Rocky Mountains, which were concentrations >5 fold over those observed in control streams. However, not all prescribed fires are low severity burns. Prescribed fire in the Tharp's Creek 16-ha catchment, Sierra Nevada of California killed most of the younger trees and understory vegetation, and the larger trees were scared, but left alive. Most forest litter was combusted in the fire leaving an ash layer throughout the catchment (Williams and Melack 1997). This prescribed burn in the Sierra Nevada of California resulted in the stream NO_3^--N concentration briefly exceeding 0.84 mg L^{-1} the first month of streamwater runoff after the fire, then exceeding 1.96 mg L^{-1} three months after the fire. The following spring NO_3^--N concentrations increased above 1.68 mg L^{-1}, persisted above 0.84 mg L^{-1} for several weeks, then returned to pre-fire conditions for the remaining years after the fire (Williams and Melack 1997). Whereas, pre-fire stream NO_3^--N concentrations seldom exceeded 0.01 mg L^{-1}.

In a recent national evaluation of forested streams, NCASI (2001) found that NO_3^--N concentrations for small forested watersheds averaged 0.31 mg L^{-1} (median 0.15 mg L^{-1}), and some streams averaged 10 times that level. In streams draining both mountain and Piedmont regions of the southeast, from a range of fire intensities (from low to high; prescribed fire and wildfire), impacts on inorganic stream nitrogen levels are much lower (Clinton and others 2003, Elliott and Vose 2005, Vose and others 2005) than the average reported from NCASI (2001).

CONCLUSIONS

Hydrologic and water quality responses to fire in the continental U.S. vary considerably. When a wildland fire occurs, the principal concerns for changes in water quality are delivery of sediment and nutrients, particularly nitrate, into the stream channel. Fire managers can influence the effects of prescribed fire on water quality by limiting fire severity, limiting fire size, and avoiding burning on steep slopes. Wildfires are typically larger and more severe consuming more fuel and releasing more nutrients than prescribed fire, which increases susceptibility to erosion of soil and nutrients into the stream. Our synthesis of a wide array of studies from across the U.S. support the following conclusions:

1. Maintaining an intact forest floor and promoting rapid vegetation recovery is critical to minimizing the magnitude and duration of sediment transport (surface erosion), sediment delivery (suspended solids) and subsequent water quality responses,
2. Burned areas are most vulnerable to surface erosion immediately post-fire and during extreme rainfall events,
3. Generally, water quality responses are much lower in the eastern U.S. than the western U.S. due to more moderate topography, lower fire severity, and rapid vegetation recovery

These regional differences emphasize the need for localized assessment and analyses of fire prescriptions, post-wildfire rehabilitation, and associated monitoring efforts.

LITERATURE CITED

Bêche, L.A., S.L. Stephens, and V.H. Resh. 2005. Effects of prescribed fire on a Sierra Nevada (California, USA) stream and its riparian zone. For. Ecol. Manage. 218: 37-59.

Benavides-Solorio, J.D. and L.H. MacDonald. 2005. Measurement and prediction of post-fire erosion at the hillslope scale, Colorado Front Range. International Journal of Wildland Fire 14: 457-474.

Benavides-Solorio, J.D. and L.H. MacDonald. 2001. Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range. Hydrological Processes 15: 2931-2952.

Benavides-Solorio, J.D. and L.H. MacDonald. 2002. Errata for: Post-fire runoff and erosion from simulated rainfall on small plots, Colorado Front Range. Hydrological Processes 16: 1131-1133.

Clinton, B.D., and J.M. Vose. 2000. Plant succession and community restoration following felling and burning in the Southern Appalachian Mountains. Pp. 22-29 *in* W.K. Moser, and C.F. Moser (eds.), Fire and forest ecology: innovative silviculture and vegetation management; Tall Timbers fire ecology conference proceedings, no. 21; 1998 April 14-16; Tallahassee, FL: Tall Timbers Research Station.

Clinton, B.D., J.M. Vose, J.D. Knoepp, and K. J. Elliott. 2003. Stream nitrate response to different burning treatments in southern Appalachian forests. Pp. 174-181 *in* K.E.M. Galley, R.C. Klinger, and N.G. Sugihara (eds.), Proceedings of the fire conference 2000: The first national congress on fire ecology, prevention, and management proceedings. Miscellaneous Publication No. 13, Tall Timbers Research Station, Tallahassee, FL.

Covert, S.A., P.R. Robichaud, W.J. Elliot, and T.E. Link. 2005. Evaluation of runoff prediction from WEPP-Based erosion models for harvested and burned forest watersheds. Transactions of the ASAE 48: 1091-1100.

DeBano, L.F., D.G. Neary, and P.F. Ffolliott. 1998. Fire's effects on ecosystems. New York: John Wiley & Sons, Inc. 333 p.

Debano, L.F. 2000. The role of fire and soil heating on water repellency in wildland environments: a review. Journal of Hydrology 231-232: 195-206.

Debano, L.F., D.G. Neary, and P.F. Ffolliott. 2005. Soil Physical properties. Pp. 29-51 *in* D.G. Neary, K.C. Ryan, and L.F. Debano (eds.), Wildland Fire in Ecosystems: Effects of fire on soil and Water. Gen. Tech. Rep. RMRS-GTR-42-vol. 4, Ogden, UT, USDA Forest Service, Rocky Mountain Research Station.

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

Douglas, J.E., and D.H. Van Lear. 1983. Prescribed burning and water quality of ephemeral streams in the Piedmont of South Carolina. For. Sci. 29: 181-189.

Earl, S.R., and D.W. Blinn. 2003. Effects of wildfire ash on water chemistry and biota in South-Western U.S.A. streams. Freshwater Biology 48: 1015-1030.

Elliott, K.J., R.L. Hendrick, A.E. Major, J.M. Vose, and W.T. Swank. 1999. Vegetation dynamics after a prescribed fire in the southern Appalachians. For. Ecol. Manage. 114: 199-213.

Elliott, K.J., J.M. Vose, B.D. Clinton, and J.D. Knoepp. 2004. Effects of understory burning in a mesic, mixed-oak forest in the southern Appalachians, Pp. 272-283 *in* T.T. Engstrom, K.E.M. Galley, and W.J. de Groot (eds.), Proceedings of the 22nd Tall Timbers Fire Ecology Conference: Fire in temperate, boreal, and montane ecosystems, Tall Timbers Research Station, Tallahassee, FL.

Elliott, K.J., and J.M. Vose. 2005. Initial effects of prescribed fire on quality of soil solution and streamwater in the Southern Appalachian Mountains. Southern Journal of Applied Forestry 29: 5-15.

Field, J.P., K.W. Farrish, B.P. Oswald, M.T. Romig, and E.A. Carter. 2005. Forest site preparation effects on soil and nutrient losses in east Texas. Transactions of the ASAE 48: 861-869.

Fredriksen, R.L. 1971. Comparative chemical water quality – natural and disturbed streams following logging and slash burning. Pp. 125-137 *in* Proceedings of a symposium on forest land uses and stream environment, 1970 October 19-21, Corvalis, OR, Oregon State University, Continuing Educations Publication.

Gilliam, F.S. 1988. Interactions of fire with nutrients in the herbaceous layer of a nutrient-poor Coastal Plain forest. Bull. Torrey Bot. Club 115: 265-271.

Hauer, F.R., and C.N. Spencer 1998. Phosphorus and nitrogen dynamics in streams associated with wildfire: a study of immediate and longterm effects. International Journal of Wildland Fire 8: 183-198.

Hendricks, B.A., and J.M. Johnson. 1944. Effects of fire on steep mountain slopes in central Arizona. Journal of Forestry 42: 568-571.

Henley, W.F., M.A. Patterson, R.J. Neves, and A. D. Lemly. 2000. Effects of sedimentation and turbidity on lotic food webs: A concise review for natural resource managers. Rev. Fisheries Sci. 8: 125-139.

Huffman, E.L., L.H. MacDonald, and J.D. Stednick. 2001. Strength and persistence of fire-induced soil hydrophobicity under ponderosa and lodgepole pine, Colorado Front Range. Hydrological Processes 15: 2877-2892.

Hutchinson, T.F., R.E.J. Boerner, S. Sutherland, E.K. Sutherland, M. Ortt, and L.R. Iverson. 2005. Prescribed fire effects on the herbaceous layer of mixed-oak forests. Can. J. For. Res. 35: 877-890.

Johansen, M., T.E. Hakonson, and D.D. Breshears. 2001. Post-fire runoff and erosion from rainfall simulations: contrasting forests with shrublands and grasslands. Hydrological Processes 15: 2953-2965.

Knoepp, J.D., and W.T. Swank. 1993. Site preparation burning to improve southern Appalachian pine-hardwood stands: nitrogen responses in soil, soil water, and streams. Can. J. For. Res. 23: 2263-2270.

Knoepp, J.D., DeBano, L.F., and D.G. Neary. 2005. Soil chemistry. Pp. 53-71 *in* D.G. Neary, K.C. Ryan, and L.F. Debano (eds.), Wildland Fire in Ecosystems: Effects of fire on soil and Water. Gen. Tech. Rep. RMRS-GTR-42-vol. 4, Ogden, UT, USDA Forest Service, Rocky Mountain Research Station.

Kunze, M.D., and J.D. Stednick. 2006. Streamflow and suspended sediment yield following the 2000 Bobcat fire, Colorado. Hydrological Processes 20: 1661-1681.

Letey, J. 2001. Causes and consequences of fire-induced soil water repellency. Hydrological processes 15: 2867-2875.

Lewis, S.A., J. Q. Wu, and P. R. Robichaud. 2006. Assessing burn severity and comparing soil water repellency, Hayman Fire, Colorado. Hydrological Processes 20: 1-16.

Miller, E.L., R.S. Beasley, E.R. Lawson. 1988. Forest harvest and site preparation effects on erosion and sedimentation in the Ouachita Mountains. Journal of Environmental Quality 17: 219-225.

Minshall, G.W., J.R. Brock, D.A. Andrews, and C.T. Robinson. 2001. Water quality, substratum and biotic responses of five central Idaho (USA) streams during the first year following the Mortar Creek fire. International Journal of Wildland Fire 10: 185-199.

Moody, J.A., and D.A. Martin. 2001. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. Earth Surface Processes and Landforms 26: 1049-1070.

Moody, J.A., and D.A. Kinner. 2006. Spatial structures of stream and hillslope drainage networks following gully erosion after wildfire. Earth Surface Processes and Landforms 31: 319-337.

National Council for Air and Stream Improvement, INC. (NCASI). 2001. Patterns and processes of variation in nitrogen and phosphorus concentration in forested streams. Technical Bulletin 836, Research Triangle Park, NC.

Neary, D.G., and J.B. Currier. 1982. Impact of wildfire and watershed restoration on water quality in South Carolina's Blue Ridge Mountains. South. J. Appl. For. 6: 81-90.

Neary, D.G., J.D. Landsberg, A.R. Tiedemann, P.F. Ffolliott. 2005. Water quality. Pp. 119-134 *in* D.G. Neary, K.C. Ryan, and L.F. Debano (eds.), Wildland Fire in Ecosystems: Effects of fire on soil and Water. Gen. Tech. Rep. RMRS-GTR-42-vol. 4, Ogden, UT, USDA Forest Service, Rocky Mountain Research Station.

Neary, D.G. K.D. Ryan, L.F. Debano, J.D. Landsberg, J.K. Brown. 2005. Introduction. Pp. 1-17 *in* D.G. Neary, K.C. Ryan, and L.F. Debano (eds.), Wildland Fire in Ecosystems: Effects of fire on soil and Water. Gen. Tech. Rep. RMRS-GTR-42-vol. 4, Ogden, UT, USDA Forest Service, Rocky Mountain Research Station.

Neary, D.G., and P.F. Ffolliott. 2005. The water resource: its importance, characteristics, and general responses to fire. Pp. 95-105 *in* D.G. Neary, K.C. Ryan, and L.F. Debano (eds.), Wildland Fire in Ecosystems: Effects of fire on soil and Water. Gen. Tech. Rep. RMRS-GTR-42-vol. 4, Ogden, UT, USDA Forest Service, Rocky Mountain Research Station.

Neary, D.G., P.F. Ffolliott, and J.D. Landsberg. 2005 Fire and streamflow regimes. Pp. 107-119 *in* D.G. Neary, K.C. Ryan, and L.F. Debano (eds.), Wildland Fire in Ecosystems: Effects of fire on soil and Water. Gen. Tech. Rep. RMRS-GTR-42-vol. 4, Ogden, UT, USDA Forest Service, Rocky Mountain Research Station.

Phillips, M.J., L.W. Swift, Jr., and D.R. Blinn. 2000. Best management practices for riparian areas. Pp. 273-286 *in* E.S. Verry, J.W. Hornbeck, and A.C. Dolloff (eds.), Riparian management in forests of the continental eastern United States, Boca Raton, FL, Lewis Publishers, CRC Press LLC.

Reardon, J.R., K.C. Ryan, L.F. Debano, and D.G. Neary. 2005. Wetlands and riparian systems. Pp. 149-169 *in* D.G. Neary, K.C. Ryan, and L.F. Debano (eds.), Wildland Fire in Ecosystems: Effects of fire on soil and Water. Gen. Tech. Rep. RMRS-GTR-42-vol. 4, Ogden, UT, USDA Forest Service, Rocky Mountain Research Station.

Richter, D.D., C.W. Ralston, and W.R. Harms. 1982. Prescribed fire: Effects on water quality and forest nutrient cycle. Science 215: 661-663.

Riedel, M.S., J.M. Vose, and D.S. Leigh. 2003. The road to TMDL is paved with good intentions – Total maximum daily loads for a wild and scenic river in the southern Appalachians. Pp. 356-366 *in* A. Saleh (ed.), Total Maximum Daily Load (TMDL) Environmental Regulations–II Proceedings of the 8-12 November 2003 Conference, Albuquerque, New Mexico, USA. ASAE Publication Number 701P1503.

Robichaud, P.R., and T.S. Waldrop. 1994. A comparison of surface runoff and sediment yields from low- and high-severity site preparation burns. Water Resources Bulletin 30: 27-34.

Robichaud, P.R. 2000. Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountains, USA. Journal of Hydrology 231-232: 220-229.

Robichaud, P.R., J.L. Beyers, and D.G. Neary. 2000. Evaluating the effectiveness of postfire rehabilitation treatments. USDA Forest Service, Rocky Mountain Research Station, Gen. Tech. Rep. RMRS-GTR-63, Fort Collins, CO.

Robichaud, P.R. 2005. Measurement of post-fire hillslope erosion to evaluate and model rehabilitation treatment effectiveness and recovery. International Journal of Wildland Fire 14: 475-485.

Robichaud, P.R., T.R. Lillybridge, and J.W. Wagenbrenner. 2006. Effects of postfire seeding and fertilizing on hillslope erosion in north-central Washington, USA. Catena 67: 56-67.

Shahlee, A.K., W.L. Nutter, L.A. Morris, and P.R. Robichaud. 1991. Erosion studies in burned forest sites of Georgia. Pp. 3.31-3.38 *in* S.S. Fan, and Y.-H. Kuo (eds.), Proceedings of the 5th Federal Interagency Sedimentation Conference, Federal Energy Regulating Commission, Washington, D.C.

Shakesby, R.A., and S.H. Doerr. 2006. Wildfire as a hydrological and geomorphological agent. Earth-Science Reviews 74: 269-307.

Spencer, C.N, K.O. Gabel, and F.R. Hauer. 2003. Wildfire effects on stream food webs and nutrient dynamics in Glacier National Park, USA. For. Ecol. Manage. 178: 141-153.

Swift, L.W., Jr., K.J. Elliott, R.D. Ottmar, and R.E. Vihanek. 1993. Site preparation burning to improve southern Appalachian pine-hardwood stands: fire characteristics and soil erosion, moisture, and temperature. Can. J. For. Res. 23: 2242-2254.

Van Lear, D.H., J.E. Douglass, S.K. Fox, and M.K. Ausberger. 1985. Sediments and nutrient export in runoff from burned and harvested pine watersheds in the South Carolina Piedmont. Journal of Environmental Quality 14: 169-174.

Van Lear, D.H., and S.J. Danielovich. 1988. Soil movement after broadcast burning in the southern Appalachians. South. J. Appl. For. 12: 49-53.

Vose, J.M., W.T. Swank, B.D. Clinton, J.D. Knoepp, and L.W. Swift, Jr. 1999. Using stand replacement fires to restore southern Appalachian pine-hardwood ecosystems: effects on mass, carbon, and nutrient pools. For. Ecol. Manage. 114: 215-226.

Vose, J.M., S.H. Laseter, G.Sun, and S.G. McNulty. 2005. Stream nitrogen response to fire in the southeastern U.S. Pp. 577-584 *in* S. Zhu, K. Minami, and G. Xing (eds.), 3rd International Nitrogen Conference, Oct. 12-16, 2004, Nanjing China, Science Press USA, Inc.

Wagenbrenner, J.W., L.H. MacDonald, and D. Rough. 2006. Effectiveness of three post-fire treatments in the Colorado Front Range. Hydrological Processes 20: 2989-3006.

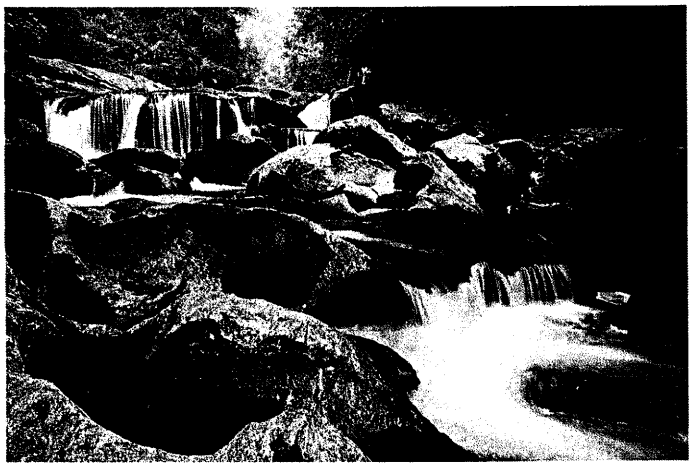
Webster, J.R., S.W. Golladay, E.F. Benfield, D.J. D'Angelo, and G.T. Peters. 1990. Effects of forest disturbance on particulate organic matter budgets of small streams. J. North Am. Benthol Soc. 9:120-140.

Webster, J.R. S.W. Golladay, E.F. Benfield, J.L. Meyer, W.T. Swank, and J.B. Wallace. 1992. Catchment disturbance and stream response: An overview of stream research at Coweeta Hydrologic Laboratory. Pp. 231-253 *in* P.J. Boon, P. Calow, and G.C. Petts (eds.), River conservation and management. John Wiley & Sons, New York.

Williams, M.R., and J.M Melack. 1997. Effects of prescribed burning and drought on the solute chemistry of mixed-conifer forest streams of the Sierra Nevada, California. Biogeochemistry 39: 225-253.

Second Interagency Conference on Research in the Watersheds

May 16 – 18, 2006



USDA SRS Coweeta Hydrologic Laboratory

1934-2006