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Chapter 18

Fire Effects on Carbon and Nitrogen Cycling in Forests of The Sierra Nevada

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Abstract

Fire removes substantial quantities of nitrogen (N) by volatilization, and prescribed fire, over time, can remove as much as or more N than wildfire. This lost N can be quickly made up if fire is followed by N_2-fixing vegetation. Wildfire often has short-term deleterious effects on water quality because of N mobilization, but long-term fire suppression allows buildups of N-rich litter, a source of labile N to runoff waters. Prescribed fire usually has less impact on water quality than wildfire. Prescribed fire has been proposed as a management tool to mitigate N saturation (a result of chronic, excessive N deposition). However, a major limitation of this strategy is that while fire removes substantial quantities of N from the forest floor, it removes only a small fraction of the large N reservoir in the mineral soil and at the same time causes increases in soil ammonium over the short term. Periodic prescribed fire, reduced atmospheric N deposition and strategies to enhance plant and microbial N demand may all be required to reduce N-saturation symptoms in catchments exposed to long-term atmospheric N inputs.

18.1. Introduction

Fire is known to have major impacts on the carbon (C) and nitrogen (N) cycles of semi-arid forests, including those in the Sierra Nevada (Belillas & Feller, 1998; Carriera et al., 1996; DeBano & Conrad, 1978; Grier, 1975; Johnson et al., 1998, 2005; Neary et al., 1999; Newland & DeLuca,

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2000; Raison et al., 1985; Trabaud, 1994). Fire has obvious and immediate effects on the carbon cycles of forest ecosystems: the process of burning itself involves converting organic C to carbon dioxide (CO_2), thereby causing a marked loss of ecosystem C capital. Because fire results in the emission of CO_2 and other greenhouse gases (Crutzen & Andreae, 1990), the recent trend toward more frequent and severe fires may contribute to a positive feedback in global warming. The contributions of fire to global CO_2 emissions are uncertain and highly variable, but may rival those of fossil fuel emissions (Mouillot & Field, 2005).

Because of its low volatilization temperature, most N is also volatilized from the materials that burn, in contrast to elements such as calcium (Ca) that are left behind in ash. Thus, fire always causes an immediate, short-term loss of ecosystem C and N capital. Fire effects on C and N cycles over the intermediate (1–3 year) and long-term (decadal to century) perspectives are far more complex than the simple removal of C and N by volatilization, however. Fire has significant and well-documented short-term effects on soil N availability and therefore water quality through soil heating effects and mid-term effects on N availability by causing changes in decomposition rates (Certini, 2005; Neary et al., 1999). Fire can have very substantial long-term effects on ecosystem C and N by causing changes in vegetation, often through the facilitation of occupancy of the burned site by N-fixing vegetation, which in turn can indirectly cause long-term increases in ecosystem C capital in N-limited ecosystems—as long as sufficient time elapses prior to the next fire (Choromanska & DeLuca, 2002; Gessel et al., 1973; Johnson & Curtis, 2001; Johnson et al., 2004, 2005).

The incidence of catastrophic wildfire in Sierra Nevada ecosystems has increased dramatically during the last few decades as a result of past fire suppression and consequent fuel buildups (Neary et al., 1999; Newland & DeLuca, 2000). Furthermore, recent analyses suggest that climate change may be causing increases in wildfire incidence and extent. Westerling et al. (2006) found that wildfire activity in the United States has increased markedly since the mid-1980s with greater frequency, longer wildfire seasons, and longer wildfire durations. These changes are associated with increased spring and summer temperatures and have taken place even in areas of the U.S. that have not strongly been affected by fuel buildups. In this chapter, we review the current state of knowledge about the effects of fire on C and N cycling in forests of the Sierra Nevada, including effects of fire on N volatilization, ammonification, nitrification, leaching, and how these compare with atmospheric N deposition in affecting long-term N budgets.

18.2. Fire effects on soil C and N and water quality

Even though there is usually a net loss of ecosystem C and N by volatilization during fire, soil C and N levels are often unaffected in all but the most severe wildfires (Certini, 2005; Neary et al., 1999). This is because soil temperatures often do not reach levels that would cause the combustion of soil organic matter aside from the very surface layers. Although in soil total C and N are usually not reduced by fire, soil NH_4^+ levels often increase following fire because of heat-induced decomposition of organic N in soil and possibly by inorganic N inputs from ash (Certini, 2005; Covington 1992; Covington & Sackett, 1984; Giardina et al., 2000; Grogan et al., 2000; Khanna & Raison, 1986; Monleon et al., 1997; Neary et al., 1999). At the same time, the reduction in biomass and leaf area (especially in wildfire), can cause increased water availability, providing good growing conditions for vegetation that is able to reoccupy the site (including undesirable invasive species). Because NH_4^+ is strongly absorbed to cation exchange sites, NH_4^+ leaching may not be substantial after fire, but the availability of substrate and good temperature and moisture conditions after fire can cause increases in nitrification and NO_3^- leaching. There are also indications that nitrification is favored by the presence of charcoal, perhaps because of the absorption of chemicals that inhibit nitrification (DeLuca et al., 2006).

The effects of fire on water quality are especially important in the Lake Tahoe Basin on the California–Nevada border (Murphy et al., 2006a; Stephens et al., 2005). Lake Tahoe is an ultra-oligotrophic freshwater lake renowned for its pristine conditions and extreme clarity. The 500-km^2 lake is surrounded by a forested watershed of approximately 800 km^2 (Boardman, 1959). The relatively small watershed to surface water area ratio has produced pristine water conditions resulting from historically low levels of nutrient input (Goldman, 1988). Since 1968 lake clarity (secchi depth) has diminished by an estimate of $0.37\,m\,yr^{-1}$ from increased primary productivity due to accelerated N and phosphorus (P) inputs (Goldman, 1988). It is now believed that the N to P ratio of inputs into Lake Tahoe has shifted and currently reflects a P rather than N-limited system (Jassby et al., 1994). A substantial portion of the Lake Tahoe Basin has been recently categorized as a high-risk environment for catastrophic wildfire (Smith & Adams, 1991).

Stephens et al. (2005) found that prescribed fire in the Lake Tahoe Basin had no effect on soluble reactive phosphate and minimal effects on nitrate in streamwaters. Similarly, Murphy et al. (2006a) found no significant increases in soil solution concentrations or leaching of mineral N or P in a prescribed fire on andesitic soils near the Tahoe Basin. In contrast, we found substantial (approximately tenfold) increases in mineral N leaching for the first 2 years following a wildfire in the Tahoe Basin (Johnson et al., 2007; Murphy et al., 2006b). Soil solution concentrations of NH_4^+ increased from <3–180 μmol L^{-1}, and NO_3^- increased from <3 to >350 μmol L^{-1} during the first year after the fire (Murphy et al., 2006b). By year three after the fire, however, N leaching levels were back down to near control levels, and the total amount of additional N leaching (20 kg ha^{-1}) constituted only 4% of that lost to volatilization (500 kg ha^{-1}) in this fire. Ortho-P concentrations and leaching were slightly elevated following this fire, but by far the greatest increases were in soil solution SO_4^{2-} concentrations: from <20 to >8000 μmol L^{-1} (Murphy et al., 2006b). Other researchers have also found large increases in SO_4^{2-} concentrations in both soil solution and streamwater following fire in the Sierra Nevada (Chorover et al., 1994; Williams & Melack, 1997). This increase in SO_4^{2-} concentration is generally thought to be due to oxidation of organic S from soil organic matter, but may also be enhanced by increases in soil pH resulting in desorption SO_4^{2-} from soil anion exchange sites (Murphy et al., 2006b).

Postfire erosion can also cause substantial short-term decreases in water quality following wildfire, but much less information is available on that subject. Fire effects on soil hydrophobicity are well-documented, and this has a major effect on postfire erosion (Certini, 2005). Heating of the soil above 200°C causes the volatilization of some hydrophobic substances in soils, and they can then migrate downward in the soil profile, usually to depths of less than 10 cm (Certini, 2005). We found that a wildfire in the Lake Tahoe Basin caused the destruction of the hydrophobic layer that is normally present in surface soils of this region, causing a new layer of hydrophobicity to form at the 8–10 cm depth. A thunderstorm after the fire caused substantial erosion of the surface soil above the new hydrophobic layer (Carroll et al., 2007). We estimated that this caused <100 kg ha^{-1} of N loss via erosion, a value lower than that estimated to have been lost by volatilization (500 kg ha^{-1}). Baird et al. (1999) made estimates of postfire erosional N losses from a fire in eastern Washington that ranged from 14 to 22 kg ha^{-1}.

One hypothesis regarding wildfire and water quality that is not intuitively obvious was recently proposed by Miller et al. (2005) for forests of the Lake Tahoe Basin and vicinity. They found that subsurface runoff water that percolated through litter layers but did not enter mineral soils (due to either hydrophobicity or frozen soil) had very high concentrations of NO_3^-, NH_4^+, and ortho-P. The source of these nutrients was clearly the litter layer, which because of past fire suppression, had built up to well above normal levels. They speculated that in this way, fire suppression had actually indirectly contributed to the decline in water quality in Lake Tahoe. Thus, whereas fire is known to cause short-term pulses of increased NO_3^-, NH_4^+, and ortho-P in some cases, the results of Miller et al. (2005) suggest that fire exclusion rather than fire itself may cause long-term increases in these ions and contribute to declines in water quality over the long term. Further research is needed on an aerial, quantitative basis to determine the effects of this water.

18.3. Long-term effects of wildfire and postfire vegetation

Wildfire burns components of the ecosystem that have low C:N ratios (forest floor and foliage), leaving large woody tissues unburned in most cases (Auclair, 1985; Johnson et al., 1998). Thus, it would seem that wildfire causes disproportionately large losses of N compared to C. Lost N is often replaced and even exceeded by inputs from N fixers after fire, and the replenishment of lost N is key to the long-term replenishment of C in these N-limited ecosystems. There is likely to be a substantial delay in the replenishment of C pools compared to N, however, until high C:N ratio woody tissues (i.e., mature trees) reaccumulate.

The invasion of N-fixing vegetation on burned sites is a double-edged sword: while the benefits of replenishing N volatilized during fire are well known (Binkley et al., 1982; Johnson, 1995; Youngberg & Wollum, 1976; Zavitovski & Newton, 1968), the presence of this vegetation often presents a significant problem for tree reestablishment. Snowbush (*Ceanothus velutinus* Dougl.) is a pioneer species that invades after site disturbances such as fire in eastern Sierran forests. Snowbush is especially adapted to fire; heat treatment followed by cold stratification is required for seed germination (Zavitovski & Newton, 1968; Youngberg & Wollum, 1976). Snowbush seeds lying dormant in forest litter for many years are activated by fire and winter weather, resulting in prolific germination in wildfire, clearcut, and slash burned sites. Snowbush is shade intolerant and therefore disappears after overstory canopy closure. Snowbush presents serious competition for tree regeneration after fire; when it is not controlled by either herbicide or mechanical means, it may persist for many decades.

For a site in the eastern Sierra Nevada, we estimated the impacts of wildfire and postfire salvage logging on carbon (C) nutrient over a 16–20-year period (Johnson et al., 2005). We reconstructed prefire biomass and nutrient contents and compared them with values from the postfire ecosystem, which was dominated by snowbush (*C. velutinus* Dougl.) and manzanita (*Arcostaphylos patula* Greene). We estimated that the wildfire caused losses of at least 300 kg ha^{-1} of N and 15,500 kg ha^{-1} of C, assuming all foliage and O-horizon (litter layer) material was combusted (Fig. 18.1). Soil losses could not be reconstructed, but would cause this estimate to increase. Postfire salvage logging is estimated to have resulted in losses of an additional 130 kg ha^{-1} of N and 53,000 kg ha^{-1} of C. Comparisons of the prefire and current N budgets suggested that the lost N was rapidly replenished in O horizons and mineral soils due to N fixation by snowbush (*C. velutinus* Dougl.), the dominant shrub on the former fire site. Two decades after the fire, there were no significant differences in ecosystem P, potassium (K), or sulfur (S) contents and no consistent, significant differences in soil extractable P or S between the shrub and forested plots (Table 18.1). Exchangeable K, Ca, and magnesium (Mg) were consistently and significantly greater in shrub-dominated than in adjacent forested soils, however, and the differences were much larger than could be accounted for by estimated ash inputs (Fig. 18.1). In the case of Ca, even the combustion of all aboveground organic matter could not account for more than a fraction of the difference in exchangeable pools. We speculate that the apparent large increase in soil and ecosystem Ca content resulted from either the release of Ca from nonexchangeable forms in the soil or the rapid uptake and recycling of Ca by postfire vegetation. Carbon losses, most of which were due to salvage logging, will not be restored until a mature forest occupies the site again.

18.4. Nitrogen losses from prescribed fire in Sierran forests

Although wildfire typically causes a greater amount of N volatilization than prescribed fire in a given year, the cumulative effects of repeated prescribed fire can be very substantial and exceed wildfire losses in the long run. In a previous chapter, we used a simple spreadsheet model to illustrate this (Johnson et al., 1998). In the model, litterfall mass and N content are kept constant over a 100-year period, and litter is allowed to decay at a constant rate (*k*-value) taken from litterbag studies in the field (Stark, 1973). Figure 18.2 gives an example of calculated N losses with prescribed fire at 10- and 20-year intervals, assuming that half of the forest floor is consumed in each burn (top panel) and with a constant 10-year burn interval assuming 25%, 50%, and 75% consumption of the forest floor (bottom panel). Cumulative N losses are plotted in these burn scenarios range from 738 to 1434 kg ha^{-1} over a 100-year period, values which exceed those calculated if the cumulative forest floor mass was left unburned until complete combustion in a wildfire at 100 years

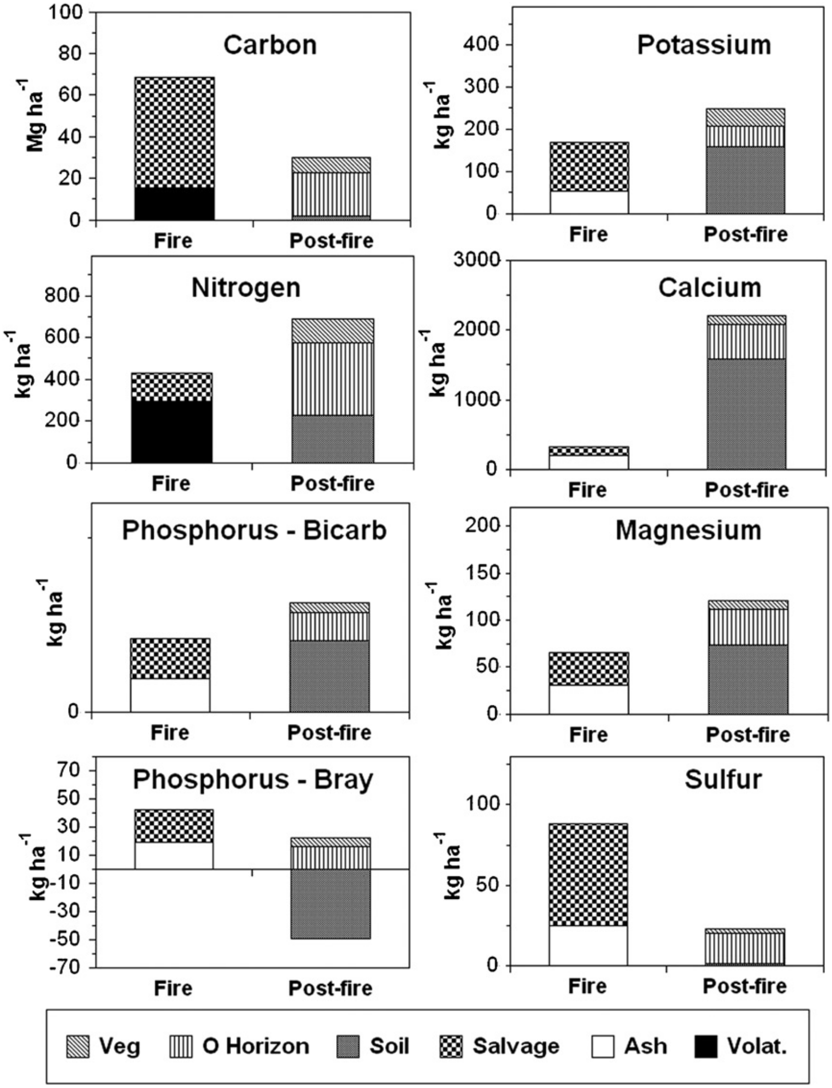

Figure 18.1. Estimated losses of carbon, nitrogen, phosphorus (showing bicarbonate- and Bray-extractable phosphorus in soils), potassium, calcium, magnesium, and sulfur by volatilization (Volat.) and conversion to ash during fire (assuming combustion of foliage and O horizons), removal by postfire salvage logging, and postfire increases in soils, O horizons, and vegetation (Veg) for the Little Valley fire site. Reprinted from Forest Ecology and Management, Johnson et al. (2005), with permission from Elsevier.

Table 18.1. Carbon and nutrient contents of shrub (burned by wildfire in 1981) and nearby forest ecosystems at Little Valley, Nevada (standard errors are shown; from Johnson et al., 2005)

Component	Carbon		Nitrogen		Phosphorus		Potassium		Calcium		Magnesium		Sulfur	
	(Mg ha^{-1})		(kg ha^{-1})											
Vegetation	9*** ±1	89 ±35	140** ±13	333 ±133	7** ±1	63 ±25	57** ±3	224 ±87	99** ±39	334 ±39	11** ±1	99** ±39	334 ±39	97 ±39
O horizon	26** ±3	15 ±1	434*** ±78	232 ±18	19* ±3	13 ±2	63* ±18	27 ±2	611** ±141	239 ±14	48*** ±5	611** ±141	239 ±14	24 ±3
Woody	10 ±9	4 ±3	16 ±15	7 ±4	3 ±2	1 ±1	12 ±11	5 ±3	14 ±13	6 ±4	4 ±4	14 ±13	6 ±4	2 ±1
Soil	58 ±8	53 ±8	3136 ±711	2529 ±699	157** ±12	106 ±7	514** ±70	301 ±32	2872*** ±399	825 ±119	172** ±37	2872*** ±399	825 ±119	71 ±23
Ecosystem	103* ±10	160 ±45	3726 ±618	3102 ±774	186 ±7	183 ±34	646 ±69	558 ±100	3573*** ±407	1168 ±115	323 ±27	3573*** ±407	1168 ±115	431 ±122

*,**, and *** refer to statistically significant differences, unpaired student's t-test.

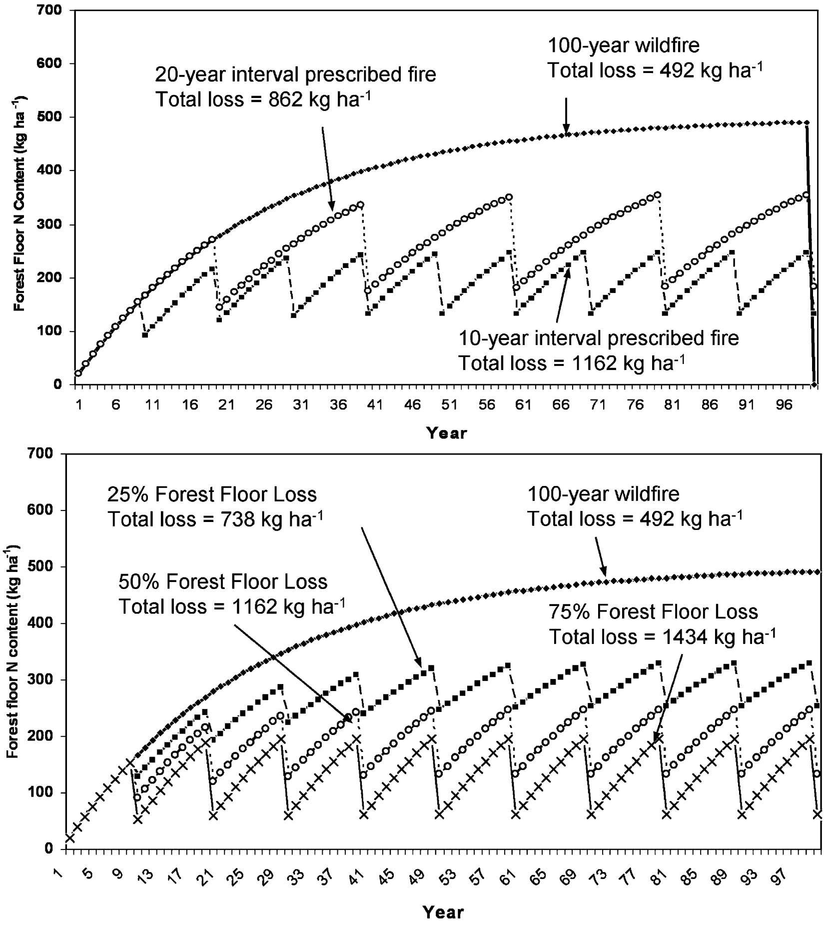

Figure 18.2. Simulated forest floor N content and cumulative N losses from the forest floor combustion using a spreadsheet model (Johnson et al., 1998). The top panel assumes that a 100-year wildfire consumes the entire forest floor, 50% of the forest floor is consumed at 10-year intervals with prescribed fire, and 75% of the forest floor is consumed at 10-year intervals with prescribed fire. The bottom panel assumes that a 100-year wildfire consumes the entire forest floor, prescribed fire at a 10-year interval consumes 50% of the forest floor, prescribed fire at a 10-year interval consumes 50% of the forest floor, and prescribed fire at a 10-year interval consumes 75% of the forest floor. Litterfall is assumed to be constant at 2000 kg ha^{-1} yr^{-1} containing 1% N (giving an N return of 20 kg ha^{-1} yr^{-1}), and decomposition constant (k) is set at 0.04 yr^{-1} (Stark 1973).

(492 kg ha^{-1}). Furthermore, prescribed fire at intervals of 10 years or less will prevent the reestablishment of N-fixing vegetation for sufficiently long intervals to allow for N fixation to commence in significant amounts. McNabb and Cromack (1983) indicate that fixation does not go "into the black" (i.e., fix more N than is taken up from the soil) until at least age 10 (primarily *C. velutinus* in the area that these fires burn in). Thus, the long-term effects of prescribed fire at short intervals can, in theory, cause very substantial amounts of N loss from the ecosystem and may actually result in growth declines, as has been observed in some studies in eastern Oregon (Monleon et al., 1997).

18.5. Fire effects on water quality in N-saturated catchments

Because fire causes considerable loss of N by volatilization (Neary et al., 1999), prescribed fire might be an appropriate tool for reducing the symptoms of N saturation in chaparral and forested watersheds in southern California where streamwater nitrate concentrations are the highest reported in North America for wildland watersheds. This strategy presumes that by reducing ecosystem N capital with the combustion of N stored in fuel, N-saturated watersheds could be returned to a state of conservative N cycling. Unfortunately, a study in chaparral catchments in the San Dimas Experimental Forest (SDEF) in the San Gabriel Mountains near Los Angeles, where N deposition inputs are approximately 35 kg ha^{-1} yr^{-1}, demonstrated that prescribed fire was not effective in improving water quality (Meixner et al., 2006).

Prescribed fire and simulated wildfire treatments, applied to N-saturated chaparral catchments in the SDEF in October 1984, provided an opportunity to test the effects of fire on streamwater nitrate export patterns. Paired catchments were either left untreated as controls, prescribe burned, or the *Ceanothus* chaparral was cut and later burned to simulate a wildfire burn. Dominant vegetation in these watersheds was a mix of *C. crassifolius* and *Adenostoma fasciculatum* chaparral. Over the subsequent winter and spring wet season, nitrate concentrations followed the predicted pattern of highest concentrations in the simulated wildfire treatment and lowest concentrations in the unburned control catchments. Volume-weighted nitrate concentrations in the wildfire burn were at or above the drinking water standard in a few instances (as high as 1120 μeq L^{-1}) and were 1.7 times higher than in the prescribed burn. Annual nitrate flux from the wildfire catchments was 7 times higher than the prescribed fire treatment and 40 times higher than the control (Riggan et al., 1994).

Long-term trends in nitrate runoff are the real test of whether prescribed fire is an effective treatment for mitigating N-saturation symptoms. Streamflow and nitrate concentrations were measured until 2002 (when the entire SDEF burned) in a subset of the catchments. For the first 7–10 years nitrate concentrations and annual flux were higher in the prescribe-burned catchments than in the unburned control, after which the order was reversed. However, nitrate concentrations remained high in both treatments for the duration of the study (varying from 40 to 200 μ eq L^{-1} in the burned catchments; Meixner et al., 2006). Considering the long lag time until nitrate concentrations were lower in the burned catchments and the persistently high nitrate concentrations in both treatments, it was concluded that prescribed fire is not an effective treatment for reversing N-saturation conditions. Only approximately 20% of the N in chaparral ecosystems is stored in the aboveground biomass plus litter (Gray & Schlesinger, 1981), with the remaining 80% found in soil storage pools, of which little is lost during or after fire (Wan et al., 2001). Presumably, the fire treatment was ineffective in improving water quality because the soil (Riggan et al., 1994) and continuing atmospheric N deposition supplied a continual source of excess nitrate.

The results from the N-saturated chaparral catchments in the SDEF beg the question of whether prescribed fire might be more effective in reversing N-saturation symptoms in forested areas of California, where N deposition inputs are elevated. To date, studies on the effects of fire on streamwater nitrate export from forests in California have only been done in areas of relatively low N deposition (Chorover et al., 1994; Murphy et al. 2006a, 2006b; Stephens et al., 2005; Williams & Melack, 1997). In these instances, burns had the effects observed in more mesic forests, with elevated nitrate concentrations for 2–3 years maximum after which concentrations returned to prefire levels. Forest N budgets also indicate that prescribed fire is not likely to remove enough N from N-saturated forested ecosystems, because typically 65–80% of the site N capital is stored belowground in California forests (Arbaugh et al., 1999; Busse & Riegel, 2005; Johnson et al., 2004).

In N-saturated forests in California, ozone is also a major stress factor, with particularly severe effects on ponderosa pine trees (Fenn et al., 2003b). In contrast to forests, ozone does not have major effects on chaparral ecosystems notwithstanding the high ozone exposures occurring in chaparral watersheds located downwind of urban centers (Stolte, 1982). Ponderosa pine is a major overstory species occurring throughout the mixed-conifer forests of California and in many forests of the western United States. Ponderosa pine is replaced by Jeffrey pine in more droughty or higher elevation sites. Ozone concentrations are often lower in Jeffrey pine sites; however, both species are sensitive to ozone injury. In polluted California forests, ozone and nitrogenous pollutants co-occur, and these pollutants have interacting effects on plant physiology and ecosystem C and N fluxes and pools (Fenn et al., 2003b). Nitrogen deposition increases aboveground growth of ponderosa pine. Ozone and increased N fertility both reduce C allocation belowground and fine root biomass (Grulke et al., 1998). Ozone causes premature foliar senescence and abscission. The results of the combined effects of ozone and elevated N deposition are increased C storage in the bole and woody aboveground biomass and accelerated foliar turnover and litter production (Arbaugh et al., 1999). This also results in increased accumulation of C and N in the forest floor. In these ozone-impacted and N-saturated mixed-conifer stands, aboveground N pools are much higher than in unimpacted stands (Arbaugh et al., 1999; Fenn et al., 2005). For example, at an N-saturated site in the San Bernardino Mountains about 30% of ecosystem N is stored in the thick forest floor, compared to about 11% at an N-limited site (Arbaugh et al., 1999; Fenn et al., 2005). The question remains whether periodic burning of this aboveground N pool would eventually reduce nitrate runoff from these catchments or if N stores in the mineral soil are a large enough source of N to sustain elevated nitrate runoff. In N-saturated Scots pine stands established on nutrient-poor sandy soils in southern Germany, 7 years of litter raking and harvesting reduced foliar N concentration (7–11%) and nitrate leaching (9%, 19%, and 71%) in the three study sites (Prietzel & Kaiser, 2005). Although nitrate leaching was high in these German forests (9.9, 16.2, and 43.0 $\mathrm{kg\,ha^{-1}\,yr^{-1}}$ in the three unraked control study sites), throughfall N deposition was low to moderate compared to most N-saturated forests, ranging from 16–18 $\mathrm{kg\,ha^{-1}\,yr^{-1}}$. A number of researchers have noted that reducing N deposition is a key factor in reducing nitrate leaching (Gundersen et al., 2006; Rothe & Mellert, 2004). It seems likely that for N-saturated California forests where N deposition is elevated (25–70 $\mathrm{kg\,ha^{-1}\,yr^{-1}}$) and where large pools of N have accumulated in soil, removal of N stores in the forest floor from periodic burns would likely need to be accompanied by decreases in N deposition in order to eventually reverse N-saturation symptoms.

Recent isotopic tracer data from the San Gabriel and San Bernardino Mountains in the Los Angeles Basin suggest that chaparral and forested systems in southern California are both highly prone to export nitrate from the watershed, and that a significant fraction of the leached nitrate is atmospheric nitrate without any prior biological assimilation (Michalski et al., 2004). During peak flow following storm events, approximately 40% of the exported N was direct throughput of atmospheric nitrate.

In the study by Michalski et al. (2004) all edaphic and aqueous samples had positive $\Delta^{17}O$ values, unambiguously showing that every sample of soil and water collected in the Transverse Ranges in southern California had some degree of unassimilated atmospheric nitrate. One of the factors thought to predispose these systems to nitrate loss under conditions of chronic N deposition is the temporal asynchrony between the period of peak N demand (spring and early summer) and peak runoff (mid-winter). Chronic nitrate export from these watersheds is also believed to be a function of actively nitrifying soils (Fenn et al., 1998). N inputs from atmospheric deposition provide a steady source of leachable nitrate and indirectly enrich organic N pools that function as substrate for mineralization and nitrification (Fenn et al., 2005). Gundersen et al. (2006) reported a threshold of N flux to the soil (50–60 $\mathrm{kg\,N\,ha^{-1}\,yr^{-1}}$) from atmospheric deposition and litterfall above which nitrate leaching occurs in undisturbed mesic forests. Considering these factors, it seems that for prescribed fire to effectively reduce nitrate runoff, atmospheric N deposition fluxes would also have to be reduced, probably by as much as 60–80% in the most polluted areas. The threshold N deposition rate at which nitrate export begins to increase above the normal background levels in California montane systems is approximately 17 $\mathrm{kg\,ha^{-1}\,yr^{-1}}$ (Fenn et al., 2008), based on regression analysis of throughfall N deposition versus streamwater nitrate. This level of N deposition has been measured in much of the Transverse Ranges in southern California and in the southwestern Sierra Nevada (Fenn et al., 2003a, 2003b).

Having said all this, however, it remains true that fire causes large losses of N from ecosystems, and simple budget calculations would suggest that periodic fire (Busse & Riegel, 2005) should reduce excess N in the ecosystem and perhaps even lead to N deficiency unless N fixers or air pollution offset these losses. These net losses of N from fire may not suffice to offset the symptoms of N saturation, however, if postfire N inputs are substantial and sustained. Success in reducing nitrate concentration in runoff from chaparral and forested catchments in southern California will likely require the removal of N in fire and reduced N deposition. NO_x emissions from the South Coast Air Basin, which includes four counties near Los Angeles, have decreased by 44% from 1975 to 2005 (Cox et al., 2006), but trends in N deposition in the San Bernardino Mountains do not reflect these decreasing NO_x emissions trends (Andrzej Bytnerowicz, pers. comm.). This may be primarily because of large increases in population and vehicle traffic in the more easterly inland areas closer to the San Bernardino Mountains. Another factor seems to be increases in ammonia emissions within the Basin.

Ammonia emissions from motor vehicles are now known to be more significant than previously thought (Huai et al., 2005).

In summary, removal of N-containing biomass or necromass from N-saturated ecosystems is one strategy considered for reversing N-saturation symptoms in forests (Fenn et al., 1998; Gundersen et al., 2006; Prietzel & Kaiser, 2005), although a necessary and ultimate solution is to reduce N emissions to the atmosphere. Accumulation of organic N pools is particularly enhanced in mixed-conifer forests in southern California because of the co-occurrence of severe ozone effects, chronic N deposition, and long-term fire suppression. All of these factors enhance C and N accumulation aboveground. The accumulated litter layer also provides a mulch layer that likely reduces the establishment (Allen et al., 2007) and N uptake of understory vegetation and provides soil conditions that enhance nitrification. High nitrification rates, reduced N demand by understory vegetation, and reduced fine root production by trees as a result of ozone stress and high N fertility, are all factors that contribute to elevated nitrate leaching and gaseous nitrogen losses from the system (Fenn et al., 2003b). Because of the multiple effects of ozone, N deposition, and fire suppression in enhancing N saturation and N accumulation aboveground in some California forests, periodic prescribed fires may have a greater impact in reducing nitrate leaching in these catchments than in forests in other regions. However, the practicality of applying prescribed burns to the impacted areas in southern California is restrained by public concerns with the risks of using fire in the wildland-urban interface and because of air-quality issues associated with fire emissions in an already polluted environment.

18.6. Potential effects of fire on mesic forests

Although arid and semi-arid ecosystems burn more frequently and often more intensely, most forests of the world experience fires at one time or another. Temperate coniferous forests experience fire on a 50- to 200-year interval, temperate deciduous forests burn on intervals ranging from decades to centuries, and montane and boreal coniferous forests burn at intervals of centuries (Fisher & Binkley, 2000). Johnson et al. (2004) calculated the potential N losses with fire in a variety of mesic ecosystems given varying assumptions about fire return interval and degree of forest floor and vegetation combustion. They found that the potential C and N losses from a fire consuming the forest floor in these sites varied by an order of magnitude: from 6.8 to 70.8 $\mathrm{Mg\,C\,ha^{-1}}$ and from 240 to 2600 $\mathrm{kg\,N\,ha^{-1}}$, or from 6% to 30% of ecosystem C capital and from 4%

to 29% of ecosystem N capital. When expressed on an annualized basis, the potential loss of N with fire was calculated to be far greater than that due to leaching in all but two N-saturated ecosystems (red alder in Washington, USA, and Smokies red spruce site in North Carolina, USA). The number of years of atmospheric deposition that would be required to restore the N loss from such a hypothetical fire ranged from 30 to 1100 years with a mean of 193 and a median of 87. In most cases, the calculated N replenishment times were greater than stand age at the time of measurement. The number of years of leaching that would equal N losses in a hypothetical fire range from 47 in an N-fixing red alder stand with very high rates of leaching to 11,567 in the Sierra Nevada. If half the forest floor is assumed to be consumed in a fire, such as might occur with a typical prescribed fire (Caldwell et al., 2002; Murphy et al., 2006a), values would range from 27 to over 4738 years (mean = 1475, median = 646) to equal leaching. If only 10% of the forest floor burns, the values would range from 5 to 1157 years (mean = 148, median = 65). Given the normally very low rate of leaching in most temperate forests, it is quite clear that even a moderate ground fire every century or so will cause as much or more N loss on an annual basis than will leaching in all but N-saturated forests.

These budget calculations are very crude, but serve to illustrate the potential role of fire in C and N balances in more humid forest ecosystems, which burn infrequently. They show that potential N losses by fire, when expressed on an annual basis (estimated by dividing the N contents of ecosystem components presumed to burn by stand age), could be substantially greater than N leaching rates in many if not most cases. The calculations also show that atmospheric N deposition rates in all but the most polluted sites fall below these annualized estimates of fire N loss. In theory, infrequent fire could substantially deplete the N reserves of many of these systems and allow them to refill from atmospheric deposition and/or N fixation over time. In eastern Sierran ecosystems, with their typically low N deposition rates, it seems clear that even infrequent fire would deplete ecosystem N reserves without postfire N fixation.

Prescribed fire typically causes much less N loss than wildfire in that the forest floor and understory is usually only partly consumed and overstory vegetation is not much affected. However, burn intervals of 20 years or less can result in substantial N losses over time, with cumulative losses even exceeding N losses with wildfire over time periods of a century (Johnson et al., 1997).

Fire and other disturbances that remove N in large amounts over short periods may be one reason that most forest ecosystems show a net annual

N accumulation. Atmospheric deposition at even very low, pristine rates for thousands of years should have caused most ecosystems to come into steady state with respect to N in the absence of such disturbances.

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