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Prescribed fire, soils, and stream water chemistry in a watershed in the Lake Tahoe Basin, California

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Abstract. Before Euro-American settlement fire was a common process in the forests of the Lake Tahoe Basin. The combination of drought, fire suppression, and past harvesting has produced ecosystems that are susceptible to high-severity wildfires. Consequently, a program of prescribed fire has been recommended but there is incomplete understanding of the ecological effects of fuels treatments, especially with regard to how treatments will affect the flow of nutrients to Lake Tahoe. Nitrogen and phosphorus are the most important nutrients affecting algal growth, and thus lake clarity. Existing data demonstrate a long-term shift from a co-limitation by both nitrogen and phosphorus to phosphorus limitation. Two high-consumption, moderate-intensity prescribed fires were conducted to determine their effects on soil and stream water chemistry. Stream water calcium concentrations increased in burned watersheds whereas soluble reactive phosphorus concentrations were not significantly different. Prescribed fires released calcium and raised soil pH and this may have resulted in the incorporation of phosphorus into insoluble forms. Stream monitoring data indicates water quality effects last for ∼3 months. Prescribed fires did not significantly increase the amount of soluble reactive phosphorus in stream waters. However, additional research is needed to determine if prescribed fire increases erosion or movement of particulate P, particularly in areas with steep slopes.

Additional keywords: Sierra Nevada; mixed conifer forests; phosphorus; nutrients.

Introduction

Lake Tahoe is a deep mountain lake that is world-renowned for its clarity. Before Euro-American settlement, high clarity was maintained because of low concentration of nutrients in lake waters (Goldman 1974). A systematic decline in clarity has been documented beginning in the 1970s (Goldman 1988; Jassby *et al.* 1999) and clarity may be reduced further if increased nutrient loading occurs (Heatherwaite *et al.* 1996). Nitrogen (N) and phosphorus (P) are the most important nutrients affecting algal growth, and thus lake clarity, in this ecosystem (Tahoe Regional Planning Agency 1996). Existing data demonstrate a long-term shift from co-limitation by both N and P to predominantly P limitation (Goldman *et al.* 1993).

Nutrients can be atmospherically deposited into the lake either directly from dry deposition and precipitation or they may be released into the lake from the surrounding watershed (Likens and Bormann 1995). A recent ecosystem assessment of the basin estimates 418 t of N is input into the lake each year and more than half comes from atmospheric deposition (Murphy and Knopp 2000). Direct runoff, stream loading, and ground water contribute ∼10, 20 and 15%, respectively, of the annual input of N into the lake.

Sources and quantities of biologically available P have not been completely assessed in the basin (Murphy and Knopp 2000). Current estimates indicate that, of the 45.7 t of total P input to the basin, ∼27% comes from the atmosphere, while direct runoff, stream loading, and ground water account for ∼34, 29, and 9%, respectively. This analysis is consistent with previous work, which determined that the majority of P input to the lake comes from local sources (Blanchard *et al.* 1996). In studying daily variations in P loading for Incline Creek, a tributary to Lake Tahoe, Hatch *et al.* (1999) found that P loading to the lake was dominated by particulate P export during snowmelt, and that fluxes of soluble reactive

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phosphorus (SRP) and dissolved organic phosphorus were greatest from steep open-space in the watershed.

Fires occurred in mixed conifer forests of the west side of the Lake Tahoe Basin every 5–25 years before Euro-American settlement (Elliott-Fisk *et al*. 1997). Fire history studies conducted in Sugar Pine Point State Park documented mean fire return intervals of ∼8 years before the fire regime was altered late in the 19th Century. Similar fire return intervals have been reported on the east side of the Lake Tahoe Basin (Taylor 1998), in the eastern Sierra Nevada (Stephens 2001), and in forests in the Sierra San Pedro Martir, Baja California, Mexico (Stephens *et al*. 2003).

Over the past century, fire exclusion and selective logging of large conifers have produced forests dominated by dense stands of relatively small, shade-tolerant trees. This change in forest structure has increased the volume and continuity of wildland fuels (Elliott-Fisk *et al*. 1997; Carlton *et al*. 2000; Murphy and Knopp 2000). As fuel conditions have become increasingly hazardous, human populations and property values endangered by fire have also increased.

Current forest structure in the basin increases the risk of high-severity wildfires (Elliott-Fisk *et al*. 1997; Murphy and Knopp 2000). A program of prescribed fire with and without forest thinning has been recommended to reduce fire hazard in the basin (Elliott-Fisk *et al*. 1997). However, there is incomplete understanding of the ecological effects of these fuel treatments, especially with regard to how different treatments, alone or in combination, will increase or decrease the flow of nutrients to the lake (Elliott-Fisk *et al*. 1997; Murphy and Knopp 2000) and there are no published studies on soil and stream water chemistry changes after prescribed fire in the Lake Tahoe basin and very few in the entire Sierra Nevada.

The objective of this study was to determine if fall-ignited prescribed fires affected soil nutrient levels and stream water chemistry. The null hypothesis tested is that prescribed fire treatments will not significantly affect soil nutrient levels and stream water chemistry when compared to controls.

Materials and methods

Study location

Research was conducted on two prescribed fires in Sugar Pine Point State Park located on the western side of Lake Tahoe, California (latitude 39°0′, longitude 120°07′). The prescribed fire units are in the Sierra Nevada mixed conifer forest type consisting of Jeffrey pine (*Pinus jeffreyi* Grev.), white fir [*Abies concolor* (Gord. and Glend.) Lindl.], lodgepole pine [*Pinus contorta* var. *murrayana* (Grev. and Balf.) Crichf.], incense-cedar [*Calocedrus decurrens* (Torr.) Floren.], sugar pine (*Pinus lambertiana* Dougl.) and red fir (*Abies magnifica* Murr.).

The park is ∼1000 ha in size and the major stream in this area is General Creek. General Creek drains an area of ∼1935 ha, of which ∼648 ha is state park land and the

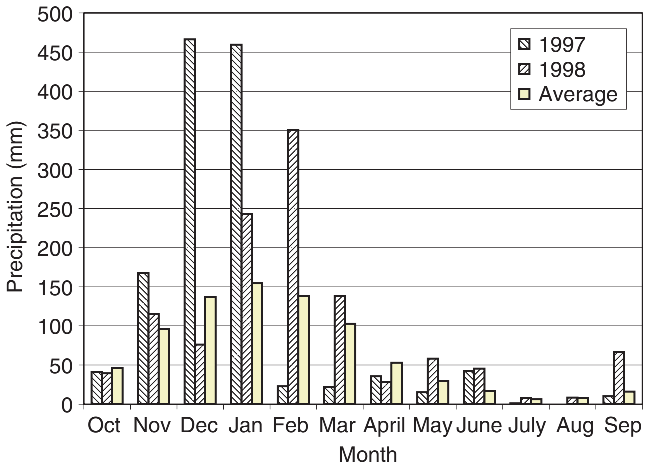

Fig. 1. Monthly precipitation at Lake Tahoe, California.

remaining area is managed by the United States Forest Service (USFS) (Kerbavaz 1989). The park receives ∼820 mm of precipitation in an average water year (starting on 1 October) (Fig. 1). The headwaters of General Creek originate in Desolation Wilderness at an elevation of ∼2390 m (T13N, R16E, Section 14). General Creek flows a distance of 14.7 km before entering Lake Tahoe (T14N, R17E, section 16). General Creek runoff varies from 12 300 000 to 246 000 000 m^3 per year (Kerbavaz 1989).

The geology of the General Creek watershed is composed of 60% glacial outwash and 40% granitic obtrusive. The majority of the soils in the Lake Tahoe basin are ultisolic with acid retention and low available P (Kerbavaz 1989). Soils within the prescribed fire units are classified as Tallac gravelly coarse sandy loams (Tahoe Regional Planning Agency 1971; Kerbavaz 1989). This soil series consists of well drained and moderately well drained soils that are 100–180 cm deep over a weakly silica cemented hardpan. Slopes within the prescribed fire units range from 0 to 12%. The elevation of the prescribed burn units is ∼1900 m and each unit was ∼4 ha in size.

Prior to the designation of Sugar Pine Point as a state park, heavy logging occurred during the gold and silver mining era in the late 1800s (Elliott-Fisk *et al*. 1997; Murphy and Knopp 2000). Drought cycles (1976 and 1977, and again in 1987 through 1992) reduced the vigor of the mixed conifer stands and allowed successful attacks by bark beetles (*Dendroctonus* and *Ips* species) (Elliott-Fisk *et al*. 1997; Rowntree 1998). The combination of drought, insect attack, fire suppression, and past forest harvesting practices (Sudworth 1900; Leiberg 1902; Stephens 2000) have produced ecosystems that are susceptible to widespread tree mortality and high severity fire. Changes in climate over the past century could have also influenced current forest structure (Millar and Woolfenden 1999).

High-consumption, moderate-intensity prescribed fires are used in the park to reduce hazardous fuel loads and to reintroduce fire as an ecosystem process. Similar prescribed fires are being used on USFS lands in the Sierra Nevada and Lake Tahoe Basin.

Fuels inventory and fire behavior

Surface and ground fuels were sampled at both the prescribed fire sites using the line intercept method (Brown 1974). One hour (diameter of 0–0.63 cm) and 10 h (diameter of 0.63–2.54 cm) timelag fuels were sampled from 0 to 2 m, 100 h (diameter of 2.54–7.62 cm) timelag fuels from 0 to 3 m, and 1000 h timelag (diameter greater than 7.62 cm) fuels from 0 to 10 m on each transect. Six randomly placed fuel transects were placed in each of the prescribed fire units.

Duff and litter fuel depths were measured at 2 and 3 m on each transect. Fuel consumption was calculated by subtracting post-burn fuel loads from pre-burn fuel loads. Regression equations developed to predict duff and litter fuel loads in Sierra Nevada forests (van Wagtendonk *et al.* 1998) were used to calculate ground fuel consumption after the prescribed fires.

Fire treatments were applied in October of 1996. Ignition patterns were manipulated to control fireline intensity (Martin and Dell 1978) on the two prescribed fire units. Strip-headfires fires were used to produce flame lengths of ~0.75–1.5 m. Average flame lengths were estimated visually during the prescribed fires. Fireline intensity, the heat produced during by flaming combustion (kW/m), was estimated using the Byram fireline intensity equation using the average flame lengths (Byram 1959). No attempt was made to exclude the prescribed fires from riparian areas or streams.

Soil characterization

Soils in Sugar Pine Point State Park were sampled ~3 weeks before and then 3 weeks after the two prescribed fires. Fifty soil cores were taken along a random transect across both burn areas with a standard 7.6 cm soil auger. At each transect location, four cores were taken and divided out into three layers, litter layer (OM), 0–5 cm of soil and 5–10 cm of soil. The four samples for each layer were composited and, after mixing, a subsample of the soil was placed into a 250 mL sample bottle for transport and chemical analysis. Soils were air-dried before analysis. Soil samples were analysed for total C and N by combustion on a Carlo-Erba CNS analyser. Soil P content was determined by acid digest and then analysis for phosphorus on a Technicon auto-analyser using colorimetric methods. Ammonium and nitrate (NO_3^-) were measured using a 2 M KCl 10 : 1 solution to soil ratio extract and then analysed using a Technicon auto-analyser using colorimetric methods. Soil pH was measured using 1 : 1 mixture of deionized water and soil and pH was then determined using an Orion pH electrode (Sparks *et al.* 1996). Some samples were not large enough to have all analyses conducted; this was particularly true for the litter samples (Table 2).

Due to large amounts of variability and data that were not normally distributed (Table 3), comparisons of soil measurements were made using non-parametric statistics and ranking (Scheaffer and McClave 1990). The Wilcoxon rank sum test was used to determine if there was a significant change in soil nutrient concentrations after the prescribed fires. The sums of ranks were used to calculate a Z score using equation (1):

$$Z = \frac{T_B - \dfrac{n_1(n_1 + n_2 + 1)}{2}}{\sqrt{\dfrac{n_1 n_2(n_1 + n_2 + 1)}{12}}}, \tag{1}$$

where T_B is the sum of ranks for the pre-fire observations, n_1 is the total number of pre-fire observations, and n_2 is the number of post-fire observations. The Z score is used to determine if the distribution of the post-fire observations was shifted to the right or left. Z scores greater than the absolute value of 1.65 (one-tail test) indicate that the distributions of ranks has shifted significantly ($P < 0.05$) to the right (greater value post-fire and a negative Z score) or the left (lesser value post-fire and a positive Z score) (Scheaffer and McClave 1990; Upchurch and Edmonds 1991).

Stream water sampling

There are no perennial streams within the two prescribed fire units to sample. However, both areas have ephemeral channels that flow during storm events and during snowmelt runoff. Flow in these channels integrates the soil response to the treatment. Stream water samples were taken weekly during the winter and spring run-off periods. Sampling commenced once runoff was noted at the site; for most sites this date was 28 November.

Two sample sites were selected in the two burned areas (burn east and burn west), and two sites at separate control sites (control east and control west). In addition to these sites a seep near control east was also monitored (control seep) and the channel for burn east was monitored above the burn area (above burn east). We do not have pre-fire stream water samples to calibrate the difference between our sites. This lack of calibration data decreases the power of inference from the experiment.

Stream water was collected in 250 mL Nalgene bottles, immediately packed in frozen carbon dioxide in a cooler, and express shipped to the laboratory for analysis. Each bottle was double rinsed in cold tap water and single rinsed in distilled water before use. The bottle was filled and emptied twice with stream water before the third fill was capped and refrigerated. A replicate of each sample was taken and analysed. Nitrate concentrations and soluble reactive phosphorus (SRP) concentrations were analysed on a Technicon auto-analyser. Calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^+) concentrations were analysed on a Varian flame AA. Sulfate was analysed using a Dionex ion chromatograph (Eaton 1995).

The Wilcoxon rank sum test was used to determine if there was a significant change in stream water nutrient concentrations after the prescribed fires (Scheaffer and McClave 1990; Upchurch and Edmonds 1991).

Modeling

The speciation model PHREEQC (Parkhurst 1995) was used to investigate the possibility that changes in Ca^{2+} concentrations and soil pH promoted precipitation of apatite and the binding of P into an immobile form. Data from this study were combined with others published in the southern Sierra Nevada (Williams and Melack 1997) for input for PHREEQC. Williams and Melack (1997) investigated stream water chemical composition impacts from a prescribed fire in the Giant Forest area of Sequoia-Kings Canyon National Park. We used sample analyses from that study for the highest soluble reactive phosphorus (SRP) concentration observed by Williams and Melack (1997) (Table 2) as input to the chemical speciation model PHREEQC (Parkhurst 1995). PHREEQC was used to calculate saturation indices. The saturation index is the ion activity product divided by the solubility constant for a given mineral (in this case apatite $K_{so} = 10^{-39.11}$ at 5°C). A saturation index greater than 1 indicates that apatite could precipitate.

Results

Fuels inventory and fire behavior

Fuel loads in the prescribed fire unit were large (Table 1). Ground fuels, which include only the duff and litter layers, contributed 60% of the total load. Large surface fuels (greater than or equal to 7.5 cm in diameter) accounted for 30% of the total fuel load. Surface and ground fuel consumption varied from 34 to 97% depending on size class and fuel condition, with the majority of fuels consumed at a minimum of 80%. Fuel consumption was similar to other fall prescribed fires in the Sierra Nevada (Stephens and Finney 2002).

Flame lengths varied from 0.7 to 2.1 m in the units. Higher flame lengths occurred in areas with localized higher fuel loads or areas with greater slopes. Fireline intensity varied from 120 to 1295 kW m^{-1} (Byram 1959) in the two burn units.

Table 1. Average fuel loads in the prescribed fires units at Sugar Pine Point State Park, Lake Tahoe, California
s.e., standard error

Fuel type (timelag)	Fuel load (tons ha^{-1})	s.e.	Consumed (%)
1-h timelag	1.65	0.71	80
10-h timelag	6.27	1.14	89
100-h timelag	9.39	2.39	81
1000-h timelag			
Sound	23.49	9.56	90
Rotten	22.06	14.15	34
Duff and litter	93.37	12.33	97
Total surface	62.85	24.48	68
Total load	156.22	29.89	86

Soil characterization

Mean concentrations of NO_3^-, NH_4^+, C, N, P and pH are different between the pre- and post-fire soil core samples for the litter layer (OM), the 0–5 cm soil depth (5 cm), and the 5–10 cm soil depth (10 cm), but there was a great deal of variability (Tables 2 and 3). The Wilcoxon rank sum test results (Tables 4 and 5) indicate that most of the constituents measured were significantly different after the fire from the pre-fire concentrations. Ammonium increased significantly while nitrate concentrations showed no significant trend other than a slight decrease at the 10 cm depth. Carbon and N percentages decreased in the post-burn soils while P content increased. Soil pH was not measured in the litter due to sample size limitations, increased at the 5 cm depth, but showed no trend at the 10 cm depth increment.

Stream water and speciation modeling

Graphical comparisons of the burned and control streams indicate that the burn west site had higher sulfate (SO_4^{2-}), nitrate, and Ca^{2+} concentrations when compared to the other five sites (Figs 2 and 3). Stream chemical concentrations showed an increase in the burned sites for Ca^{2+} and SO_4^{2-} (Table 6). The Wilcoxon rank sum test determined that only SO_4^{2-} and Mg^{2+} significantly increased between the control and burned sites. Ca^{2+} increased but it was not statistically significant (although the −1.13 Z score indicates that it is approaching a significant change) (Table 7). There are no significant differences for any of the other species.

Table 2. Average pre- and post-fire soil chemical measurements at Sugar Pine Point State Park, Lake Tahoe, California
OM, organic matter layer. Values in parentheses are number of samples. n.a., not available

Horizon	Ammonium (mg kg^{-1})		Nitrate (mg kg^{-1})		Carbon (% mass)		Nitrogen (% mass)		Phosphorus (% mass)		pH	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
OM	5.46	25.12	3.52	3.92	10.49	6.79	0.33	0.33	0.05	0.09	n.a.	n.a.
	(22)	(49)	(22)	(49)	(24)	(52)	(24)	(52)	(19)	(45)		
5	1.56	38.43	1.91	2.30	4.61	3.54	0.16	0.16	0.03	0.04	5.07	6.17
	(49)	(50)	(50)	(50)	(50)	(50)	(50)	(50)	(48)	(46)	(28)	(27)
10	0.87	11.13	2.26	1.27	2.42	1.89	0.1	0.07	0.03	0.04	5.23	5.12
	(50)	(50)	(50)	(50)	(50)	(50)	(50)	(50)	(48)	(46)	(37)	(51)

Table 3. Coefficients of variation for pre and post fire soil chemical measurements at Sugar Pine Point State Park, Lake Tahoe, California

n.a., not available

Horizon	Coefficient of variation (% of mean)											
	Ammonium		Nitrate		Carbon		Nitrogen		Phosphorus		pH	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
OM	123	107	131	93	128	92	133	76	40	56	n.a.	n.a.
5	90	113	45	89	69	80	63	106	33	50	9	11
10	68	105	75	84	43	37	50	57	33	50	9	11

Table 4. Wilcoxon rank sum test results for soil chemical measurements at Sugar Pine Point State Park, Lake Tahoe, California

* = Significant at 5% level

Horizon	Ammonium			Nitrate			Carbon		
	Sum of ranks		Z	Sum of ranks		Z	Sum of ranks		Z
	Pre	Post		Pre	Post		Pre	Post	
OM	523	2033	3.3*	816	1740	0.3	1367	1424	5.0*
5	1193	3757	8.8*	2330	2720	−1.3	2835	2215	2.1*
10	1312	3638	8.4*	2990	2060	3.2*	2828	2222	2.1*

Table 5. Additional Wilcoxon rank sum test results for soil chemical measurements at Sugar Pine Point State Park, Lake Tahoe, California

* = Significant at 5% level. n.a., not available

Horizon	Nitrogen			Phosphorus			pH		
	Sum of ranks		Z	Sum of ranks		Z	Sum of ranks		Z
	Pre	Post		Pre	Post		Pre	Post	
OM	1268	1451	3.8*	386	1694	−3.4*	n.a.	n.a.	n.a.
5	2674	2376	1.0	1662	2803	−4.7*	489	1051	−5.0*
10	2950	2100	2.9*	1932	3118	−2.6*	1766	2150	1.0

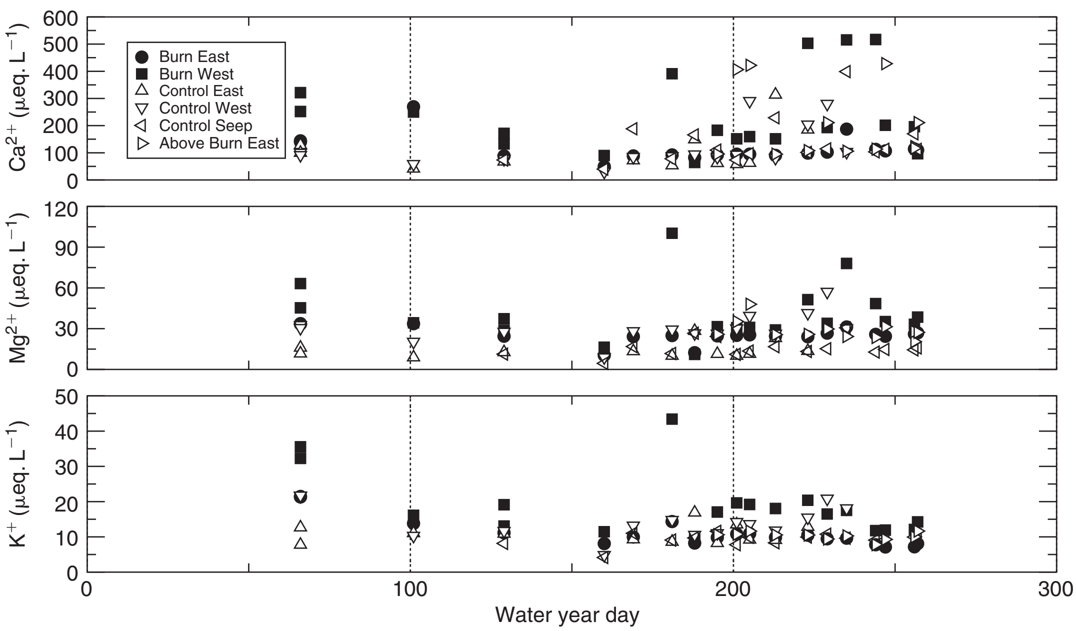

Fig. 2. Cation concentrations in ephemeral channels in the General Creek watershed, Lake Tahoe, California.

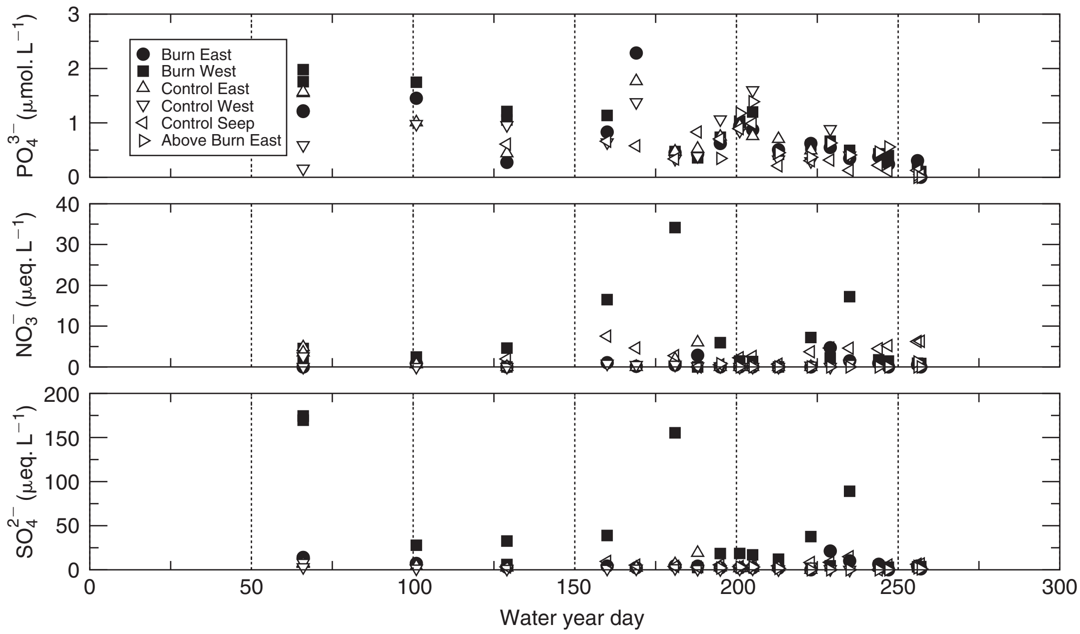

Fig. 3. Anion concentrations in ephemeral channels in the General Creek watershed, Lake Tahoe, California.

Table 6. Mean and coefficient of variation for stream chemical measurements at Sugar Pine Point State Park, Lake Tahoe, California

Species	Mean (CV %)	
	Control	Burn
NO_3^- (µequiv. L^{-1})	3.01 (150)	3.23 (168)
SO_4^{2-} (µequiv. L^{-1})	4.27 (87)	54.78 (101)
SRP (µM)	0.53 (85)	0.59 (98)
Ca^{2+} (µequiv. L^{-1})	137 (66)	172 (51)
Mg^{2+} (µequiv. L^{-1})	27 (75)	33 (37)
K^+ (µequiv. L^{-1})	11 (22)	15 (42)

Table 7. Wilcoxon rank sum test results for stream chemical measurements at Sugar Pine Point State Park, Lake Tahoe, California

* = Significant at 5% level

Species	Sum of ranks		Z
	Control	Burn	
NO_3^-	3054	2617	0.37
SO_4^{2-}	2394	3277	−3.81*
SRP	2910	2761	−0.54
Ca^{2+}	1525	3076	−1.13
Mg^{2+}	1423	3178	−2.13*
K^+	1620	2981	−0.20

The PHREEQC speciation modeling resulted in a saturation index of 3.24 indicating that, on a thermodynamic basis, apatite should be precipitating. Apatite precipitation is likely to be kinetically limited. Still, the saturation index results indicate that precipitation of P in some form is likely in burn-impacted ecosystems.

Discussion

The soil analysis indicated there were several changes in soil chemistry following the prescribed fires. The large increase in mean ammonium in the post-burn soils indicates that the fire converted organic N to this reduced N species. The ammonium can then be nitrified at a later time and can contribute to high nitrate concentrations (Riggan *et al.* 1994; Williams and Melack 1997) in streams. The lack of change in nitrate immediately following the fire is also corroborated by other studies where nitrate increases either do not exist or are significantly less than increases in ammonium in the post-fire soil environment (Wienhold and Klemmedson 1992; Laubhan 1995; Overby and Perry 1996; Kennard and Gholz 2001; Romanya *et al.* 2001). If we had sampled for a longer period of time we might have expected to see an eventual increase in extractable soil NO_3^- as has been found in a meta-analysis of fire–soil studies (Wan *et al.* 2001).

The decrease in soil percentage carbon and N is probably indicative of loss of carbon and N from subsurface heating of the shallow soil. Prescribed fires with lower intensities than those used here may not reduce percentage carbon and N in forested ecosystems (Johnson and Curtis 2001). Our results also contrast with those found in a meta-analysis of soil N concentration after fire that found no significant differences (Wan *et al.* 2001). However, this difference in result may be due to the shallow sampling depth in this study (0–10 cm). The meta-analysis also reported a decrease in nitrogen content in shallow soil layers (Wan *et al.* 2001). The increase in P in the soil is probably due to the addition of ash from the fire.

The significantly higher chemical concentrations in the burn west site were probably produced because of site differences (less buffering because of narrower riparian areas, higher fuel consumption near the stream channel) that probably caused the stream to be more impacted by the burn. Complicating the interpretation of the results is the lack of flow data from these sites. The results are not volume weighted but are arithmetic averages. It should be noted that, under prescribed conditions, others have not found significant differences in stream flow between prescribed burn and control sites (Van Lear *et al*. 1985; Townsend and Douglas 2000).

Stream monitoring data from this study indicates that the water quality effects of high-consumption, moderate-intensity prescribed fires last for ~3 months (Figs 2 and 3). There is not an increase in any chemical species other than Ca^{2+}, Mg^{2+}, and sulfate and, to a much lesser degree, nitrate. All of the other species either never increase or return to unburned conditions in a matter of weeks. This result indicates that these prescribed burns had a limited impact on stream chemical composition. Most significantly is the lack of differences in SRP concentrations in the burned *v.* unburned areas.

Reintroducing prescribed fire to the Lake Tahoe Basin may not have a significant impact on lake clarity since SRP concentrations did not increase in the burn *v.* the unburned sites. This conclusion is further corroborated by a post-fire study at Yellowstone and Sequoia National Parks that found that there was no significant difference in P export for streams in burned and unburned catchments (Minshall *et al*. 1997; Williams and Melack 1997). Additionally a study in Australia found that P export did not significantly differ between an unburned watershed and a watershed that was subjected to a prescribed burn while there was significantly more P export in a stream subjected to wildfire (Townsend and Douglas 2000).

Lack of long-term changes in P export in coniferous forests from prescribed burning is further corroborated by a study in northern Arizona. This study compared a control and a site subjected to interval burning over a 20-year period and found no change in soil P content while soil N content decreased in the burned site (Wright and Hart 1997). High-intensity wildfires may increase P export due to dramatic increases in sediment export and higher fuel consumption (Minshall *et al*. 1997) but low-moderate intensity prescribed fires do not cause a significant increase in sediment export over unburned conditions (Townsend and Douglas 2000; Letey 2001), particularly in areas with gentle slopes (Townsend and Douglas 2000). The prescribed fire units in this study had gentle slopes. We did not measure suspended or particulate phosphorus as part of this study so this remains an area for future research in the Lake Tahoe basin.

There are several possible explanations for why the phosphorus ash developed during prescribed burning does not increase stream water concentrations of SRP. First, our results indicate that increased cation concentrations and increased pH may lead to the precipitation of apatite or similar solid phase phosphate species. Others have argued for a similar precipitation mechanism for phosphorus in the post-fire environment (Cade-Menum *et al*. 2000). Second, soil heating could lead to the transformation of soil minerals leading to increased Fe-oxide surfaces or clay mineral surfaces onto which phosphate could adsorb (Sposito 1989). Such changes in soil chemistry and mineralogy have been observed in areas subjected to either prescribed or wildfires (Ulery and Graham 1993; Ulery *et al*. 1993, 1996). We did not assess which mechanism explains the lack of difference in SRP concentrations in this study (while it is possible in some cases, see Cade-Menum *et al*. 2000) but either mechanism would explain our results.

There are advantages of the use of prescribed fire in the Lake Tahoe Basin when compared to the inevitable wildfire. Prescribed fires did not significantly increase SRP concentrations in the monitored streams and can be used to reduce the probability of high-severity wildfires (Stephens 1998). Previous work indicates that higher-severity wildfires significantly increase steam water P concentrations (Minshall *et al*. 1997; Townsend and Douglas 2000) and this could lead to further loss of lake clarity.

Conclusions

The spatial scale of wildland fire before Euro-American settlement in the Lake Tahoe Basin was large but varied depending on yearly weather and ignition frequency. Annual area burned in the basin is estimated to have varied from 840 to 3200 ha before Euro-American settlement began late in the 19th Century (Manley *et al*. 2000). Fire history studies have revealed that ~90% of these fires occurred in the dormant period (later summer and fall) with the remaining 10% occurring in the active growing period (Taylor 1998).

Presently 50–100 ha of mixed conifer and Jeffrey pine forests are burned annually with prescribed fire in the Lake Tahoe Basin. This is a very small fraction of what burned in the pre Euro-American period. The use of prescribed fire is forecasted to increase in the basin over the next few decades (Elliott-Fisk *et al*. 1997) but the area treated will probably never approach pre Euro-American levels because of constraints from urbanization and air quality.

The release or export of nutrients from the surrounding watersheds into the lake is a function of natural characteristics of the watershed, but is also strongly affected by human-induced disturbances within the forests and other ecosystems in the basin. Atmospheric deposition, timber harvesting, urbanization, and fire can all change the release of nutrients from forests (Riggan *et al*. 1994; Likens and Bormann 1995; Fenn *et al*. 1996; Elliott-Fisk *et al*. 1997; Murphy and Knopp 2000). The effect of any land management activity in this area must ultimately be judged as to its effect on nutrient cycling in the basin.

More monitoring is needed in prescribed burn areas to quantify the long-term response of P after burning. Initial results indicate that the use of high consumption, moderate intensity prescribed fires may not significantly increase SRP concentrations in streams. However, additional research is needed to determine if prescribed fire increase erosion or movement of particulate P, particularly in areas with steep slopes.

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