Streamflow and Water Quality Responses to Preharvest Prescribed Burning in an Undisturbed Ponderosa Pine Watershed[1]

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Abstract.—Mean annual streamflow for the 6 years following burning did not increase significantly over pretreatment levels. Water quality changes were evaluated by comparing prefire and postfire levels of nitrate-nitrogen, ammonium-nitrogen, phosphates, calcium, magnesium, sodium, and potassium. Fire significantly changed the concentrations of some nutrients in stream water, but the changes were too small to adversely affect water quality.

Forest history studies (Arno 1980, Dieterich 1983) indicate that before fire suppression was initiated at the start of this century, most forest fires were surface fires. These fires reduced fire hazards and improved stand conditions by preparing seedbeds, thinning advance regeneration, and retarding the invasion of more shade-tolerant species. Current USDA Forest Service policy allows managers to use planned and unplanned fires for maintaining or enhancing resources (Arno 1980).

The effects of prescribed burning on streamflow and water quality have not been studied, although the effects of stand-replacing wildfires are well documented (Campbell et al. 1977, Tiedemann et al. 1979). The possible effects of prescribed burning for augmenting streamflow are of interest to forest managers. Dieterich (1983) hypothesized that prescribed burning, which reduces stand density and total forest floor depth, could increase runoff, or at least make more soil water available on a site. Watershed experiments (Rich 1972, Rich and Gottfried 1976) have shown increased runoff after the creation of openings or after severe reductions in stand density. The degree of density reduction would be critical if enhanced streamflow were expected. Haase (1986) measured greater surface soil water and subsequent ponderosa pine seed germination following burning.

Soil changes that increase the surface runoff would be expected to increase streamflow volumes and peak flows. Although intense fires can decrease infiltration into the soil by reducing porosity or creating hydrophobic conditions (DeBano 1981), prescribed burning has not produced surface runoff, or accelerated erosion, as long as the forest floor was not completely consumed during a fire (Biswell and Schultz 1957). Cooper (1961) studied the effects of controlled burning east of White River, Arizona, and found that although erosion and soil exposure increased, only small amounts of soil were moved, most of which never reached perennial streams. He also found the water-holding capacity of burned and unburned humus was similar and concluded prescribed burning did not influence streamflow and only slightly affected watershed condition.

Clary and Ffolliott (1969), working in an Arizona ponderosa pine stand, determined that the humus layer, the lowest layer of the forest floor, had to be modified, or removed, before the forest floor's ability to intercept and hold precipitation was significantly reduced. Agee (1973) found that prescribed burning reduced forest floor water-holding capacity in two California mixed conifer habitat types but concluded erosion could be avoided if the litter cover was not destroyed.

Several studies have shown available nitrogen increases following prescribed burning (Covington and Sackett 1986, Ryan and Covington 1986, Vlamis et al. 1955). A two-stage increase in nitrogen availability occurs. Immediately after burning, ammonium-nitrogen (NH_4-N) is high because of the pyrolysis of organic matter. High levels of NH_4-N are followed by increasing levels of nitrate-nitrogen (NO_3-N) when nitrification begins. Readily available phosphorus is also increased by fire (DeBano and Klopatek 1988, Vlamis et al. 1955).

Sims et al. (1981) measured chemical properties of water from small runoff plots before and after a controlled burn in a ponderosa pine-mixed conifer stand near Tucson, Arizona, and found that mean concentrations of calcium, magnesium, and fluoride increased significantly. However, it has not been determined whether an increase in readily available nutrients on a burned site increases nutrient loading in adjacent streams. This is important because higher concentrations of nutrients could adversely affect water quality for domestic and livestock consumption and lead to eutrophic conditions in affected aquatic ecosystems.

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In 1981, a prescribed fire was ignited on the East Fork of Castle Creek, a gaged ponderosa pine-mixed conifer watershed by the Alpine Ranger District personnel. The main objectives were to reduce fuels with a minimum of mechanical disturbance, maintain fuel loading at a manageable level, and evaluate the effects of prescribed fire in virgin ponderosa pine and mixed conifer stands on the timber, watershed and forage resources. This prescribed burn provided us the opportunity to evaluate the impacts of fire on water augmentation and quality.

Table 1.—Average measurements of the West Fork and East Fork watersheds.[1]

Measurement	West Fork	East Fork
Size (acres)	900	1,163
Aspect (direction, average of plots)	S 43°E	N 14°W
Slope (average of all measured points, percent)	12.6	13.8
Forage production (pounds per acre)	78.2	119.8
Litter (pounds per acre)	33,177	31,085
Soil mantle depth (feet)	2.6	2.8
Forest conditions 1964 (per acre) before harvesting		
Basal area	135	122
Board-foot volume[2]	11,060	10,680
Forest conditions (per acre) before burning	1975	1981
Trees	328	608
Basal area	60	139
Board-foot volume[2]	2,759	11,843

[1]*Data prior to 1975 from Rich, Lowell R. 1972. Managing a ponderosa pine forest to increase water yield. Water Resources Research 8: 422-428.*

[2]*Scribner Rule.*

The Study Area

The East Fork and adjacent West Fork of Castle Creek (fig. 1) are within the Apache-Sitgreaves National Forests of east-central Arizona, approximately 14 miles south of Alpine. Elevations vary from 7835 to 8583 feet. Soils are derived from basalt. The primary soil subgroups on East Fork are Mollic Eutroboralfs, Lithic Argiborolls, and Eutric Glossoboralfs (Laing et al. 1988). Additional information on these watersheds is presented in table 1, primarily from Rich (1972).

Annual precipitation between 1956 and 1987 averaged 27 inches; the highest, 39.02, occurred in 1979 and the lowest, 16.86 inches, in 1974. Winter precipitation between October 1 through May 31 averaged 15 inches, about 57% of the annual total. Much of the winter precipitation occurs as snow, although occasional late fall rainstorms have produced large amounts of precipitation and accompanying peak stormflows. Summer precipitation is normally produced by convection storms during the regional monsoon.

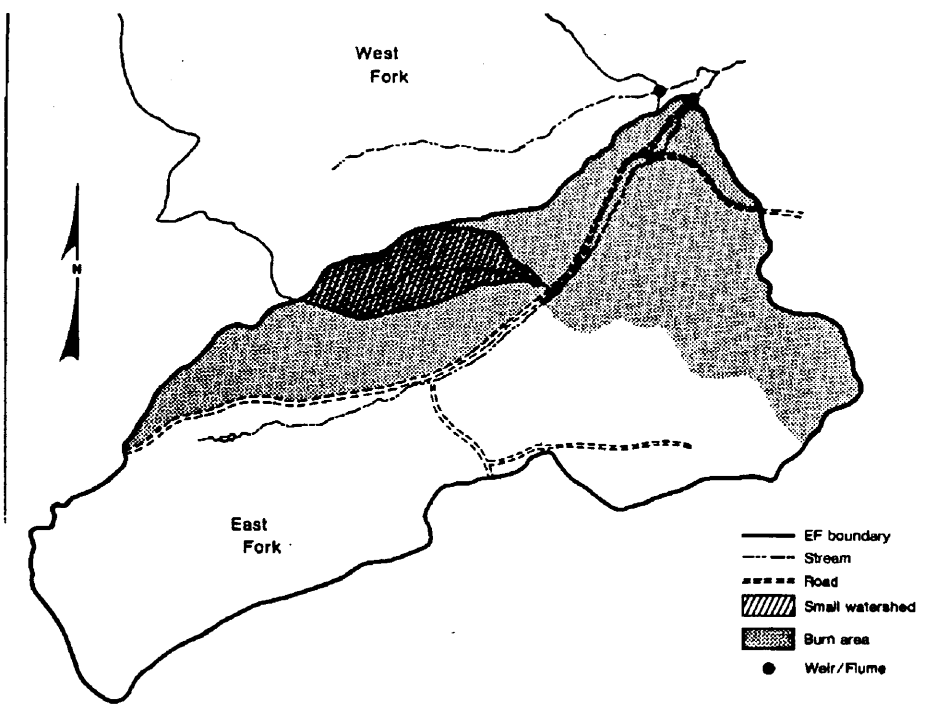

Figure 1.—The prescribed burn covered 43% of the East Fork of Castle Creek.

Vegetation on Castle Creek has been classified as a *Pinus ponderosa* var. *scopulorum*/*Q. gambelii* type (Laing et al. 1988). Ponderosa pine accounts for 81% of the total basal area (table 1). Mixed conifer stands found on north-facing slopes and along drainages include ponderosa pine, Douglas-fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), southwestern white pine (*P. strobiformis*), and quaking aspen (*Populus tremuloides*). Mixed conifer vegetation occupies about 303 acres on East Fork.[3] Gambel oak (*Quercus gambelii*) and

[3]*Soto, Edward L. 1981. Environmental analysis report: East Castle Creek Prescribed Burn, 23 p. USDA Forest Service, Apache-Sitgreaves National Forests, Alpine Ranger District, Alpine, AZ (Unpublished report).*

New Mexico locust (*Robinia neomexicana*) are found throughout both watersheds. The stream channel runs through a 68-acre meadow in the upper part of Castle Creek East.

Watershed History

The two experimental watersheds were established in 1955 when 120° v-notch weirs were constructed across the intermittent streams on each drainage. The original objective on Castle Creek was to evaluate the effects of an improved type of timber harvesting on water and sediment yields, wildlife and scenic values, and on the timber resource (Rich 1972). Both watersheds were calibrated for 10 years (1956-1965); mean annual flow during this period was 1.97 ± 0.61 inches on West Fork and 2.97 ± 0.89 inches on East Fork. In 1966, West Fork was harvested so that one-sixth of the watershed was clearcut in blocks fitted to stand conditions, and the remaining area was put into the best growing condition by removing poor risk, overmature, and diseased trees and releasing residual trees (Rich 1972). East Fork served as the hydrological control. The blocks were planted with ponderosa pine seedlings. Rich (1972) reported this treatment increased the average water yield by 29%; any streamflow increases greater than 0.4 inch were statistically significant.

The Prescribed Fire

Before the burn, Sackett (1979) measured 31.9 tons per acre of fuel on the East Fork; 47% of the fuel was in rotten material over 3 inches in diameter. Total dead fuel load (of 31.9 tons per acre) on Castle Creek was greater than the average 21.7 tons per acre measured in relatively undisturbed stands throughout Arizona and New Mexico.

The burning plan specified a 70% reduction in fine fuels and a 40% reduction in heavy fuels. Burning began during the first week of November 1981; however, an administrative decision was made to terminate the prescribed burn before completion because the burn did not appear to be meeting fuel reduction objectives. Consequently, only 503 acres, 43% of the watershed, was actually burned (fig. 1). The burned blocks were on the south-facing slopes, and on north-facing slopes in downstream areas near the weir. Ninety-three percent of the trees in these areas were ponderosa pine. An average acre in the burned zone contained 624 trees, 132 square feet of basal area and 9,610 board feet. The burned area contained 73 permanent timber inventory points.

A formal evaluation of fuel consumption was never conducted. However, Michael Harrington, research forester with the Station, reporting on his observations on November 4 and 5, 1981, considered fuel consumption satisfactory from a fire hazard standpoint considering the dense, deep forest floor common in undisturbed stands. Surface fuels were consumed and the middle forest floor layers were only slightly charred over most of the southern exposures. The duff layer was only consumed near sawtimber trees or adjacent to heavy fuels. Few of the downed logs were totally consumed. Mixed conifer pockets burned poorly. Although more fuel consumption would have occurred if fuel and weather conditions had been warmer and drier, the dense duff layer would probably not have been completely consumed even under ideal conditions.

Changes in the residual stand were minimal: only 4% of the trees sampled within the burned blocks using point sampling techniques showed evidence of more than 10% crown scorch. This was equivalent to 79 trees per acre or 13% of the total stand; 89% of the damage was in the 2- and 4-inch diameter (d.b.h.) classes. Approximately 78% of the scorched trees contained over 90% scorch, 42% of these trees subsequently died by 1986. However, most of the damage and mortality was confined to 3 of the 73 points; 11% of the stocked points were completely unburned. Mortality was equivalent to 1% of the preburn average basal area, and to 0.2% of the board-foot volume. No new basal scars were found on the sample trees.

Methods

Streamflow

We used a paired watershed approach to analyze the impacts of prescribed burning on water yields. Prefire regressions were developed between East Fork and West Fork, the control watershed (fig. 2). Similar regressions were prepared after the treatment period (1982-1987),[4] and the two were compared by covariance analysis to determine whether significant changes occurred. The October 1 - September 30 water year was used for all hydrological analyses. The current analyses was unusual because we reversed control watersheds for this experiment; East Fork had been the control for an earlier West Fork harvesting experiment (Rich 1972). This reversal only works if the relationship between the two watersheds has remained constant since the initial harvest treatment. To check for this we developed a linear regression for the 15-year postharvest period (1967-1981). The regression (fig. 2) had a coefficient of determination (r^2) of 0.994 and a standard error of 0.323 indicating the relationship had remained constant. The standard error for the postfire regression was 1.072. Since many watershed studies have shown a decline in treatment effects with time, the prefire relationship was also checked for

[4]*Colmer, Gerald K. 1988. Castle Creek hydrologic data for the 1984-1987 water years. USDA Forest Service, Apache-Sitgreaves National Forests, Springerville, AZ.*

changes over time using a technique described by Baker (1986), but again no significant influence was noted. Long-term mean annual runoff for West Fork (1967-1987) was used as our average independent variable (x) for calculating percent changes in water yield. This made the analysis less sensitive to extremely high or low streamflows, and gave a better indication of average changes. The same regression techniques and appropriate long-term means were used for analyzing seasonal and monthly runoff changes. Statistical significance was indicated by values above the 5% level.

Water Quality

Stream water samples were collected at the main gaging station of Castle Creek East (CC-East) and at a small flume installed at the base of a subwatershed (CC-Sub) in CC-East (fig. 1) during the snowmelt periods immediately preceding (spring 1981) and following the prescribed fire (spring 1982). A small Parshall flume had been installed in October 1979 to measure streamflow originating from the 61-acre subwatershed on the East Fork of Castle Creek. Water samples were collected at both gaging stations twice daily at 0500 and 1700 hours, when minimum and maximum stream discharges commonly occur during snowmelt in eastern Arizona. Sample bottles were charged with phenyl mercuric acetate (PMA) to eliminate microbial activity. Ambient temperatures were near freezing for most of the collection period, which further minimized changes in the water chemistry.

Water samples were analyzed for NH_4-N, NO_3-N, orthophosphate, calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K). Concentrations of N and P compounds were determined colorimetrically, and concentrations of the cations were determined using atomic absorption. All concentrations were reported in parts per million.

Changes in water quality were tested for statistical differences by using t-tests on averages of nutrient concentrations obtained during three snowmelt periods between February and May in 1981 (prefire) and 1982 (postfire). The three periods during snowmelt were: the first 10 days, the second 10 days, and the remainder of snowmelt. Although arbitrary, these periods were selected because we expected soluble nutrients produced by burning to dissolve and leave the watershed during initial snowmelt. Separate analyses were used for each watershed and nutrient for each of the three snowmelt periods.

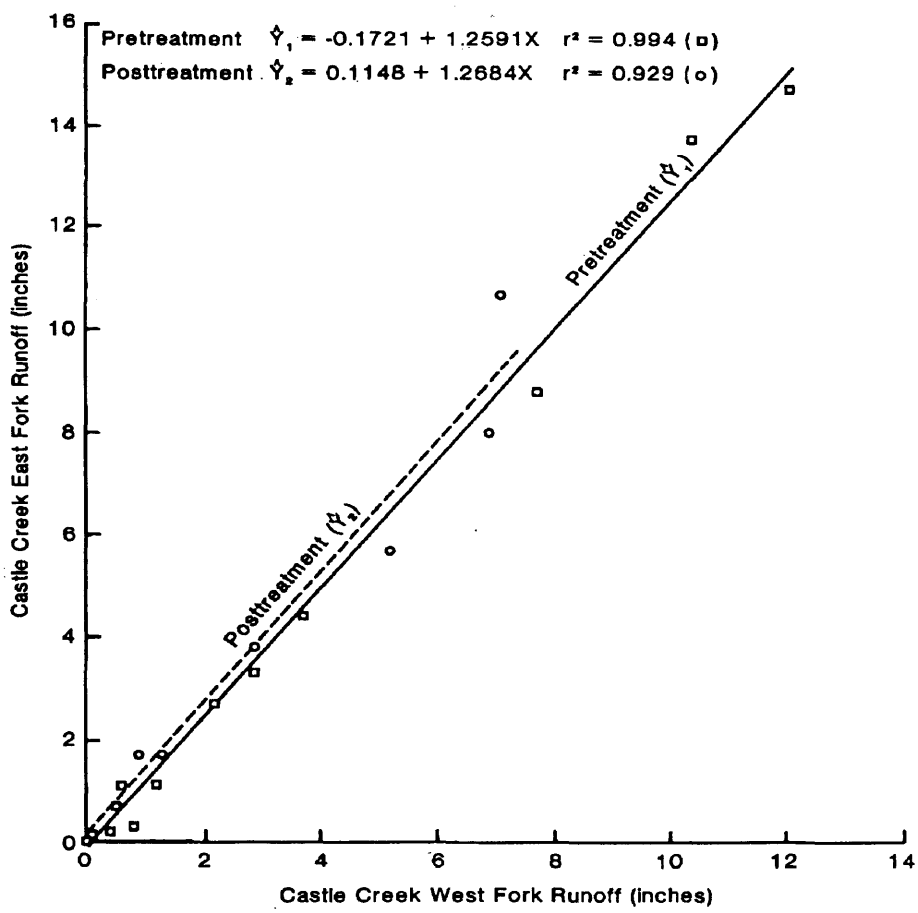

Figure 2.—The prescribed fire did not produce significant changes in annual streamflow; the pretreatment and posttreatment regressions were similar.

Results

Streamflow

The prescribed fire on East Fork, did not significantly increase average annual water yield (fig. 2). Analysis of six years (1982-1987) data during posttreatment showed streamflow increased 0.32 ± 0.70 inch (8% ± 18%) for the entire watershed, but this amount was small enough to have occurred by chance. If this increase were prorated over the burned area only, it would be equivalent to 0.74 inch, or an increase of about 19%. Analyses of pretreatment and posttreatment regressions for the 8-month winter period and for the summer period also showed fire did not significantly increase seasonal streamflow.

Evaluations of monthly runoff volumes indicated no statistically significant changes for January; for March and April, the two months with the greatest runoff; and for July and August, the two driest months. Analyses for the other seven months indicated some generally small but statistically significant differences. The February data showed the largest monthly increase of 0.11 ± 0.08 inch or 46% ± 34%. Increases of 0.03 ± 0.04 inch (24% ± 36%) were indicated for May and 0.02 ± 0.01 (26% ± 17%) for September. The other four months showed declines in runoff, but again the amounts were very small. Some of these differences may reflect the smaller data range in the posttreatment period rather than changes in actual hydrological processes.

Water Quality

Nutrients in stream water produced during snowmelt on both the large watershed (CC-East) and the subwatershed (CC-Sub) reflected the effects of prescribed burning (table 2). Concentrations of NH_4- and NO_3-N in stream water from CC-Sub increased upon the onset of spring runoff in contrast to CC-East where the increases occurred 10-20 days following the beginning of snowmelt. Phosphorus concentrations in stream water did not change significantly as a result of burning with the exception of a small, but significant, increase of PO_4 in the stream water leaving CC-Sub during the first snowmelt period (table 2).

The responses of cations to burning was variable (table 2). Changes in concentrations of Ca and Mg in response to burning were inconsistent between the two watersheds. Concentrations of K in stream water from CC-Sub increased significantly during the first two snowmelt periods following burning, in contrast to CC-East where it increased only during the second snowmelt period. Little change in concentrations of Na occurred in stream water as a result of burning.

Table 2.—Nutrient concentrations (ppm) of streamflow from Castle Creek East Fork (CC-E) and a small subwatershed (CC-Sub) during snowmelt periods before (spring 1981) and after (spring 1982) a moderately intense prescribed burn in a ponderosa pine forest in eastern Arizona.

Watershed		Nutrient						
Snowmelt period[1]	Fire	NH_4-N	NO_3-N	PO_4	Ca	Mg	K	Na
CC-Sub								
0-10	Pre	0.0017a[2]	0.0002a	0.32a	10.08a	6.95a	0.20a	2.48a
	Post	0.1550a	0.0018b	0.37a	10.06a	6.82a	0.38b	2.59a
11-20	Pre	0.0020a	0.0006a	0.32a	10.26a	6.90a	0.18a	2.58a
	Post	0.0222b	0.0016b	0.34a	9.62	6.48b	0.32b	2.58a
21+	Pre	0.0104a	0.0013a	0.33a	12.20a	8.12a	0.27a	2.89a
	Post	0.0101a	0.0029b	0.34a	10.68b	7.34b	0.31a	2.71a
CC-East								
0-10	Pre	0.0196a	0.0020a	0.47a	9.76a	5.93a	0.97a	2.42a
	Post	0.0251a	0.0019a	0.53b	11.45b	6.63b	1.05a	2.65a
11-20	Pre	0.0039a	0.0010a	0.49a	11.22a	6.71a	0.85a	2.76a
	Post	0.0104b	0.0010a	0.49a	12.77b	7.60b	0.98b	2.82a
21+	Pre	0.0041a	0.0004a	0.49a	15.72a	5.37a	0.77a	2.84a
	Post	0.0124b	0.0019b	0.49a	12.93b	8.00b	0.74a	2.88b

[1]*Days since the start of snowmelt.*

[2]*Prefire and postfire values for individual watersheds and nutrients having the same letter are not significant at the 0.05 level.*

Discussion

The prescribed fire did not significantly increase streamflow volumes. This is not surprising because forest conditions were not really affected by the fire, only 5% of the trees per acre and 1% of the preburn basal area per acre were destroyed. Most water yield increases in southwestern forests occurred when mature conifers were replaced by grass, herbaceous species, or by conifer seedlings (Rich 1972, Rich and Gottfried 1976). The replacement vegetation uses less soil water during the growing season, and consequently less winter precipitation is needed to recharge the soil. Also, there is an earlier and more efficient movement of soil water into the stream system. On East Fork, no large openings were created—even the heavily damaged areas remained stocked. Some streamflow increases have also been attributed to partial cutting. The single-tree selection harvest at Workman Creek produced a small (0.23 inch) but statistically significant runoff increase (Rich and Gottfried 1976); Troendle and King (1987) have reported increases from partial cutting during wet years in Colorado. However, the stand loss on East Fork was much less than that which would have occurred in even the most conservative timber harvesting operation. A more severe reduction in stand density could have produced water yield increases, but it is uncertain how large a reduction would have been necessary.

Fire consumed little of the forest floor, which protects the soil and enhances infiltration. Most water movement on Castle Creek occurs as subsurface flow. A more complete loss of the forest floor could have produced more soil surface runoff and increased streamflow but at the cost of increased soil erosion.

The small but statistically significant changes in monthly streamflow were interesting even if they did not affect annual or seasonal volumes.

The largest increase, in February, could be related to higher infiltration during initial melting periods because of forest floor depth reductions and to more rapid snowmelting because of charred slash and tree trunks, which absorb more heat. Early season snowmelt, after soil recharge, is more efficient because evapotranspiration is low, and more water can reach the channels. Unfortunately, postfire measurements of forest floor depth, soil water, and infiltration to the soil were not made. May and September increases could be related to more water reaching the soil and less being held by, or evaporating from, the forest floor. Greater soil water on relatively deep soils results in longer runoff periods in the spring and greater runoff during the late summer. The decline in June flows could be related to higher flows in February and May, but this study could not demonstrate this. However, these volumes are too small to be considered in management planning.

It is unfortunate that the entire project area could not have been burned. However, the fact that only 43% of the watershed was treated does not preclude the possibility of measuring water yield changes. Increases were detected on the North Fork of Workman Creek when 32% of the watershed was treated (Rich and Gottfried 1976) and on the West Fork of Castle Creek when only 16% of the area was cleared (Rich 1972). The fact that burned areas were concentrated adjacent to the weir or channel (fig. 1) would have enhanced the chances of detecting increases because transmission distances, and resulting losses, would be smaller. We cannot assume that a more complete burn would have resulted in significant changes; variations in stand density, soil depth, water storage capacity, topography, or distances to stream channel lead to variations in a site's potential for water yield improvement even under severe vegetation reduction. East Fork is, in fact, a more realistic example of what could occur on a larger watershed where it is unlikely that the entire area would be burned.

Most changes in stream water chemistry in response to prescribed burning were expected. The increased concentrations of NH_4- and NO_3-N in stream water leaving the two gaged watersheds following fire probably occurred because NH_3 produced during the fire volatilized slowly over winter, became trapped in the snow pack, and remained there until spring snowmelt. Ammonia-N can remain high in soil for several months following fire before being decreased by nitrification and further volatilization. The increased concentrations of NO_3-N in the stream water following burning probably reflect nitrification because NO_3-N is usually not formed directly by burning. Phosphorus did not respond as expected because fire usually releases significant quantities of highly available phosphorus (DeBano and Klopatek 1988). The inconsistent increases and decreases in Ca and Mg between CC-Sub and CC-East cannot be explained. The increases in concentrations of K in the stream water leaving CC-Sub following burning probably represented losses of highly mobile K produced during burning.

Conclusions

The prescribed fire, which covered 43% of a previously undisturbed ponderosa pine watershed, did not result in statistically significant increases in annual or seasonal streamflow. These results were anticipated because damage to the forest stand was minimal, and the forest floor remained intact even though surface fuels were generally consumed.

Although statistically significant changes in nutrient concentrations occurred as a result of the prescribed fire on Castle Creek East, the changes were very small and of little consequence in terms of site productivity or downstream water quality. Changes in N and P compounds, which are important from the standpoint of water quality, only changed a fraction of one part per million, which is insignificant in terms of adversely affecting water quality.

Literature Cited

Agee, James K. 1973. Prescribed fire effects on physical and hydrological properties of mixed-conifer forest floor and soil. Water Resource Center, Davis, CA: University of California Contributed Report 143. 57 p.

Arno, Stephen F. 1980. Forest fire history in the northern Rockies. Journal of Forestry. 78: 460-465.

Baker, Malchus B. 1986. Effects of ponderosa pine treatments on water yields in Arizona. Water Resources Research. 22: 67-73.

Biswell, H. H.; Schultz, A. M. 1957. Surface runoff and erosion as related to prescribed burning. Journal of Forestry. 55: 372-374.

Campbell, R. E.; Baker, M. B., Jr.; Ffolliott, P. F.; Larson, F.R.; Avery, C. C. 1977. Wildfire effects on a ponderosa pine ecosystem: an Arizona case study. Res. Pap. RM-191. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 12 p.

Clary, Warren P.; Ffolliott, Peter F. 1969. Water holding capacity of ponderosa pine forest floor layer. Journal of Soil and Water Conservation. 24: 22-23.

Cooper, Charles F. 1961. Controlled burning and watershed condition in the White Mountains of Arizona. J. of Forestry. 59: 438-442.

Covington, W. W.; Sackett, S. S. 1986. Effect of periodic burning on soil nitrogen concentrations in ponderosa pine. Soil Science Society of America Journal. 50: 452-457.

DeBano, L.F. 1981. Water repellent soils: a state-of-the-art. Gen. Tech. Rep. PSW-46. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. 21 p.

DeBano, Leonard F.; Klopatek, Jeffrey M. 1988. Phosphorus dynamics of pinyon-juniper soils following simulated burning. Soil Science Society of America Journal. 52: 271-277.

Dieterich, John H. 1983. Fire history of southwestern mixed conifer: a case study. Forest Ecology and Management. 6: 13-31.

Haase, Sally M. 1986. Effect of prescribed burning on soil moisture and germination of southwestern ponderosa pine seed on basaltic soils. Res. Note RM-462. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 6 p.

Laing, Larry; Ambos, Norman; Subirge, Tom; McDonald, Christine; Nelson, Chris; Robbie, Wayne. 1988. Terrestrial ecosystem survey of the Apache-Sitgreaves National Forests. Albuquerque, NM: U.S. Department of Agriculture, Forest Service, Southwestern Region. 453 p.

Rich, Lowell R. 1972. Managing a ponderosa pine forest to increase water yield. Water Resources Research. 8: 422-428.

Rich, Lowell R.; Gottfried, Gerald J. 1976. Water yields resulting from treatment on the Workman Creek experimental watersheds in central Arizona. Water Resources Research. 12: 1053-1060.

Ryan, Michael G.; Covington, W. Wallace. 1986. Effect of a prescribed burn in ponderosa pine on inorganic nitrogen concentrations of mineral soil. Res. Note RM-464. Fort Collins: CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 5 p.

Sackett, Stephen S. 1979. Natural fuel loading in ponderosa pine and mixed conifer forests of the Southwest. Res. Pap. RM-213. Fort Collins, CO; U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 10 p.

Sims, Bruce D.; Lehman, Gordon S.; Ffolliott, Peter F. 1981. Some effects of controlled burning on surface water quality. In: Hydrology and water resources in Arizona and the Southwest. Vol 11. Proceedings of the 1981 Meetings of the Arizona Section—American Water Resources Association and the Hydrology Section—Arizona-Nevada Academy of Science; 1981 May 1-2; Tucson, AZ: 87-90.

Tiedemann, Arthur, R.; Conrad, Carol E.; Dieterich, John H.; Hornbeck, James W.; Megahan, Walter F.; Viereck, Leslie A.; Wade, Dale D. 1979. Effects of fire on water. Gen. Tech. Rep. WO-10. Washington, DC: U.S. Department of Agriculture, Forest Service. 28 p.

Troendle, C. A.; King, R. M. 1987. The effect of partial and clear cutting on streamflow at Deadhorse Creek, Colorado. Journal of Hydrology. 90: 145-157.

Vlamis, J.; Biswell, H. H.; Schultz, A. M. 1955. Effects of prescribed burning on soil fertility in second growth ponderosa pine. Journal of Forestry. 53: 905-909.