Reports

Prescribed Fire: Effects on Water Quality and Forest Nutrient Cycling

Abstract. *Prescribed fire, a practice applied annually to about 10^6 hectares of forests in the southeastern United States, had limited effects on soils, nutrient cycling, and hydrologic systems of a coastal plain pine forest. Hydrologic fluxes of nitrogen, phosphorus, sulfur, and basic cations, from burned pine litter to ground and stream waters, are not likely to have appreciable impacts on water quality in the Atlantic and Gulf Coastal Plain.*

Fire has affected many if not most of the world's forests. The effects of fire on forest ecosystems vary greatly and depend on the quality and quantity of fuels, soil properties, topography, climate, weather, and fire frequency and intensity (*1, 2*). Although wildfires can radically alter forest nutrient cycling and in some cases diminish site productivity, many fires apparently have little effect on long-term nutrient reserves or site productivity and serve purposes useful to forest management (*3*).

In the southeastern United States, about 10^6 ha of forestlands are annually subjected to prescribed fire, a practice that has taken on major importance in the multiresource management of southern pine forests. Prescribed fire is controlled burning of forested areas for specific land management objectives. Controlled burning in forest management was largely developed in pine forests of the Atlantic and Gulf Coastal Plain, ecosystems with important natural fire cycles. In this region, prescribed fire reduces the risks of wildfire, controls certain tree pathogens, manipulates the density and composition of understory vegetation, and promotes food and habitat for wild and domestic animals, all with a remarkable degree of economy (*4*). Although the effects of prescribed fire on forest nutrients have received increasing attention over the last 50 years (*3, 5, 6*), comprehensive studies of the effects of fire on the quality of stream and ground waters are notably absent.

This report examines both the off-site and on-site effects of a series of prescribed fires on experimental watersheds in the Lower Coastal Plain of South Carolina (*7*). Studies of off-site effects were concerned with fire-caused exports of materials from a pine forest ecosystem to drainage waters and the atmosphere, whereas studies of on-site effects focused on the magnitude and extent of hydrologic fluxes of nutrients from burned litter to mineral soils and ground waters (*8*).

Despite early recognition of N volatilization during forest fires, nutrient losses to the atmosphere have received relatively little study. Fire-caused releases of forest floor nutrients to the atmosphere, by volatilization and particulate transport in turbulent updrafts, were estimated as a result of intensive sampling of the forest floor before and immediately after four fires (*9*). Releases of N and S from the forest floor to the atmosphere varied greatly between fires, with largest releases of 40.0 kg of N per hectare and 8.0 kg of S per hectare (Table 1). These N loss estimates suggest that losses of N from southern pine forest floors during prescribed fires may be lower than those commonly quoted from the data of one field estimate at an N-rich site (*3, 6, 10*). Several factors apparently limit forest floor N releases during prescribed fires. A steep moisture gradient between the forest floor surface and mineral soil tends to restrict combustion to surficial litter layers, so that most prescribed fires consume less than one-third of the total forest floor mass (*11*). Furthermore, as a result of decomposition processes, N is most concentrated in the basal layers of the forest floor (*12*). Thus, fires that burn only surface layers of litter consume organic layers with the lowest N concentrations. Several long-term studies of prescribed fire in southern pine forests have not indicated soil N depletions of consequence to forest productivity (*3*); in fact, N additions by microbiological fixation may be stimulated by fires (*3, 13*). Release of S by prescribed fires is not expected to be of consequence to the S nutrition of forest vegetation on the study watersheds, as annual S inputs in bulk precipitation (7.5 kg of SO_4^{2-}-S per hectare) equaled or exceeded the S released by fires (Table 1). Releases of forest floor P, Ca, Mg, and K to the atmosphere from burning were small and consistently within the limits of sampling error.

Table 1. Reductions in forest floor weight and contents of N and S caused by prescribed fires on four different areas of Santee Experimental Watershed 77 (mean ± the standard error of the mean).

Fire date	Ash-free weight loss (ton/ha)	N release (kg/ha)	S release (kg/ha)
Winter, 1978	2.5 ± 1.2	11 ± 12	1.4 ± 1.6
Summer, 1978	5.0 ± 3.1	23 ± 25	5.4 ± 5.0
Winter, 1979	7.5 ± 1.1	34 ± 11	8.0 ± 1.7
Summer, 1979	5.0 ± 2.3	40 ± 20	6.3 ± 3.9
Mean*	5.0 ± 0.8	24 ± 9	4.8 ± 1.1

*Weighted in terms of the area burned in each fire. Before fires, the mean forest floor mass was 21.7 ± 0.6 ton/ha (ash-free) and contained 170.8 ± 6.6 and 27.3 ± 0.9 kg per hectare of N and S, respectively. The weight estimate was from 110 samples, and nutrient estimates were from 55 composited samples.

Hydrologic nutrient fluxes from burned forest floors were evaluated from the nutrient contents of litter samples collected immediately after the fire and again after postburn rainfall of about 15 cm. The contents of total N, P, and S in burned forest floors were not significantly altered by this initial rainfall. Concentrations of water-soluble K^+, Mg^{2+}, and Ca^{2+} and NH_4Cl-extractable K^+ in burned forest floor samples were significantly reduced by the initial 15 cm of rainfall, although the quantities were small, for example, equivalent to about 1.0, 0.5, and 0.5 kg per hectare of water-soluble K^+, Mg^{2+}, and Ca^{2+}, respectively.

Analysis of mineral soil collections before fire and after fire and rain indicated minor effects of fires on mineral soil chemical properties, despite variations in fire intensities and in postburn leaching conditions (*14*). Changes in the total mineral soil C, N, and P were small, as were those for acid-extractable NH_4^+, NO_3^-, PO_4^{3-}, Ca^{2+}, Mg^{2+}, K^+, and Na^+, after fires and about 15 cm of rainfall. All variations in soil nutrients were within the limits of sampling errors, and these results were consistent with those found for litter-leaching experiments described above.

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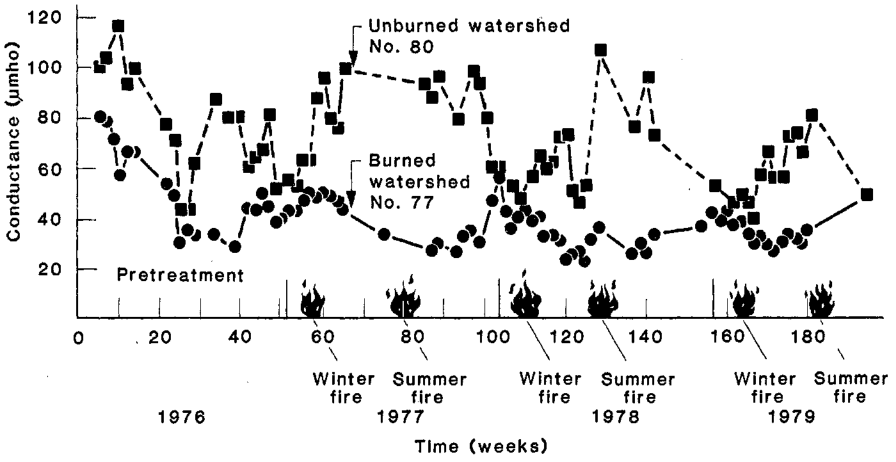

Fig. 1. Weekly specific conductance of streamflows from burned and unburned watersheds at the Santee Experimental Forest in South Carolina. Higher conductance values for the unburned watershed result from ground water inputs from shallow calcareous substrata.

The effects of fire on the ground water chemistry were evaluated from a 32-well network located in burned and unburned areas of the treatment watershed that was sampled weekly in pre- and postburn periods (*15*). The results indicated no fire effects on specific conductance, *p*H, or dissolved concentrations of NH$_4^+$, NO$_3^-$, PO$_4^{3-}$, SO$_4^{2-}$, Cl$^-$, Ca^{2+}, Mg^{2+}, K$^+$, or Na$^+$ in ground waters collected from surface soil and subsoil horizons. Ground water concentrations of NO$_3^-$-N, NH$_4^+$-N, and PO$_4^{3-}$-P were low throughout the 20-week sampling period, averaging about 0.01, 0.20, and 0.02 mg/liter, respectively, in surface soil horizons, and 0.006, 0.03, and 0.01 mg/liter, respectively, in subsoil horizons. Periodic sampling for 1 year after the burns indicated no effects of fire on *p*H or specific conductance.

Paired, gaged watersheds were used from 1976 to 1979 to evaluate the effects of prescribed fires on stream water quality (*7*). The experimental method consisted of comparing stream nutrient outputs from treatment and control watersheds before and after fires. After 1 year in an undisturbed condition (1976), a sequence of six prescribed fires was administered to a total of about 60 percent of the treatment watershed during a 2.5-year period (1977 to mid-1979). The treatment watershed was subjected to winter and summer fires in accordance with the burning prescription used for managing many pine stands in the coastal plain (5-year fire cycle). Thus, nutrient outputs from the treatment watershed reflect responses of an operational forest, something quite distinct from those of a number of watershed experiments where treatments have been applied to entire watersheds (*16*).

Weekly stream sampling in combination with 12 chemical analyses of each sample (total N, NH$_4^+$, NO$_3^-$, PO$_4^{3-}$, SO$_4^{2-}$, Cl$^-$, Ca^{2+}, Mg^{2+}, K$^+$, Na$^+$, HCO$_3^-$, and H$^+$) was conducted throughout the 3.5-year period. Paired watershed regression models of dissolved chemical contents in weekly streamflows before and after fires revealed no changes in the chemical constituents of the stream that were attributable to the fire treatments. A plot of the specific conductance of streamflows from treated and control watersheds (Fig. 1) confirms this conclusion. Volume-weighted stream water concentrations of NO$_3^-$-N, NH$_4^+$-N, and PO$_4^{3-}$-P averaged about 0.02, 0.03, and 0.03 mg/liter, respectively, in water draining from both burned and unburned watersheds, with no significant differences between the pre- and postburn periods.

There are several reasons why prescribed fires produced no detectable changes in the chemical composition of stream water during the course of this study. First, prescribed fires consumed less than one-third of the forest floor mass, which was composed of pine litter materials having low ash contents. Thus, rather small quantities of ash elements were released by burning. Second, suspensions of ash particulates and solutions of water-soluble elements were filtered by unburned litter and soil layers before emerging as streamflow. Additional filtration was provided by 20-m-wide unburned buffer strips adjacent to stream channels. Third, application of fire treatments on a 5-year fire cycle introduced a substantial dilution factor, since stream water collected at the weir included runoff from both burned and unburned portions of the treatment watershed. However, it is not likely that this dilution effect had a major influence on the findings of this study, as samplings at points immediately upstream and downstream of burned compartments showed no detectable fire effects on the chemical composition of stream water (*17*).

The results of this study indicate that periodic prescribed fires in southeastern coastal plain pine forests are not likely to have appreciable effects on the quality of ground or stream waters. Considering the utility of prescribed fire in the multiresource management of these forests, it is doubtful that alternative practices could accomplish these objectives with such small environmental costs.

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7. The coastal watersheds are located in the Santee Experimental Forest within the Francis Marion National Forest near Charleston, S.C. Treatment and control watersheds are about 160 and 200 ha in area, respectively, with topographic relief less than 5.5 m. Soils are primarily strongly acid, infertile Aquults, characterized by seasonally high water tables and argillic horizons with low base saturation. A calcareous soil, Meggett series, is found along stream drainages of the control watershed. Forests now present on the watersheds are primarily natural stands of loblolly pine (*Pinus taeda L.*). The treatment watershed was divided into 20 management compartments (each 7.1 ha) with 20-m-wide buffer strips left bordering the stream channels. During the winters of 1976–77, 1977–78, and 1978–79, a total of 12 compartments were burned, four each year. A series of three summer burns was administered to the four compartments winter-burned in 1976–77.
8. Water samples were analyzed for *p*H, conductivity, and HCO$_3^-$ on the day of collection then preserved with phenylmercuric acetate and stored at 4°C prior to chemical analysis. Forest floor samples were dried at 65°C, weighed, and ground in a Wiley mill; subsamples were ashed at 500°C to convert weight and nutrient contents to an ash-free basis. Mineral soil samples were air-dried, weighed, and ground to pass through a 2-mm screen; subsamples were dried in an oven at 105°C to convert weight and nutrient contents

to an oven-dry basis. In the chemical analyses of water, forest floor, and mineral soil we followed well-established procedures, using a Technicon Auto Analyzer for colorimetric determinations (NH_4^+, NO_3^-, Cl^-, SO_4^{2-}, and PO_4^{3-}) and an atomic absorption spectrophotometer for the analyses of metal cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+).
9. Forest floor composite samples were collected before and after fires at each of 110 randomly located semipermanent plots. The sample area totaled about 80 ha of the treatment watershed.
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14. Composite mineral soil samples were collected from three soil depths at each of 110 semipermanent plots before fires and again after fires and about 15 cm of rainfall (a 2- to 3-month interval). Soil sampling was organized in a randomized complete block design with blocks (7-ha burning compartments), soil horizons, and fire as main effects and fire and horizon interaction effects as potential sources of variation of experimental importance.
15. Wells sampled two types of ground water: ground water flow through surface soils and ground water from subsoils (at 10- to 15-cm and at 30- to 35-cm soil depths, respectively). Prefire concentration means for individual wells were used as covariates in an analysis of covariance, since they markedly improved the precision of fire-test models for most chemical constituents. Rainfall was above average during the postburn sampling period.
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18. Supported by cooperative research grants from the Southeastern Forest Experiment Station, U.S. Department of Agriculture Forest Service, and Duke University. Partial support for manuscript preparation was received from Oak Ridge National Laboratory, U.S. Department of Energy, under contract W-7405-eng-26 with Union Carbide Corporation. We thank O. G. Langdon, J. E. Douglass, J. E. Henderson, and W. P. LeGrande, members of the U.S. Forest Service. We also thank more than 15 graduate students of the School of Forestry and Environmental Studies, Duke University, and especially D. A. Binstock and Phu van Nguyen. Publication No. 1739, Environmental Sciences Division, Oak Ridge National Laboratory.
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Salt Diapirs Bordering the Continental Margin of Northern Kenya and Southern Somalia

Abstract. *The presence of newly discovered diapirs of presumed salt origin is documented for the continental margin of northeastern Kenya and southeastern Somalia. These structures are probably a manifestation of a significant thickness of Lower Jurassic evaporites deposited during the rift and early-drift stages of the separation of Madagascar from the African continent.*

The proximity and parallelism of salt formations to continental margins and their presence at conjugate locations on both sides of the mid-ocean ridges have led several investigators to believe that the deposition of salt is related to processes active during the very early separation of the continents (*1*). In this report we document the presence of newly discovered diapiric structures that border the continental margin of northeastern Kenya and southeastern Somalia. We believe that these structures are salt diapirs on the subsided continent and on the embryonic ocean floor created during the separation of Madagascar from the mainland of Africa.

Salt deposits have been inferred on the basis of geophysical measurements beneath the sea floor of many rifted or passive continental margins and have in some instances been confirmed by drilling (*1*, *2*). Often, these deposits appear on seismic reflection profiler records as prominent diapiric structures. In places, they border the margins at conjugate locations on both sides of the mid-ocean ridges; for example, salt diapirs are observed on seismic reflection profiles on the continental margins of the South Atlantic Ocean north of the Rio Grande Rise–Walvis Ridge complex (*3*) and bordering the conjugate margins of Morocco and Nova Scotia (*1*, *4*) and of the Red Sea (*5*). Similar salt deposits have been inferred on the Atlantic continental margin of the United States as well as its predrift location off northwestern Africa (*6*).

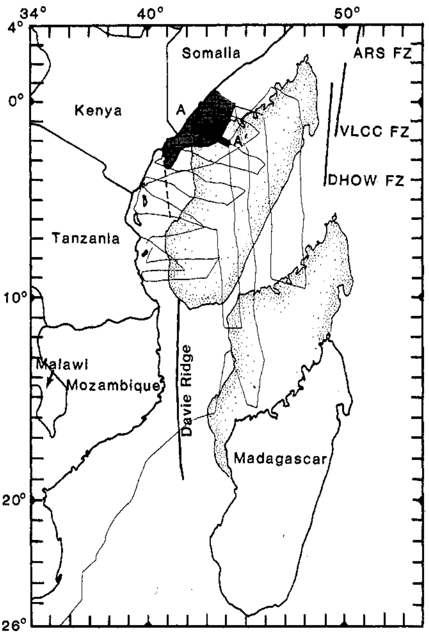

Fig. 1. Map of the study area. Madagascar is rotated back to its prebreakup position adjacent to East Africa according to the parameters of Bunce and Molnar (*10*). The track lines of R.V. *Vema* cruises 3618 and 3619 are shown as thin solid lines. Davie Ridge, the fracture zones (*FZ*) of Bunce and Molnar (heavy solid lines), and the gravity high (dashed line) are marked. The evaporite province is cross-hatched. Profile *A*–*A′* appears in Fig. 2.

Cruises 3618 and 3619 of R.V. *Vema* (see Fig. 1 for navigation) were devoted to studying the evolution of the western Somali Basin and East African continental margin by the use of geophysical techniques (multichannel seismic reflection, seismic refraction, gravity, magnetics, and echo sounding). Implicit in this study were the kinematics of the Madagascar-Africa separation.

Investigators have proposed several reconstructions for the fit of Madagascar in the Gondwana supercontinent (*7*). The weight of paleomagnetic evidence (*8*), physiographic evidence (*9*, *10*), and inferences from gravity measurements (*11*) strongly suggests that Madagascar moved south from northeastern Kenya and southeastern Somalia (Fig. 1). If this is correct, the margin bordering most of Kenya and Tanzania was created by the transform motion of Madagascar along Africa; the margin of northeastern Kenya and southeastern Somalia was formed by the rifting and drifting of Madagascar from Africa. The ship's track for the first of the two cruises was planned to determine the structures associated with the separation of Madagascar from the African continent. A major discovery of this cruise was the observation of a diapir field located on the continental margin of northeastern Kenya and southeastern Somalia. The diapiric structures are observed only on that portion of the continental margin formed by the rifting of Madagascar from Africa; they are not observed on the transform margin. Figure 1 shows the relative motion of Madagascar from Africa, based on the poles and rotations given by Bunce and Molnar (*10*), together with the location of the zone of diapiric structures as observed on seismic reflection records.

A typical crossing of the rifted section of the margin showing the diapirs is given in Fig. 2. The tops of the diapirs are covered, in general, by sediments with thicknesses between ~ 0.50 and ~ 0.75 second of the two-way travel time (~ 450 to ~ 675 m, based on a sediment velocity of 1.80 km/sec deter-

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