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EFFECTS OF FIRE ON NUTRIENT MOVEMENT IN A SOUTH CAROLINA PINE FOREST[1]

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Abstract. The movement of major cations, nitrate, and phosphate was studied in burned and control areas of a South Carolina pine forest. Artificial leaching of litter showed that fire increased the solubility of cations by the following factors: Ca^{++}, 20×; Mg^{++}, 10×; Na^{+}, 2.3×; K^{+}, 2.3×. Natural leaching over a 1-mo period reduced the ion yield of burned litter by 80%–83% for divalent cations and 45%–63% for monovalent cations. Amounts of soluble nitrate and phosphate were identical in burned and unburned litter samples. Nitrate and phosphate were substantially higher in the first rainfall at the burned area after the burn, but not in subsequent rains. Collections of rainfall plus fallout from the burned area consistently contained about twice the amounts of cations present in similar collections from the unburned area. Runoff was low but contained greater amounts of cations in the burned area. Samples of superficial groundwater provide some evidence for changes in ionic balance due to burning.

Biologically available N and P in the litter is apparently not increased directly by burning, but a rise in soluble nitrate and phosphate occurs some time after the burn and is probably due to increased microbial activity. Large amounts of N are probably volatilized and could exercise important effects on the productivity of systems remote from the burn if some biologically active compounds are included in the vapor. Although the upper soil layers are an efficient adsorption trap for cations, there is a potentially important movement of ions in runoff, in groundwater, or in the wind as particulate matter following a fire.

Key words: *Fire ecology*; *forest fires*; *nutrient movement*; *prescribed burning.*

INTRODUCTION

A growing portion of the landscape in the southeastern United States is intentionally burned at intervals of one to several years in connection with timber management. Fire stimulates pine growth, eliminates or reduces hardwood competition, controls brown spot disease (*Scirrhia acicola* (Dearn.) Siggers) in longleaf pine, and reduces wildfire hazard by elimination of litter. Since prescribed burning is an economical means of preserving and purifying pine monocultures, many private and government timber farms are convinced that increases in yields will more than compensate the cost of a burning program. One author (Dieterich 1971) estimates that a total of 2.5 million acres were burned in the South during 1970 as a management practice. It is reasonable to expect that both the extent and frequency of prescribed burning will continue to increase as the value of timber rises. Ecological consequences of burning are thus of great interest.

Prescribed burning actually includes two separate management practices. Cleared land may be burned as a means of site preparation, which facilitates the forced transition from hardwood or mixed timber to a uniform pine crop. This type of burning of course occurs only once during each management cycle. Periodic burning of established pine populations, to which this work is specifically directed, is a second type of prescribed burning. In this case, pine stands of all except the youngest ages are burned during winter at intervals of one to several years.

Obvious problems associated with prescribed burning include uncontrolled fires, inevitable air pollution, and, in the case of government tree farms at least, a glaring conflict between the rationale of Smokey the Bear and that of the prescribed burner. An additional host of more subtle ecological effects has been recognized but not yet fully investigated. Soil properties may change in response to heat and increased exposure (DeBano et al. 1970, Ralston and Hatchell 1971), and burning apparently alters the partitioning of nutrients between litter and mineral soil (Metz et al. 1961, Wells 1971). Biological effects are less well understood. Although fire might reasonably be expected to interrupt many decomposer-based food chains and even further simplify the biotic composition of even-aged pine forests, few generalizations can be made at present. Equally obscure is the potential effect of fire in translocating substantial amounts of nutrients between major ecosystem compartments or across ecosystem boundaries.

Prescribed burning reduces a large portion of the forest litter to ash. Substances that would otherwise

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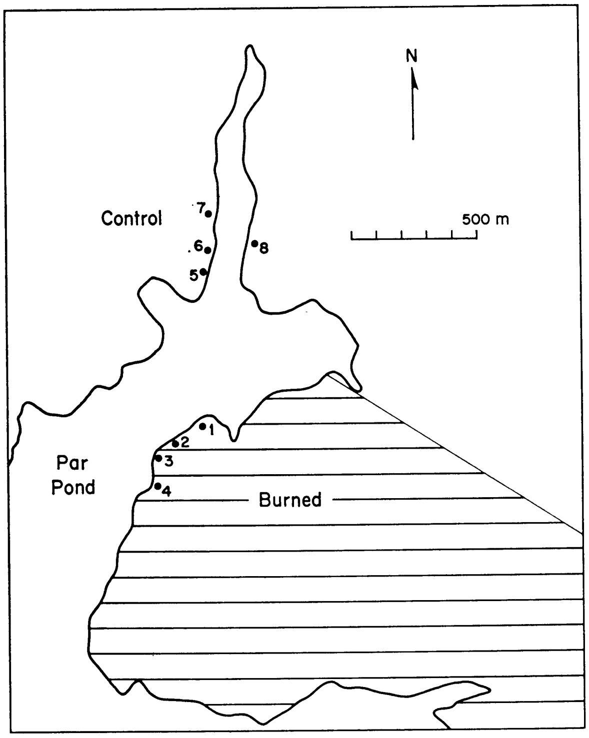

FIG. 1. Map of the study area showing location of the stations and extent of the burned area. Prevailing winds blew from control area toward burned area during the study period.

be locked into the nutrient reservoir of the litter may thus be rendered volatile, water soluble, or suitable for suspension in air as fine particulate matter. Burned litter is also likely to retain less rainwater than does unburned litter, so both runoff and seepage could be higher than in unburned forests. The possibilities for movement of essential plant nutrients are thus numerous. Nutrient movement is likely to be manifested as a decrease in the amounts of nutrients stored in litter and an increase in the amounts stored in all other major compartments of the ecosystem. In addition, there may be sudden massive losses of nutrients across ecosystem boundaries. This work compares nutrient partitioning and movement in burned and unburned areas of a tree farm located in the coastal plain of South Carolina. Emphasis is placed on the release of nutrients from terrestrial to aquatic systems.

Study Site and Methods

The study was conducted on the USAEC's Savannah River Plant within the watershed of Par Pond, a 2,600-acre reservoir. The soil in the region of the study site is sandy and infertile with an ion exchange capacity of approximately .01–.03 meq/g (Langley and Marter 1973). Most of the watershed is planted with loblolly, slash, and longleaf pines (*Pinus taeda* L., *P. elliottii* Engelm., *P. palustris* Mill.). None of the stands in the vicinity of the study area had ever been burned prior to initiation of the study except at the time of site preparation.

The control and burned areas (Fig. 1) vary somewhat in timber composition. All four of the sampling stations inside the burned area are within a stand of loblolly pine (23 yr). The adjacent control area is predominately slash pine (18 yr), except that station 8 is loblolly (ca. 30 yr). Exact composition and age were not considered critical to comparisons made, and no differences between loblolly control and slash control were obvious in the results.

Stations were positioned just subsequent to the prescribed burn on 21 February 1973. Site selections were not entirely random, as obviously unusual relief or vegetational features in the watershed were avoided. The stations were situated a minimum of 100 m apart and exactly 4 m inland from the water's edge. Collections of rainwater, runoff, groundwater, and litter were made in duplicate at points 10 m apart at each station. A verbal distinction is thus preserved between the stations, of which there are 8 (4 control and 4 treatment, Fig. 1), the collection points (2 at each station), and the samples (1 or more at each collection point depending on date and type of sampling).

One rainfall/runoff collector was situated at each of the 16 collection points, and these collectors were sampled and emptied immediately subsequent to each rain or continuously rainy period during the study period. Open-topped rectangular plastic chambers measuring 33 × 28 × 13 cm served as rainfall/runoff collectors. The chambers were divided into separate upper and lower halves by insertion of a plastic false bottom. The upper half was thus open to the air and collected both dry fallout and rainfall. The lower half, which collected runoff, was sealed except for a slot 25 cm long and 2 cm high running parallel to the bottom of the chamber. To the bottom edge of the slot was attached a flat plastic lip 2 cm broad extending the length of the collector. A hole was dug at each site to accommodate the bottom of the collector, and the depth of this hole was adjusted so that the plastic lip just beneath the slot on the lower half of the collector could be inserted below the upper margin of the mineral soil layer. The lower half of the collector thus trapped all runoff along the 25-cm uphill face of the collector while the upper half separately collected rainfall and fallout. Runoff was so low that scarcely any large debris was moved; hence the runoff slot never became occluded during collection as it might in other habitats. The slope 1 m in front of the 16 collectors averaged 9.4% (SE 1.3%).

The specific conductance of rainfall and runoff samples was obtained shortly after the collection of samples as an indication of total ionic load. Samples were treated with chloroform at the time of collection to prevent biological activity pending analysis for cations, nitrate, and phosphate. Since the samples were stored prior to analysis, small differences or low levels of any substance may have been determined with less precision than if the samples had been fresh. Major cations were determined by atomic absorption. Levels of NO_3-N were obtained by nitrite analysis (Bendschneider and Robinson 1952) following reduction to nitrite with a cadmium-copper couple (Wood et al. 1967). The determination actually measures nitrite plus nitrate, but for convenience the sum will be referred to as nitrate, which is likely to be the major constituent. At the same time PO_4-P was determined by an ascorbic acid/molybdate method (Strickland and Parsons 1972).

Litter samples were collected immediately after the burn in both burned and control areas. Two points 1 m on either side of each rainfall/runoff collector were cleared over an area 25 × 25 cm. Sixteen of the 32 samples collected in this way were dried to constant weight at 105°C to provide an estimate of total dry weight of litter. The remaining 16 (duplicate) samples were weighed and washed in a quantitative manner shortly after collection to provide an estimate of leachable nutrients in the litter. All samples were thoroughly agitated by hand for exactly 30 s with 1.0 liter of distilled water. The wash was then decanted and filtered under a 0.5 atm vacuum onto rinsed glass fiber paper with a pore size of 2 μm. Analysis followed the same procedure as for rainwater and runoff. A second set of litter samples was put through the same procedure after the study areas had been rained on several times.

Groundwater samples were taken at control and burned areas 5 wk after the burn to test for groundwater penetration of soluble nutrients. An aluminum pipe 8 cm in diameter was driven 75 cm into the ground exactly 1 m from the water's edge at each collection point. Water was allowed to seep into the hole until equilibrium was established at some point 14–22 cm below the soil surface. Two 500-cm^3 samples were then removed from each hole with an aspirated plastic tube placed 2 cm below the water surface in the hole. The water was clean and did not require filtration, but was treated with chloroform. Analysis followed the same procedure as for other samples.

The data analysis required repeated comparisons of mean measurements at burned and control stations. Such comparisons were conducted by means of the nonparametric Wilcoxon two-sample test

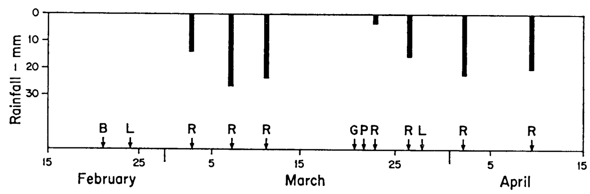

FIG. 2. Schedule of events and rainfall over the study period. Symbols along the abscissa indicate the incidence of burning (B), litter collection (L), rainfall (R), groundwater collection (G), and pine pollen peak (P).

(Sokal and Rohlf 1969) except where other tests are specifically mentioned.

RESULTS

The sampling schedule and its relation to rainfall are shown in Fig. 2. The burn was conducted on a relatively calm, cool day in accordance with standard management practice. The fire was probably hot compared to some prescribed burns because the area had not been previously burned. Trunks were scorched to a height of 2–4m on the windward side and about 0.5 m on the lee side. The uppermost surface of the burned litter was covered with fine white ash. Beneath this was a much larger quantity of black ash and partly burned litter.

The dry weight of litter from the burned area averaged 85% of the wet weight (range 80%–89%). Litter from the control area did not differ significantly from burned litter in this respect (mean 85%, range 85%–89%). The absence of a significant reduction in percent water content of litter by fire is of course explained by the small weight of the ash compared to the weight of residual (unburned) litter on the burned area. The total dry weight of litter in the burned area just subsequent to the burn was 890 g/m^2 (SE 190 g/m^2), and reduction in dry weight of litter by fire averaged 33%.

The total amount of leachable material was greatly increased by fire, but the effect varied for specific cations (Table 1). Divalent cations increased dramatically in solubility after burning. Monovalent cations were also much more soluble after burning, and the relative increases in sodium and potassium were essentially identical. Statistical significance dropped somewhat below the 5% level for sodium and potassium because of low values for station 1, which was very lightly burned. There is little doubt, however, that the solubility of these ions does increase several times after burning, as indicated in Table 1. The high amounts of potassium in the litter are especially striking.

Nitrate and phosphate, which contribute insignificantly to the ionic load of the leachate, were extracted in identical amounts from burned and unburned litter. Nitrate is especially low for both the treatment and the control.

Synthetic rainwater is somewhat more effective than distilled water in leaching bases from litter (Allen 1964). The difference is not great, however, and is therefore disregarded. The chemistry of the leach water may exercise some unsuspected effects on solubility that would bear further investigation, but those must be passed over here.

Table 1 documents the movement of cations from the burned litter with rainfall. Approximately 70% of the total leachable ions were removed by 80 mm of rainfall within a 30-day period following the burn. The decline of all four major cations is significant and dramatic, but divalent cations appear to have been removed more readily from the litter than were monovalent cations. The data suggest accretion of both N and P in the litter, although the difference between the two collection dates is not significant at the 5% level. There is certainly no evidence for net loss of NO_3 and PO_4 as there is for cations.

The first rain following the burn occurred on 3 March (Fig. 2). The variability of data taken from the rainfall collectors on this date is summarized in Table 2. The coefficients of variation in Table 2 are broadly typical of those obtained for all other sampling dates. Variability of cations is usually within the 25%–60% range. Nitrate and phosphate data are more irregular because of the very low background concentration of these substances.

The amounts of cations, nitrate, and phosphate in the rainfall collectors on 3 March are shown in Table 2. The collectors were installed 3 days subsequent to the burn, at which time the particulate and volatile material put directly into the air by the fire were considered to have largely dissipated. The contents of the collectors included particulate fallout that gathered during the 7 days prior to the rain as well as substances dissolved in the rain. Since the sides of the collector extended substantially above the ground surface (9.5 cm), splatter from rainfall striking the ground around the collector did not affect the contents of the collector.

Just after the rain of 3 March the collectors in the burned portion of the watershed contained greater amounts of all substances tested than did the collectors in the control area. The differences between control and burned areas are in all cases significant at the 5% level, except for phosphate. Phosphate is brought outside the 5% level only by the very low value for the lightly burned area around station 1. The amounts of dissolved substances in the collectors of the burned area are approximately double those in the control area. Rainfall/fallout data are shown in Table 3 for all of the collection dates. The amounts of cations delivered by rainfall and fallout to a unit of burned watershed surface area are approximately twice as high as for the control area. The difference between control and burned areas for each cation is highly significant according to the Wilcoxon signed-ranks test. Although both nitrate and phosphate were collected in greater total amounts in the burned area, the difference between treatment and control is neither consistent nor significant.

Only a small portion of the total rainfall appeared in the runoff collectors (Table 4), since the coarse soil permits efficient percolation. The two lightest rains (Fig. 2) produced an insignificant amount of runoff. Other rains produced measurable runoff,

TABLE 1. Amounts of leachable material in various kinds of litter, including litter collected from the burned area immediately after the burn (Feb. 24), litter collected at the same time from the unburned control area, and litter collected from the burned area after 1 mo of natural leaching by rainfall (82 mm). Leachable material in each litter type was determined in the laboratory as described in this text. Asterisks indicate values for controls and rain-leached burned litter that showed significant (*) or highly significant (**) differences from the litter collected just after the burn

Litter type	Total ions μmho/cm	Soluble material mg/m²					
		Ca^{++}	Mg^{++}	Na^{+}	K^{+}	NO_3-N	PO_4-P
Burned (prerain)							
Mean	2622	191	11.5	18.8	126	.188	6.2
SE	754	52	2.6	5.6	30	.029	1.7
Burned (postrain)							
Mean	795**	36.2**	2.5**	11.6*	44**	.477	5.7
SE	203	10.8	0.6	3.9	10	1.560	0.9
% remaining (postrain/prerain)	27.7	17.4	19.8	55.0	32.1	220.7	109.6
Control							
Mean	588*	9.7*	1.2*	8.3	54	.186	5.9
SE	77	1.6	0.3	2.4	6	.018	0.5
Ratio:B/C	4.45	19.7	10.0	2.26	2.33	1.01	1.05

TABLE 2. Summary of rainfall data taken on 3 March, just after the first rain following the burn. Coefficients of variation illustrate typical relative variability of data taken on a particular date. Data are from 16 collectors open for 7 dry days prior to the rain on 3 March. Means for stations in the burned area are all higher than at control stations, and significance levels are indicated by asterisks

Location	Conductance μmho/cm	Concentration mg/m²					
		Ca^{++}	Mg^{++}	Na^{+}	K^{+}	NO_3-N	PO_4-P
Burned							
Mean	92.5*	29.0*	3.00*	35.6*	43.0*	14.0*	1.033
SE	14.1	4.2	0.44	7.1	11.1	2.2	0.033
C. V., %	30.4	29.0	29.3	39.9	51.6	31.4	101.5
Control							
Mean	43.3	8.4	1.40	18.9	13.8	5.3	0.077
SE	8.4	1.8	0.27	3.3	3.7	2.3	0.010
C. V., %	38.8	42.8	38.6	34.9	53.6	86.8	26.0

but the average distance traveled by a molecule of runoff water prior to percolation was obviously quite low and there was consequently little downslope accumulation of surface water. Runoff present in the collectors thus did not carry high concentrations of solutes. The runoff data are reported in terms of yield per running meter of shoreline to emphasize export to the adjoining aquatic system and to avoid assigning areal equivalents to the material being transported, since such figures would be essentially fictitious in these highly porous soils. There is little doubt that almost all runoff originated in the immediate vicinity of the collector.

Mean amounts of all cations in runoff from the burned area are greater than in runoff from the control area (Table 4). Because of high variability the difference is not significant at the 5% level except for sodium. Several of the nitrate and phosphate analyses could not be completed since the sample volume was meager. The higher nitrate content of runoff from the burned area may be an artifact of small sample size, especially since variability of the nitrate data is characteristically high, but no firm conclusions can be drawn from the data on hand.

The groundwater analyses are summarized in Table 5. Calcium, magnesium, and sodium were all considerably more concentrated in groundwater from the burned portion of the watershed, but the difference is significant at the 5% level only for sodium. Potassium shows the opposite trend but the difference is not significant. Nitrate and phosphate are

TABLE 3. Amounts of rainfall, conductance of rainfall plus fallout, and amounts of cations and nutrients transported in rainfall plus fallout in burned and unburned portions of the Par Pond watershed. Each figure is a mean for 8 separate sample collectors

Location	Date	Rain (cm)	Conductance μmho/cm	Cations mg/m²					
				Ca^{++}	Mg^{++}	Na^{+}	K^{+}	NO_3-N	PO_4-P
Burned									
	3 March	1.25	92	29.0	3.00	35.6	43.0	14.000	1.033
	8 March	2.61	30	8.3	1.77	16.4	24.8	.195	.065
	12 March	2.23	19	10.3	1.18	9.5	26.7	.090	.111
	23 March	0.70	33	9.5	1.44	12.1	20.1	1.122	.007
	27 March	1.51	70	26.8	2.88	28.5	55.0	7.519	.083
	2 April	2.30	31	10.6	2.26	27.7	52.9	1.115	.264
	10 April	1.99	34	13.4	1.73	10.1	33.8	2.631	.228
Total	(mean)	12.59	(44)	107.9**	12.53**	139.9**	256.3**	26.672	1.791
Control									
	3 March	1.60	43	8.4	1.40	19.0	13.8	5.300	.077
	8 March	2.71	24	6.5	0.95	9.0	6.7	.216	.108
	12 March	2.39	22	6.8	0.67	5.4	7.1	.177	.060
	23 March	1.29	21	5.9	0.97	7.3	17.8	.170	.036
	27 March	1.56	36	12.8	1.61	16.9	34.3	7.894	.086
	2 April	2.20	21	6.3	0.87	11.8	21.4	.352	.220
	10 April	2.00	26	5.7	1.42	7.5	30.0	1.180	.170
Total	(mean)	13.75	(27)	52.4	7.89	76.9	131.1	15.289	.757
Ratio:	B/C	0.92	1.63	2.06	1.59	1.82	1.96	1.74	2.36

TABLE 4. Amounts of runoff, specific conductance of runoff, and amounts of nutrients transported as runoff over burned and control portions of the Par Pond watershed. Runoff figures for each date are associated with a separate rainfall. All figures are means taken from 8 separate collectors.

Location	Date	Runoff cm^3/m of shore	Conductance μmho/cm	Ion transport mg/m of shoreline					
				Ca^{++}	Mg^{++}	Na^{+}	K^{+}	NO_3-N	PO_4-P
Burned									
	8 March	584	64	3.04	0.24	1.19	—	—	—
	12 March	464	39	0.73	0.07	0.41	1.6	—	.150
	27 March	452	198	3.11	0.46	2.90	5.9	.475	.279
	2 April	392	123	0.48	0.08	1.09	2.9	.110	.293
	10 April	1940	61	1.72	0.43	2.77	7.7	.415	.399
Total (mean)		3832	(97)	9.08	1.28	8.36*	18.1	1.000	1.121
Control									
	8 March	812	86	3.19	0.18	0.82	—	—	—
	12 March	404	87	1.06	0.05	0.33	1.6	—	.334
	27 March	236	99	0.44	0.07	0.66	1.1	.004	.116
	2 April	848	45	0.57	0.12	1.09	2.6	.012	.131
	10 April	916	60	0.42	0.09	1.90	3.2	.084	.515
Total (mean)		3216	(75)	5.68	0.51	4.80	8.5	.100	1.096
Ratio: B/C		1.19	1.29	1.60	2.51	1.74	2.13	10.00	1.02

essentially identical in concentration and occurred in extremely low amounts at the two locations.

DISCUSSION

The leaching of burned and unburned litter in the laboratory indicates the relative amounts of nutrients that could be potentially moved by rainwater, whereas data on natural leaching, runoff, groundwater, and rainfall/fallout show the amounts of nutrients that were actually moved under the conditions prevailing in the Par Pond watershed after the burn. Movement of substances having indirect nutritional importance is not considered here. For example, nonsoluble nitrogenous compounds incorporated in fine particulate material might move into an aquatic system during or following a fire and would contribute to nutrient supply after biological decomposition. The following discussion is concerned only with the transport of nutrients in elementary forms that could be expected to exercise an immediate biological effect; however, transfer of other less active materials cannot be considered unimportant.

The burning of forests is known to alter the availability of at least some nutrients important for plant growth (Ahlgren and Ahlgren 1960). In the Par Pond watershed, all cations were rendered soluble in large amounts by burning. The amounts of soluble salts present following the burn verify the expectation that volatile losses of cations due to fire

TABLE 5. Amounts of soluble material in superficial groundwater at sampling stations in the burned and control portions of the Par Pond watershed

Location	Station	Total ions μmho/cm	Concentration mg/l					
			Ca^{++}	Mg^{++}	Na^{+}	K^{+}	NO_3-N	PO_4-P
Burned								
	1	68.2	1.68	0.34	2.94	.20	.007	.0021
	2	84.5	3.35	0.49	2.42	.30	.006	.0080
	3	39.7	0.39	0.17	3.69	.10	.008	.0036
	4	24.4	0.29	0.10	2.35	.10	.008	.0051
	Mean	54.2	1.42	0.28	2.85*	.18	.007	.0047
	SE	13.5	0.71	0.09	0.31	.05	.0005	.0012
Control								
	1	57.0	0.17	0.34	1.52	.15	.006	.0019
	2	36.7	0.56	0.14	1.35	.87	.007	.0034
	3	18.2	0.08	0.07	1.50	.15	.004	.0040
	4	37.0	0.68	0.14	1.64	.50	.008	.0067
	Mean	37.2	0.62	0.17	1.50	.42	.006	.0040
	SE	7.9	0.22	0.05	0.06	.17	.0009	.0010
Ratio: B/C		1.46	2.29	1.65	1.90	0.43	1.17	1.18

are minor. The great increase in leachability of divalent cations is, however, in seeming conflict with some extensive studies of heather burns in which potassium was much more readily dissolved than divalent cations following a burn (Allen 1964, Lloyd 1971). This conflict may be only apparent, since the heather studies stressed the amounts of cations released as a proportion of the amounts of the ions available in litter. The Par Pond data are presented in terms of the amounts of cations released relative to the amounts released by an unburned control. Potassium is known to be released from unburned litter much more rapidly than are divalent cations because it is not a structural component of leaves (Gosz et al. 1973). Burning may thus have a greater relative effect on movement of calcium and magnesium than on potassium because potassium moves rapidly even if the litter has not been burned. Sodium has received little attention but behaves like potassium in the Par Pond studies.

Natural leaching of the burned area by rain did not result in the marked depletion of monovalent ions that might have been expected. Throughfall could easily replenish monovalent ions selectively, and thus the net change in divalent ions is greater. This is particularly likely if fire kills some plant tissues so quickly that resorption of sap with its high concentrations of monovalent cations is not possible. A lesser possibility is that litter ash selectively holds monovalent cations in some instances.

Several studies have documented large losses of nitrogen during fires due to volatilization (Allen 1964, Knight 1966, Debell and Ralston 1970). No excess of nitrite or nitrate compounds was left behind by the Par Pond burn, so nitrogen compounds were either volatilized or not decomposed by heat. Assuming a 0.65% N for content for unburned needles (Biswell 1972) and a 60% volatilization rate (Debell and Ralston 1970), approximately 1,200 mg/m^2 of N would have been freed by the fire. Considering the enormous biological potential of this much nitrogen, it is surprising that composition of volatile nitrogen compounds from forest fires has received little attention.

Debell and Ralston (1970) showed that only about 1% of the nitrogen released in their laboratory burns was biologically active (ammonia, nitrate); the rest presumably consisted of gaseous nitrogen. This is a critical determination. If 99% of the nitrogen from the Par Pond burn was released as nitrogen gas, the amount of biologically active nitrogen from 1 m^2 of burned watershed would still be sufficient to approximately double the amount of useful dissolved nitrogenous compounds beneath an average square meter of Par Pond. A significant but short-term effect on the productivity of Par Pond or other aquatic habitats more distant from the site is thus possible. Most important, however, is that under some burning conditions (e.g., low temperature) the proportion of biologically active compounds in the volatilized nitrogen might be much greater than 1%.

It is reasonable to infer from the Par Pond data that phosphorus was lost to the air or not decomposed to phosphate. There are no obvious mechanisms for volatilization of P, but the matter has not been closely studied. Lloyd (1971) reported high losses of total phosphorus due to burning, but Allen (1964) reported no effect. As with nitrogen, specific conditions may be critical. The effect on aquatic systems of phosphate in rain is of course potentially as great as that of nitrate.

The data suggesting a slow increase in nitrate and phosphate following the fire are in accord with studies of microbial communities that follow fire. Ahlgren and Ahlgren (1965) have documented increases in microbial activity following fire that are apparently connected with the increase in structural vulnerability of litter after burning. Gosz et al. (1973) have clearly shown a steady increase of both N and P during ordinary decomposition of leaves, which is similarly due to increasing microbial activity. The apparent increase in leachable nitrate in the Par Pond study area is a trivial fraction of the unaccountable N that was probably volatilized. Apparently there is a massive loss of N to physicochemical processes during the fire and a small steady gain of N due to biological processes after the fire. Most authors who have reported higher N or P in plants or soils following burns (e.g., Vlamis et al. 1955, Ahlgren 1960, Wells 1971, Ahlgren and Ahlgren 1965, Biswell 1972) have selectively stressed stimulation of biological processes by burning. There is some danger in overlooking significant losses of N and possibly P that occur by physicochemical means during a fire. Net loss of nutrients from the soil-litter system can clearly occur even if nitrification and other biological processes are stimulated by fire and so soil nutrients rise after burning.

Burning increases the potential for nutrient transfer by wind because it lowers wind resistance in the understory and radically lowers the density of litter. The consistently higher transport of cations into rainfall/fallout collectors in the burned portion of the watershed can probably be explained in this way. Higher amounts of nitrate and phosphate in the collectors within the burned area cannot be thus explained since nitrate and phosphate availability in the litter itself was not affected by burning. High nitrate and phosphate in the first rain are best accounted for as the return of a small portion of volatile or fine particulate material that did not leave the general region of the burn. A seemingly enigmatic peak in nitrate in late March is probably explained by a heavy pollen fall (Fig. 2), especially since the peak is much the same for burned and unburned areas. Burned and unburned areas are thus essentially identical in movement of nitrate and phosphate after the first post-fire rain, while cations are steadily moved by wind from the burned area for at least a month following the fire.

Runoff did not move large amounts of cations despite the marked increase in solubility of cations following the burn. This is due simply to the insignificance of runoff in the sandy soils of the study area. On the piedmont clays, however, the same rain regime might easily have produced massive ion transfers to aquatic systems via runoff. Nitrate and phosphate would in such a case be of little concern, because burning does not mobilize these substances to runoff water.

Since cations did not volatilize or leave as runoff, but were nevertheless highly soluble, they obviously percolated into the remaining organic layers and perhaps into the mineral soil. The groundwater samples were intended to reveal any sizable intrusion of percolating nutrients into the groundwater communicating with the lake. There is tentative evidence for changes in the ionic balance of superficial groundwater, especially for an increase in sodium following the burn. Samples unfortunately were not taken in the burned area prior to the burn, so there may be other explanations for the different ionic proportions. The upper soil layers are known to be highly efficient adsorption traps for cations following a burn (Ahlgren 1960, Allen 1964, Johnson and Needham 1966, Lloyd 1971), but groundwater penetration in some soils is still an important possibility. Litter reduction also reduces the homeostatic effect of litter on percolation and could easily account for changes in the ionic balance of groundwater such as those observed on Par Pond.

The data as a whole suggest that translocation of nitrate and phosphate by runoff or groundwater is not directly affected by burning, but that possible inclusion of biologically active N and P compounds in volatile losses could affect metabolism of systems remote from a burn. Cations, on the other hand, are made vulnerable by burning to translocation by wind as particulate matter or by water as runoff or groundwater. The extent of transloaction for cations will be greatly affected by soil properties, topography, and weather. For nitrate and phosphate, the heat of the fire and composition of the litter are more likely to be important. A more diverse experience with the effects of such variables is clearly needed as timber management expands its burning programs.

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