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THE IMPACT OF FOREST FIRE ON THE NUTRIENT INFLUXES TO SMALL LAKES IN NORTHEASTERN MINNESOTA[1]

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Abstract. The Little Sioux fire of May 1971 burned most of the mixed coniferous-deciduous forest on the watersheds of Meander and Lamb lakes, two small, low conductivity lakes located in the Boundary Waters Canoe Area (BWCA) of northeastern Minnesota, USA. During 1972, hydrologic and chemical (Ca, Mg, K, Na, and P) budgets were determined for the terrestrial watersheds of Meander and Lamb lakes and for the lakes themselves. Budgets were also measured for Dogfish Lake, a lake physically and chemically similar to Meander Lake but whose watershed was not burned in the Little Sioux fire.

These budgets show that the atmosphere supplies a significant fraction of the cations and phosphorus (Ca, 90%; Mg, 35%; K, 95%; Na, 55%; P, 95%) to the BWCA watersheds, with the remainder coming from chemical weathering. The budgets are similar to those reported for other Canadian Shield lakes and watersheds.

The impact of the Little Sioux fire on nutrient fluxes was evaluated by comparing the budgets measured at Dogfish Lake with those measured at Meander Lake. This comparison showed that as a result of the burning of Meander Lake watershed, runoff increased 60% and the K and P exports increased 265% and 93%, respectively. The exports of Ca, Mg, and Na did not change significantly. The increase in runoff, probably due to the reduction in vegetative transpiration, is comparable to that measured after the 1970 Entiat fire (western Washington) and to that resulting from clear-felling experiments at Hubbard Brook (New Hampshire) and Coweeta (North Carolina). The increased nutrient losses after fire are less than those observed at Hubbard Brook and Coweeta. There was no indication of a drastic increase in nitrate export such as occurred after the Entiat fire and at Hubbard Brook.

The increase in phosphorus loading of Meander Lake due to the fire was 38% (to 25 $mg/m^2 \cdot yr$), a value that probably falls within the natural year-to-year variation in supply, and it did not represent a major impact on Meander Lake.

Fire is a natural part of the BWCA forest ecosystems. The results of this study indicate that nutrient losses after the Little Sioux fire were minimal, perhaps because it was a spring fire. Fall fires may cause larger nutrient losses because more of the forest-floor material is likely to be consumed and revegetation does not begin until the following spring.

Key words: Chemical budgets; chemical weathering; ecosystem; forest fire; hydrological budgets; lakes; Minnesota; nutrient-cycling; phosphorus; virgin forests.

INTRODUCTION

In May 1971 the Little Sioux wildfire burned 5,900 ha in and adjacent to the Boundary Waters Canoe Area (BWCA), a 400,000 ha wilderness of forest and lakes in northeastern Minnesota (Fig. 1). The fire burned most of the virgin-forested watersheds of Lamb and Meander lakes, two small low-conductivity lakes located on granitic bedrock of the Canadian Shield. Because it was the first major fire in the area since the U.S. Forest Service instituted effective fire-suppression policies in 1910, the Little Sioux fire offered a rare opportunity to study the effects of forest fire on the nutrient inputs to lakes.

Fire plays an integral role in the mixed deciduous-coniferous forests of northern Minnesota by periodically killing much of the aboveground vegetation and initiating a new round of vegetation succession (Heinselman 1973). By blocking nutrient uptake and creating large amounts of nutrient-rich ash, fire might result in considerable nutrient losses from forested watersheds—nutrients potentially available for the enrichment of streams and lakes.

That a major disturbance of the forest ecosystem results in dramatic changes in nutrient export has been clearly demonstrated by the paired-watershed experiments at Hubbard Brook, New Hampshire, where felling all standing vegetation and preventing its regrowth produced drastic increases in the amounts of major cations (Ca, Mg, K, Na), phosphorus and nitrogen exported from the ecosystem (Likens et al. 1970, Hobbie and Likens 1973, Likens and Bormann 1974). For lakes, the 10-fold increase in phosphorus export would be particularly critical, because that element often limits algal production (Vollenweider 1968). Whole-lake enrichment experiments conducted in the Experimental Lakes Area, Ontario, showed that phosphorus is the limiting nutrient for phytoplankton growth in these lakes (Schindler 1974). Since the ELA lakes are physically, chemically, and biologically similar to lakes

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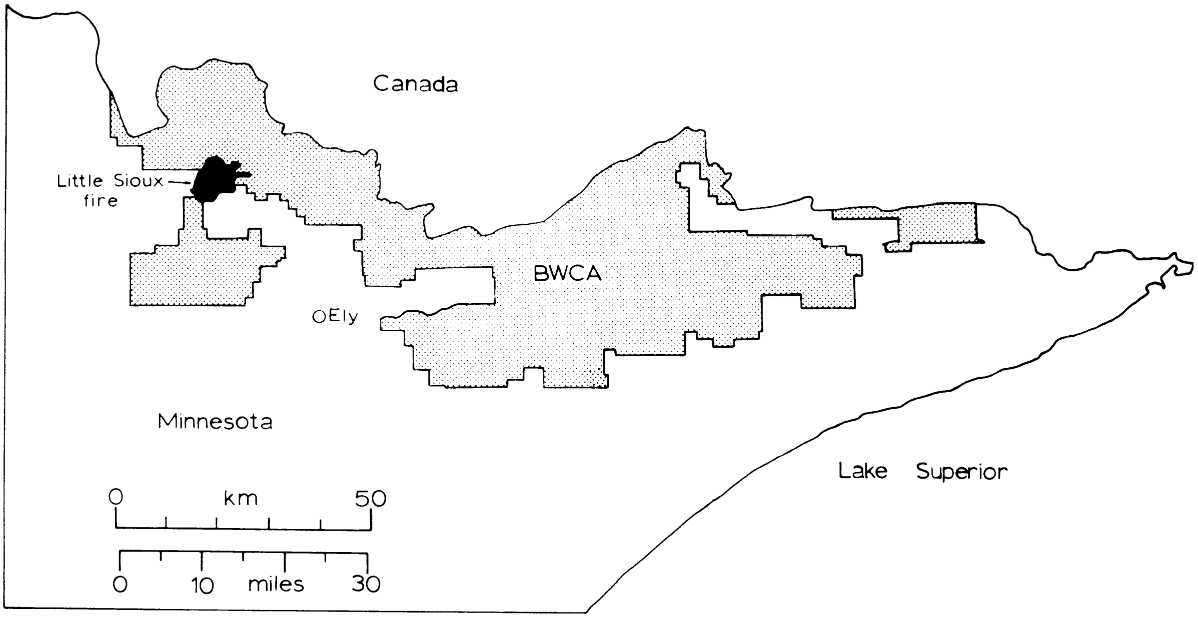

FIG. 1. Map of the BWCA, northeastern Minnesota, showing the location of the Little Sioux fire.

in the Little Sioux fire area (Table 1), it is likely that phosphorus limits growth in them also.

The effects of fire on nutrient and hydrologic fluxes to Meander and Lamb lakes were assessed by comparing nutrient and hydrologic budgets with those for Dogfish Lake, a lake similar to Meander Lake that lies 2 km west of the burned area (Fig. 2).

Because it was a wildfire, neither the timing nor the location of the Little Sioux fire could be known in advance. Thus, not only did no pretreatment data exist, but it was not until a year after the fire that this study was begun in a systematic manner. The results reported here, therefore, are from the second year after the fire, and therefore may not reflect the full impact of the fire. Estimates of the first-year

TABLE 1. Physical and chemical features of Dogfish, Meander, and Lamb lakes and Rawson Lake, Experimental Lakes Area, Ontario. Chemical concentrations are means of samples collected during 1972 (1968–69 for Rawson Lake)

	Dogfish	Meander	Lamb	Rawson ELA
Drainage basin area (Ad) (ha)	59.1[a]	133.0[a]	156.2[a]	342.1[b]
Lake surface area (Ao) (ha)	29.1[a]	36.0[a]	39.7[a]	54.28[b]
Total Ad + Ao (ha)	88.2	169.0	195.9	396.4
Ratio Ad:Ao	2.03	3.70	3.94	6.30
Maximum depth (m)	5.5	7.0	5.5	30.4[c]
Average depth (m)	4	5	4	10.5[c]
Ca (mg/l)	2.2	1.9	7.6	2.09[d]
Mg (mg/l)	0.69	0.63	2.2	0.79[d]
K (mg/l)	0.42	0.61	0.59	0.50[d]
Na (mg/l)	0.60	0.65	1.52	1.16[d]
HCO_3 (mg/l)	8.0	5.0	30.0	----
Total P (mg/m^3)	7	6	7	6[d]
NO_3-N (mg/m^3)	5	7	4	4[d]
pH	6.0	5.6	6.4	----
Conductivity (μmho/cm)	15.5	16.5	48.0	22[d]

[a] Nordin 1974.
[b] Schindler et al. 1975.
[c] Brunskill and Schindler 1971.
[d] Armstrong and Schindler 1971.

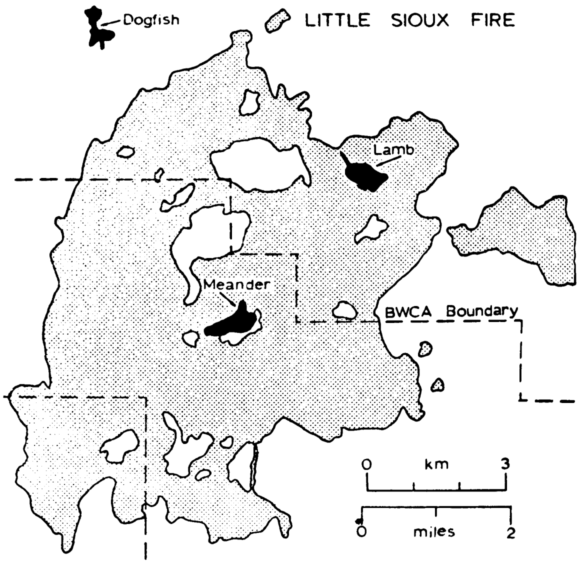

FIG. 2. Map of the Little Sioux fire, May 1971, showing the locations of the three study lakes. Map courtesy of M. L. Heinselman.

FIG. 3. Typical view of areas intensely burned by the Little Sioux fire. Photo was taken a few weeks after the fire in the Lamb Lake watershed.

effects come from data collected immediately following a small prescribed fire conducted in May 1973, at Perent Lake by the U.S. Forest Service and from laboratory experiments (R. F. Wright 1974).

THE STUDY AREA

The Little Sioux fire, as with many spring wildfires, burned unevenly, leaving patches of unburned forest (Fig. 2). In some areas all standing vegetation was killed by intense crown fires, while adjacent areas experienced only a light ground fire (Sando and Haines 1972). The ground was for the most part still cool and moist, and even in regions of intense fire only the uppermost 1–3 cm of the surface was burned (Fig. 3).

The Little Sioux fire area lies within the Vermilion granite batholith, a massive, uniform Precambrian intrusion measuring 125 km E–W by 50 km N–S (Goldich et al. 1961). The granite outcrops extensively along ridges and knobs as bare rock surfaces covered only by lichens and mosses. The intervening low areas are commonly mantled by a thin layer of ground moraine, deposited by the Rainey Lobe of the Wisconsin ice-sheet more than 14,000 years ago (Wright and Watts 1969). The till is typically brown, sandy, and highly permeable. Deposits of gray calcareous clays occur in areas lying below $\approx$ 400 m. These clays were laid down in a proglacial lake, perhaps a precursor of Glacial Lake Agassiz. The clays form a low bench around much of Lamb Lake and greatly affect the major-ion chemistry of the lake and inflowing streams. The soils of the area exhibit very poor development and are generally $<$ 25 cm thick (Nordin 1974).

Northeastern Minnesota has a typical midcontinental climate with long, cold winters and warm, moist summers. The mean annual precipitation is $\approx$ 700 mm. Mean monthly temperatures average ≈ -10°C in January and 17°C in July. The growing season is $\approx$ 100 days (Ohmann and Ream 1971).

The study area lies in the belt of mixed coniferous-deciduous forest, and the overstory is dominated locally by pines (*Pinus strobus, P. resinosa, P. banksiana*), spruces and fir (*Picea glauca, P. mariana, Abies balsamea*), and aspen and birch (*Populus tremuloides, Betula papyrifera*). The forest is a mosaic of 12 community types (Ohmann and Ream 1971), the product of natural forest fires that have occurred in the area over the last 9,000 years (Heinselman 1973, Swain 1973).

The watersheds of the three study lakes consist mostly of undisturbed virgin forests. The Little Sioux fire killed the overstory of 70% of the Meander Lake watershed and 65% of the Lamb Lake water-

FIG. 4. Meander Lake looking west. The forest on the north shore was consumed by crown fire while the forest along the south shore was left unburned.

shed (Fig. 4) (Nordin 1974). Regrowth began immediately, and by the end of the first growing season, only 4 mo after the fire, the ground was covered by a lush growth of herbs, tree seedlings, and shrub and tree sprouts.

Meander, Lamb, and Dogfish lakes all occupy major fractions of their drainage basins (Table 1). No major streams enter any of the lakes. The lakes are dilute and oligotrophic, typical of small undisturbed lakes on the Canadian Shield (Armstrong and Schindler 1971). Dogfish and Meander lakes are similar in depth, area, watershed size, and water chemistry—indeed, the major difference between these two lakes is that the watershed of Meander was burned, while the watershed of Dogfish was not.

METHODS

Hydrologic budgets

For the lakes of this study the hydrologic budget is given by:

$$\Delta S = P + R - E - O, \qquad (1)$$

where P is precipitation on the lake, R is runoff from the watershed, E is evaporation from the lake surface, O is the outlet discharge, and ΔS is the change in storage (Fig. 5). All components are expressed in centimeters (volume of water/lake surface area). Groundwater inputs and outputs are negligible because the massive bedrock forms a watertight seal.

Precipitation was measured directly on 11 rain gauges. Evaporation was obtained from the evaporation-pan data from Hoyt Lakes, Minnesota, a United States Weather Bureau Station located 70 km south of the study area. Pan data were converted to lake surface evaporation by a factor of 0.70. Level recorders placed at each lake provided a continuous record of lake level. Outlet discharges were measured with a pygmy current meter and a dye-dilution technique (Cobb and Bailey 1965). In addition, daily outlet discharges were obtained by differences from Eq. 1 for days on which no rain fell and runoff was negligible; the daily observed evaporation was subtracted from the daily ΔS value read from the lake level recorders. These measured and calculated points allowed the preparation of discharge rating curves (outlet discharge vs. lake level) for each lake. From these curves the outlet discharges for each day were obtained and summed over each 2-wk sampling period. Runoff was determined by differences from Eq. 1.

Hydrologic budgets were constructed for each 2-wk sampling period and then summed over the entire ice-free season (20 May–30 October). Annual budgets were obtained by including snowmelt runoff (estimated from spring snowpack data kindly supplied by D. F. Grigal and J. G. McColl, University of Minnesota) and net snow accumulation on the lake-ice surface.

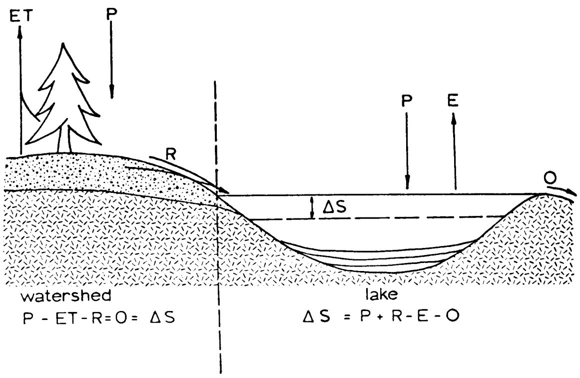

FIG. 5. Schematic diagram of the hydrologic balances for the watershed and lake ecosystems of this study. Groundwater inputs and outputs are assumed to be negligible.

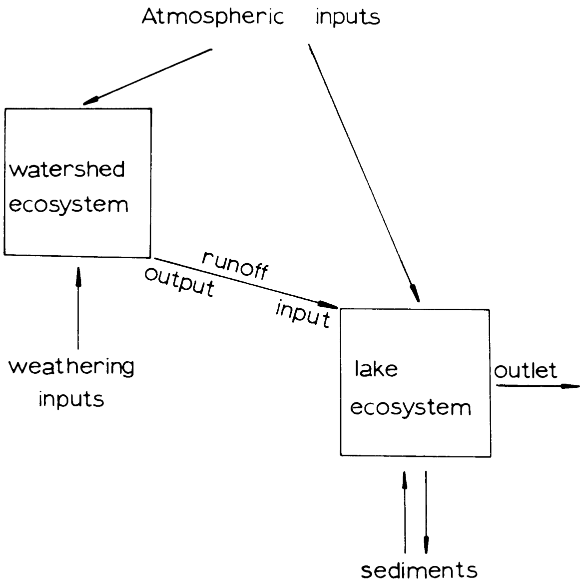

FIG. 6. Schematic diagram of the chemical inputs and outputs for the watershed and lake ecosystems studied in the Little Sioux fire area.

For the terrestrial watersheds the hydrologic budget becomes:

$$P - ET = R, \qquad (2)$$

where ET is the water leaving the watershed by evapo-transpiration, and P and R are precipitation and runoff as before (Fig. 5). Again groundwater is negligible, and long-term storage is assumed to be constant. For the watersheds, P was measured, R obtained from the hydrologic budgets of the lakes, and ET obtained by difference.

Chemical budgets

For the lakes of this study the chemical budgets for dissolved elements (Ca, Mg, K, Na, and P) are given by:

$$\Delta M = M_p + M_r - M_o - M_s, \qquad (3)$$

where M_p is the mass of element entering the lake in precipitation, M_r is that entering the lake dissolved in runoff, M_o is that leaving the lake via the outlet, M_s is that incorporated in the lake sediments and, ΔM is the change in mass of the element contained in the lake water (Fig. 6). Each of these quantities was obtained by multiplying the volume of water from the hydrologic budgets by the concentration of each element in each aqueous component.

Chemical budgets for the terrestrial watersheds were constructed in a similar fashion from:

$$\Delta M = M_p + M_w - M_r, \qquad (4)$$

where M_p is the mass of element entering the watershed in precipitation, M_r is that leaving the watershed dissolved in runoff, M_w is the mass of element introduced into the watershed by the weathering of parent material, and ΔM is the change in mass of the element stored in the watershed biomass and soils (Fig. 6).

An estimate of weathering and change in storage was obtained by difference from:

$$M_w - \Delta M = M_r - M_p. \qquad (5)$$

The M_w values obtained from the undisturbed watershed of Dogfish Lake were used to construct the chemical budgets for the burned watersheds.

Water samples for chemical analysis were collected every 2 wk during the ice-free season of 1972. Precipitation was collected in polyethylene rain gauges. Grab samples of lake and stream waters were taken in 300-ml polyethylene bottles. Overland flow was collected with 1-m-long polyethylene troughs placed horizontally under the organic soil or duff layer such that the water seeping down a gentle slope was trapped and funneled into a 1-liter polyethylene bottle. Soil water was collected with soil-moisture tubes constructed from a plastic pipe 1 m long and 1 cm diam with a porous ceramic tip bonded to the lower end. All water samples were stored in the dark at 5°C pending analysis.

In the laboratory the samples were filtered through a medium paper (Whatman™ 541) that had been prerinsed with 100 ml of distilled water. Conductivity, total alkalinity, and pH were measured with procedures modified from Brown et al. (1970). The concentrations of cations (Ca, Mg, K, Na) in the filtrates were measured on an atomic absorption spectrophotometer (Brown et al. 1970) with lanthanum added to mask interferences in the Ca and Mg determinations. Total phosphorous concentration was measured using the Harvey phosphomolybdate method with either stannous chloride or ascorbic acid reduction (Strickland and Parsons 1968) after digestion of the samples with potassium persulfate for 45 min in a pressure cooker. Nitrate concentrations were measured colorimetrically after reduction to nitrite by cadmium and complexing by sulfanilamide and N-(1-naphthyl)-ethylene-dichloride (Strickland and Parsons 1968).

RESULTS AND DISCUSSION

Hydrology

The hydrologic budgets calculated according to Eq. 1 and Eq. 2 for Dogfish, Meander, and Lamb lakes and their terrestrial watersheds are presented in Tables 2 and 3. The lakes are hydrologically quite similar. During the summer, frontal storms and thunderstorms lasting a few hours or days move

TABLE 2. Hydrologic budgets (1972) for the terrestrial watersheds of Dogfish, Meander, and Lamb lakes and for nearby Shagawa Lake (Malueg et al. 1975) and Rawson Lake (Schindler et al. 1975)

	Dogfish	Meander	Lamb	Shagawa	Rawson ELA
Precipitation (cm)	70.5	69.5	71.4	59.5	70.1
Evapotranspiration (cm)	50.1	37.1	44.8	39.0	47.8
Runoff (cm)	20.4	32.4	26.6	20.5	22.3
Increase in runoff attributed to fire (cm)		12.0	6.2		
% increase in runoff attributed to fire		60%	30%		

across the area, and the lake levels rise rapidly in response to the direct precipitation on the lake surface and to runoff from the watershed. During the days between storms this water is discharged and the lake levels drop in a roughly logarithmic fashion. During sunny days water is also lost by evaporation from the lake surface, whereas at night, when the air is cool and still, the high humidity minimizes evaporation. Thus, the typical graph of lake level over time is marked by sudden rises followed by a logarithmic decay punctuated by small steps (Fig. 7).

Assessment of the effects of the Little Sioux fire on the hydrology of the terrestrial watersheds requires that the watershed of Dogfish Lake is a suitable control for the burned watershed of Meander Lake. Although no prefire data could be collected to test this assumption, the two watersheds are similar in many aspects, including geology, soils, and vegetation.

The hydrologic budgets for the terrestrial watersheds of Dogfish and Meander lakes (Table 2) indicate that the annual runoff in 1972 at Meander Lake was 60% greater than the runoff at Dogfish Lake. This increase is attributed to the Little Sioux fire and may be an underestimate because the greater average slope at Dogfish Lake tends to enhance runoff.

Fire acts to increase runoff by (1) killing much of the aboveground vegetation and thereby reducing transpiration by plants, and (2) decreasing the water adsorbance of the moss carpet and litter layer. The latter factor is particularly important in the Meander Lake watershed, for here large areas of granitic outcrop are covered by only a thin veneer of moss carpet (Nordin 1974).

TABLE 3. Hydrologic budgets for Dogfish, Meander, and Lamb lakes in 1972. Data for ΔS are estimated

	Dogfish	Meander	Lamb
Precipitation (cm)	70.5	69.5	71.4
Runoff (cm)	41.3	116.4	104.5
Evaporation (cm)	49.4	49.4	49.4
Outlet discharge (cm)	62.4	136.5	126.5
ΔS (cm)	0	0	0

Also listed in Table 2 are the 1972 hydrologic budgets for the forested watershed of Shagawa Lake (Malueg et al. 1975), 40 km southwest of the Little Sioux fire, and for Rawson Lake (Lake 239) in the Experimental Lakes Area, Ontario (Schindler et al. 1975). (For Shagawa Lake only the portion of the watershed drained by the "minor tributaries" was included, because most of the watershed first drains through another lake.) Budgets for these two watersheds are very similar to that of Dogfish Lake, further supporting the conclusion that the increases in runoff observed at Meander and Lamb lakes are due to the fire.

The increase in runoff may have been greater in 1971, the first year after the fire; unfortunately no data exist for this period. The increases observed in 1972, however, are similar to the 60% increase reported by Tiedemann and Helvey (1973) on three gauged watersheds burned by the 1970 Entiat fire, Washington, and to increases measured following vegetation renewal by artificial means (Hibbert 1967).

Chemistry

Table 4 lists the chemistry of various types of water collected in 1972 at Dogfish, Meander, and Lamb lake watersheds. The concentrations are averages weighted for the volume entering or leaving

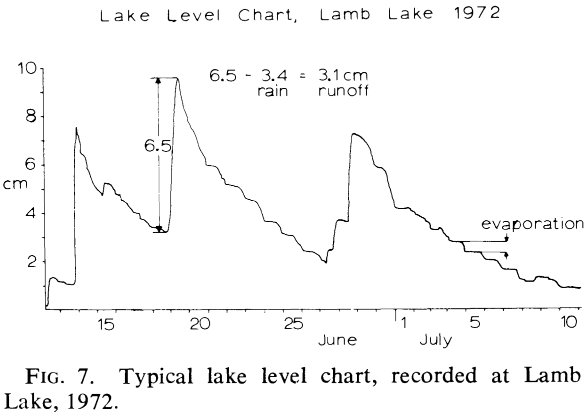

FIG. 7. Typical lake level chart, recorded at Lamb Lake, 1972.

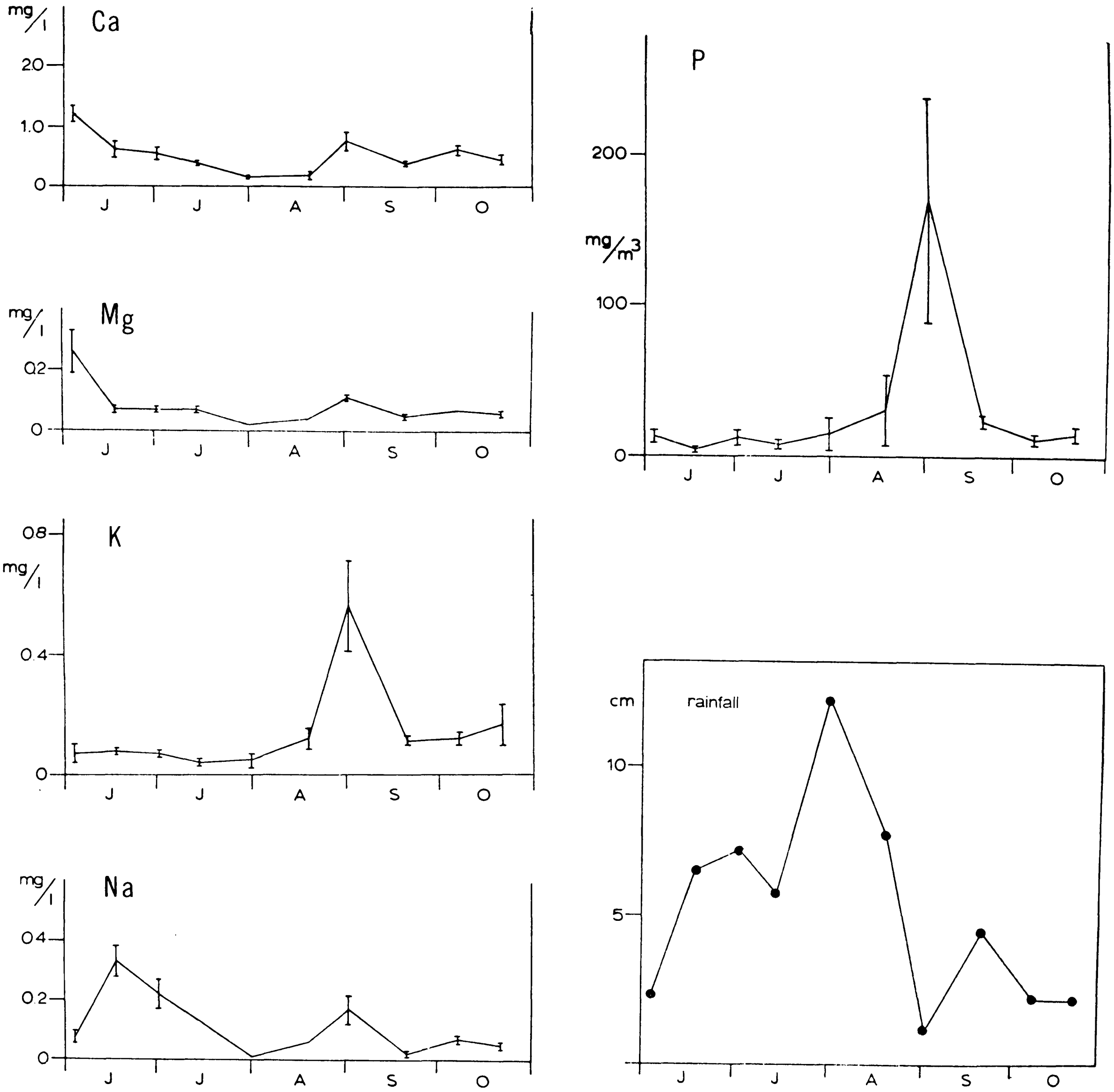

FIG. 8. Concentrations of cations and phosphorus in rain for the ice-free season in 1972. Averages of up to 8 samples; error bars show standard errors.

the lake. The water chemistry at Meander Lake was generally similar to that at Dogfish Lake, with the important exceptions of higher K and P concentrations in overland flow at Meander Lake. These are ascribed to the fire. At Lamb Lake the relatively high Ca and Mg concentrations reflect the presence of calcareous clays in the watershed.

Precipitation chemistry.—The concentration of cations, phosphorus, and nitrate varied inversely with the amount of precipitation (Fig. 8) reflecting the fact that the chemicals in the lower atmosphere are flushed out by the initial rains; thus, rain falling during later phases of a storm is more dilute (Gorham 1961).

Stream-water chemistry.—Two small, ephemeral streams enter each lake, and chemical analyses show that, with the exception of the stream on the north side of Lamb Lake, the concentrations of Ca, Mg, and K in these streams were remarkably constant throughout the ice-free season of 1972 (Fig. 9). Sodium concentrations, on the other hand, varied inversely with discharge, with low concentrations during periods of high discharge in the spring and after the heavy rains of late July. This relationship suggests that the stream water is a mixture of two waters—a sodium-rich water (such as the soil solution), and a sodium-poor water (such as precipitation and overland flow) that contributes to the storm

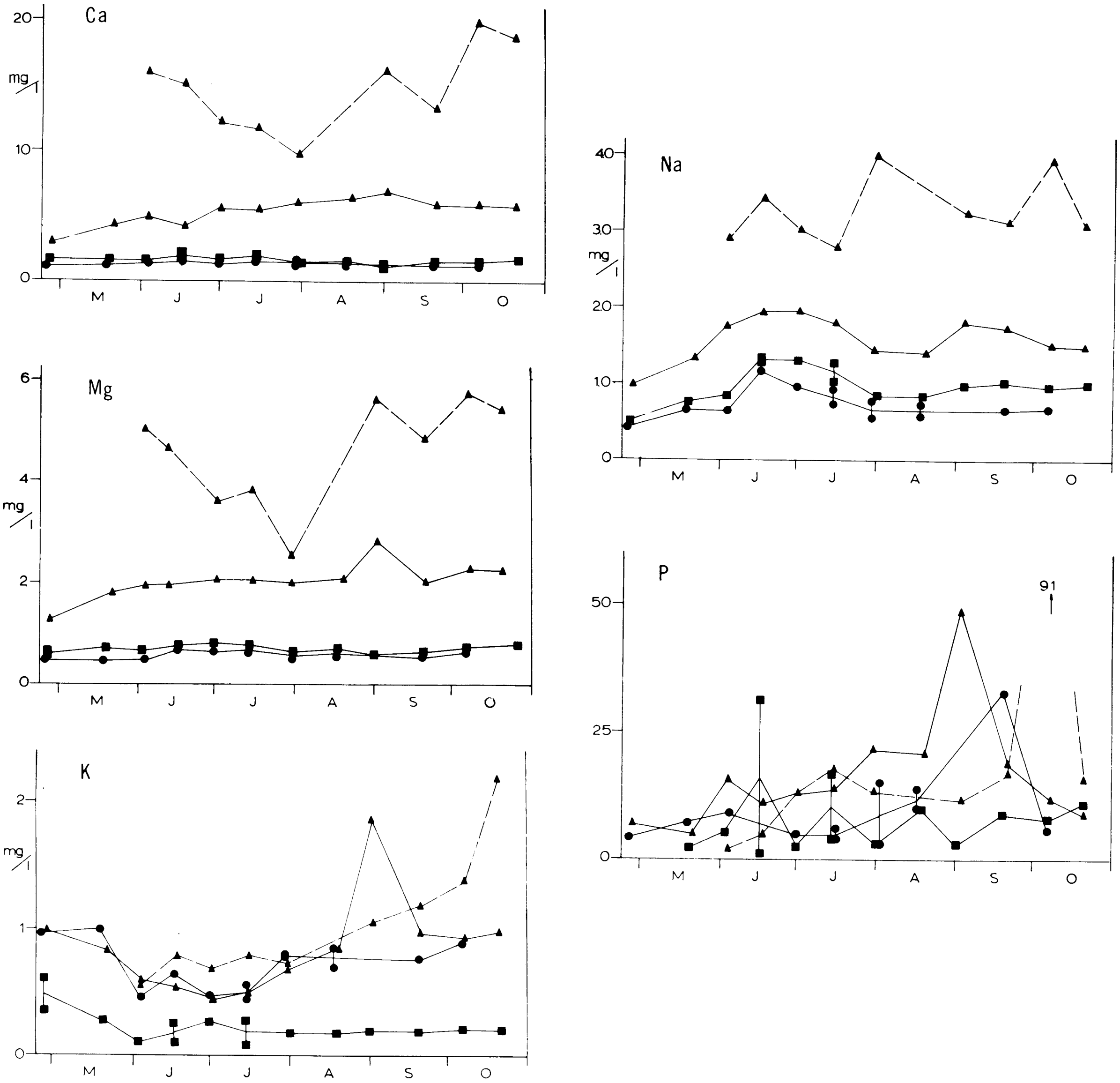

FIG. 9. Cations (mg/l) and phosphorus (mg/m^3) concentrations in the inflowing streams of Dogfish Lake (squares), Meander Lake (circles), and Lamb Lake east stream (triangles and solid line) and Lamb Lake north stream (triangles and dashed line) during the ice-free season 1972.

flow (Table 4). A similar situation has been described at Hubbard Brook (Johnson et al. 1969).

Runoff chemistry.—In general, four types of flow contribute to runoff: overland flow, stream flow, subsurface flow, and groundwater flow.

Groundwater is negligible in the watersheds and lakes of this study because the massive granitic bedrock forms a watertight seal. Evidence for the lack of groundwater is given by the fact that the adjacent lakes in the area often differ in elevation by tens of meters, indicating a general lack of connection to a regional groundwater system. The outlet streams of both Meander and Dogfish lakes flow down rather steep slopes, and no groundwater seepage in the outlet area is evident.

The remaining three water types differ greatly in chemistry (Table 4). Overland flow from burned areas has very high concentrations of phosphorus. Stream water has low concentrations of both phosphorus and cations. Subsurface flow, which moves laterally through the soil at levels high above the regional groundwater level, has high concentrations of cations. To obtain a reliable estimate for the chemical budgets of the lakes and terrestrial watersheds, the relative contribution of each water type must be assessed.

TABLE 4. Chemistry of various types of water collected at Dogfish, Lamb, and Meander lakes in 1972. Values for precipitation, overland-flow (O-F), stream water (ST-W), and soil water (SL-W) are averages weighted for volume entering each lake over the entire season. Lake-water values are averages weighted for outlet-discharge volumes

	Ca (mg/l)	Mg (mg/l)	K (mg/l)	Na (mg/l)	P (mg/m^3)
Precipitation	0.42	0.07	0.11	0.10	21
Dogfish Lake					
O-F	2.04	0.59	0.99	0.58	22
ST-W	1.47	0.64	0.28	0.76	7
SL-W	7.6	17.3	0.79	1.97	23
Lake	2.2	0.69	0.42	0.60	7
Meander Lake					
O-F	3.1	0.88	1.8	0.58	190
ST-W	1.3	0.54	0.67	0.65	11
SL-W	6.3	5.0	0.52	1.04	10
Lake	1.92	0.63	0.61	0.65	6
Lamb Lake					
O-F	3.4	0.80	3.3	0.42	625
ST-W	7.7	2.08	0.80	1.90	16
SL-W	19.2	21.8	1.7	5.8	35
Lake	7.6	2.2	0.59	1.52	7

For those portions of the lake watershed drained by permanent streams, hydrologic and chemical measurements of runoff are relatively straightforward. But the runoff from large portions of the watersheds of Dogfish, Meander, and Lamb lakes reaches the lakes in ephemeral flows or seepages during and soon after storms. Although samples of overland flow and subsurface flow were collected for chemical analysis, it is difficult to estimate the volumes of such waters. The limited amount of evidence available, however, indicates that the stream-water chemistry is the best approximation of the runoff chemistry.

1) The major-cation chemistry of the lakes closely resembles that of the inflowing streams (Table 4). Biological or inorganic processes do not remove significant quantities of these cations from the lake water. If runoff had the chemical composition of soil water or overland flow, elaborate enrichment or depletion mechanisms would be necessary to account for the observed lake-water chemistry.

2) If overland flow or soil water contributed significant amounts of dissolved ions to the lakes, then they would also contribute to the storm flow and base flow of the streams, respectively. But no major changes in stream-water chemistry are observed over large variations in discharge (Fig. 6).

3) The permanent streams drain small but representative portions of the total watershed. Because of the watertight bedrock, the streams carry the entire runoff from these portions of the watersheds. if these sub-watersheds are typical of the entire watershed, then the stream water is representative of runoff from the entire watershed.

4) Except for spring-melt when the ground is still frozen, overland flow is not a common phenomenon in undisturbed temperate forests, for water travels overland only a few meters at most before collecting into rills and small channels (Pierce 1967). For example, in the watershed of Meander Lake sprinkling several plots with the equivalent of 27 cm of rain failed to produce significant quantities of overland flow (Nordin 1974). Instead most of the water moved quickly down through the thin soil; horizontal flow was apparently restricted to subsurface channels. Aubertin (1971) found that rapid, subsurface flow is a common phenomenon in temperate forests, facilitated by soil macropores such as old root channels.

5) The large amounts of phosphorus in overland flow on burned areas are probably removed by the inorganic soil horizons as the water percolates down before collecting in subsurface channels. The fact that phosphorus is efficiently removed from solution by soils has been extensively reported, mostly by agriculture researchers studying phosphate fertilizers (Singer 1972).

Thus, the following general picture describes the fate of rain water falling on the terrestrial watersheds of the three study lakes. The water first moves a short distance on the surface or just below the surface where, in the burned area, it picks up large amounts of phosphorus. This water then flows horizontally along a granitic boulder until the edge of the boulder or other macropore is reached, whereupon it moves quickly vertically down through the generally highly permeable soil. Here the dissolved phosphorus is efficiently removed from the water by adsorption onto the soil particles, and the low cation concentrations are enhanced somewhat by mixing with the soil solution. Upon reaching the impermeable bedrock the water resumes horizontal flow, either along subsurface channels or on the surface in permanent or ephemeral streams, finally reaching the lake with a chemical composition similar to that of the permanent streams (Table 4).

Chemical budgets for the terrestrial watersheds

The cation and phosphorus budgets for the terrestrial watersheds calculated according to Eq. 4 are presented in Table 5. The budgets for Rawson Lake are included for comparison. These budgets show that atmospheric precipitation supplies major amounts of these elements. Weathering of the silicate rocks supplies additional amounts of cations, especially sodium. Since much more phosphorus entered the ecosystem than was exported in runoff, the forest watershed is accumulating this important plant nutrient.

TABLE 5. Chemical budgets for the terrestrial watersheds of Dogfish, Meander, and Lamb lakes (1972) and for Rawson Lake, ELA (1970–73 average; data from Schindler et al. 1975). All values are mg/m^2 watershed · year

	Ca	Mg	K	Na	P
Dogfish watershed					
Inputs:					
Precipitation (M_p)	275	42.5	74	71.5	13.7
Weathering and storage change[a] ($M_w - \Delta M$)	23	82	–16	55	–12.2
Outputs:					
Runoff (M_r)	298	125	58	127	1.5
Meander watershed					
Inputs:					
Precipitation (M_p)	292	47	75	67	14.4
Weathering and storage change[b] ($M_w - \Delta M$)	23	82	–16	55	–12.2
Outputs:					
Total runoff (M_r)	393	169	212	204	3.6
Runoff due to fire[c]	78	40	153	82	1.4
% increase	26%	29%	265%	65%	93%
Lamb watershed					
Inputs:					
Precipitation (M_p)	290	46	75	72	14.0
Weathering and storage change	ND	ND	ND	ND	ND
Outputs:					
Total runoff (M_r)	2,052	552	214	490	4.2
Rawson Lake watershed (1970–73)					
Inputs:					
Precipitation (M_p)	378	93	110	160	32.7
Weathering and storage change ($M_w - \Delta M$)	224	147	14	207	–27.6
Outputs:					
Runoff (M_r)	602	240	124	367	5.1

[a] By difference; negative values indicate net accumulation in watershed.

[b] Values from Dogfish watershed.

[c] By difference $M_r - (M_p + M_w - \Delta M)$.

Only small amounts of cations and phosphorus are exported from the undisturbed watersheds. Chemical weathering is slow because of the highly resistant granitic bedrock and the cold and relatively dry climate. The nutrient cycling in the undisturbed forest is thus very efficient, and only minor amounts leak from the system. The value of 1.5 mg/m^2 P exported at Dogfish Lake is similar to values reported from other forested igneous rock areas such as Shagawa Lake, Minnesota (4.0 mg/m^2; Malueg et al. 1975), Ontario (5.0 mg/m^2; Schindler et al. 1975), Switzerland (0–4 mg/m^2; Gächter and Furrer 1972), and Sweden (4.7 mg/m^2; Ahlgren 1967).

The effect of fire on nutrient exports is revealed by comparing the chemical budgets for the burned watershed of Meander Lake with the unburned watershed of Dogfish Lake (Table 5). Assuming that fire does not alter the rate of weathering by solution, the increased exports of cations and phosphorus can be attributed to forest fire.

At Meander Lake potassium and phosphorus exports increased 265% and 93% relative to the exports at Dogfish Lake. The observed 60% increase in runoff volume accounts for ≈ ⅕ of the K increase and ⅔ of the P increase, with the remainder due to increased concentrations of these elements in the runoff.

The fire probably altered the chemical budgets for the watershed of Lamb Lake also, but here the effects of fire are difficult to assess because of the presence of calcareous clays in the watershed, and no data from a suitable control watershed are available.

Potassium and phosphorus are efficiently conserved and cycled in an undisturbed forest (Ovington 1968). Fire apparently disrupts the system by converting forest-floor material into a readily soluble form, while at the same time greatly reducing the normal uptake of nutrients by vegetation. Increased cation export also occurred after the Entiat fire (Tiedemann and Helvey 1973); phosphorus was not measured. Johnson and Needham (1966) report no increases in cation concentrations in stream water draining a burned conifer forest in the Sierra Nevada of California. However, since the amount of runoff was not measured, increased cation exports are not

TABLE 6. Chemical budgets for Dogfish, Meander, and Lamb lakes (1972) and for Rawson Lake (1970–1973 average; data from Schindler et al. 1975). All values are mg/m^2 lake surface · year

		Ca	Mg	K	Na	P
Dogfish Lake						
Inputs:						
Precipitation	(M_p)	275	42.5	74	71.5	13.7
Runoff	(M_r)	606	253	117	313	3.1
Outputs:						
Effluent	(M_o)	1,365	430	260	374	4.4
Sedimentation[a]	(M_s)	–484	–134	–69	10	12.4
Meander Lake						
Inputs:						
Precipitation	(M_p)	292	46.5	80	62.4	14.4
Runoff	(M_r)	1,456	628	785	765	13.2
Outputs:						
Effluent	(M_o)	2,620	864	827	890	7.7
Sedimentation[a]	(M_s)	–872	–190	38	–71	20.0
Lamb Lake						
Inputs:						
Precipitation	(M_p)	290	46	75	72	14.0
Runoff	(M_r)	8,093	2,177	841	1,993	16.6
Outputs:						
Effluent	(M_o)	9,650	2,750	743	1,930	8.9
Sedimentation[a]	(M_s)	–1,267	–527	173	135	21.7
Rawson Lake (ELA)						
Inputs:						
Precipitation	(M_p)	378	93	110	160	32.7
Runoff	(M_r)	3,790	1,510	780	2,310	32.1
Outputs:						
Effluent	(M_o)	4,130	1,530	800	2,165	18.1
Sedimentation[a]	(M_s)	38	73	90	305	46.7

[a] By difference; $M_s = M_o - (M_p + M_r)$, negative values indicate net loss from the sediments.

precluded. Lewis (1974) also observed increased cation losses following a prescribed burn in a second-growth pine forest in South Carolina. No significant change in phosphorus was observed, however.

The nitrate concentrations in water samples collected from the Meander Lake watershed and from a prescribed burn at Perent Lake (R. F. Wright 1974) give no indication of large exports of nitrate from these burned areas. This result contrasts with the 240-fold increase in nitrate loss (0.008 kg/ha to 1.92 kg/ha) after the Entiat fire (Tiedemann and Helvey 1973).

Similar increases in cation and phosphorus exports also result from artificial disturbance of the forest cover. The clear-felling experiments conducted at Hubbard Brook (Likens et al. 1970, Hobbie and Likens 1973), Coweeta Hydrologic Laboratory, North Carolina (Johnson and Swank 1973), and H. J. Andrews Experimental Forest, Oregon (Fredrikson 1970) all showed that blockage of the nutrient-uptake pathway results in increased nutrient exports.

Chemical budgets of the lakes

The 1972 cation and phosphorus budgets for Dogfish, Meander, and Lamb lakes and Rawson Lake are presented in Table 6 and are calculated on the basis of milligrams of element per square meter of lake surface times year (mg/m^2 · yr). This unit, termed the specific surface loading, allows the useful comparison of data from lakes that may differ greatly in area and volume (Edmondson 1961, Vollenweider 1968).

Cations.—The cation budgets reveal that an important fraction of the cation supply comes from the atmosphere. This source is not affected by processes occurring in the watersheds, and therefore changes in inputs from the watershed will tend to be masked by the atmospheric contributions.

The net sedimentation rates (M_s), obtained by difference from the cation budgets, are with few exceptions negative. This suggests that cations are being released from the lake sediments to the water. These budgets are for one year only, however, and over the long term a small positive sedimentation rate is most likely, as Schindler et al. (1975) found in the 4-yr budgets for Rawson Lake.

Phosphorus.—The role of phosphorus in lakes is much different from that of cations. While the cations are normally present in quantities vastly exceeding those required for growth, phosphorus is usually so low in concentration that the growth of

TABLE 7. Specific surface loading and percent retention of phosphorus in undisturbed and disturbed lakes. Loading values are mg/m^2 lake surface · year. NA = not available; no control watershed data exist for Lamb Lake

		Year	Loading	Retained (%)	Source
A. Undisturbed Lakes					
BWCA Dogfish		1972	16.8	74	Present study
ELA Lake 227	Natural supply only	1969	21.7		Schindler et al. 1971
		1970	101		Schindler et al. 1973
		1971	106		
ELA Lake 239 (Rawson)		1970	62	72	Schindler et al. 1975
		1971	96	67	
		1972	53	79	
		1973	46	76	
Clear Lake, Ontario		long-term	40	80	Schindler and Nighswander 1971

	Treatment	Year	Loading	Increase in loading due to treatment (%)	Retained (%)	Source
B. Disturbed Lakes						
BWCA Meander	Forest fire	1972	27.6	38	72	Present study
BWCA Lamb	Forest fire	1972	30.6	NA	71	Present study
ELA Lake 227	P + N added	1969	362	1,600	62	Schindler et al. 1971
		1970	582	578	69	Schindler et al. 1973
		1971	592	550	91	

aquatic organisms, particularly algae, is limited. Enrichment experiments conducted in several lakes in the Experimental Lakes Area (Schindler 1974) demonstrate that phosphorus is the limiting nutrient for algal productivity in oligotrophic lakes of the Canadian Shield.

The phosphorus budgets of the terrestrial watersheds indicate that in 1972, the second year after the fire, forest fire resulted in a 93% increase in phosphorus exported from the Meander Lake watershed, relative to the export from the Dogfish Lake watershed (Table 5). Translated from mg/m^2 watershed to mg/m^2 lake surface, this runoff-export increased the phosphorus loading of Meander Lake 38% (Table 7). This increase probably lies within the normal year-to-year variations in P supply, and thus does not represent a major impact on Meander Lake.

The Little Sioux fire may have produced a larger increase in P export during 1971, immediately following the fire. Although no budget data exist to assess the first-year impact, there is no evidence from the phosphorus concentrations in the lake (Tarapchak and Wright 1975) or from the phytoplankton populations (Bradbury et al. 1974) to suggest any significant enrichment of Meander Lake as a result of the fire.

McColl and Grigal (1975) reached the same conclusion based on a separate study of the effect of the Little Sioux fire on phosphorus movement in the terrestrial watersheds. Their data were not sufficient to calculate phosphorus fluxes to Meander and Dogfish lakes, but based on phosphorus concentrations in precipitation, throughfall, overland flow, soil water, stream, and lake water they concluded that although phosphorus was mobilized in the forest as a result of the fire, most of this phosphorus was taken up in the soil and very little reached the lakes.

IMPLICATIONS FOR FOREST MANAGEMENT

The Little Sioux fire occurred in the spring. Although much of the overstory was killed, the cool and moist ground protected the duff layer and only a small fraction of the forest-floor material was consumed. Revegetation began immediately, and in only a few months the area was marked by a lush cover of new vegetation.

Spring fires are one common fire type in the BWCA, but fall fires are also typical. Fall fires, occurring often after a prolonged drought in August and September, consume not only standing vegetation but the litter and humus layers as well (Heinselman 1973). Many of the historic great fires of the region occurred in the fall (Haines and Sando 1969).

A fall fire is likely to cause larger changes in the hydrologic and chemical budgets of the terrestrial watersheds and lakes than are caused by a spring fire such as the Little Sioux fire. A greater quantity of nutrients would probably be released as a result of the more thorough burning of the forest-floor material, and the uptake of nutrients would be delayed for many months until the new growing season begins the following spring. Thus, a greater fraction of nutrients is likely to be lost from the forest floor and exported from the terrestrial watersheds to the lakes.

Fire plays a natural, important, and crucial role in the forest ecosystems of Minnesota. Heinselman's (1973) detailed study of the fire history of the BWCA shows that forest reproduction depends on periodic fires, and that fire has been present for at least 375 years. This record is extended over the last 9,000 years by Swain (1973) on the basis of charcoal stratigraphy of lake sediments. The natural role of fire has also been documented for several other major forest-types of North America (Wright and Heinselman 1973).

The dominant United States forest management policy of fire exclusion thus thwarts the natural functions of fire-dependent ecosystems. If forest managers aim to maintain forested ecosystems in the natural state, then fire must be allowed to play its natural part. The U.S. National Park Service has begun to do just that, and present policy now includes a let-burn policy toward some wildfires (Kilgore 1973).

In northern Minnesota, however, the U.S. Forest Service has yet to reintroduce fire to the BWCA, the largest remaining block of virgin forest in the eastern United States. Instead, to maintain the wilderness nature of this ecosystem, the new management plan (U.S. Forest Service 1974) calls for commercial logging and "administrative cutting" to reduce the fuel that would normally be consumed by fire. This policy must be self-defeating, for the removal of a major ecosystem process such as fire can only result in a change in the ecosystem itself, thereby converting a natural ecosystem into an ecosystem altered by man (H. E. Wright 1974).

The results of the present study and that of McColl and Grigal (1975) show that although fire might redistribute nutrient elements within the forest ecosystem, only a very small fraction of the nutrient capital of the forest is lost, and no lake eutrophication occurs. Logging, on the other hand, could severely deplete the available nutrient supply because large quantities of nutrients are removed (Cole et al. 1968). For the forest ecosystems of the BWCA, logging might severely deplete the nutrient capital that has accumulated slowly through the weathering of parent material and influx of nutrients from the atmosphere.

CONCLUSIONS

The watersheds of Dogfish, Meander, and Lamb lakes are underlain by an impermeable granite typical of the Canadian Shield. Under the cold and relatively dry climate, the highly resistant parent materials weather very slowly, and the solution-weathering rates are low, comparable to those reported from other shield watersheds.

The atmosphere supplies a significant fraction of the cations and phosphorus (Ca 90%, Mg 35%, K 95%, Na 55%, P 95%) to the BWCA watersheds. The forest ecosystem is very efficient at retaining this pool of nutrients, built up since deglaciation more than 14,000 years ago. The nutrients normally move in the internal cycle of uptake–litterfall–decomposition–uptake, and only a very small part is lost from the system in the runoff.

The loss from the terrestrial-watershed ecosystem comprises much of the cation supply for the lakes, however, although here again atmospheric precipitation falling directly on the lakes contributes a major fraction of the cations and nearly all the phosphorus to the lakes. Because of the extremely low phosphorus supply, lake productivity is low and the lakes remain dilute, oligotrophic, and transparent. Most of the cations leave the lakes by the outlet; they are not affected by internal lake-ecosystem processes and are merely flushed out along with the water. Phosphorus, on the other hand, is efficiently retained in the lakes; rapid uptake by aquatic organisms followed by death and deposition in the sediments results in the removal of over 70% of the annual phosphorus supply from the lakes.

Fire disrupts the cycling processes in the terrestrial watersheds and the lakes. In 1972, two years after the Little Sioux fire, the export of the two important plant nutrients, K and P, were 265% and 93% higher at Meander Lake than from the unburned watershed of Dogfish Lake. This loss is small compared to the available nutrient capital of the forest, and thus the forest ecosystem retains most of its nutrients even after a major fire.

The increased loss from the watershed resulted in a larger supply of potassium and phosphorus to Meander Lake. The increase in potassium had no major impact on the lake ecosystem, for it is present in amounts vastly exceeding those needed for algal growth. The increase in phosphorus loading was only 38%, for most of the phosphorus is supplied by the atmosphere. No evidence of an increased phosphorus loading was seen in the phosphorus concentrations of the lake water, presumably because the phosphorus was rapidly incorporated into organic matter. The 38% increase in phosphorus loading probably lies within the normal year-to-year variations in phosphorus supply to Meander Lake. Thus, Meander Lake continues to be dilute, oligotrophic, and transparent, and shows no apparent response to the Little Sioux fire that killed two-thirds of the standing vegetation on its watershed.

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LITERATURE CITED

Ahlgren, I. 1967. Limnological studies of Lake Norrviken, a eutrophicated Swedish lake. Schweiz. Z. Hydrol. **29**:53–90.

Armstrong, F. A. J., and D. W. Schindler. 1971. Preliminary chemical characterization of waters in the Experimental Lakes Area, northwestern Ontario. J. Fish. Res. Board Can. **28**:171–187.

Aubertin, G. M. 1971. Nature and extent of macropores in forest soils and their influence on subsurface water movement. U.S. For. Serv., Northeast For. Exp. Stn., Res. Pap. NE-192.

Bradbury, J. P., S. J. Tarapchak, J. C. B. Waddington, and R. F. Wright. 1975. The impact of forest fire on a wilderness lake in northeastern Minnesota. Verh. Int. Ver. Limnol. **19**:875–883.

Brown, E., M. W. Skougstad, and M. J. Fishman. 1970. Methods for collection and analysis of water samples for dissolved minerals and gasses. U.S. Geol. Surv., Tech. Water-Resources Invest., Book 5, Chapter A1.

Brunskill, G. J., and D. W. Schindler. 1971. Geography and bathymetry of selected lake basins, Experimental Lakes Area, northwestern Ontario. J. Fish. Res. Board Can. **28**:139–155.

Cobb, E. D., and J. F. Bailey. 1965. Measurement of discharge by dye-dilution methods. U.S. Geol. Surv., Surface Water Tech., Book 1, Chapter 14.

Cole, D. W., S. P. Gessel, and S. F. Dice. 1968. Distribution and cycling of nitrogen, phosphorus, potassium and calcium in a second-growth Douglas-fir ecosystem, p. 197–232. *In* H. E. Young (ed.) Symposium on primary production and mineral cycling in natural ecosystems. Univ. Maine Press, Orono.

Edmondson, W. T. 1961. Changes in Lake Washington following an increase in the nutrient income. Mitt. Int. Ver. Limnol. **14**:167–175.

Fredriksen, R. L. 1970. Comparative water quality—natural and disturbed systems, p. 125–137. *In* J. T. Krygier and J. D. Hall (eds.) Forest land uses and stream environment. Oregon State Univ., School of Forestry, Corvallis, Oregon.

Gächter, R., and O. J. Furrer. 1972. Der Beitrag der Landwirtschaft zur Eutrophierung der Gewässer in der Schweiz. Schweiz. Z. Hydrol. **34**:41–70.

Goldich, S., A. O. Nier, H. Baadsgaard, J. H. Hoffman, and H. W. Krueger. 1961. The Precambrian geology and geochronology of Minnesota. Bull. Minn. Geol. Surv. 41.

Gorham, E. 1961. Factors influencing the supply of major ions to inland waters, with special reference to the atmosphere. Bull. Geol. Soc. Am. **72**:795–840.

Haines, D. A., and R. W. Sando. 1969. Climatic conditions preceding historically great fires in the North Central region. U.S. For. Serv., North Central For. Exp. Stn., Res. Pap. NC-34.

Heinselman, M. L. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. Quat. Res. **3**:329–382.

Hibbert, A. R. 1967. Forest treatment effects on water yield, p. 527–543. *In* W. E. Sopper and H. W. Lull (eds.) Proceedings, International Symposium on Forest Hydrology. Pergamon Press, New York.

Hobbie, J. E., and G. E. Likens. 1973. Output of phosphorus, dissolved organic carbon, and fine particulate carbon from Hubbard Brook watersheds. Limnol. Oceanogr. **18**:734–742.

Johnson, C. M., and P. R. Needham. 1966. Ionic composition of Sagehen Creek, California, following an adjacent fire. Ecology **47**:636–639.

Johnson, N. M., G. E. Likens, F. H. Bormann, D. W. Fisher, and R. S. Pierce. 1969. A working model for the variation in stream water chemistry at the Hubbard Brook Experimental Forest, New Hampshire. Water Resour. Res. **5**:1353–1363.

Johnson, P. L., and W. T. Swank. 1973. Studies of cation budgets in the southern Appalachians on four experimental watersheds with contrasting vegetation. Ecology **54**:70–80.

Kilgore, B. M. 1973. The ecological role of fire in Sierran conifer forests. Quat. Res. **3**:496–513.

Lewis, W. M., Jr. 1974. Effects of fire on nutrient movement in a South Carolina forest. Ecology **55**: 1120–1127.

Likens, G. E., and F. H. Bormann. 1974. Effects of forest clearing on the northern hardwood forest ecosystem and its biogeochemistry. *In* Proc. First Internat. Cong. Ecol., Sept. 1974, The Hague.

Likens, G. E., F. H. Bormann, N. M. Johnson, D. W. Fisher, and R. S. Pierce. 1970. Effects of forest cutting and herbicide treatment on nutrient budgets in the Hubbard Brook watershed-ecosystem. Ecol. Mono. **40**:23–47.

McColl, and D. F. Grigal. 1975. Forest fire: Effects on phosphorus movement to lakes. Science **188**:1109–1111.

Malueg, K. W., D. P. Larsen, D. W. Schults, and H. T. Mercier. 1975. A six-year water, phosphorus, and nitrogen budget for Shagawa Lake, Minnesota. J. Environ. Qual. **4**:236–242.

Nordin, J. O. 1974. The mapping and characterization of the soils and vegetation of the Little Sioux Burn Area in northeastern Minnesota. M.S. thesis, Univ. Minnesota, St. Paul.

Ohmann, L. F., and R. R. Ream. 1971. Wilderness ecology: Virgin plant communities of the Boundary Waters Canoe Area. U.S. For. Serv. Res. Pap. NC-63.

Ovington, J. D. 1968. Some factors affecting nutrient distribution within ecosystems, p. 95–105. *In* F. E. Eckardt (ed.) Functioning of terrestrial ecosystems at the primary production level. Proceedings, Copenhagen Symposium, UNESCO. Vaillant-Carmanne S.A., Liege, Belgium.

Pierce, R. S. 1967. Evidence of overland flow on forest watersheds, p. 247–252. *In* W. E. Sopper and H. W. Lull (eds.) Proceedings, International Symposium on Forest Hydrology. Pergamon Press, New York.

Sando, R. W., and D. A. Haines. 1972. Fire weather and behavior of the Little Sioux fire. U.S. For. Serv. Res. Pap. NC-76.

Schindler, D. W. 1974. Eutrophication and recovery in experimental lakes: Implications for lake management. Science **184**:897–898.

Schindler, D. W., and J. E. Nighswander. 1970. Nutrient supply and primary production in Clear Lake, eastern Ontario. J. Fish. Res. Board Can. **27**:2010–2036.

Schindler, D. W., F. A. J. Armstrong, S. K. Holmgren, and G. J. Brunskill. 1971. Eutrophication of Lake 227, Experimental Lakes Area, northwestern Ontario, by addition of phosphate and nitrate. J. Fish. Res. Board Can. **28**:1763–1782.

Schindler, D. W., H. Kling, R. V. Schmidt, J. Prokopowich, V. E. Forest, R. A. Reid, and M. Caper. 1973. Eutrophication of Lake 227 by addition of phosphate and nitrate: the second, third and fourth years of enrichment, 1970, 1971, and 1972. J. Fish. Res. Board Can. **30**:1415–1440.

Schindler, D. W., R. W. Newbury, K. G. Beaty, and P. C. Campbell. 1976. (*in press*) Natural water and chemical budgets for a small Pre-Cambrian lake basin in central Canada. J. Fish. Res. Board Canada.

Singer, M. J. 1972. Phosphorus cycling in an east-central Minnesota deciduous hardwood forest. Ph.D. thesis. Univ. Minnesota, St. Paul.

Strickland, J. D. H., and T. R. Parsons. 1968. A practical handbook of seawater analysis. Bull. Fish. Res. Board Can. 167.

Swain, A. M. 1973. A history of fire and vegetation in northeastern Minnesota as recorded in lake sediments. Quat. Res. **3**:383–396.

Tarapchak, S. J., and R. F. Wright. 1976. (*in press*) Three oligotrophic lakes in northern Minnesota. *In* The North American Project, U.S. Environ. Prot. Agency, Ecol. Res. Series.

Tiedemann, A. R., and J. D. Helvey. 1973. (*Abstract*) Nutrient-ion losses after fire and fertilization in Eastern Washington. Am. Inst. Biol. Sci., Annual Meeting 1973.

U.S. Forest Service. 1974. Boundary Waters Canoe Area plan, and draft environmental impact statement. Superior National Forest, Duluth, Minnesota.

Vollenweider, R. A. 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication. Tech. Rep. O.E.C.D. Paris DAS/SCI/68.27, p. 1–182.

Wright, H. E., Jr. 1974. Landscape development, forest fires, and wilderness management. Science **186**: 487–495.

Wright, H. E., Jr., and M. L. Heinselman. 1973. The ecological role of fire in natural conifer forests of western and northern North America. Quat. Res. **3**: 319–328.

Wright, H. E., Jr., and W. A. Watts. 1969. Glacial and vegetational history of northeastern Minnesota. Minn. Geol. Surv., Spec. Pub. SP-11.

Wright, R. F. 1974. Forest-fire: Impact on the hydrology, chemistry, and sediments of small lakes in northeastern Minnesota. Ph.D. thesis. Univ. Minnesota, Minneapolis.