# Effects of Multiple Fires on Nutrient Yields from Streams Draining Boreal Forest and Fen Watersheds: Nitrogen and Phosphorus

S. E. Bayley,[1] D. W. Schindler,[2] K. G. Beaty, B. R. Parker,[2] and M. P. Stainton

*Department of Fisheries and Oceans, 501 University Crescent, Winnipeg, Man. R3T 2N6, Canada*

Bayley, S. E., D. W. Schindler, K. G. Beaty, B. R. Parker, and M. P. Stainton. 1992. Effects of multiple fires on nutrient yields from streams draining boreal forest and fen watersheds: nitrogen and phosphorus. Can. J. Fish. Aquat. Sci. 49: 584–596.

Wildfire in the boreal forests at the Experimental Lakes Area in Ontario caused significant losses of nitrogen and phosphorus in streams. Both watershed type and fire intensity appear to determine the extent of losses. The Northeast wetland basin lost more N and P, especially TDN, TDP, TN, and TP, than did terrestrial basins, although nitrate losses were higher from terrestrial basins. Losses of nutrients after the second fire generally were not as high as after the first fire. In the East basin, which burned twice with a high fire intensity, stream concentrations of $NO_3^-$, TDN, and TN were elevated for 6 yr between the fires and remained elevated for 9 yr after the second fire. In contrast, the Northwest basin burned with a lower intensity and had no significant increase in annual concentrations of P or most forms of N in the first 3 yr after the fire; only $NO_3^-$ concentrations increased during this period. Despite the increases in export after wildfire, net retention of TN and TP over the 18-yr period was high. In the Northeast, East, and Northwest basins, retention of TN averaged 77, 80, and 87% compared with TP retention of 51, 67, and 84%.

Des feux échappés dans les forêts boréales de la zone des lacs expérimentaux de l'Ontario ont entraîné des pertes importantes d'azote et de phosphore dans les cours d'eau. Le type de bassin versant et l'intensité du feu semblent tous deux déterminer l'ampleur des pertes. Le bassin nord-est des terres humides a perdu une plus grande quantité de N et de P, surtout du NDT, du PDT, du NT et du PT, que les bassins terrestres, quoique les pertes de nitrate étaient plus importantes dans les bassins terrestres. Les pertes de bioéléments après le deuxième feu étaient en général moins élevées qu'après le premier feu. Dans le bassin est, qui a été deux fois l'objet d'un feu de forte intensité, les concentrations de $NO_3^-$, de NDT et de NT ont été élevées pendant les 6 ans séparant les feux, et le sont demeurées pendant 9 ans après le deuxième feu. Par contre, le bassin nord-ouest a été l'objet d'un feu de moindre intensité et n'a pas montré d'augmentation marquée des concentrations annuelles de P ou de la plupart des formes de N au cours des trois années après le feu; seules les concentrations de $NO_3^-$ ont augmenté pendant cette période. Malgré l'augmentation des teneurs en bioéléments exportés après les feux échappés, la rétention nette de NT et de PT pendant ces 18 ans a été élevée. Dans les bassins nord-est, est et nord-ouest, la rétention de NT a atteint en moyenne 77, 80 et 87 %, respectivement, pour une rétention de PT de 51, 67 et 84 %.

*Received January 29, 1991*
*Accepted October 10, 1991*
*(JA880)*

*Reçu le 29 janvier 1991*
*Accepté le 10 octobre 1991*

Fire is an important pertubation in terrestrial ecosystems in the boreal forest. Natural wildfires commonly occur at a frequency of one to several times per century in the southern boreal forest (Heinselman 1973; Swain 1973; Clark 1990). In addition, prescribed burning following clearcutting is used extensively in forest management. In the southeast United States, prescribed fires did not cause an increase in chemical concentrations in downstream waters (Richter and Ralston 1982). However, most studies of the effect of fire on the chemistry of surface soil report increased concentrations of $NH_4^+$, P, $K^+$, $Na^+$, and $Mg^{2+}$ for several months after a fire (DeByle and Packer 1972; McColl and Grigal 1975, 1977; Smith and James 1978). There are few studies documenting the effect of wildfire in boreal forests on stream chemistry (Wright 1976; Schindler et al. 1980). A few studies of wildfire in temperate and mountain ecosystems have shown increased concentrations of various ions in streams (Brown et al. 1973; Wright 1976; Tiedemann et al. 1978). Most of the published studies on fire emphasize effects on hydrologic budgets and sedimentation (Tiedemann et al. 1978, 1979; Riekerk 1983; Megahan 1983). Studies of the effects of wildfire on nutrient budgets which include pre- and postburn data for the same watershed are rare (Schindler et al. 1980) and none reports data for more than 3 yr after a fire. Nutrient budgets have been constructed for a variety of forest management strategies (Likens et al. 1970; Johnson and Swank 1973).

The purpose of this paper is to describe nitrogen (N) and phosphorus (P) budgets in three small boreal watersheds before and after forest fires. We will describe long-term effects of a 1974 fire in the boreal watersheds (first described by Schindler et al. 1980) and will describe the effects of a 1980 fire in the same basins. In addition, we compare 9 yr of prefire data on one stream with 9 yr of postfire data on the same stream. We will also describe the effects of these fires on the chemical budget of the adjacent oligotrophic lake. Our objectives are to compare the retention and loss of N and P in the two terrestrial and one wetland watersheds. We compare the effects of fire on

[1]Present address: Department of Botany, University of Alberta, Edmonton, Alta. T6G 2E9, Canada.

[2]Present address: Department of Zoology, University of Alberta, Edmonton, Alta. T6G 2E9, Canada.

these watersheds with other published fire studies and with forest management techniques such as clearcutting and herbicide application (Likens et al. 1970; Johnson and Swank 1973; Aubertin and Patric 1974; Bormann et al. 1974; Feller and Kimmins 1984; Swank 1987).

## Materials and Methods

### The Study Watersheds

The study area is in the Experimental Lakes Area (ELA) of northwestern Ontario (lat. 49°40'N, long. 93°44'W). The watershed of Rawson Lake (Lake 239) is composed of three distinct stream drainages (referred to here as subbasins), plus an area which drains directly to the lake (Fig. 1). All three subbasins are underlain primarily by pink granodiorite composed of 40% quartz, 40% plagiocase, and 10% K-feldspar, with traces of ilmenite, muscovite, and kaolinite (Brunskill and Schindler 1971). Lower lying areas and valley bottoms are typically occupied by orthic brunisols, underlain by sand and boulder till which are from a few centimetres to a few metres in thickness.

The Northwest (NW) subbasin (56.4 ha) drains directly to a 120-m stream segment, through a 2-ha wetland, and enters the lake over a V-notch weir. The East (E) subbasin (170.3 ha) is larger than the NW subbasin and more complex, with a much longer (1100 m) stream segment. While there is a small boggy area high in the watershed, 80% of the surface is upland. The Northeast (NE) subbasin (12.43 ha) contains an acid bog (pH 3.9–4.5), which occupies 30% of the basin, into which all upland areas drain. The bog outflow collects in a short stream channel monitored by a weir and then disperses over surface rocks into the lake.

### The Fires

*The 1973 Windstorm and 1974 fire*

On July 7, 1973, a powerful windstorm accompanied by a severe thunderstorm struck the experimental watersheds. Estimated blowdown was less than 20% in the NW subbasin but 50–100% in the other two subbasins. Blowdown was most severe on the hilltops. Trees in the bog areas in the NE subbasin were relatively untouched.

On June 26, 1974, an extremely hot forest fire burned both the NE and E subbasins. The flame-front intensity was 13 000 $kw \cdot m^{-1}$ (Schindler et al. 1980). Virtually all vegetation less than 2.5 cm in diameter was consumed, and organic matter in surface soils was mineralized to a depth of several centimetres. In the NE subbasin, the southern end (35%) of the bog burned as well as upland areas. The NW subbasin was not touched by the fire.

*The 1980 fire*

On June 20, 1980, a second forest fire occurred in the Lake 239 (L239) basin. Set by a lightning strike to the SW of the L239 watershed, the fire swept up both sides of the lake. On the east side of the lake, in the E subbasin, much of the timber killed in the 1974 fire had fallen, lying criss-crossed in a layer up to a metre deep, with a new, thick cover of *Populus tremuloides* Michx., *Pinus banksiana* Lamb., and herbaceous vegetation reaching up to 2 m in height. This provided fuel for a very hot, fast-moving fire in the E subbasin, which consumed almost all of the vegetation, leaving bare bedrock with isolated pockets of thin overburden. Almost all organic matter in the soils was also combusted.

Approximately 50% of the upland portion of the NE subbasin burned in the 1980 fire, but the wetland and some adjacent upland did not burn.

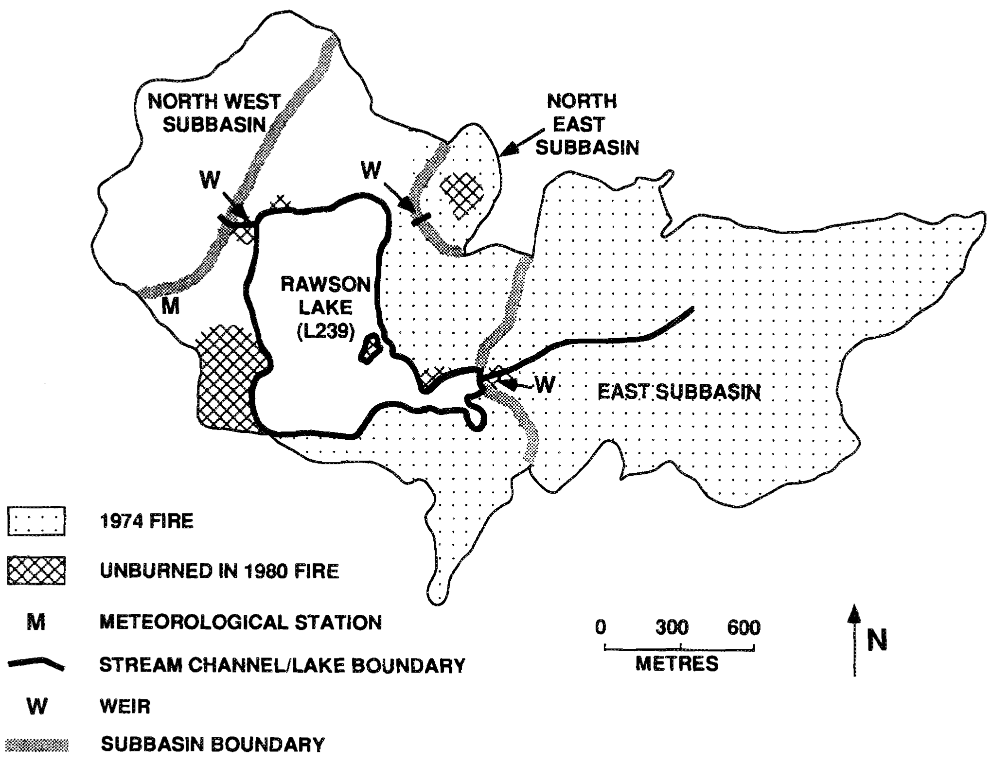



FIG. 1. The L239 watershed at ELA showing the NW, NE, and E subbasins. Grey areas burned in 1974. All of the L239 watershed burned in 1980 except for the hatched areas.

The NW subbasin was burned in the evening and overnight on June 21. Winds were low and humidity was high. As a result, vegetation was killed, but little was consumed. Needles and leaves were left intact on trees and many shrubs. Figure 1 shows the extent of both the 1974 and 1980 fires. For a year after the 1980 fire, black clouds of charcoal and dust reduced visibility in the area on windy days.

## Vegetation before and after the Fires

Before the fires, hilltops and steep slopes were thinly forested, while less steeply sloping areas were thickly forested and covered with moss and lichens to a depth of a few centimetres. Before the fires, all upland areas were vegetated by a mature virgin community of jackpine (*Pinus banksiana*) and black spruce (*Picea mariana* (Mill.) BSP), with paper birch (*Betula papyrifera* Marsh.) and trembling aspen (*Populus tremuloides*) also abundant. Red pine (*Pinus resinosa* Ait.), white pine (*Pinus strobus* L.), and white spruce (*Picea glauca* (Moech) Voss) were also present in small numbers.

After the first fire in the E and NE subbasins, all areas revegetated rapidly. Small jackpine, black spruce, poplar, birch, balsam poplar (*Populus balsamifera* L.), and pin cherry (*Prunus pensylvanica* L.) were present. Dense herbaceous and shrub vegetation was dominated by fireweed (*Epilobium angustifolium* L.), black bindweed (*Polygonum convolvulus* L.), blueberry (*Vaccinium* spp.), and raspberry (*Rubus strigosus* (Michx.)). Within 3 yr after the fire, jackpine stands were so dense as to be almost impenetrable, except in high, rocky areas of the E subbasin where cones were totally combusted. Revegetation of the NW subbasin after the 1980 fire (the only fire in that subbasin) was also rapid.

After the second fire, revegetation in the E subbasin was very slow. Some ridgetop areas had almost no plant cover (<1 plant in 100 $m^2$) 2 yr later. Lower-lying areas were sparsely covered with jackpine, trembling aspen, pin cherry, saskatoon (*Amelanchier alnifolia* Nutt.), and balsam poplar. Herbaceous and shrub cover, of the above-mentioned species, was also very sparse.

While upland areas of the NE subbasin were very similar to those of the E subbasin after the second fire, the vegetation in the boggy areas of the NE subbasin was little affected by the fire and was (and still is) dominated by black spruce and *Sphagnum* species, chiefly *Sphagnum fuscum* (Schimp.) Klinggr., *S. angustifolium* (Russ.) C. Jens., and *S. magellanicum* Brid. Some trees in the bog were killed, and surface *Sphagnum* was scorched in places. Except for black spruce trees, recovery was rapid in the bog, and Vitt and Bayley (1984) detected no difference in understory vegetation in the burned and unburned portions of the bog. After the 1974 fire, jackpine invaded the southerly (downstream) end of the bog, while the upper end still has an open stand of black spruce.

## Data Collection and Analyses

### *Hydrologic and chemical budgets*

Water flows in the NW and E subbasins were measured continuously with weirs and stage recorders during the ice-free season. The NW subbasin weir was installed in 1970. The E subbasin weir was installed in mid-June 1971. The NE subbasin was measured intermittently from 1971 to 1973; in 1974, a continuous recorder was installed. Regressions of E or NE flow versus NW flow were used to estimate daily flow from E and NE weirs during periods of missing record. Winter discharge of water was rare in all three subbasins and measured manually when necessary. A year-round weir at the outlet of L239 and a level recorder on the lake provided a check on hydrological measurements. All precipitation and stream discharge data are presented based on a water year (November 1 through October 31).

Water samples for chemical analyses were collected weekly during the ice-free season (May–October) at the weir in each subbasin. Samples also were taken occasionally in early spring, fall, and winter. During spring melt, there was an intensive sampling effort (see later). Chemical methods are reported in Schindler et al. (1976, 1980) and Stainton et al. (1977).

The chemical budgets for the subbasins were calculated by estimating the daily chemical concentration (based on linear interpolations between weekly chemical measurements) and multiplying these by daily water flows. Mean annual concentrations are volume-weighted concentrations for each year calculated from the total export divided by the total water flow. Monthly concentrations and annual exports of mass are similarily calculated. The budget data (1970–76) presented in Schindler et al. (1980) have been recalculated and include better estimates of spring melt and October and November hydrology.

Weekly water sampling may lead to poor representation of stormflow chemistry relative to base flow conditions and thus give only poor estimates of annual mass transport. This probably has not produced a significant bias in the annual subbasin budgets at ELA for the following reasons: (1) while the rising limb of the storm hydrographs generally had increased concentrations of $NO_3^-$, total dissolved nitrogen (TDN), total dissolved phosphorus (TDP), suspended nitrogen (Susp N), and suspended phosphorus (Susp P), the peak flow and falling limb had lower concentrations than the base flow and the volume-integrated concentrations were usually only slightly higher than base flow conditions and (2) there was no statistically significant relationship between flow and concentration in the NW subbasin (unburned period 1971–79, $n = 288–330$) for the following parameters: $NO_3^-$ ($r^2 = 0.0006$), $NH_4^+$ ($r^2 = 0.0000$), TDN ($r^2 = 0.0005$), and TDP ($r^2 = 0.0019$). Susp P concentrations significantly correlated with flow at a low level ($r^2 = 0.027$) in the NW subbasin during the prefire years and therefore the failure to measure flows following some storms could result in a slight underestimation of annual export of Susp P. Flows and concentrations during many of the large storms were actually measured, so it is the small to medium-sized summer and fall storms that could cause an underestimation, but this is unlikely to be serious because the relationship between flow and concentration for summer and fall was poor (Susp P had $r^2 = 0.054$ and $n = 231$). Bias in mass export generally did not occur during the high flows in spring melt since these were measured. According to Johnson (1979), acceptable estimates of annual mass flux can be obtained from samples collected weekly provided all flow stages are represented.

### *Statistical approach and analysis*

To perform statistical analyses of subbasin exports and streamwater concentrations before and after fires, masses exported and streamwater concentrations were calculated on the basis of the fire (and windstorm) events. The events occurred on July 7, 1973 (windstorm), June 26, 1974 (first fire), and June 20, 1980 (second fire). The following time periods for the NE and E subbasins were used in Tables 1–5. Prefire period:

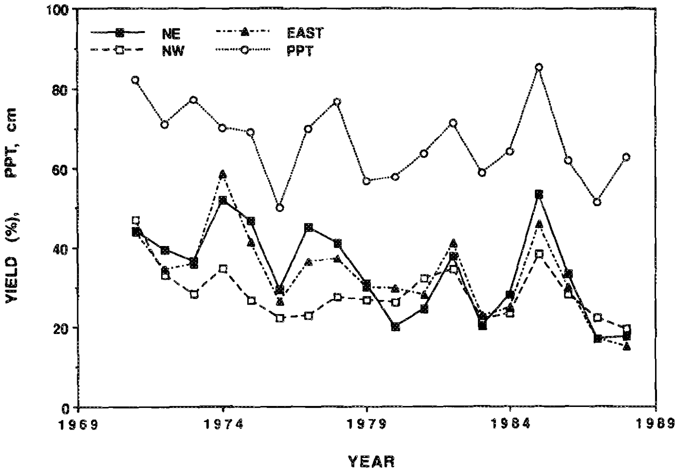



FIG. 2. Annual yield from the three ELA streams and annual precipitation from 1971 to 1989.

June 1971 to July 6, 1973; windstorm period: July 7, 1973 to June 25, 1974; postfire period 1a: June 26, 1974 to June 25, 1977; postfire period 1b: June 26, 1977 to June 19, 1980; postfire period 2a: June 20, 1980 to June 19, 1983; postfire period 2b: June 20, 1983 to June 19, 1986; postfire period 2c: June 20, 1986 to June 20, 1989.

In the NW subbasin, the prefire period was 9 yr (June 1971 to June 19, 1980) and the 9 yr of the postfire period then follow as described for periods 2a, 2b, and 2c above.

To determine statistically the effect of fires on chemical exports and streamwater concentrations, a Student $t$-test was used to test the null hypothesis that the mean of the exports (for streamwater concentrations) for the postfire periods was the same as that prior to the fire. If the test statistic was significant at $\alpha = 0.05$, then the postfire period was considered significantly different from the prefire mean.

Statistical analysis of the impact of fire on the seasonal concentrations of nutrients was similarly performed. Monthly concentrations and standard errors were calculated for all prefire years and compared with the mean monthly concentrations and standard errors in the 3 yr after fire. For the NW subbasin, the postfire period was June 24, 1980 to October 26, 1983. Prefire years are calculated from data from 1971 through June 19, 1980. For the E and NE subbasins, the period of June 17, 1974, to November 30, 1977, was considered to be "postfire." Any recovery during this period was ignored. Likewise, effects of the 1973 windstorm are ignored and because of this, interpretations of seasonal fire effect are conservative.

To present the effect of fires visually (in Fig. 2–4), volume-weighted mean annual concentrations were calculated starting in late June to avoid bias due to the late June fires.

## Results

### Changes in Basin Exports after Fire

*Water yields*

Annual precipitation varied almost twofold, from 854 mm in 1985 to 500 mm in 1976 (Fig. 2). The high interannual variability in rainfall made interpretation of the effects of fires on water yield difficult because the basins were responding to a variety of changes in vegetation and soil moisture, temperature, evapotranspiration, and wind velocity. In particular, below-average annual precipitation from 1979 to 1988 (except 1982 and 1985) followed the fire years and confounded simple interpretations (Fig. 2). In addition, the windstorm in 1973 caused increased yield of water (Schindler et al. 1980).

However, the effect of the 1974 fire and the 1973 windstorm can be seen by comparing the increased yield from the wind-damaged and burned NE and E subbasins with the lower yield in the same years from the unburned and slightly wind-damaged NW subbasin (Table 1). The yield remained higher in the NE and E subbasins compared with the unburned NW subbasin for 5 yr after the fire (individual years not shown).

By 1979, annual water yields in the NE and E subbasins were close to that from the unburned NW basin (individual years not shown). After the 1980 fire in which the NW subbasin burned as well, yields increased in the NW and E subbasins (Table 1). The water yield from the E basin after the second fire was lower than the yield after the first fire.

The water yield from the wetland basin after the 1980 fire (1980–83) was less than the yield after the 1974 fire (1974–77) for two possible reasons: the precipitation in 1978–83 was lower than in the early 1970's creating a greater storage deficit in the past, and the wind speed was higher causing higher evapotranspiration.

### Changes in Chemical Exports after Fire

In the NW subbasin, annual export of $NO_3^-$ was low and variable until the 1980 fire. In 1981, 1 yr after the fire, exports

TABLE 1. Precipitation, discharge, and yield (discharge/precipitation) on an annual basis in three ELA watersheds during the periods before and after fires (data in mm of water). The symbol † denotes significantly ($p > 0.95$) higher and ◊ denotes significantly lower than the prefire period (June 1971 to June 1973) in the NE and E subbasins. Double underline denotes when the first fire occurred.

| Period | No. of years | Annual precipitation | Annual discharge | | | Annual yield | | |
|---|---|---|---|---|---|---|---|---|
| | | | NW[a] | E | NE | NW[a] | E | NE |
| Prefire | 2 | 743.1 | 266.9 | 267.4 | 286.4 | 0.359 | 0.360 | 0.385 |
| Windstorm | 1 | 849.4 | 325.9 | 436.8 | 393.1 | 0.384 | 0.514 | 0.463 |
| Postfire 1a | 3 | 630.5◊ | 151.5 | 238.7 | 281.2 | 0.239 | 0.373† | 0.445† |
| Postfire 1b | 3 | 614.2 | 156.9 | 213.8 | 219.5 | 0.243 | 0.335◊ | 0.336◊ |
| Postfire 2a | 3 | 668.6◊ | 221.1 | 228.5 | 187.7◊ | 0.328 | 0.338◊ | 0.274◊ |
| Postfire 2b | 3 | 675.9 | 213.3 | 257.5 | 282.3 | 0.307 | 0.369 | 0.402† |
| Postfire 2c | 3 | 615.8◊ | 147.3◊ | 117.9◊ | 133.7◊ | 0.229◊ | 0.185◊ | 0.208◊ |

[a]In the NW watershed, fire did not occur until period 2a and the statistical comparisons are based on a prefire period of 1971–80.

TABLE 2. Input, export, and retention of N in the three ELA watersheds before and after fire (data in kg·ha$^{-1}$·yr$^{-1}$). $\%R$ = % retention. The symbol † denotes data significantly higher ($p > 0.95$) and ◇ denotes data significantly lower than the prefire period (June 1971 to June 1973) in the NE and E subbasins. Double underline denotes when the first fire occurred.

| Period | No. of years | Input | NW[a] Export | NW[a] Retention | NW[a] %R | E Export | E Retention | E %R | NE Export | NE Retention | NE %R |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | $NO_3^-$ | | | | | |
| Prefire | 2 | 4.22 | 0.035 | 4.185 | 99 | 0.061 | 4.159 | 99 | 0.017 | 4.203 | 99 |
| Windstorm | 1 | 1.71 | 0.049 | 1.661 | 97 | 0.175 | 1.535 | 90 | 0.034 | 1.676 | 98 |
| Postfire 1a | 3 | 1.72◇ | 0.051 | 1.669 | 97 | 0.420† | 1.300 | 76 | 0.041† | 1.679 | 98 |
| Postfire 1b | 3 | 1.62◇ | 0.026 | 1.594 | 98 | 0.110† | 1.510 | 93 | 0.006◇ | 1.614 | 99 |
| Postfire 2a | 3 | 2.03◇ | 0.292† | 2.000 | 99 | 0.187† | 1.843 | 91 | 0.023† | 2.000 | 99 |
| Postfire 2b | 3 | 2.94◇ | 0.059 | 2.881 | 98 | 0.142† | 2.798 | 95 | 0.019 | 2.921 | 99 |
| Postfire 2c | 3 | 2.51◇ | 0.102† | 2.408 | 96 | 0.109† | 2.401 | 96 | 0.021 | 2.489 | 99 |
| | | | | | | $NH_4^+$ | | | | | |
| Prefire | 2 | 3.38 | 0.036 | 3.340 | 99 | 0.043 | 3.337 | 99 | 0.052 | 3.328 | 98 |
| Windstorm | 1 | 1.77 | 0.051 | 1.719 | 97 | 0.099 | 1.671 | 94 | 0.106 | 1.664 | 94 |
| Postfire 1a | 3 | 1.73◇ | 0.028 | 1.702 | 98 | 0.089† | 1.641 | 95 | 0.114† | 1.616 | 93 |
| Postfire 1b | 3 | 1.57◇ | 0.030 | 1.540 | 98 | 0.049 | 1.521 | 97 | 0.048 | 1.522 | 97 |
| Postfire 2a | 3 | 2.25◇ | 0.051 | 2.199 | 98 | 0.055† | 2.195 | 98 | 0.047 | 2.203 | 98 |
| Postfire 2b | 3 | 2.61◇ | 0.070 | 2.540 | 97 | 0.114† | 2.496 | 96 | 0.111† | 2.499 | 96 |
| Postfire 2c | 3 | 2.34◇ | 0.046 | 2.294 | 98 | 0.048 | 2.292 | 98 | 0.038 | 2.302 | 98 |
| | | | | | | *TN* | | | | | |
| Prefire | 2 | 10.18 | 0.820 | 9.360 | 92 | 1.029 | 9.151 | 90 | 1.185 | 8.995 | 88 |
| Windstorm | 1 | 5.53 | 1.060 | 4.470 | 80 | 1.797 | 3.733 | 68 | 1.993 | 3.537 | 64 |
| Postfire 1a | 3 | 5.94◇ | 0.709 | 5.230 | 88 | 1.824† | 4.116 | 69 | 2.051† | 3.889 | 65 |
| Postfire 1b | 3 | 5.13◇ | 0.713 | 4.417 | 86 | 1.193 | 3.937 | 76 | 1.372 | 3.758 | 73 |
| Postfire 2a | 3 | 7.44◇ | 1.141† | 6.269 | 84 | 1.389† | 6.051 | 81 | 1.381 | 6.059 | 81 |
| Postfire 2b | 3 | 9.63 | 1.194 | 8.436 | 88 | 1.681† | 7.949 | 83 | 1.907† | 7.723 | 80 |
| Postfire 2c | 3 | 7.77 | 1.231 | 6.540 | 84 | 0.900 | 6.870 | 88 | 1.115 | 6.655 | 86 |
| | | | | | | *TDN* | | | | | |
| Prefire | 2 | 9.41 | 0.740 | 8.670 | 92 | 0.892 | 8.518 | 91 | 0.990 | 8.420 | 89 |
| Windstorm | 1 | 4.28 | 0.944 | 3.336 | 78 | 1.555 | 2.725 | 64 | 1.478 | 2.802 | 65 |
| Postfire 1a | 3 | 4.74◇ | 0.638 | 4.102 | 87 | 1.622† | 3.118 | 65 | 1.822† | 2.918 | 62 |
| Postfire 1b | 3 | 3.98◇ | 0.642 | 3.338 | 84 | 1.066 | 2.914 | 73 | 1.226 | 2.754 | 69 |
| Postfire 2a | 3 | 6.01† | 1.079† | 4.931 | 82 | 1.194† | 4.816 | 80 | 1.288 | 4.722 | 79 |
| Postfire 2b | 3 | 8.66 | 1.057 | 7.603 | 88 | 1.493 | 7.167 | 83 | 1.748† | 6.912 | 80 |
| Postfire 2c | 3 | 7.13 | 1.062 | 6.068 | 85 | 0.816 | 6.314 | 89 | 1.010 | 6.120 | 86 |
| | | | | | | *Susp N* | | | | | |
| Prefire | 2 | 0.77 | 0.080 | 0.690 | 90 | 0.138 | 0.632 | 82 | 0.195 | 0.575 | 75 |
| Windstorm | 2 | 1.25 | 0.116 | 1.134 | 90 | 0.243 | 1.007 | 81 | 0.515 | 0.735 | 59 |
| Postfire 1a | 1 | 1.20 | 0.071 | 1.129 | 94 | 0.203† | 0.997 | 83 | 0.228† | 0.972 | 81 |
| Postfire 1b | 3 | 1.15† | 0.071 | 1.079 | 94 | 0.128 | 1.022 | 89 | 0.145◇ | 1.005 | 87 |
| Postfire 2a | 3 | 1.43 | 0.062 | 1.368 | 96 | 0.195 | 1.235 | 86 | 0.093◇ | 1.337 | 94 |
| Postfire 2b | 3 | 0.97 | 0.137† | 0.833 | 86 | 0.188† | 0.782 | 81 | 0.159 | 0.811 | 84 |
| Postfire 2c | 3 | 0.64 | 0.097 | 0.543 | 85 | 0.083◇ | 0.557 | 87 | 0.105◇ | 0.535 | 84 |

[a]In the NW subbasin, fire did not occur until period 2a and the statistical comparisons are based on a prefire period of 1971–80.

increased 15-fold. Effects were short-lived, with a return to near-normal exports in 1983–86 (Table 2). In the E subbasin, fire caused a striking increase in annual nitrate export. Exports peaked in 1975 at 550 g N·ha$^{-1}$·yr$^{-1}$ (over 7 times background), 1 yr after the first fire, and did not return to prefire levels before the second fire (Table 2). The second fire caused a smaller increase in export in 1980–83 and levels remained higher than background until the 1986–88 period. The windstorm in 1973 also increased $NO_3^-$ export in both E and NE subbasins as reported by Schindler et al. (1980).

Nitrate export in the NE subbasin doubled after the first fire in 1974 and increased slightly after the 1980 fire. Nitrate export was 10-fold lower after both fires in this peatland subbasin than in the two terrestrial subbasins (Table 2).

Ammonium exports from the NW subbasin were low (15–50 g N·ha$^{-1}$·yr$^{-1}$) before the fire. However, ammonium exports were equally elevated after fire (1980–83), windstorm (1973–74), and the 1983–86 period (Table 2). Exports from the NE subbasin were higher after the first fire, with peaks in 1974–75 and 1977 at 150–180 g N·ha$^{-1}$·yr$^{-1}$ (2 times prefire). There was no apparent effect of the second fire compared with the prefire period. Exports were elevated in the 1983–86 period. Exports of ammonium from the E subbasin increased more after the windstorm and in the 1983–86 period than during the two periods immediately postfire (Table 2).

The annual export of TDN increased significantly in the NE and E subbasins after the 1974 fire (Table 2). After the 1980 fire, TDN was significantly higher than prefire exports in the E subbasin but not in the boggy NE subbasin. After the first fire in the NW subbasin, there was a significant increase in TDN export.

The annual export of total nitrogen (TN) and Susp N increased significantly in the NE and E subbasins after the 1974 fire (Table 2). After the second fire (1980), the E subbasin showed a significant increase in TN, but the boggy NE subbasin did not show an increase. The NW subbasin showed a significant increase in export of TN after the 1980 fire that was due primarily to the increased export of TDN.

Annual retention of all N forms was high in all subbasins regardless of fire or windstorm (Table 2). Nitrate retention was generally greater than 90% of inputs except for just after the 1974 fire in the E subbasin. In the NW subbasin, percent retention ranged from 80 to 92% of all N inputs regardless of fire. The greatest export (or lowest percent retention) was observed for TDN in the E and NE subbasins after both windstorm and fire. The second fire did not decrease percent retention in either the E or NE subbasin.

Percent retention of N was higher than percent retention of P in both wetland and upland subbasins. In the wetland, net TN retention averaged 77% of deposition versus 80 and 87% for the E and NW upland subbasins for the entire 18-yr period of record. The comparable retention of total phosphorus (TP) was 51% in the wetland subbasin versus 67 and 84% for the E and NW subbasins, respectively. Presumably more N is retained than P because these boreal forest ecosystems are N limited. There was no significant difference between the subbasins due to the wide variance caused by the fire events.

The annual export of TDP and TP increased in the NE subbasin after the first burn (1974) (Table 3), with the peak loss of TDP and TP in 1975 at 152 and 183 $g \cdot ha^{-1} \cdot yr^{-1}$, respectively. There was no significant increase in export of TDP or TP from the E subbasin after the 1974 fire. There was no increase in Susp P export from any subbasin (data not shown). The 1980 fire had no effect on P export from any subbasin. Percent retention of TP and TDP was lower after fire in the NE subbasin than in the upland subbasins.

## Changes in Mean Annual Stream Concentrations after Fire

### *Nitrate*

The first burning affected both upland subbasin streams similarly. In the E subbasin stream, the 1974 fire caused the mean annual concentration of $NO_3^-$ to increase from 22 to 173 $\mu g \cdot L^{-1}$. In the 3 yr after the fire, there was an average sixfold increase over the prefire concentrations. The second (1980) burning of the E subbasin did not cause an effect of similar magnitude, although concentrations had not returned to levels observed in 1971–73 before the fire occurred (Fig. 3A). In the 3 yr after the first fire (1980) in the NW subbasin, stream concentrations of $NO_3^-$ increased sixfold compared with the prefire period (1971–80) (161 versus 24.6 $\mu g \cdot L^{-1}$) (Table 4).

In the wetland stream (NE), $NO_3^-$ concentrations increased after both fires compared with the prefire period, but the concentrations were much lower than in the terrestrial basins (Table 4).

### *Ammonium*

After the first fire (1974), $NH_4^+$ concentrations increased rapidly in both the E and NE subbasin streams, peaking 3 yr later in 1977 (Fig. 3B). Values after that time remained above the 1971–73 value, but were little affected by the 1980 burn (Table 4).

TABLE 3. Input, export, and retention of TDP and TP in the three ELA watersheds before and after fire (data in $kg \cdot ha^{-1} \cdot yr^{-1}$). *%R* = % retention. The symbol † denotes data significantly higher ($p > 0.95$) and ◇ denotes data significantly lower than the prefire period (June 1971 to June 1973) in the NE and E subbasins. Double underline denotes when the first fire occurred.

| | | | NW[a] | | | E | | | NE | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Period | No. of years | Input | Export | Retention | *%R* | Export | Retention | *%R* | Export | Retention | *%R* |
| | | | | | *TDP* | | | | | | |
| Prefire | 2 | 0.41 | 0.023 | 0.387 | 94 | 0.032 | 0.378 | 92 | 0.039 | 0.371 | 90 |
| Windstorm | 1 | 0.12 | 0.022 | 0.098 | 82 | 0.050 | 0.070 | 58 | 0.060 | 0.060 | 50 |
| Postfire 1a | 3 | 0.10◇ | 0.012 | 0.088 | 88 | 0.039 | 0.061 | 61 | 0.103† | −0.003 | −3 |
| Postfire 1b | 3 | 0.07◇ | 0.010 | 0.060 | 86 | 0.028 | 0.042 | 60 | 0.040 | 0.030 | 43 |
| Postfire 2a | 3 | 0.10◇ | 0.019 | 0.081 | 81 | 0.038 | 0.062 | 62 | 0.039 | 0.061 | 61 |
| Postfire 2b | 3 | 0.10◇ | 0.026 | 0.074 | 74 | 0.038 | 0.062 | 62 | 0.037 | 0.063 | 63 |
| Postfire 2c | 3 | 0.06 | 0.010◇ | 0.050 | 83 | 0.015◇ | 0.045 | 75 | 0.021◇ | 0.041 | 68 |
| | | | | | *TP* | | | | | | |
| Prefire | 2 | 0.58 | 0.032 | 0.548 | 95 | 0.050 | 0.530 | 91 | 0.060 | 0.520 | 90 |
| Windstorm | 1 | 0.25 | 0.033 | 0.277 | 87 | 0.080 | 0.170 | 68 | 0.125 | 0.125 | 50 |
| Postfire 1a | 3 | 0.24◇ | 0.017 | 0.223 | 93 | 0.061 | 0.179 | 75 | 0.126† | 0.114 | 48 |
| Postfire 1b | 3 | 0.21◇ | 0.015 | 0.195 | 93 | 0.042 | 0.168 | 80 | 0.053 | 0.157 | 75 |
| Postfire 2a | 3 | 0.29◇ | 0.027 | 0.263 | 91 | 0.065 | 0.225 | 78 | 0.048◇ | 0.242 | 83 |
| Postfire 2b | 3 | 0.20◇ | 0.039 | 0.161 | 81 | 0.059 | 0.141 | 71 | 0.054 | 0.416 | 73 |
| Postfire 2c | 3 | 0.12 | 0.025 | 0.095 | 79 | 0.024◇ | 0.096 | 80 | 0.032◇ | 0.088 | 73 |

[a]In the NW subbasin, fire did not occur until period 2a and the statistical comparisons are based on a prefire period of 1971–80.

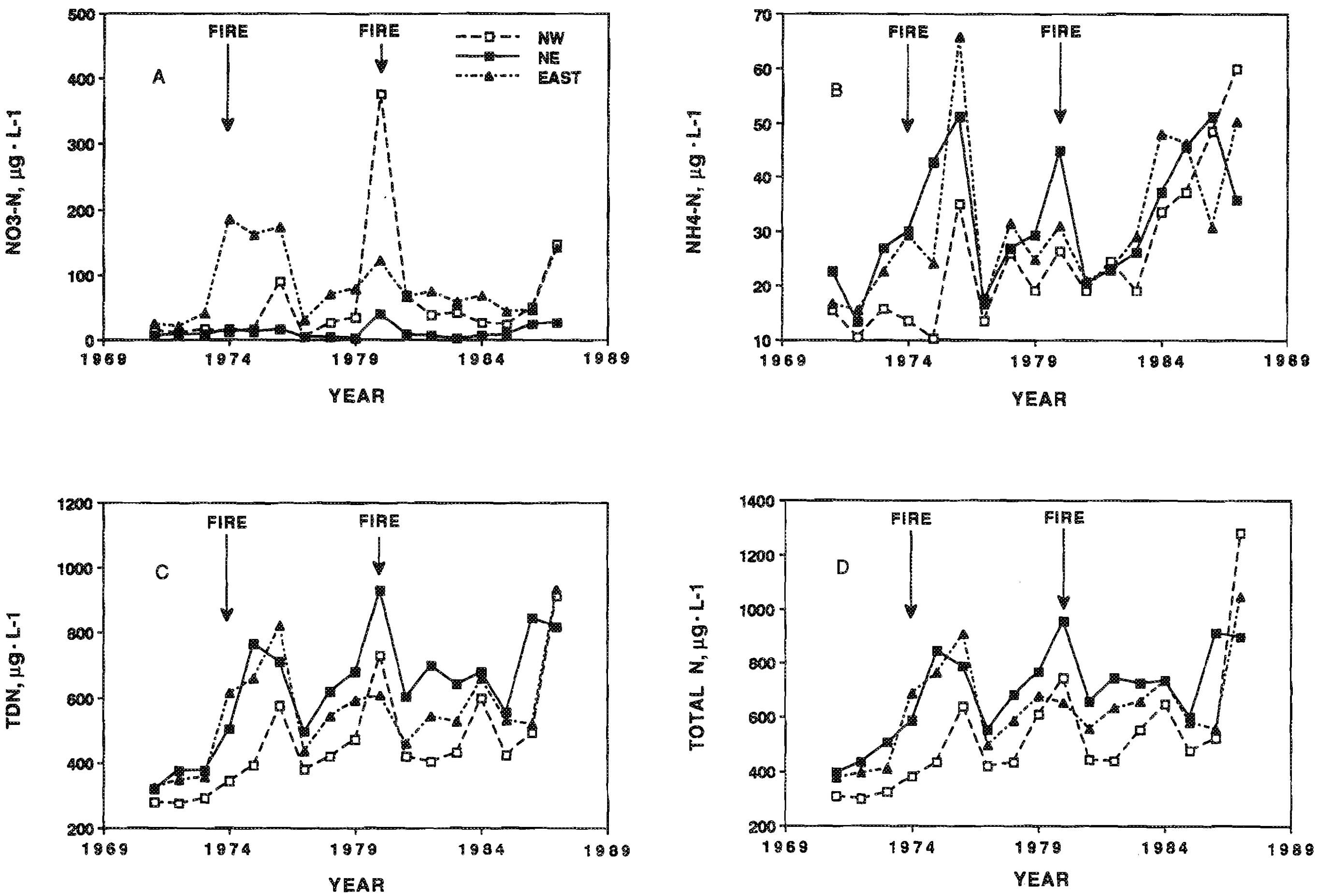



FIG. 3. Mean annual concentration of N species in the three ELA streams from 1971 to 1989.

TABLE 4. Concentrations of N in streamwater from three ELA watersheds before and after fire (data in $\mu g \cdot L^{-1}$). The symbol † denotes data significantly higher ($p > 0.95$) and ◇ denotes data significantly lower than the prefire period (June 1971 to June 1973) in the NE and E subbasins. Double underline denotes when the first fire occurred.

| Period | No. of years | $NO_3^- - N$ | | | $NH_4^+ - N$ | | | Susp N | | | TDN | | | TN | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | NW[a] | E | NE | NW[a] | E | NE | NW[a] | E | NE | NW[a] | E | NE | NW[a] | E | NE |
| Prefire | 2 | 12.8 | 22.5 | 6.0 | 13.0 | 16.1 | 18.1 | 29.7 | 51.3 | 67.7 | 276.7 | 334.4 | 347.1 | 306.4 | 385.7 | 414.8 |
| Windstorm | 1 | 15.1 | 40.1 | 8.7 | 15.7 | 22.6 | 26.9 | 35.5 | 55.5 | 131.0 | 289.7 | 355.6 | 376.0 | 325.1 | 411.1 | 507.0 |
| Postfire 1a | 3 | 38.8 | 173.4† | 14.4† | 19.6 | 39.7† | 41.3† | 48.7 | 88.1† | 80.9† | 436.7 | 696.7† | 659.1† | 485.4 | 784.8† | 740.0† |
| Postfire 1b | 3 | 21.5 | 58.9† | 2.8◇ | 19.5 | 24.3† | 24.6† | 64.1 | 64.2 | 72.4 | 424.2 | 522.4† | 596.7† | 488.2 | 586.6† | 669.1† |
| Postfire 2a | 3 | 161.1† | 87.2† | 18.2 | 23.5 | 25.0† | 29.5† | 26.8 | 80.0† | 44.5◇ | 516.5 | 536.0† | 742.4† | 543.3 | 616.0† | 787.0† |
| Postfire 2b | 3 | 30.4 | 56.0† | 5.8 | 30.1† | 41.1† | 36.4† | 76.5† | 87.0† | 61.9 | 484.6 | 570.4† | 625.1† | 561.2 | 657.4† | 687.0† |
| Postfire 2c | 3 | 84.0† | 96.3† | 18.0† | 40.3† | 31.7† | 34.3† | 65.6† | 75.0 | 77.3† | 730.8† | 720.2† | 785.7† | 890.7† | 795.1† | 863.2† |

[a]In the NW subbasin, fire did not occur until period 2a and the statistical comparisons are based on a prefire period of 1971–80.

In the NW subbasin stream, there was little evidence that fire caused an increase in $NH_4^+$ concentrations after the 1980 fire (Table 4). Concentrations in all three basins increased in the dry periods (1984, 1986, and 1987). Drought in 1976 also caused an increase in $NH_4^+$ in the unburned NW subbasin (Fig. 3B).

*Suspended nitrogen*

In the NE stream, the concentration of Susp N increased significantly after the 1974 fire compared with the prefire conditions (Table 4). Postfire peaks were also observed in the E stream, but the peaks followed both fires by 2 yr. Susp N concentrations in the NW stream were fairly constant from 1971 to 1978 and were erratic thereafter without apparent cause (drought or fire).

*Total dissolved nitrogen*

TDN constituted about 66% of the TN lost from all three subbasin streams (Fig. 3C). The 1974 fire caused approximately a twofold increase in TDN in both the NE and E subbasin streams (Table 4). There is some evidence for a partial recovery in 1977, but the 1980 burn caused the TDN concentrations to remain high in both subbasins (Fig. 3C). In the NW stream, there was no significant effect of the fire on TDN concentrations based on the 3-yr fire period (Table 4), but during the fire year (1980), concentrations increased dramatically (Fig. 3C) and then returned to background levels within a year.

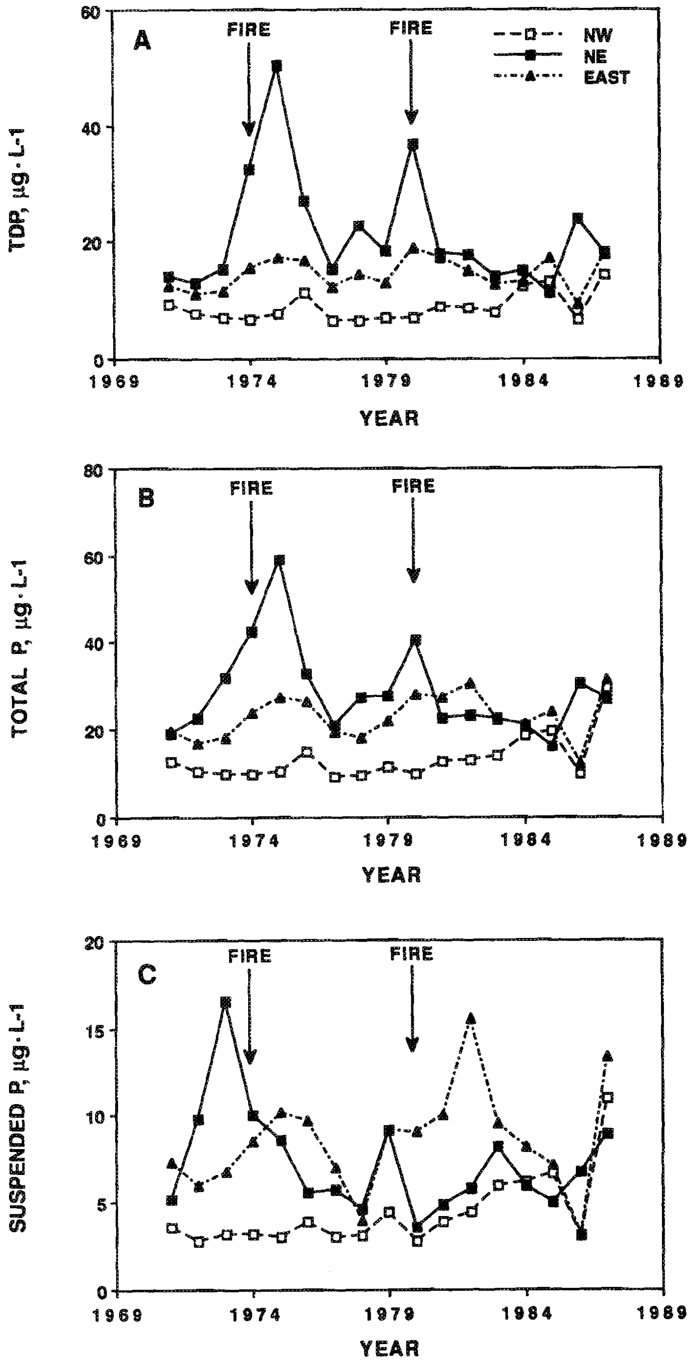



FIG. 4. Mean annual concentration of P in the three ELA streams from 1971 to 1989.

Concentrations in the NW stream in the period 1974–80 before the first fire were significantly higher than in 1971–73, presumably due to leaching of imported ash from fires in the adjacent subbasins (Fig. 3C).

*Total nitrogen*

TN concentrations largely mirrored patterns in TDN (Fig. 3D). Concentrations after the 1974 fire were doubled in both NE and E streams (Table 4) and remained higher than prefire values through 1979. After the second fire, concentrations of TN increased again in the NE stream, but not in the E stream. In the NW stream, concentrations of TN generally increased through the 1970's, with peaks in 1975 and 1979 (Fig. 3D). The fire in 1980 produced a significant increase in TN if the entire prefire record (1971–80) was compared with the 1980 fire year alone (429 versus 745 $\mu g \cdot L^{-1}$), but not if the fire period 1980–83 was used (543 $\mu g \cdot L^{-1}$ in Table 4). In 1979–88, all streams usually had high concentrations of TN and TDN, but the effects of drought and fire cannot be separated. In the 1976 drought, the unburned NW subbasin had elevated stream concentrations of both TDN and TN.

*Total dissolved phosphorus and total phosphorus*

Concentrations of TDP in the NW stream ranged from 6 to 10 $\mu g \cdot L^{-1}$, with no apparent impact of the 1980 fire (Fig. 4A). In contrast, both fires caused a 30% increase in the concentrations in the E stream. The wetland-dominated NE stream had dramatic increases (over 3 times in 1975) in concentration following the 1974 fire, although the second fire caused increased concentrations only for 1 yr, not the entire 1980–83 period (Table 5). The pattern of TP concentrations in the three streams (Fig. 4B) was similar to those described for TDP, with the wetland stream showing the largest response to fire.

*Suspended phosphorus*

While more variable than TDP, Susp P concentrations in the NW stream were similar, showing no effect of fire (Fig. 4C). However, concentrations increased during the 1983–88 period, but this increase cannot be attributed to fire during this very dry period. In the E stream, concentrations increased after both fires (Table 5). The windstorm but not the fire increased Susp P in the NE stream (Fig. 4C). There was no detectable increase in Susp P after the 1980 fire in the NE subbasin.

## Effect of Fire on Monthly Concentrations and Flows

*Nitrate*

The greatest effect of fire on $NO_3^-$ concentration in all streams was during the nonvegetative season with increased concentrations and high variability (Fig. 5; only NW stream shown). During summer months, growing vegetation took up $NO_3^-$ so that stream concentrations did not differ significantly from preburn years.

*Ammonium and suspended nitrogen*

The pattern for $NH_4^+$ in the E stream was similar to that for $NO_3^-$ in the NW stream, with postfire concentrations above prefire values during early spring and fall, but relatively unchanged during the vegetative season. An exception was the NW subbasin, where postfire values were not significantly different from prefire values (Fig. 6). There was little evidence of postfire changes in Susp N. Values exceeded the normal prefire range only in a few incidental samples collected in midwinter in the NE stream (data not shown).

*Total dissolved nitrogen*

In both upland (E) and wetland (NE) subbasins, concentrations of TDN were much higher throughout the year after fire, with little evidence of a seasonal pattern (Fig. 7A; NE data not shown). In contrast, the seasonal pattern for TDN in the NW stream following the 1980 fire showed a pronounced spring maximum and summer minimum, similar to $NO_3^-$ concentrations (Fig. 7B).

*Total dissolved phosphorus*

Evidence for seasonally elevated concentrations of TDP due to fire was observed only in the NE stream. The increase was most pronounced in winter (5 times), dropping to less than 2 times for the remainder of the year (Fig. 8).

TABLE 5. Concentrations of Susp P, TDP, and TP in the three ELA streams before and after fire (data in $\mu g \cdot L^{-1}$). The symbol † denotes data significantly higher ($p > 0.95$) and ◇ denotes data significantly lower than the prefire period (June 1971 to June 1973) in the NE and E subbasins. Double underline denotes when the first fire occurred.

| Period | No. of years | Susp P | | | TDP | | | TP | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | NW[a] | E | NE | NW[a] | E | NE | NW[a] | E | NE |
| Prefire | 2 | 3.2 | 6.6 | 7.5 | 8.5 | 11.7 | 13.4 | 11.7 | 18.4 | 20.9 |
| Windstorm | 1 | 3.2 | 6.8 | 16.5 | 6.9 | 11.5 | 15.3 | 10.0 | 18.3 | 31.9 |
| Postfire 1a | 3 | 3.4 | 9.5† | 8.1 | 8.5 | 16.5† | 36.6† | 11.9 | 26.0† | 44.7† |
| Postfire 1b | 3 | 3.5 | 6.7 | 6.5 | 6.6 | 13.1† | 18.9† | 10.1 | 19.9† | 25.4† |
| Postfire 2a | 3 | 3.7 | 11.5† | 4.8◇ | 8.2 | 17.0† | 24.1† | 12.0 | 28.6† | 28.9† |
| Postfire 2b | 3 | 6.3† | 8.3† | 6.4 | 11.2† | 14.3† | 13.4 | 17.5† | 22.7† | 19.9 |
| Postfire 2c | 3 | 7.1† | 8.3† | 7.8 | 10.3 | 13.3 | 17.9† | 18.9† | 21.5 | 25.9† |

[a]In the NW subbasin, fire did not occur until period 2a and the statistical comparisons are based on a prefire period of 1971–80.

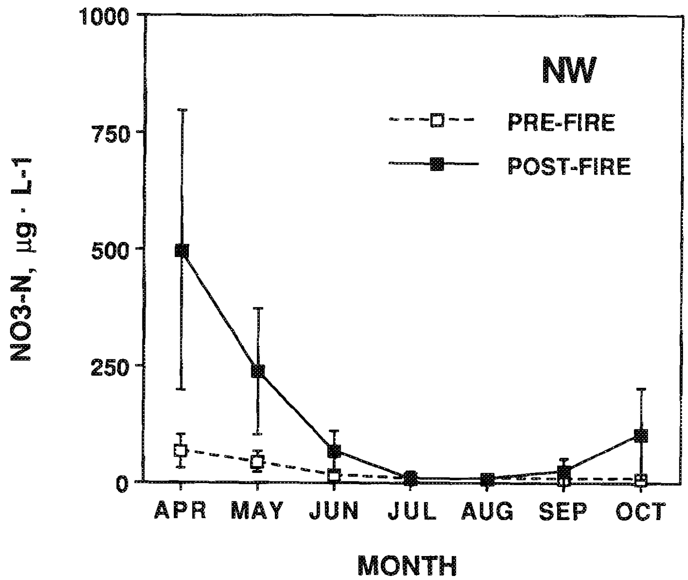



FIG. 5. Monthly concentrations of $NO_3^-$-N before and after fire in the NW stream (mean ± 2 SE).

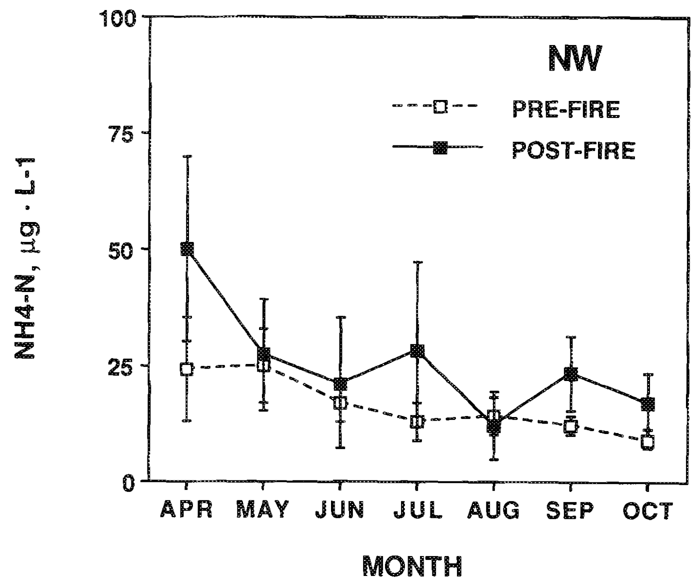



FIG. 6. Monthly concentrations of $NH_4^+$-N before and after fire in the NW stream (mean ± 2 SE).

### Nitrogen and Phosphorus Budgets of Lake 239

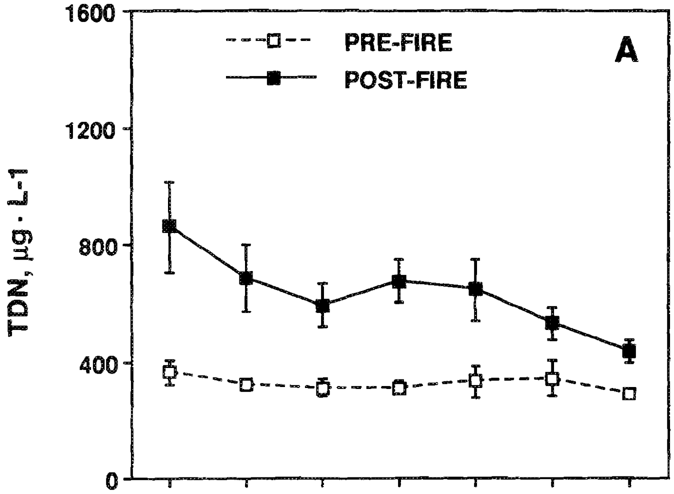
Fire in the subbasins of L239 increased the inputs of TN to the lake. However, fire was not an important contributor because TN inputs from precipitation ranged from 36 to 59% of the total inputs and were independent of the fires. The most striking feature of the long-term data set is the decrease in outflow of N over the 18-yr record (Table 6). In the 1980's, a greater proportion of the N entering the lake has been retained, and Schindler et al. (1990) attributed this to the decrease in the flushing time of the lake caused by the decreased precipitation and increased temperature during this period. Net retention of TN ranged from 54% of inputs in the year of the windstorm to 88% of inputs in the dry 1983–86 period. TP patterns of input and outflow in L239 are similar to those of TN (Table 6), with inputs of TP from runoff 38–65% of total inputs to the lake. TP export from the lake decreased over the period of record due to the decrease in the flushing rate of the lake. Fires in the three main subbasins of the lake were not as important to the nutrient budgets as the changes in precipitation, runoff volumes, and flushing rate during that period.

## Discussion

### Net Retention and Loss of Nutrients from Upland Watersheds

In the past, some fear has been expressed that nutrient losses from fires would be high enough to hinder the regrowth of new vegetation. This seems unlikely in the forested watersheds at ELA, given the small increases and relatively short period of elevated losses following a fire. In the NW subbasin, annual stream losses of N after the fire were only 15% of atmospheric input, compared with 12% before fire (Table 2). In the E subbasin the losses of N after the first fire were greater; 31% of annual atmospheric inputs were lost compared with 10% before fire. P losses were not great, with net losses after fire only slightly higher than prefire losses in the NW subbasin. In the E subbasin, a maximum of 39% of annual atmospheric P inputs were lost in the 1974 fire.

Upland areas retained most of the N and P entering with precipitation, even after two burns. It is probable that the fire actually increased the N available for forest growth, for concentrations of $NH_4^+$ in soil water of the E subbasin after the 1974 burn were a 1000-fold higher than concentrations in the unburned NW subbasin (D. W. Schindler, unpubl. data).



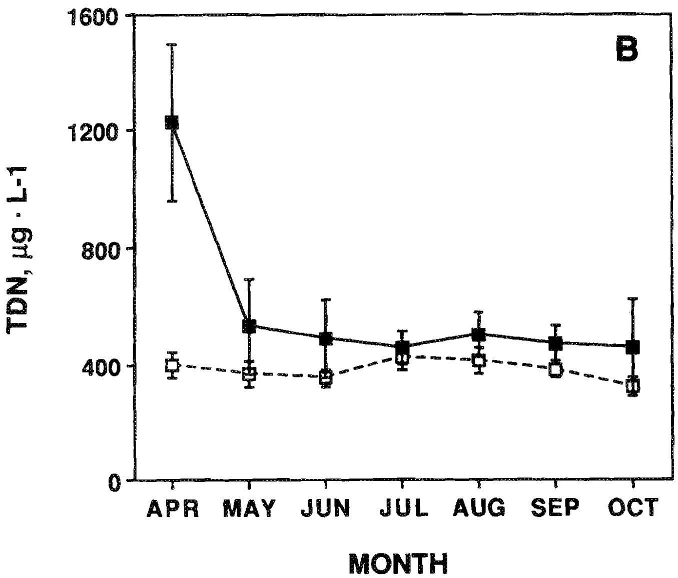




FIG. 7. Monthly concentrations of TDN before and after fire in the (A) NW stream and (B) E stream.

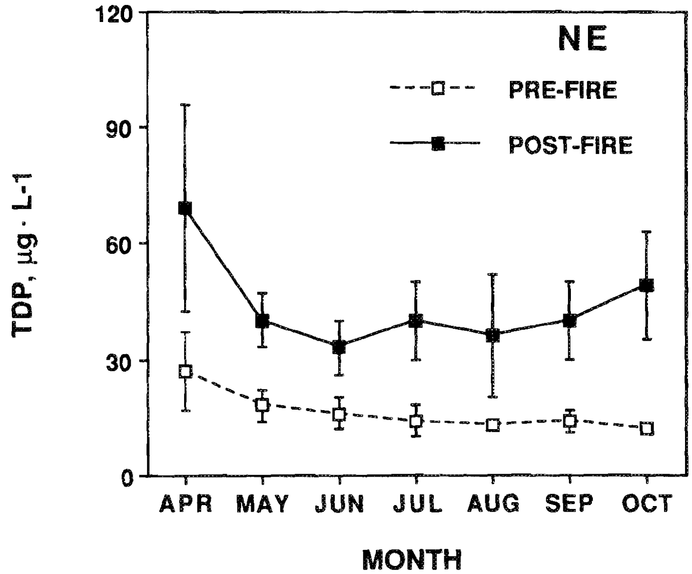



FIG. 8. Monthly concentrations of TDP in the NE stream before and after fire (mean ± 2 SE).

During the period of active plant growth, concentrations of $NO_3^-$ in outflow were lower than in early spring and late fall, as one might expect (Fig. 5). This biological regulation was intense enough to prevent $NO_3^-$ losses from exceeding the prefire confidence limits in the summer. During spring and fall when vegetation was dormant, the effect of fire was evident. In contrast, the $NH_4^+$ and TDN (which was primarily organic N) in the NW stream showed little evidence of a seasonal pattern, indicating that it was reasonably unaffected by vegetative uptake (Fig. 7).

## Net Retention and Loss of Nutrients from the Wetland Watershed

Exports of P from the wetland (NE) subbasin were higher than from the upland areas, both before and after burning (Table 3). In the 3 yr after the 1974 fire, outflow losses were over half of the TP and all of the TDP supplied annually by precipitation. Net retention of TDP continued to be low until 6 yr after the second fire. After that time, over 60% of the TDP was retained. Net retention of TP (and Susp P) was higher than TDP and increased after the 1974–77 fire period so that net retention was generally greater than 70%. Retention of TP in the ELA wetland was higher than the retention measured by Devito et al. (1989) in eastern Canadian wetlands and was similar to values obtained by Verry and Timmons (1982) in Minnesota wetlands.

Exports of TN, TDN, and Susp N from the wetland subbasin (NE) were higher than exports from the terrestrial (E) subbasin for the comparable fire periods. This is expected because wetlands are known to export organic forms and retain inorganic forms of N (Devito et al. 1989). However, retention of TN by the wetland at ELA, even with the fire, was greater than 77% of inputs. This is also much higher than the net retention in eastern Canadian wetlands (Devito et al. 1989). $NO_3^-$ export from the wetland subbasin was 7 times lower than from the upland subbasin. The low export of $NO_3^-$ was expected because retention experiments with *Sphagnum* have shown $NO_3^-$ assimilation to be extremely high (Bayley et al. 1987; Urban et al. 1988). $NH_4^+$ exports were sometimes higher from the wetland and sometimes higher from the terrestrial subbasins.

## Effect of Multiple Fires and Fire Intensity on Nutrient Concentrations

A second fire in the basin within such a short time period might be expected to aggravate soil loss, increase erosion, and cause nutrient shortages for the vegetation. Such results were not investigated, although the terrestrial and wetland subbasins differed in behavior in terms of nutrient retention. While the first fire in the NE and E subbasins caused increased concentrations of N and P in those streams, recovery of P generally occurred within 2–3 yr after the first fire (Fig. 4). After the second fire, TP concentrations in the terrestrial E subbasin increased again and did not return to prefire levels. In the wetland subbasin (NE), the second fire did not cause an increased loss of P.

The elevated N concentrations (particularly TDN) in the streams were more prolonged than P. Baseline conditions in the NE and E streams had still not been reached by the time of the 1980 fire (Fig. 3C and 3D) and remained elevated through

TABLE 6. N and P budgets of L239 on an annual basis during periods before and after fire in the watershed (data in $kg \cdot ha^{-1} \cdot yr^{-1}$). %$R$ = % retention.

| Period | No. of years | Export from terrestrial areas to lake NW | EAST | NE | Direct runoff | Total runoff | Precipitation input | Total input | Output | %R |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | *TN* | | | | | |
| Prefire | 2 | 0.974 | 1.169 | 1.414 | 1.217 | 1.160 | 9.915 | 17.152 | 5.632 | 67 |
| Windstorm | 1 | 0.673 | 1.037 | 1.155 | 1.046 | 0.984 | 5.410 | 11.554 | 5.338 | 54 |
| Postfire 1a | 3 | 0.691 | 1.754 | 1.908 | 1.735 | 1.577 | 5.337 | 15.187 | 6.023 | 60 |
| Postfire 1b | 3 | 0.836 | 1.478 | 1.755 | 1.510 | 1.391 | 5.890 | 14.579 | 5.433 | 63 |
| Postfire 2a | 3 | 1.082 | 1.360 | 1.374 | 1.349 | 1.311 | 5.950 | 14.137 | 4.245 | 70 |
| Postfire 2b | 3 | 1.137 | 1.548 | 1.815 | 1.589 | 1.501 | 10.100 | 19.479 | 2.274 | 88 |
| Postfire 2c | 3 | 0.932 | 0.739 | 0.951 | 0.883 | 0.822 | 7.937 | 13.437 | 2.334 | 82 |
| | | | | | *TP* | | | | | |
| Prefire | 2 | 0.050 | 0.062 | 0.082 | 0.066 | 0.062 | 0.530 | 0.916 | 0.204 | 78 |
| Windstorm | 1 | 0.019 | 0.041 | 0.049 | 0.042 | 0.038 | 0.380 | 0.615 | 0.129 | 79 |
| Postfire 1a | 3 | 0.020 | 0.066 | 0.135 | 0.080 | 0.065 | 0.220 | 0.626 | 0.131 | 79 |
| Postfire 1b | 3 | 0.019 | 0.049 | 0.069 | 0.052 | 0.046 | 0.247 | 0.531 | 0.115 | 78 |
| Postfire 2a | 3 | 0.023 | 0.062 | 0.047 | 0.056 | 0.053 | 0.207 | 0.539 | 0.100 | 82 |
| Postfire 2b | 3 | 0.035 | 0.050 | 0.051 | 0.050 | 0.047 | 0.263 | 0.559 | 0.102 | 82 |
| Postfire 2c | 3 | 0.026 | 0.033 | 0.030 | 0.032 | 0.031 | 0.123 | 0.318 | 0.058 | 82 |
| Areas of basins (ha) | | 56.38 | 170.28 | 12.43 | 99.97 | 339.06 | 54.28 | 54.28 | 54.28 | |

1988. While the 1980 fire caused new increases in concentration of N and P, the relative increase was weaker than after the 1974 fire. The TDN concentrations in 1986–89 were higher in all three subbasins than during any other period in the 18-yr record (Table 4). This 3-yr period was also a very dry period (Table 1).

Both fires in the E subbasin were much more intense than the one in the NW. In the former basin, almost all organic matter was completely consumed whereas in the NW subbasin, most vegetation was killed by the fire, but little organic matter was oxidized and even the dead needles on coniferous trees were left intact. It is likely that the more intense fire consumed more organic matter which in turn made more N and P available to be leached. This difference may explain why increased losses of N and P occurred for several years after the E subbasin burned, but not in the NW where increased losses of $NO_3^-$ and TDN occurred only in 1980 fire year but not in subsequent years.

TABLE 7. Comparison of ELA subbasin outflow altered by fire and by clearcutting (data in $\mu g \cdot L^{-1}$).

| | Clearcut subbasins[a] Uncut | After 1 yr | After 2 yr | East subbasin 1971–73 (prefire) | 1975 (after 1 yr) | 1976 (after 2 yr) |
|---|---|---|---|---|---|---|
| $NO_3^-$ | 40 | 20 | 10 | 28 | 193 | 194 |
| $NH_4^+$ | 10 | 60 | 20 | 15 | 25 | 34 |
| TDN | 480 | 790 | 560 | 330 | 660 | 720 |
| Susp N | 40 | 70 | 50 | 53 | 81 | 120 |
| TDP | 10 | 30 | 10 | 12 | 18 | 19 |
| Susp P | 3 | 8 | 4 | 6 | 11 | 11 |

[a]Data from Nicolson (1975) (no standard error given). Data are from weekly samples collected during the 1973 growing season and analysed by the Freshwater Institute laboratory. The subbasins included three uncut subbasins, two subbasins cut 1 yr previously, and three subbasins cut 2 yr previously.

## Changes in the Nutrient Budget of Lake 239

The total inputs of P and N to the lake were only slightly affected by fire. Approximately half of the input of both nutrients was by direct precipitation on the lake surface, and this was unaffected by the fire. Runoff of TP to the lake from the entire watershed increased by only 5%, while the TN exported to the lake from the entire watershed increased by 26% in the 3 yr after the fire (Table 2). Given that the long-term water renewal time for L239 is 9.1 yr and that inputs (particularly of P) would be elevated for much less than that period, it is unlikely that nutrient concentrations, productivity, or phytoplankton standing crop of the lake would increase due only to fire. Schindler et al. (1990) did observe increases in N concentration, productivity, and phytoplankton biomass in the 18-yr period, but decreased precipitation and increased water renewal times of L239 cannot be separated from the influence of fire on lake nutrient chemistry.

It seems reasonable to conclude that forest fires in the ELA region have minimal effect on the quality of any lakes with water renewal times long enough to minimize the effect of a few years of slightly elevated nutrient input. Because most Precambrian Shield lakes are P limited (Schindler 1977), the relatively small (average 2 times) and short duration (2–3 yr) of increased P losses from upland watersheds makes it unlikely that a fire would cause eutrophication of larger lakes. However, in small streams and rapidly flushed lakes, eutrophication could occur for several years following fire. The highest likelihood of eutrophication in lakes would be in situations where catchments with high proportions of wetlands were burned, and where these drained to lakes with high rates of water renewal, i.e. where new, higher steady-state nutrient concentrations

TABLE 8. Comparison of chemical concentrations in outflow from forested watersheds after fire or clearcutting. The upper number is the baseline concentration; the number in parentheses is the concentration after the fire or disturbance. % + denotes percent increase.

| | E subbasin[a] | % + | Hubbard Brook[b] | % + | Coweeta[c] | % + | Andrews[d] | % + |
|---|---|---|---|---|---|---|---|---|
| $NO_3^-$ | 28.3 | | 212.0 | | 5.5 | | ≈3.0 | |
| | (141.3) | 500 | (11973.0) | 5627 | (91.0) | 1655 | (62.0) | 2067 |
| $NH_4^+$ | 14.9 | | 109.0 | | 4.0 | | 4.0 | |
| | (32.1) | 215 | (39.0) | 0 | (4.5) | ≈0 | (3.0) | ≈0 |

[a]ELA (this study).
[b]Bormann et al. (1968, 1974) and Likens et al. (1969, 1970).
[c]Swank and Douglass (1977).
[d]Dahm (1980).

could be reached in a short time. Due to prolonged increases in N, increasing ratios of N:P might be expected following fire, as shown by Schindler et al. (1991). Such changes might cause eutrophication of N-limited lakes and are correlated with increases in phytoplankton diversity in L239.

### Effects of Fire versus Clearcutting on Stream Chemistry at ELA

Effects of clearcutting on chemical concentrations in boreal streams at ELA were studied by Nicolson in the early 1970's and are summarized in Nicolson (1975). Both fire and clearcutting increased the concentrations of most ions exported in the outflow of ELA subbasins. The increased concentrations following fire appeared to last longer than the effects due to clearcutting, although Nicolson's study included only 2 yr after clearcutting. In the first year after clearcutting, Nicolson (1975) found that concentrations of seven ions in streams from a clearcut area were significantly different from undisturbed subbasins (Table 7). Most of the ions were significantly higher in the streams from clearcut areas, but $NO_3^-$ concentrations were significantly *lower* than in the undisturbed basins.

$NO_3^-$ concentrations in streams were lower in the clearcut basins (10–20 $\mu g \cdot L^{-1}$) than from undisturbed basins (40 $\mu g \cdot L^{-1}$). After fire, $NO_3^-$-N concentrations were higher (193 $\mu g \cdot L^{-1}$) than in undisturbed basins (Tables 4 and 8). The reasons for the decline in $NO_3^-$ after clearcutting at ELA detected by Nicolson (1975) are not known, although high $NO_3^-$ uptake by the remaining vegetation, slow rates of remineralization of slash and detritus, and the very low N concentration of soil organic matter and vegetation could contribute. Nicolson's finding is contrary to most other watershed studies of clearcutting (Bormann et al. 1968, Likens et al. 1969, 1970; Aubertin and Patric 1974; Swank and Douglass 1977; Dahm 1980; Swank and Caskey 1982).

### Comparisons of Nitrogen Concentrations in Streams Draining Perturbed Forested Ecosystems

Increases in $NH_4^+$ concentrations after burning in the E and NE subbasins (Fig. 3B) and from clearcutting at ELA (Table 8) contrast with the effects of clearcutting in other regions where no increases in $NH_4^+$ were detected (Bormann et al. 1968; Likens et al. 1970; Aubertin and Patric 1974; Swank and Douglass 1977; Dahm 1980). The increase in $NH_4^+$ was very large for some weeks after the 1974 fire. The short-term increase in $NH_4^+$ may be due to the intensity of the burn, which remineralized the forest vegetation and organic matter in soil. Leaching experiments in soil columns from the E subbasin just after the 1974 fire revealed that most of the water-leachable N was present as $NH_4^+$ (D. W. Schindler and G. Morrison, unpubl. data). Nonetheless, most of the inorganic N leaving the watershed was $NO_3^-$ (Fig. 3A and 3B). This presumably resulted from nitrification, as was found at Hubbard Brook following clearcutting (Likens et al. 1969; Bormann et al. 1974).

Concentrations of $NO_3^-$ exported from unmodified ELA subbasins were lower than baseline concentrations from Hubbard Brook (Likens et al. 1970) but higher than most values from Coweeta Basin and H. J. Andrews Experimental Forest (Table 8) (Swank and Douglass 1977; Dahm 1980). Postfire concentrations of $NO_3^-$ were higher than clearcutting effects at Coweeta Basin or H. J. Andrews Forest but not as high as the effects of clearcutting plus herbicide at Hubbard Brook. Wright (1976) did not detect increases in $NO_3^-$ in streams from burned forests located only 300 km south of ELA, although he did not start sampling until 1 yr after the fire event. Since we detected only temporary increases (<1 yr) in $NO_3^-$ concentrations after the fire in the NW basin and more persistent increases in concentration in the E stream, it is apparent that increases in $NO_3^-$ concentration are not a consistent result of either fire or clearcutting in boreal watersheds. Vitousek et al. (1979) also found that N-poor forest ecosystems did not leach $NO_3^-$, as was observed in streams from a more nutrient-rich temperate forest.

## Summary

The first wildfire in the wetland watershed (NE) increased water yields and mass export of $NO_3^-$, $NH_4^+$, TDN, Susp N, TN, TDP, and TP compared with the prefire levels. In the upland watershed (E), water yields and mass export of $NO_3^-$, $NH_4^+$, TDN, Susp N, and TN increased, while export of TDP and TP did not. Concentrations of all forms of N and P in stream water also increased after the first fire in the E subbasin. In general, N losses partially recovered 5–6 yr after the fire, while P losses returned to normal 2–3 yr after the fire.

A second fire in 1980 reburned the E and NE subbasins and burned the NW subbasin for the first time. Weaker, but distinct, increases in $NH_4^+$ and TDN were noted in the wetland outflow and in $NO_3^-$, Susp N, TDP, and Susp P in the twice-burned upland stream. In the NW subbasin, which was first burned in 1980, there was no significant increase in the annual concentration of P for the 3 yr after the fire or in most forms of N. The lack of response in most forms of N and P fractions was probably due to the lower intensity of fire in the NW subbasin.

Fire caused changes in seasonal export patterns in $NO_3^-$, TDN, and TDP in all subbasins. In the case of TDN, a significant increase in concentration was noted throughout 1980 in all basins. For other chemical species, baseflow concentrations in early spring and late fall were elevated, while concentrations in midsummer were within the prefire range.

## Acknowledgments

We thank G. Linsey and M. A. Turner for their assistance in the chemical analysis of samples and preparation of data and numerous field and laboratory staff who helped to collect, analyse, and maintain the 18-yr record of stream chemistry and hydrology at ELA. We also thank Sandi Vitt for the preparation of the manuscript. This study was funded by the Canadian Department of Fisheries and Oceans. The World Wildlife Fund and NSERC Strategic Grant No. 40628 provided support for analysis of the long-term data set.

## References

AUBERTIN, G. M., AND J. H. PATRIC. 1974. Water quality after clearcutting a small watershed in West Virginia. J. Environ. Qual. 3: 243–249.

BAYLEY, S. E., D. H. VITT, R. W. NEWBURY, K. G. BEATY, R. S. BEHR, AND C. MILLER. 1987. Experimental acidification of a *Sphagnum*-dominated peatland: first year results. Can. J. Fish Aquat. Sci. 44(Suppl. 1): 194–205.

BORMANN, F. H., G. E. LIKENS, D. W. FISHER, AND R. S. PIERCE. 1968. Nutrient loss accelerated by clear-cutting of a forest ecosystem. Science (Wash., DC) 159: 882–884.

BORMANN, J. H., G. E. LIKENS, T. G. SICCAMA, R. S. PIERCE, AND J. S. EATON. 1974. The effect of deforestation on ecosystem export and the steady-state conditions at Hubbard Brook. Ecol. Monogr. 44: 255–277.

BROWN, G. W., A. R. GAHLER, AND R. B. MARSTON. 1973. Nutrient losses after clear-cut logging and slash burning in the Oregon Coast Range. Water Resour. Res. 9: 1450–1453.

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.

CLARK, J. S. 1990. Fire and climate change during the last 750 years in northwestern Minnesota. Ecol. Monogr. 60: 135–159.

DAHM, C. N. 1980. Studies on the distribution and fates of dissolved organic carbon. Ph.D. dissertation, Oregon State University, Corvallis, OR. 145 p.

DEBYLE, N. V., AND P. E. PACKER. 1972. Plant nutrients and soil losses in overland flow from burned forest clearcuts, p. 296–305. *In* S. C. Crallany, T. G. McLaughlin, and W. D. Striffler [ed.] Watersheds in transition. American Water Resources Association, Urbana, IL.

DEVITO, K. V., P. J. DILLON, AND B. D. LAZERTE. 1989. Phosphorus and nitrogen retention in five Precambrian shield wetlands. Biogeochemistry 8: 185–204.

FELLER, M. C., AND J. P. KIMMIMS. 1984. Effects of clearcutting and slash burning on streamwater chemistry and watershed nutrient budgets in southwestern British Columbia. Water Resour. Res. 20: 29–40.

HEINSELMAN, M. L. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. Q. Res. 3: 329–282.

JOHNSON, A. H. 1979. Estimating solute transport in streams from grab samples. Water Resour. Res. 15: 1224–1228.

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.

LIKENS, G. E., F. H. BORMANN, AND N. M. JOHNSON. 1969. Nitrification: importance to nutrient losses from a cutover forested ecosystem. Science (Wash., DC) 163: 1205–1206.

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. Monogr. 40: 23–43.

MCCOLL, J. G., AND D. F. GRIGAL. 1975. Forest fire: effects on phosphorus movement to lakes. Science (Wash., DC) 188: 1109–1111.

1977. Nutrient changes following a forest wildfire in Minnesota: effects in watersheds with differing soils. Oikos 28: 105–112.

MEGAHAN, W. F. 1983. Hydrological effects of clearcutting and wildfire on steep granitic slopes in Idaho. Water Res. 19: 811–819.

NICOLSON, J. A. 1975. Water quality and clearcutting in a boreal forest ecosystem. Can. Hydrol. Symp. 75 Proc. NRCC No. 15195: 734–738.

RICHTER, D. D., AND C. W. RALSTON. 1982. Prescribed fire: effects on water quality and forest nutrient cycling. Science (Wash., DC) 215: 661–662.

RIEKERK, H. 1983. Impacts of silvaculture on flatwoods runoff, water quality and nutrient budgets. Water Resour. Bull. 19: 73–79.

SCHINDLER, D. W. 1977. Evolution of phosphorus limitation in lakes. Science (Wash., DC) 195: 260–262.

SCHINDLER, D. W., S. E. BAYLEY, P. J. CURTIS, B. R. PARKER, M. P. STAINTON, AND C. A. KELLY. 1991. Synchronization of the carbon, nitrogen and phosphorus cycles in precambrian shield lakes and their watersheds. Hydrobiologia. (In press)

SCHINDLER, D. W., K. G. BEATY, E. J. FEE, D. R. CRUIKSHANK, E. R. DEBRUYN, D. L. FINDLAY, G. A. LINSEY, J. A. SHEARER, M. P. STAINTON, AND M. A. TURNER. 1990. Effects of climatic warming on lakes of the central boreal forest. Science (Wash., DC) 250: 967–970.

SCHINDLER, D. W., R. W. NEWBURY, K. G. BEATY, AND P. CAMPBELL. 1976. Natural water and chemical budgets for a small Precambrium lake basin in central Canada. J. Fish. Res. Board Can. 33: 2526–2543.

SCHINDLER, D. W., R. W. NEWBURY, K. G. BEATY, J. PROKOPOWICH, T. RUSZCZYNSKI, AND J. A. DALTON. 1980. Effects of a windstorm and forest fire on chemical losses from forested watersheds and on the quality of receiving stream. Can. J. Fish. Aquat. Sci. 37: 328–334.

SMITH, D. W., AND T. D. JAMES. 1978. Characteristics of prescribed burns and resultant short-term environmental changes in *Populus tremuloides* woodland in southern Ontario. Can. J. Bot. 56: 1782–1791.

STAINTON, M. P., M. J. CAPEL, AND F. A. J. ARMSTRONG. 1977. The chemical analysis of fresh water. Fish. Environ. Can. Freshwater Inst. (Winnipeg, Man.) Spec. Publ. No. 25.

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

SWANK, W. T. 1987. Stream responses to disturbance, p. 339–357. *In* W. T. Swank and D. A. Crossley, Jr. [ed.] Forest hydrology and ecology at Coweeta. Springer-Verlag, New York, NY.

SWANK, W. T., AND W. H. CASKEY. 1982. Nitrate depletion in a second-order mountain stream. J. Environ. Qual. 11: 581–584.

SWANK, W. T., AND J. E. DOUGLASS. 1977. Nutrient budgets for undisturbed and manipulated hardwood forest ecosystems in the mountains of North Carolina, p. 343–363. *In* D. L. Correll [ed.] Watershed research in eastern North America. Smithsonian Institution, Edgewater, MD.

TIEDEMANN, A. R., C. E. CONRAD, J. H. DIETERICH, J. W. HORNBECK, W. F. MEGAHAN, L. A. VIERECK, AND D. D. WADE. 1979. Effects of fire on water. U.S. Dep. Agric. For. Serv. Gen. Tech. Rep. WO-10: 28 p.

TIEDEMANN, A. R., J. D. HELVEY, AND T. D. ANDERSON. 1978. Stream chemistry and watershed nutrient economy following wildfire and fertilization in eastern Washington. J. Environ. Qual. 7: 580–588.

URBAN, M. B., S. J. EISENREICH, AND S. E. BAYLEY. 1988. The relative importance of denitrification and nitrate assimilation in mid-continental bogs. Limnol. Oceanogr. 33: 1611–1617.

VERRY, E. S., AND D. R. TIMMONS. 1982. Waterborne nutrient flow through an upland peatland watershed in Minnesota. Ecology 63: 1456–1467.

VITOUSEK, P. M., J. R. GOSZ, C. C. GRIES, J. M. MELILLO, W. A. REINERS, AND R. L. TODD. 1979. Nitrate losses from disturbed ecosystems. Science (Wash., DC) 204: 469–474.

VITT, D. H., AND S. E. BAYLEY. 1984. The vegetation and water chemistry of four oligotrophic basin mires in northwestern Ontario. Can. J. Bot. 62: 1485–1500.

WRIGHT, R. F. 1976. The impact of forest fire on the nutrient influxes to small lakes in northeastern Minnesota. Ecology 57: 649–663.