Watershed responses to clear-cutting: Effects on soil solutions and stream water discharge in central New Brunswick

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Jewett, K., Daugharty, D., Krause, H. H. and Arp, P. A. 1995. **Watershed responses to clear-cutting: Effects on soil solutions and stream water discharge in central New Brunswick**. Can. J. Soil Sci. **75**: 475–490. Elemental concentrations (H, Ca, Mg, K, Na, NH_4-N, NO_3-N, P) and water flux data for precipitation and stream discharge as well as ion concentration data for soil solutions were collected and summarized for the **Hayden Brook (HB)** and **Narrows Mountain Brook (NMB)** watersheds of the **Nashwaak Experimental Watershed Project (NEWP)** in Central New Brunswick. Elemental concentrations, fluxes and stream discharge from both watersheds were compared for pre- and post-harvest periods (1972–1978 and 1978–1984, respectively). For soil and streamwater solutions, elemental concentrations were typically highest in late summer to fall, and continued to be high throughout the dormant season. For the soil solution, concentrations of NO_3-N, NH_4-N, Ca and K peaked in midsummer. Highest NO_3-N concentrations were found in post-harvest soil solutions taken from hardwood sites. Nitrate levels were low in soil solutions taken from conifer sites, with post-harvest levels slightly higher than pre-harvest levels. Soil solution concentrations were found to vary with soil depth: pH values were lowest at the surface, and increased uniformly with depth; bases (Ca, Mg, K, Na) and NO_3-N tended to be lowest at intermediate soil depth. Seasonally divergent trends were observed for post-harvest NO_3-N in soil solutions and in streamwater: midsummer levels were high in the former, but low for the latter. Several aspects likely contributed to this divergence: (1) enhanced rates of N mineralization and nitrification in upland soils during post-harvest midsummers, (2) reduced post-harvest vegetational N uptake, (3) possibly accelerated N absorption by microbes and vegetation in the wet areas of the cut watershed. Altogether, post-harvest effects on stream discharge and streamwater chemistry were short-term: differences for elemental concentrations and stream discharge became insignificant after about 5 and 10–12 yr, respectively. Vegetation, especially tolerant hardwoods, recovered rapidly from stump and root sprouts.

Key words: Clearcutting, stream discharge, soil solution, pH, Ca, Mg, K, Na, P, NO_3-N, NH_4-N, seasonal trends

Jewett, K., Daugharty, D., Krause, H. H. et Arp, P. A. 1995. **Effets à l'échelle du bassin versant de la couple à blanc sur la solution du sol et sur le débit des eaux courantes dans le centre du Nouveau-Brunswick.** Can. J. Soil Sci. **75**: 475–490. Les concentrations au niveau élémentaire de H, Ca, Mg, K, Na, N ammoniacal et N nitrique et P ainsi que les données sur les flux hydriques comportant les précipitations et le débit des voies d'eau, de même que les concentrations ioniques de la solution du sol, ont été recueillies et résumées pour les bassins Hayden Brook (HB) et Narrows Mountain Brook (NMB). Ces deux bassins sont compris dans le cadre du projet expérimental Nashwaak dans le centre du Nouveau-Brunswick. Les concentrations élémentaires, les flux et le débit des cours d'eau dans les deux bassins étaient comparés entre la période précédant la coupe à blanc c-a-d les années 1972–1978 et la période immédiatement postérieure à la coupe, 1978–1984. Dans les solutions du sol et dans les voies d'eau les concentrations élémentaires atteignaient généralement un sommet en fin d'été et en automne et demeuraient élevées tout au long de la saison morte. Dans les solutions du sol, les concentrations de N nitrique, de N ammoniacal, de Ca et de K présentaient un pic vers la mi-été, les concentrations de N nitrique les plus élevées étant retrouvées dans la solution prélevée après la coupe dans les emplacements sous feuillus. Dans la solution du sol sous couvert de conifères les niveaux des nitrates étaient faibles, avec des valeurs légèrement plus hautes après la récolte qu'avant. Les concentrations de la solution du sol variaient selon la profondeur du sol, le pH était plus bas en surface, pour augmenter de façon uniforme avec la profondeur et les bases Ca, Mg, K, Na et N nitrique affichaient leurs valeurs les plus basses à mi-profondeur. Des tendances divergentes selon la saison étaient observées pour les valeurs valeurs post-abattage de N nitrique dans la solution du sol et dans les voies d'eau: valeurs élevées à la mi-été dans le sol et valeurs basses dans les cours d'eau. Plusieurs aspects peuvent expliquer cet écart: (1) les taux plus élevés de minéralisation de N et de nitrification dans les sols de bas-plateau à la mi-été dans les années suivant l'abattage, (2) la diminution de l'absorpotion de N par la végétation après l'abattage et (3) l'accélération éventuelle de l'absorption de N par les populations microbiennes et par la végétation dans les zones humides du bassin coupées à blanc. Dans l'ensemble, les effets de la coupe à blanc sur le débit et sur la composition chimique des eaux courantes étaient de courte durée, les différences affectant les concentrations élémentaires disparaissant virtuellement au bout de 5 ans et celles affectant le débit au bout de 10 à 12 années. La végétation, en particulier les feuillus tolérants n'a pas tardé à repousser à partir des rejets de souche et de racine.

Mots clés: Coupe à blanc, eau courante, solution du sol, pH, Ca, Mg, K, Na, P, N nitrique, N ammoniacal, tendances saisonnières

Commercial clearcutting of forests continues to be the primary forest harvesting technique, and has been a focal point for much research in relation to forest hydrology (effects on streamwater, quantity and quality; see Hornbeck et al. 1986; McClurkin et al. 1987; Fowler et al. 1988; Miller et al. 1988; Verry 1988; Hicks et al. 1991), and forest soils (effects on pH, nutrient cycling, and leaching; see Vitousek et al. 1979; Lawrence et al. 1987; Fuller et al. 1988; Harr and

Frederikson 1988; Tiedemann et al. 1988; Martin and Harr 1989). This paper reports on effects of commercial clear-cutting on hydrology, soil solution composition, water quality and elemental outputs (NO_3-N, NH_4-N, Ca, Mg, K, Na, P, and H) for the Narrows Mountain Brook (NMB) and Hayden Brook (HB) basins in Central New Brunswick. These watersheds formed the basis of a paired watershed experiment (Hewlett and Nutter 1969), with NMB cut in 1978–1979, and HB serving as the control (Dickison et al. 1981; Daugharty 1984). The purpose of this experiment was to examine impacts of commercial clearcutting on streamwater yield (Daugharty and Dickison 1988), snow-cover (Dickison and Daugharty 1980; Daugharty 1984), albedo (Daugharty and Dickison 1988; Bourque et al. 1995), streamwater chemistry (Bacon 1981; Krause 1982), soils and soil solutions (Krause 1982) and vegetative cover (MacDonald and Powell 1983).

At the time of Project establishment (1970), information about harvest effects on forested watersheds was sparse (Hibbert 1967; Likens et al. 1970). For its time, the Project was unique in the sense that:

- harvesting operations and logging road construction were done by local forest industry, and did not follow any particular scientific specifications or manipulations other than the expressed need that harvest lines should conform with natural watershed contours;

- the area, once cut, was to regenerate naturally with no further silvicultural treatments until precommercial thinning might become necessary (approximately 20 yr later);

- there was no local information on how forest streams would react to the harvesting operation in terms of stream discharge and ion composition.

In this report, emphasis is placed on the analysis of the hydrogeochemical information generated by the project. Particular items considered are:

- monthly and annual streamwater and elemental (H, Ca, Mg, K, Na, NH_4-N, NO_3-N and P) discharge rates for each basin;

- net pre- and post-harvest inputs and differences between the two watersheds;

- pre- and post-harvest trends associated with the elemental concentrations in precipitation, streamwater and soil solution according to month of year (to express seasonality);

- pre- and post-harvest trends associated with the elemental concentrations in the soil percolates according to vegetative cover type (coniferous, deciduous or mixed forest stands) and soil depth (15, 30, 60 and 90 cm).

Project background, and methods used were described by Krause (1982), Blais (1985), Daugharty and Dickison (1988), and Palmer (1988).

STUDY AREA

The Nashwaak Experimental Watershed Project is located in west central New Brunswick approximately 70 km north of Fredericton (46°18′N. lat., 67°02′W. long.; Fig. 1). The NMB basin spans 391 ha, and the HB Brook basin spans 660 ha. Elevations in NMB range from 220 to 420 m (asl.), with a mean of 296 m, an average slope of 7.6%, and a predominantly southeastern aspect. Elevations in HB range from 197 to 478 m, with a mean of 317 m, an average slope of 11.4 %, and a predominantly southern aspect (Daugharty 1984).

Forest cover was similar for both basins: 50% deciduous (located mainly at higher elevations), 25% coniferous (located mainly in the lower elevations), and 25% mixed wood (Fig. 1). Dominant tree species were beech (*Fagus grandifolia* Ehrh.), sugar maple (*Acer saccharum* Marsh.), red spruce (*Picea rubens* Sarg.) and balsam fir (*Abies balsamea* (L.) Mill) (Powell 1984).

The climate, according to the Koeppen Classification system (Lutgens and Tarbuck 1982), is humid continental, with at least 4 mo of mean temperatures greater than 10°C. The mean annual temperature from 1972 and 1983 was 3.5°C. Precipitation is distributed fairly evenly, with lowest monthly rates in August, and highest monthly rates in December (Palmer 1988). Mean annual precipitation from 1972 to 1985 amounts to 1322 mm (Palmer 1988). Approximately one-third of the precipitation falls as snow. The snowpack is generally persistent, and lasts from late November to mid April (Daugharty and Dickison 1988).

Both watersheds are underlain by argillite which is covered with till (usually ablation till on top of basal till) at a depth varying from less than 50 cm to several meters. The till is derived from the underlying bedrock, but also contains granite, diorite and gabbro from areas northwest of the watersheds (Krause 1982). Soils of the area are: Orthic Humo-Ferric and Ferro-Humic Podzols on hill tops and gentle to strong slopes, Gleyed Ferro-Humic Podzols on very gently sloping and level areas, and Orthic Gleysols in small areas next to streams (Krause 1982).

Harvesting the NMB basin started in May 1978 and ended in February 1979. Logging roads were constructed before the cut. Harvesting was done with chainsaws. Trees with a breast height diameter greater than 10 cm were cut, limbed and topped at the stump. Tree-length logs were transported to road sides with cable skidders on rubber tires. A 75-m wide riparian strip was left on each side of the main NMB branch (Fig. 1). In total, approximately 90% of the basin was harvested. The residual stand [mainly eastern white cedar (*Thuja occidentalis* L.)] had a wood volume of 5 m^3 ha^{-1}, and a stem density of 450 trees ha^{-1} (Krause 1982).

In the first post-harvest summer, eighteen 1-ha blocks representing various slope, soil and former stand types were randomly assigned throughout the NMB basin to assess slash distribution (percent coverage of ground) and soil disturbance. Within each block, 100 2 × 2-m plots were established along evenly spaced, parallel transects. It was found that approximately half of the area was covered with logging slash. Forty three percent of the plots showed some form of soil disturbance (such as water-filled skidder trails),

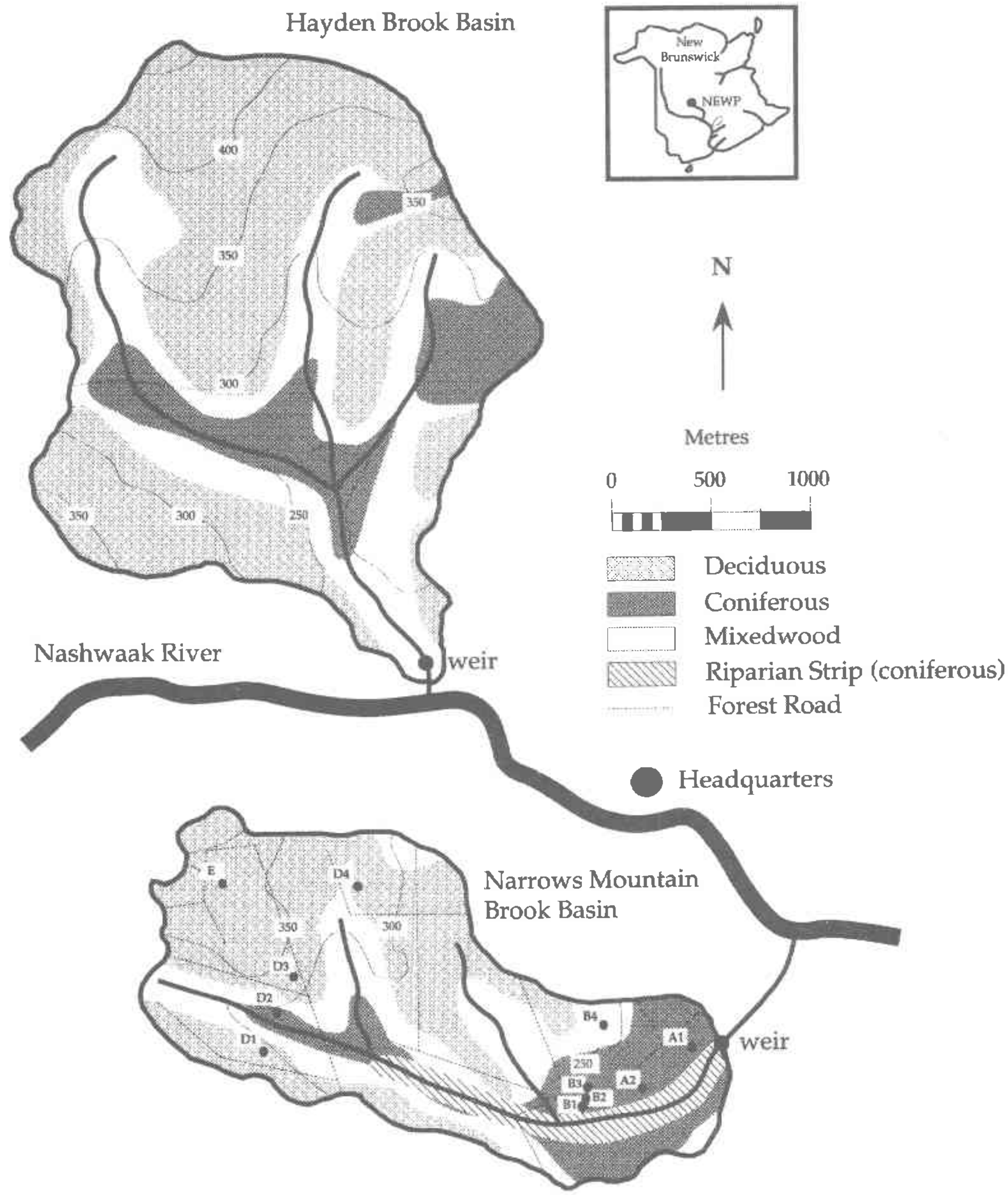

Fig. 1. Map of the Nashwaak Experimental Watershed Project showing covertype, lysimeter locations, road network and weir locations.

and 14% of the plots showed some degree of mixing the forest floor organic matter with the mineral soil. Figure 2 presents an example of the conditions found.

METHODS

Data type and collection periods are summarized in Table 1. Precipitation volume and chemistry were sampled at NEWP headquarters, approximately 0.5 km from the bottom of the basins. Precipitation was sampled continuously with sterile collection bags. Samples were collected weekly throughout the year. Air temperatures were monitored continuously at the same location.

Snow survey data were collected from permanent sample plots located along parallel lines transecting the narrow axes of the basins at a grid spacing of 316 × 316 m and 283 × 283 m, for HB and NMB, respectively. Additional snow depths were measured at two equally spaced intervals between plots (Daugharty 1984). Standard Federal-type snow samplers were used to determine both depth and snow water equivalent to 0.25-cm increments (Daugharty 1984). Snow survey data were averaged if sampled more than once a month.

Soil percolate solutions were collected with ceramic suction cups at 12 sites throughout the NMB basin (Krause 1982; Fig. 1). Most sampling stations had four ceramic cups, one installed at each of four depths: 15, 30, 60, and 90 cm. At the top of the basin, the soils were rocky, and cups were not installed at soil depths greater than 60 cm. Solution samples were obtained by applying suction to the tubes over periods of 1–5 d depending on the water potential of the soil (Krause 1982). Sampling was carried out from May to October.

Fig. 2. View of a clear-cut portion of the Narrows Mountain Brook basin, with protected riparian zone in the background.

A natural control stream gauge was used to monitor stream discharge rates near the outlet of HB. A concrete 90° v-notched weir was constructed for NMB approximately 0.75 km from its outlet. Both streams were monitored with Stevens-type A-35 automatic water level recorders. These locations also served as sampling sites for streamwater chemistry. Streamwater was sampled continuously with automatic collectors. Samples were analyzed weekly from May to October, and biweekly for the remainder of the year (Krause 1982).

Streamwater, precipitation and soil percolate were all analyzed in the same manner: Ca, Mg, K and Na concentrations were determined with atomic absorption spectrophotometry (McKeague 1978). Phosphorous concentrations were determined colorimetrically, by producing the ascorbic-acid reduced molybdophosphoric blue complex (Watanabe and Olsen 1965). Nitrate-N and NH_4-N were determined by steam distillation, with and without Devarda's alloy (Bremner 1965).

Soil solution data were averaged by month, depth, sampling station, and harvest period. Precipitation and streamwater data were volume-weighted to give monthly means. Ion concentrations of weekly or biweekly precipitation and streamwater samples were multiplied with corresponding precipitation and streamwater volumes (respectively) to estimate monthly and annual flux rates. Continuous records of pre- and post-harvest flux rate differences between the NMB and HB basins were obtained for water and ion discharge rates. The resulting differences were analyzed by plotting cumulative differences over time. These plots would have a zero slope for the case when water and ion flux discharge rates from both basins are identical, i.e., when average differences between the basins are zero and have a mean zero random residual. Systematic pre- and post-harvest differences between the basins would be signalled by a sustained slope other than zero, or by a sustained change in slope.

Table 1. Collection periods for data at the NEWP

	HB	NMB
Air temperature	1971–1990	
Precipitation volume	1972–1990	
Snowpack	1973–1978	1973–1982
Soil percolate	N/A	1972–1984
Stream chemistry	1972–1984	1972–1984
Stream flow	1971–1991	1972–1991
Precipitation chemistry	1972–1984	1972–1984

RESULTS AND DISCUSSION

Hydrological Aspects

Mean monthly air temperature, precipitation for the area, and stream discharge rates were plotted in Fig. 3 for HB and NMB from 1971/1972 to 1990. Also shown are the snowpack water equivalents for both basins (when determined), and the annual cycle of air temperature and precipitation (Fig. 3). This was done to illustrate the annually recurring effects of snow, rain, and air temperature on streamwater discharge rates, and to demonstrate that the resulting hydrological situation was similar for both basins, and remained so after harvest. There were, however, systematic pre- and post-harvest discharge rate differences between the basins as well, and these are shown by the cumulative difference plot in Fig. 4. This Figure reveals the following:

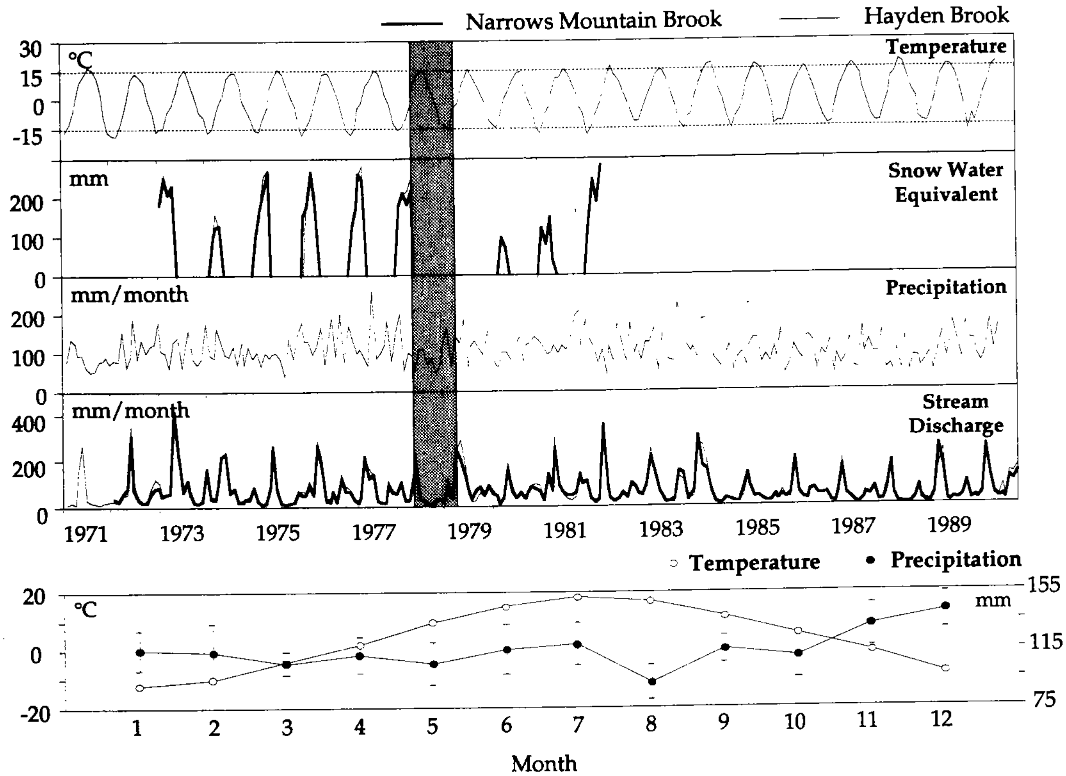

Fig. 3. Nashwaak Experimental Watershed Project, environmental data. Top: Mean monthly values for temperature, snow water equivalent, precipitation and stream discharge. Bottom: Mean monthly values (annual averages) for temperature and precipitation Shaded area = harvest time.

- The top line shows the monthly differences in stream discharge between the two basins. No particular pre-and post-harvest differences are evident from this plot.
- The curved line below shows the cumulative effects of the monthly differences. From this, it is evident that the HB basin discharged more water than the NMB basin for the

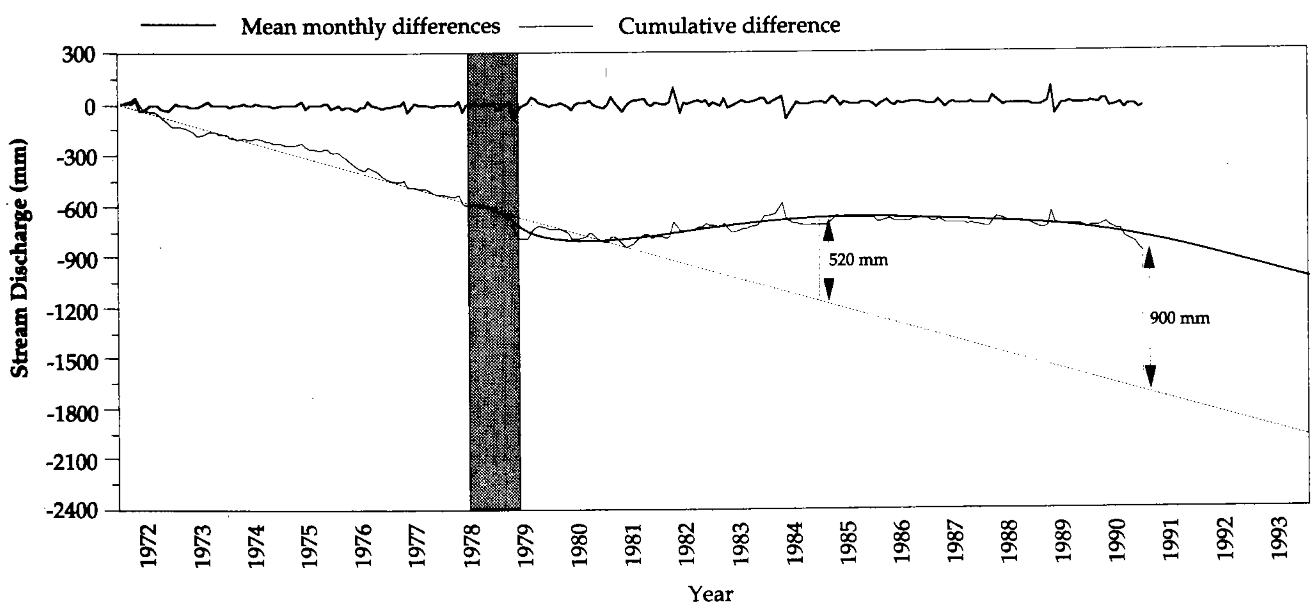

Fig. 4. Differences and cumulative differences between Narrows Mountain Brook and Hayden Brook monthly stream discharge. The dashed line represents the linear pre-harvest cumulative discharge difference trend between the two basins. This trend, as shown, was extended into the post-harvest time, in order to simulate the expected cumulative Narrows Mountain Brook discharge if cutting had not occurred. The post-harvest cutting effect on stream discharge appears to be 520 and 900 mm at the end of the 6th and 12th post-harvest years.

pre-harvest period (the pre-harvest cumulation of the differences between HB and NMB had a negative trend). This effect was possibly due to the steeper slopes and few wetland locations within the HB basin (Fig. 1).

• The curvilinear plot suggests that the post-harvest water yield from NMB was at least as much and slightly higher than the water yield from HB for the same time: the post-harvest cumulation of the differences levelled off and turned positive from mid-1980 through 1984.

• After 1984, the cumulative difference curve slowly turned toward its pre-harvest slope, meaning that the discharge rate of the NMB basin gradually returned to its pre-harvest condition. The cumulative difference plot shows that this recovery was complete or nearly complete at 10–12 yr after harvest, as illustrated by the superposed, hand-fitted curve that attains the pre-harvest slope at about 10–12 yr.

The cumulative difference plot in Fig. 4 was used to estimate the total harvest effect on the NMB water yield for post-harvest years 6 (end of the water chemistry record) and 12 (end of the hydrological records). The corresponding numbers were 516 and 896 mm, respectively. These numbers, in relation to the total post-harvest NMB discharge at the end of years 6 and 12 (5813 and 9776 mm) amounted to 8.9 and 9.2%, i.e. the total harvest effect on water yield for the first 12 yr was < 10%.

Increased run-off and stream discharge following harvest is generally attributed to a reduced rate of evapotranspiration caused by the drastic leaf-area reduction (Likens et al. 1970; Brandt et al. 1988; Nicolson 1988). If this were true for the post-harvest situation in the NMB basin, then stream discharge difference should be highest immediately after harvest. This, however, was not so (see also Daugharty and Dickison 1988). Three vegetation-mediated factors may have contributed to this slow, gradual, and slightly delayed response:
(1) A post-harvest reduction in vegetational snow catch efficiency may have led to a reduced rate of snow input of about 180 mm in the first year after harvest (Daugharty and Dickison 1988); vegetation regrowth would subsequently re-establish the pre-harvest snow catch efficiency.
(2) Vegetational catch efficiency of fog and cloud water may have been reduced, and this could have produced a loss of approximately 80 mm water input during the first year after harvest (Yin and Arp 1993).
(3) Measured midsummer surface reflectance (albedo) values dropped immediately after harvest, increased beyond the pre-harvest level to a maximum value in the third year, and then gradually declined toward pre-harvest levels (Daugharty and Dickison 1988; Bourque et al. 1995). Changes in albedo (or net absorption rate of solar radiation) would affect the rate

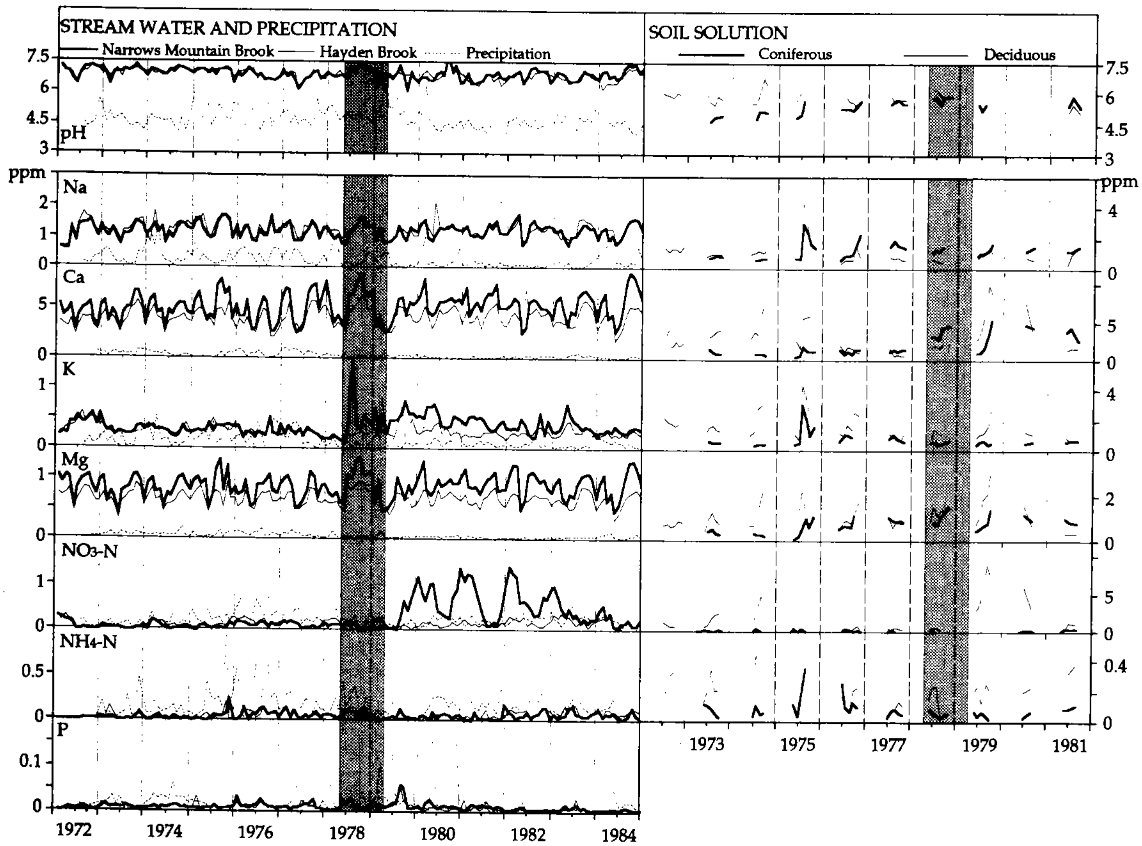

Fig. 5. Mean monthly concentrations (Ca, Na, K, Mg, NO_3-N, P) and pH for stream water (Narrows Mountain Brook and Hayden Brook), precipitation and soil solutions (by cover type, Narrows Mountain Brook basin only). Shaded block indicates cutting period.

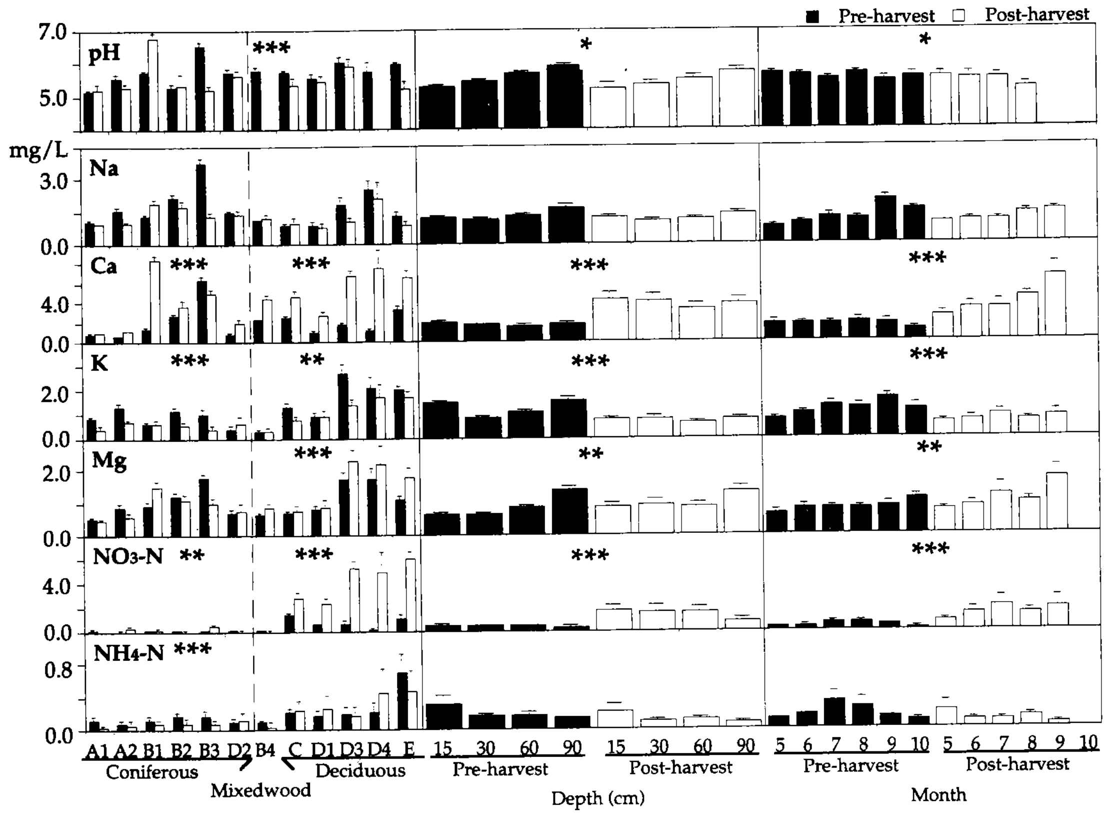

Fig 6. Mean soil solution concentrations (Na, Ca, K, Mg, NH_4-N, NO_3N) and pH for the Narrows Mountain Basin, pre- versus post-harvest. Left: All depths and months by sampling station and vegetative cover. Middle: All stations by depth and harvest period. Right: all stations by month and harvest period. *,**,*** $P < 0.1$, $P < 0.05$ and $P < 0.01$, respectively. Bars give standard errors.

of evapotranspiration: high albedo values 2–3 yr after harvest could mean less energy available for evapotranspiration.

Other factors may have also contributed to this situation, namely:

- the marked disturbances of the ground (ruts, skidder trails, see Fig. 2) in the wet portions of the NMB basin may have increased basin-wide water retention because of localized surface ponding and soil compaction;

- a small but unquantifiable amount of water was temporarily diverted from the measuring weir because of road construction.

Elemental Concentrations in Precipitation, Soils and Streams

Pre- and post-harvest elemental concentrations for H, Ca, Mg, K, Na, NH_4-N, NO_3-N and P (monthly volume-averaged means) are plotted in Fig. 5 against time. On the left side, elemental concentrations are shown for NMB and HB streamwater, and for total precipitation. On the right side, elemental concentrations are shown for NMB soil percolates, by vegetation type (deciduous/mixed-woods versus coniferous). Three trends emerged from these plots:
(1) Precipitation was generally acidic, and fluctuated about pH 4.5. In contrast, streamwater was nearly pH neutral, and fluctuated from 6 to 7.5. Soil percolates had intermediate pH levels. Hence, the soil–vegetation complex of the area was acid buffering, and much acid buffering must have been due to soil mineral weathering, as evident from the enhanced Ca, Mg, K and Na concentrations in the soil and streamwater solutions.
(2) Phosphorus and NH_4-N concentrations in precipitation tended to exceed P and NH_4-N concentrations in the soil and streamwater solutions. With respect to NH_4-N, this difference was especially noted for soil solutions on conifer sites.
(3) There were post-harvest increases for the K and NO_3-N concentrations in NMB streamwater for about 5 years. This effect was immediate for K, and somewhat delayed for NO_3-N.

Pre- and post-harvest elemental concentrations were highly variable and, as such, depended on year, season and vegetation type. To clarify these trends, we analyzed the data displayed in Fig. 5 as follows:

- by performing simple means tests on the soil percolate concentrations, with vegetation type, soil depth, month of growing season and pre- and post-harvest conditions as main factors (Fig. 6);

- by plotting mean seasonal trends for the streamwater concentrations against time of year, and comparing pre- and post-harvest averages by simple means tests (Fig. 7);

- by showing plots of mean monthly concentration trends in precipitation (Fig. 8).

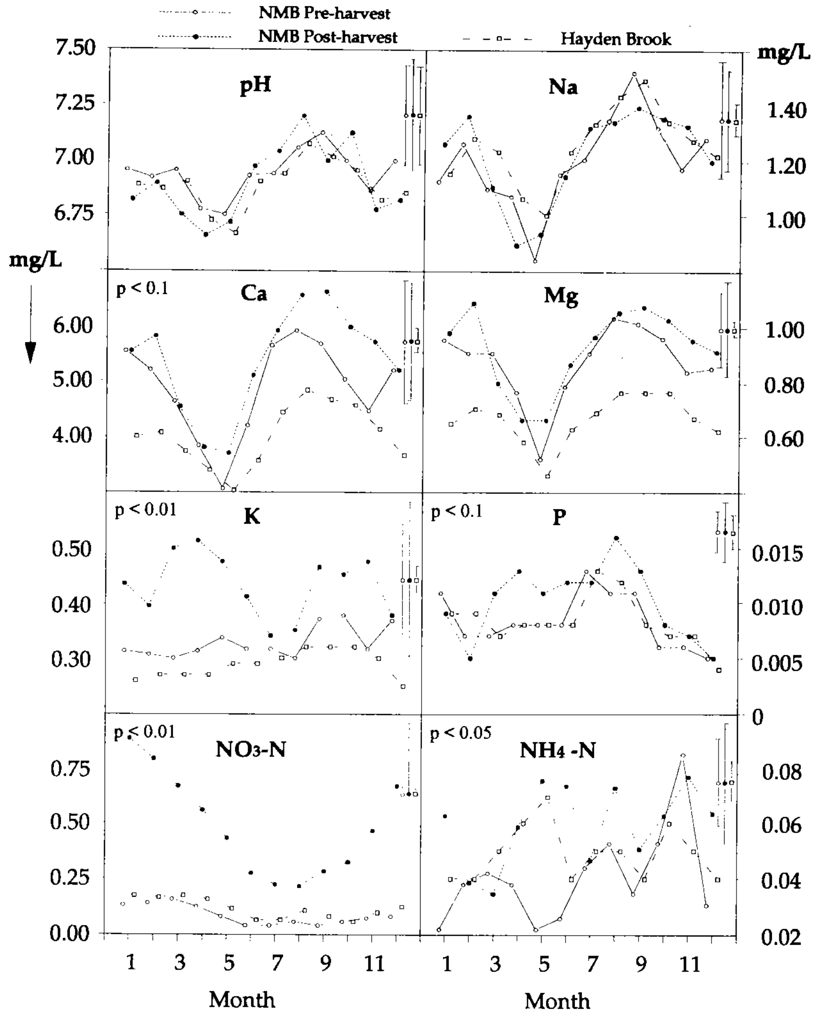

Fig 7. Mean monthly stream water concentrations (Na, Ca, K, Mg, NH_4-N, NO_3N) and pH for the Narrows Mountain Basin (pre- and post-harvest) and for Hayden Brook. Pre- versus post-harvest significance levels (*P* values) are given for NMB. Bars give average standard error for the monthly averages.

Pre- and Post-harvest Concentrations in Soil Percolates

Across the sites, consistent post-harvest increases were registered for NO_3-N (Fig. 6). These increases were most pronounced in the topsoil (Fig. 6, middle) under hardwoods (Fig. 6, left), and occurred throughout the growing season, with separate peaks in July and at the end of the percolate sampling period (Fig. 6, right). The same was generally true for Ca, except that Ca concentrations increased steadily from the beginning to the end of the growing season. In contrast to NO_3-N and Ca, post-harvest levels for pH, Na, K, and NH_4-N were generally depressed.

To interpret these and other trends implied by Fig. 6, we found it best to visualize the soil solution as a pool that is affected by various input/output factors and processes that either increase or decrease the elemental concentrations in the soil percolates. Some of these factors and processes are described below.

Soil weathering (i.e., release of Ca, Mg, K, Na from soil minerals into solution). For podzolic soils such as those of the NMB basin, one would expect that the topsoil would already be most weathered and leached, and that the amounts of weatherable minerals would gradually increase with increasing soil depth (Brady 1984; Kimmins 1987). From Fig. 6, we note the podzolic effect by way of the steadily increasing pH values with soil depth. We further note that Na, Mg, and K levels tended to increase with increasing soil depth below 15 cm. As well, streamwater Ca concentrations generally exceeded the Ca concentrations in the soil percolate (Fig. 5).

Nutrient cycling. Nutrient uptake, litterfall, and mineralization by the forest vegetation may affect the nutrient concentration profile of forest soils by accumulating nutrient elements such as K, Ca, and N in the topsoil (Sopper 1975; Martin et al. 1986; Foster et al. 1989), as seen in Fig. 6

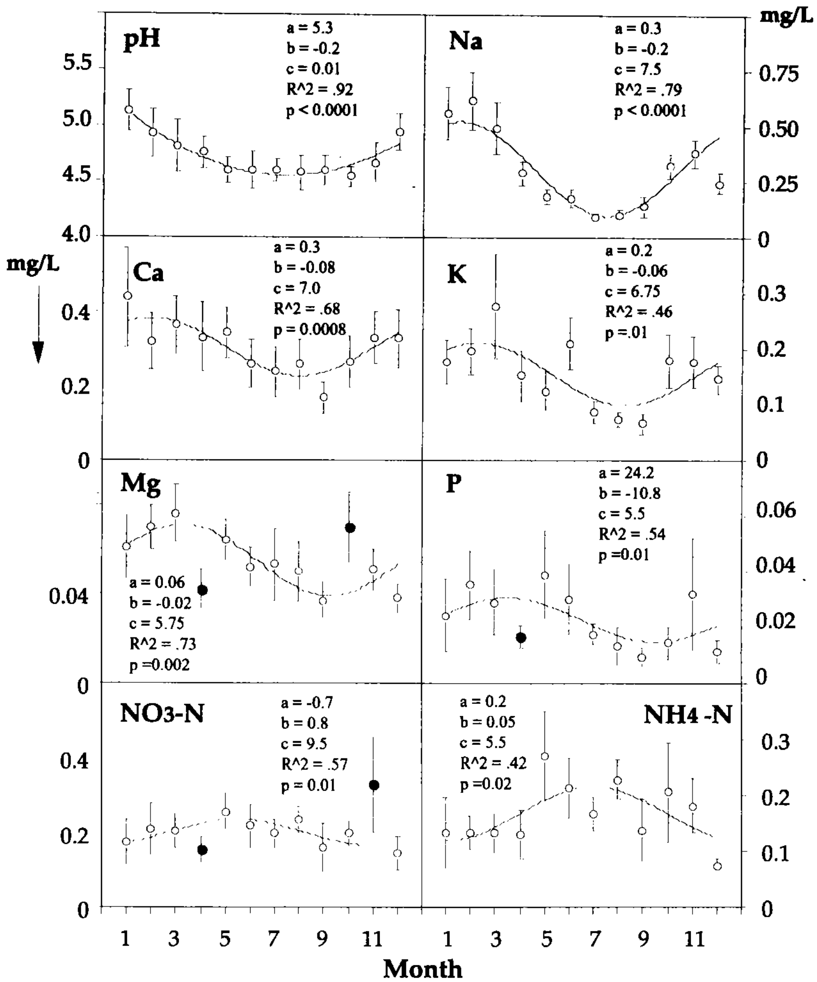

Fig. 8. Mean monthly ion concentrations (mg L^{-1}) and pH in precipitation at NEWP, with best-fitted seasonal models to show within-year trends. Error bars show standard error per month; closed dots were not included in the models presentation.
Models: pH = $a + bx + cx$^2; log $NO_3 = a + b$ {sin [(month + c)/6]}.
Other variables: $Y = a + b$ {sin [(month + c)/6]}.

(middle). Low nutrient concentrations in the middle of the soil profile suggest uptake in excess of nutrient inflow into this portion of the soil. The pre-harvest case for K in Fig. 6 (middle) is perhaps an example. After harvesting, elemental concentrations tended to be more uniformly distributed throughout the vertical soil profile.

ORGANIC MATTER MINERALIZATION AND NITRIFICATION. High temperatures during midsummer should stimulate organic matter mineralization rates throughout the basins (Johannessen and Henriksen 1978; McColl 1978; Feller and Kimmins 1979), and this may have caused the midsummer concentration peaks for Na, K, Mg, NH_4-N and NO_3-N in Fig. 6 (right). Similarly, a fresh supply of litter at the time when the soils are moist and warm may have stimulated nutrient mineralization in the fall, as shown by the pronounced post-harvest September peaks for Ca, Mg, and NO_3-N in Fig. 6 (right).

The strong post-harvest emergence of NO_3-N in NMB soil percolates underneath mixed wood and hardwood sites suggests that the soil-acidifying nitrification reaction (McColl 1972; Jenny 1980) is an important process at these locations (Krause 1982). We further note that the NO_3-N emergence was also related to a consistent pH drop of the soil percolates (Fig. 6, left). In contrast, NO_3-N production underneath conifer sites was low.

The gradual post-harvest increase of soil solution NO_3-N concentrations, and its decline toward pre-harvest concentrations during the 3rd post-harvest year (Fig. 6, right) was likely due to: reduced NO_3-N uptake under absent to sparse forest vegetation (Vitousek et al. 1979; Krause 1982; Martin et al. 1986); on-going and perhaps slightly accelerated soil nitrification throughout the soils of the basin (Sopper 1975; Federer 1983); eventual acceleration of NO_3-N uptake by the rapidly recovering forest vegetation (Vitousek et al. 1979; Krause 1982; Martin et al. 1986).

HYDROLOGY. Increased water input into the soil may depress elemental concentrations in soil percolates. This would be most pronounced during spring at the time of snowmelt as evident from the low Na, Ca and Mg concentrations at this time of year (Fig. 6, right). In contrast, enhanced rates of evapotranspiration during summer should decrease the general soil moisture level, thereby contributing in part to the already noted midsummer concentration peaks for some of the nutrients. There may, however, be pre- and post-harvest differences, because post-harvest soil moisture levels would be higher than pre-harvest levels because of reduced rates of evapotranspiration (Johannessen and Henriksen 1978; McColl 1978; Feller and Kimmins 1979). Post-harvest K, Na, Mg and NH_4-N concentrations were depressed in most soil solutions on conifer sites (Fig. 6, left). Post-harvest K concentrations were also depressed in soil solutions on hardwood sites.

With respect to K, lack of post-harvesting canopy leaching may be a factor in depressing post-harvest K concentrations in the soil solution. For example, Eaton et al. (1973) summarized through fall and stemflow data about canopy nutrient leaching in a northern tolerant hardwood forest. In terms of equivalents (mole charges) per hectare per summer, net cation leaching losses from the canopy followed this sequence:

K (762) >> Ca (337) >> Mg (167) >> Na(13) >>>
H (–439).

This suggests that K leaching from the canopy should add significantly to K in soil solutions, and notably so in the topsoil, where K mineralization occurs as well. Canopy removal would reduce this input, thereby depressing post-harvest K levels in the soil solution, as already noted.
For anions, the net canopy leaching sequence was

SO_4 (1312) >> Cl (125) >> H_2PO_4 (22).

ION EXCHANGE. (McColl 1972; Bohn et al. 1985). Ion exchange reactions may further complicate soil percolate concentration trends: a high post-harvest mineralization release of water-soluble Ca could have accelerated the post-harvest loss of other more easily displaced cations (e.g., Na, K and Mg) from the soil by way of ion exchange. We have already noted significant and watershed-wide post-harvest depressions of K concentrations in the soil percolates (Fig. 6, left), and we have also noted the increased post-harvest K concentrations in the streamwater (Fig. 5, left). Apparently, the depressed post-harvest K concentrations in the soil solutions do not necessarily lead to reduced K losses from the basin. Evidently, some of the more easily mobilized K was leached from the soil, thereby adding to the otherwise low K concentrations of the stream water. Figure 7 suggests that much of the post-harvest mobilization of K would occur during the dormant season.

MINERAL FIXATION OF P, NH_4 AND K. Mineral fixation of P, NH_4 and K within the mineral matrix of the soil and its subsoil may also play a role: note the generally low concentrations for P, NH_4 and K in stream water (Fig. 7). Here, P fixation would be particularly strong, because P would/should precipitate within the Al- and Fe-oxide/hydroxide enriched podzolic B layers of the soils (Bohn et al. 1985). In fact, P concentrations were very low in the soil percolates of this study, and could not be quantified reliably by way of the above P analysis procedures.

What emerges from all of the above is that pre- and post-harvest trends within the soil percolate concentrations arise from a multiplicity of interacting and inter-dependent factors and processes which are not easily interpreted in terms of simple cause and effect relationships. It is clear, however, that soil depth, month of growing season, and vegetation type had measurable effects on pre- and post-harvest elemental concentrations of the soil percolates, and some of the spatial and temporal aspects of these effects are represented in Figs. 5, 6 and 7.

Pre- and Post-harvest Streamwater Concentrations and Seasonal Trends

The seasonal results obtained from streamwater sampling tended to complement the seasonal results obtained from soil percolate sampling. For example, streamwater pH and Na, Mg, and Ca concentrations peaked in the fall, as was observed for the soil percolates (compare Fig. 6 with Fig. 7). These concentrations also remained fairly high during the winter, and we expect that the related soil percolate concentrations would have behaved similarly. In the spring, streamwater pH and Na, Ca, and Mg concentrations paralleled their soil percolate counterparts again: they were at their lowest. During midsummer, peak concentrations were registered for NO_3-N (pre-harvest conditions only), and for NH_4-N and P (pre- and post-harvest conditions). Harvesting affected the seasonal pattern by elevating the streamwater K and NO_3-N concentrations in spring, winter and fall.

For midsummer, there was a strong contrast between the post-harvest soil percolate and streamwater NO_3-N concentrations: the former peaked (see above), but the latter were at their lowest point (Figs. 6 and 7). This trend was likely due to vegetational and microbial NO_3 interception as soil water flows and seeps into and through the riparian zones of the watershed, as noted by Hill and Shackleton (1989). Additional vegetational and microbial NO_3 interception may have also occurred along and within the streams and streamlets before reaching the water sampling stations (Stewart et al. 1982).

The fact that the harvest effect lasted longer in streamwater NO_3-N than in soil percolates may have been due to deep percolation and groundwater flow. We contend that deep percolation would be enhanced by the harvest operation, because loss of vegetative cover should lead to reduced rates of evapotranspiration. This, in turn, should lead to higher moisture inputs not only into the fairly permeable soil, but also into the less permeable subsoil. We also observe that the maximum winter streamwater NO_3-N concentrations (about 1 mg L^{-1}) were similar to the measured NO_3-N ion concentrations in the soil percolates below the rooting zone (soil depths > 60 cm). Hence, the harvest operation likely increased groundwater NO_3-N concentrations from a pre-harvest level of about 0.2 mg L^{-1} to a temporary post-harvest winter level of about 1 mg L^{-1}, and this effect lasted for about 3–4 yr.

The full post-harvest development of the NO_3-N response in the soil solution and the streamwater required one summer season (Fig. 5). Sollins and McCorson (1981) found a time lag of 7–18 mo for elevated streamwater NO_3 levels after harvesting. Tiedemann et al. (1988) and Clayton and Kennedy (1985) reported NO_3 lags of about 1 yr. We suggest that these initial post-harvest lags for NO_3-N may have soil microbiological causes which, in turn, would be affected by general post-harvest soil and site conditions. This suggestion arises from considering the following factors.

AVAILABILITY OF READILY METABOLIZED SUBSTRATES. Increased availability of readily metabolized carbohydrates (woody litter, decaying roots and slash in general) could initially keep soil nitrate levels at low concentrations due to enhanced microbial N immobilization (Vitousek et al. 1979; Vitousek and Matson 1985).

LOCAL SOIL COMPACTION. Reduced rates of infiltration due to local soil compaction and skidder ruts may have kept some water at the surface, especially in the shallow areas of the watersheds (Fig. 2). During summer, standing water would cause increased microbial activities within puddles and adjacent soils (Kühnelt 1976; Insam 1990). Lowered redox potentials in waterlogged soils, should stimulate the transformation of NO_3 into volatile N_2 and/or NO_x (Broadbent and Clark 1965).

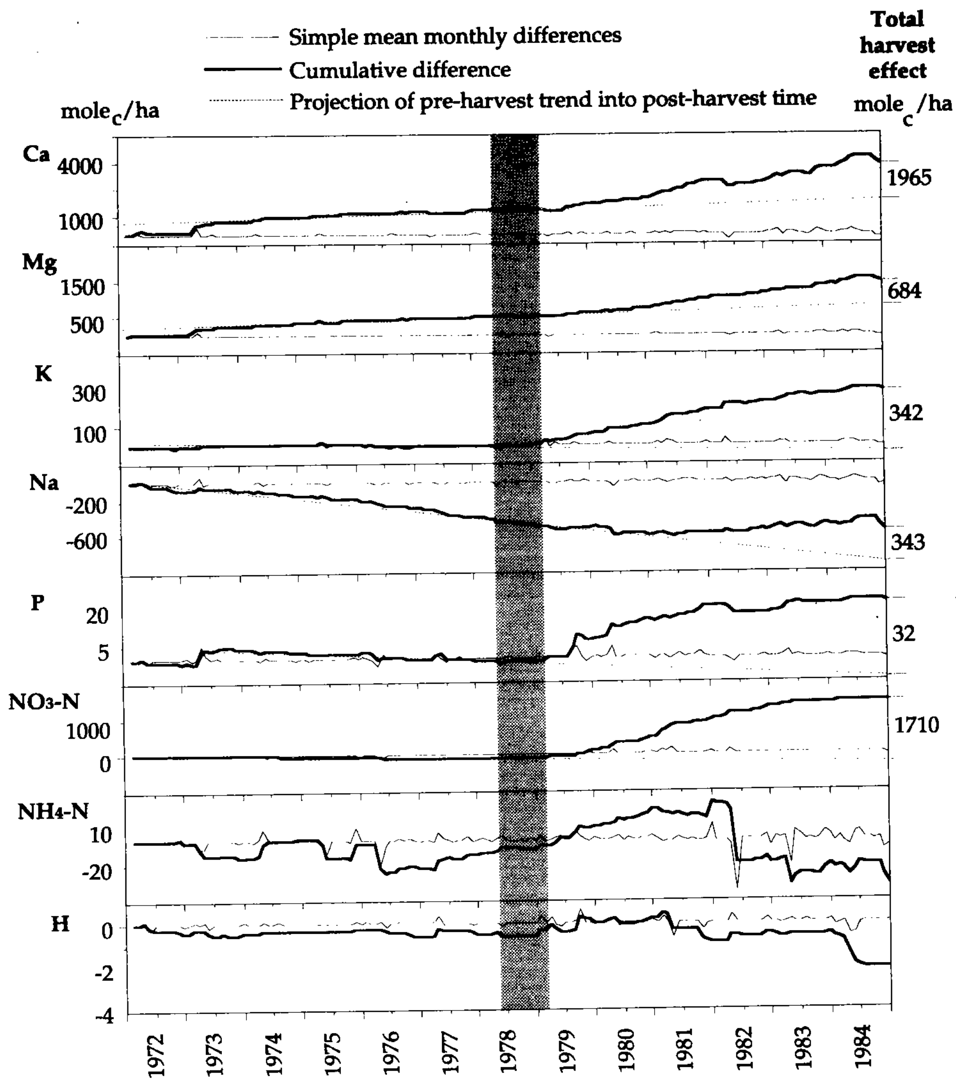

Fig. 9. Differences and cumulative differences between mean monthly streamwater ion fluxes of Narrow Mountain and Hayden Brook. Values on the right-hand side are the graphically obtained estimates for the cumulative harvest effects, obtained from the final (1984) differences between the cumulative post-harvest plots and their linear extensions of the cumulative pre-harvest trends into post-harvest time. Ammonium and H concentrations were not evaluated in this manner because the cumulative trends associated with these ions did not yield a clear pattern. Shaded block indicates cutting period.

Table 2. Annual fluxes for stream discharge of H, Na, Ca, Mg, NH4–N, NO3–N, P and water for the Nashwaak Experimental Watershed project. Numbers in bold represent post-harvest values

	Water (mm)	H	Na	K	Ca	Mg	NH_4–N	NO_3–N	P
		mole C ha^{-1} yr^{-1}							
						Precipitation			
1972	807	166	94	27	97	15	86	25	3.8
1973	1526	444	147	41	277	75	128	119	8.8
1974	1234	374	204	47	197	61	149	97	10.6
1975	1173	199	126	52	151	50	169	130	6.3
1976	1549	288	225	73	303	106	363	227	5.8
1977	1277	242	146	43	310	66	202	187	8.1
1978	1050	182	146	26	108	36	147	121	5.4
1979	1499	189	123	71	186	51	112	63	15.0
1980	1197	472	112	45	83	45	175	144	16.2
1981	1501	918	102	30	119	38	212	143	4.3
1982	1121	295	65	25	133	34	193	142	3.9
1983	1375	235	103	33	217	54	222	116	3.1
$\bar{\chi}$[z]	1318	349	136	44	189	56	188	135	8.0
SE	52	61	13	5	23	6	19	12	1.3
						Hayden Brook			
1972	584	2	212	44	664	222	3	1	0.3
1973	1332	2	644	88	2325	623	43	26	3.0
1974	983	1	494	73	1715	499	5	81	2.6
1975	706	1	359	66	1325	356	22	49	1.5
1976	1172	2	547	79	1762	569	62	140	4.0
1977	924	3	456	56	1733	439	30	67	2.8
1978	685	1	336	34	1230	341	24	64	2.1
1979	1258	2	496	91	1921	531	13	48	5.0
1980	810	1	448	60	1622	440	11	66	1.7
1981	1102	4	534	58	2125	563	38	90	2.7
1982	810	2	378	55	1780	428	93	115	2.3
1983	947	2	432	81	1715	472	70	162	2.0
$\bar{\chi}$*	975	2	466	67	1750	478	37	82	2.7
SE	63	0	26	5	90	26	8	12	0.3
						Narrows Mountain Brook			
1972	511	2	162	39	641	224	2	1	0.3
1973	1287	2	564	88	2633	741	21	42	4.0
1974	926	1	441	74	1976	581	20	56	2.1
1975	660	1	307	64	1486	412	17	34	1.5
1976	1013	1	452	69	1856	620	43	93	3.5
1977	823	3	364	55	1745	476	41	69	2.7
1978	610	1	256	42	1344	390	28	44	2.0
1979	1132	3	464	152	2176	606	31	243	6.6
1980	730	1	363	107	1933	548	25	433	3.4
1981	1138	3	555	134	3062	841	43	567	3.7
1982	869	2	403	97	1677	546	42	429	1.7
1983	1007	2	448	119	2369	664	61	282	2.6
$\bar{\chi}$*	927	2	420	91	2023	584	34	208	3.1
SE	61	0	27	10	146	39	4	56	0.4
Conversion factor from mole c to kg:		0.001	0.023	0.039	0.02	0.012	0.014	0.014	0.031

[z]Values for 1972 are from July to December; these values were not used in the average or standard error calculations.
$\bar{\chi}$, average; SE, standard error.

TIME. In time, local soil compaction and surface ponding would decrease because of the combined action of roots, soil fauna, wetting and drying, and freezing and thawing on high-density topsoil structures (Brady 1984). This would reduce the extent of waterlogging, and subsequent volatilization of soil N. Also, the availability of easily metabolized carbohydrates would eventually be reduced basin-wide. At that point, nitrate losses would accelerate.

Streamwater levels for K, in contrast to NO_3-N, peaked right away during the cutting operation (Fig. 5). This contrast suggests that the post-harvest movement of K was likely controlled by hydrogeochemical factors, and the ease with which K was leached from the fresh vegetation litter and from the disturbed forest floor. In addition, this contrast supports the suggestion that the post-harvest movement of NO_3-N was at first retarded by microbial processes.

Precipitation Concentrations

Ion composition in the precipitation varied with season (Fig. 8), but the related seasonal patterns were generally not related to the seasonal trends seen for the soil and streamwater solutions. From Fig. 5, it follows that atmospheric deposition rates for Na, K, and Mg were too small to have had a significant influence on Na, K, and Mg concentrations in soil and stream solutions. Precipitation concentrations were lowest in the fall and highest in the spring, when the soil and stream solution concentrations for these ions were highest. For P, the situation was similar: streamwater P levels were generally highest in the fall when precipitation P levels were lowest. Atmospheric deposition rates NO_3-N and NH_4-N were highest in the summer and lowest in winter. This coincided in part with what was seen for the soil solutions, but the changes in the May to October deposition concentrations were insignificant, and would not have produced a corresponding signature on the soil and stream solutions.

Streamwater Ion Flux Rates, Pre- and Post-harvest Periods

To quantify net harvesting effects on watershed-level ion balances, we calculated monthly and annual elemental fluxes from the observations displayed in Figs. 3 and 5, where

elemental flux = mean monthly volume-weighted elemental concentration × monthly water flux

for precipitation and stream discharge. We expressed the results in terms of charge moles per hectare per year, with 2+ charges for Ca and Mg, a 1+ charge for H, Na, K and NH_4-N, and a 1- charge for NO_3-N and P (H_2PO_4), see Table 2. We also compared the resulting pre- and post-harvest streamwater flux differences between the two basins (Tables 2 and 3), and accumulated these difference with time (Fig. 9).

As shown, harvest effects on monthly and annual streamwater ion fluxes were masked by large month-to-month (Fig. 5) and year-to-year variations (Tables 2 and 3). Yet systematic pre- and post-harvest streamwater ion flux differences between the NMB and HB basins did occur not only for K and NO_3-N, but also for Na, K, Ca, Mg, and P, as revealed by the time-cumulative plots in Fig. 9. As shown, Ca and Mg discharge rates from NMB exceeded those from HB, and these differences accelerated after harvesting. For NO_3-N, K and P, discharge rates were about the same for both basins before harvesting, but NMB discharges increased thereafter. For Na, pre- and post-harvest discharge rates were lower for NMB, and the resulting pattern was similar to that of the cumulative water discharge differences in Fig. 4. In fact, pre- and post-harvest streamwater concentrations were about the same for NMB and HB (Fig. 5).

The harvest effect on the streamwater H fluxes was very small: there was a slight increase at first, which was followed by a slight decrease. Streamwater NH_4-N fluxes were also small, and were too erratic to suggest a clear post-harvest trend.

Total harvest-induced element losses from the NMB basin were obtained:

- by noting that the post-harvest cumulative flux slope in Fig. 9 generally returned to the corresponding pre-harvest slope about 6 years after harvesting; and

- by determining the final difference between the post-harvest cumulative plot and the straight-line projection of the pre-harvest cumulative plot into the post-harvest period.

The resulting numbers indicate that the post-harvest effect on elemental exports from the NMB basin was relatively small: the total sum of cations lost due to harvesting was about 5800 eq ha^{-1}. Calcium ions were lost the most. For the measured anions (NO_3 and H_2PO_4), this number was about 3000 eq ha^{-1}, with NO_3 adding the most to the total anion loss. The remaining anion loss would be due to unmeasured anions, especially SO_4, HCO_3, Cl and organic anions.

Net Elemental Input/Output Budget for the NMB Basin

Elemental losses (net basis: atmospheric deposition – stream discharge rates) followed these sequences (Table 3):

HB and NMB, pre-harvest: K << Na < Mg << Ca.
NMB, post-harvest: K << NO_3-N < Na < Mg << Ca.

Table 3. Net mean annual fluxes for stream discharge of H, Na, Ca, Mg, NH_4–N, NO_3–N, P and water for the Nashwaak Experimental Watershed project (NMB basin)

	Water (mm)	H	Na	K	Ca	Mg	NH_4–N	NO_3–N	P
		mole C ha^{-1} yr^{-1}							
						Pre-harvest			
$\bar{\chi}^z$	410	307	–256	–19	–1691	–494	173	93	5.0
SE	52	40	37	8	163	47	34	14	0.9
						Post-harvest			
$\bar{\chi}$	376	380	–306	–70	–1952	–556	138	–211	4.6
SE	28	106	43	11	218	55	12	63	1.8
						Difference			
$\bar{\chi}$	34	–73	50	51	261	62	35	304	0.4
SE (estimated)	41	82	40	10	195	52	24	47	1

$\bar{\chi}$, average; SE, standard error; SE (estimated) = SQRT {[5*SE(pre)^2+6*SE(post)^2]/11}.

Elemental gains followed these sequences (Table 3):

HB and NMB, pre-harvest: H >> NH_4-N >> NO_3 >> P.

NMB, post-harvest: H >> NH_4-N >> P.

Tables 2 and 3 show that the HB and NMB watersheds were generally undersaturated with respect to H, N and P, i.e. the net watershed absorption of incoming H, N and P was positive. The net positive influx of N and P, and the low loss of K, could be a result of a high vegetational pre- and post-harvest demand for N, P, and K. In addition, there is the above-mentioned possibility of P, K and NH_4-N fixation within the mineral soil.

General Implications

As shown in Fig. 9, the overall harvest effects on water and nutrient exports from the basins were small. Low rates of post-harvest water and nutrient losses for the NMB basin were likely caused by several, mutually compensating factors and processes, and by a relatively fast rate of vegetational post-harvest re-establishment (MacDonald and Powell 1983). Air-photographs taken in successive post-harvest summers revealed a rapid "regreening" of the area, which was much in line with a rapidly changing pattern of midsummer reflectance measurements (Bourque et al. 1995). Obviously, the post-harvest re-growth of the forest vegetation served as a nutrient sink, and should reduce and gradually eliminate the post-disturbance release of nutrients from the forest soils of the area. The emergence of a post-disturbance nutrient release that gradually disappears again is a common phenomenon and occurs, for example, after forest fires (Tiedemann et al. 1978: Feller and Kimmins 1984), and in old growth forests after individual tree fall (Foster et al. 1989). Post-disturbance nutrient release can also be examined experimentally, by forcing tree die-back as was done by Boutin and Robitaille (1993) through manipulating the extent of snow cover and related soil insulation against frost, and through root trenching (Vitousek et al. 1982). Attempts to retard vegetative regrowth would increase nutrient losses from forest soils, as was observed for the Hubbard Brook Watershed Experiment, where the forest was cut, and the regenerating vegetation was suppressed by herbicide applications (Likens et al. 1970).

This study has shown that watersheds mostly covered with eastern deciduous and mixed woods are fairly nutrient-resilient to clearcutting. This result could be generalized to the extent that forest conditions similar to those of the NMB basin exist throughout the temperate region of Eastern North America. The results of this study, however, are specific to the particular harvest operation. Cutting and removing whole trees to the road side, followed by delimbing and burning of slash at that location ("whole tree harvesting"), would likely have produced results that would differ from the ones produced with this study, where most of the post-harvest ground was littered with decaying slash (Fig. 2). Also, a follow-up of herbicide applications to suppress deciduous regeneration to favour fir and spruce regeneration would likely have changed the results by prolonging the period of enhanced nutrient leaching.

CONCLUSIONS

Clearcutting increased water yield and elemental discharge from the NMB basin. The effects were immediate and positive for area-wide P, K, Ca and Mg losses, but were slightly delayed for NO_3-N and streamwater discharge. Total cumulative harvest effects on nutrient export were small, and did not exceed the annual pre-harvest export rates by more than 17 %. Measurable streamwater discharge effects were small, but effects were noticeable up to about 10–15 yr.

Nitrate-N effects on soil solution were more intense but also more short-lived than NO_3-N effects on streamwater. Effects were lagged: a build-up period was required for NO_3-N concentrations to reach maximum concentrations in soil and streamwater. Effects on streamwater concentrations lasted for a few years only. Post-harvest NO_3-N levels in soils and streamwater differed by season. During mid-summer, NO_3-N levels were high in soil percolates, but low in streams.

Vegetation type (hardwoods, mixed woods, conifers) and related soil/site types influenced the pre- and post-harvest soil solution concentrations. Most notable were the post-harvest increases of Ca and NO_3-N on hardwood sites. In some cases, water-soluble ion concentrations were suppressed (e.g., K and NH_4-N on conifer sites). Harvest effects on basin hydrology and related nutrient exports were likely affected by changing patterns of basin-wide snow and rain catch efficiencies, by local soil disturbances (skidder trails), by changing surface reflectance, and by the rapid regrowth of the vegetation.

ACKNOWLEDGEMENTS

Work on this report was supported by the Joint and NSERC-sponsored CEA-CPPA-Forestry-Canada-Environment-Canada Project on *Simulating the effects of acid sulfate/nitrate loads on forest soils*. The Nashwaak Experimental Watershed Project was initially sponsored by the University of New Brunswick, Environment Canada, the Province of New Brunswick and the St. Anne Nackawic Pulp and Paper Co. Special thanks are also due to Professor R.B.B. Dickison for collecting meteorological data, Mr. D. Palmer for a thorough check on snow catch data, Mr. D. Blais for a thorough check on rain catch data, and to the many individuals involved with the Nashwaak Experimental Watershed Project.

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