The importance of catchment slope to soil water N and C concentrations in riparian zones: implications for riparian buffer width

P. Hazlett, K. Broad, A. Gordon, P. Sibley, J. Buttle, and D. Larmer

Abstract: Buffer zones are an important component of forest-management strategies and are thought to reduce the impact of nutrients released after harvesting on water quality. Conceptually, steep slopes have shorter water residence times than shallow slopes, have a reduced capacity to moderate water quality, and therefore, require wider buffers. Carbon and N concentrations in riparian zone shallow soil water at 30 cm depth and lake water were measured on shallow and steep slopes at the Esker Lakes Research Area in northeastern Ontario to determine if nutrient concentrations were correlated to catchment terrain attributes. Field measured slope, slope class obtained from a triangular irregular network model, and upslope contributing area and topographic index calculated from a digital elevation model were calculated for each sampling location. Modeled terrain properties, including those currently used during forest-management planning, were not significantly correlated with soil water N and C concentrations, whereas only dissolved organic carbon levels were significantly greater on field measured steep slopes. Forest species composition and soil N levels were positively correlated with soil water N concentrations. These results from the undisturbed boreal ecosystem highlight the potential limitation of using only catchment slope as a tool for prescribing riparian buffers during harvesting when considering terrestrial nutrient export.

Résumé : Les zones tampons constituent une composante importante des stratégies d'aménagement forestier et pourraient réduire l'impact de la libération des nutriments sur la qualité de l'eau après la coupe. De façon conceptuelle, les pentes fortes sont caractérisées par des temps de résidence de l'eau plus courts que ceux des pentes douces et une moins grande capacité à atténuer les effets sur la qualité de l'eau et, par conséquent, exigent des zones tampons plus larges. La concentration en C et N de l'eau située à une profondeur de 30 cm dans le sol de zones riveraines et de l'eau de lac a été mesurée le long de pentes fortes et douces de l'aire de recherche des lacs Esker dans le nord-est de l'Ontario dans le but de déterminer si la concentration en nutriments était corrélée aux attributs de terrain des bassins versants. Pour chaque point d'échantillonnage, nous avons mesuré la pente sur le terrain, obtenu la classe de pente à l'aide d'un modèle de terrain basé sur un réseau triangulé irrégulier et calculé l'aire contributoire de haut de pente ainsi qu'un indice topographique avec un modèle altimétrique numérique. Les propriétés du terrain modélisées, incluant celles couramment utilisées au cours de la planification de l'aménagement forestier, n'étaient pas significativement corrélées aux concentrations de N et de C dans l'eau du sol alors que seuls les niveaux de carbone organique dissous étaient significativement plus élevés sur les pentes fortes mesurées sur le terrain. La composition en espèces forestières et les niveaux de N dans le sol étaient positivement corrélés à la concentration de N de l'eau du sol. Ces résultats issus d'un écosystème boréal non perturbé mettent en évidence les limites potentiellement associées à l'utilisation seule de la pente des bassins versants comme outil pour déterminer les zones riveraines tampons lors de la coupe lorsque l'exportation des nutriments terrestres est considérée.

[Traduit par la Rédaction]

Introduction

Riparian areas are three-dimensional ecotones of interaction between terrestrial and aquatic ecosystems that extend down into the groundwater, above into the canopy, outward across the floodplain, up near-slope areas that drain to the water, laterally into the terrestrial ecosystem, and along the water course at variable widths (Ilhardt et al. 2000). Riparian zones within forest ecosystems are generally characterized by differences in vegetation, soils, and hydrology compared with upslope forests. As a result, processes within riparian zones of undisturbed forests strongly influence the movement of water and nutrients from terrestrial to aquatic ecosystems (Fölster 2000; Hazlett and Foster 2002). Within the aquatic system, N, P, and dissolved organic carbon (DOC) are primary influences on productivity, nutrient cycling, and light dynamics (Putz et al. 2003). The functional capacity of a particular riparian ecotone and its regulatory influence on the productivity of aquatic systems is dependent on numerous factors, such as width, slope, vegetation composition, organic matter and soil nutrient content, watershed area and gradient, soil texture and chemistry, depth to bedrock, and soil depth (Correll 1997).

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Extensive research conducted in agricultural systems has clearly demonstrated the value of undisturbed riparian areas or buffer zones as a management tool for the mitigation of nonpoint-source pollution, particularly with regard to N movement (Lowrance et al. 1983; Sabater et al. 2003). Removal of nitrate (NO_3^-) from soil water within riparian zones by nutrient uptake by vegetation, denitrification, and microbial immobilization has constituted a particularly strong research focus because of the mobility of NO_3^- in the soil and its potential deleterious impact on surface water quality (Hill 1996; Vidon and Hill 2004*a*). Additional studies have demonstrated the importance of hydrological connectivity between upland and riparian zones as an important factor regulating the efficiency of nutrient removal (Lowrance 1997; Vidon and Hill 2004*b*). The initial development of riparian buffer zones (or shoreline reserves) as a best management practice (BMP) in forestry operations in North America was related primarily to the control of sedimentation (Trimble and Sartz 1957; Martin and Hornbeck 1994). Studies in a variety of forest ecosystems have also demonstrated that uncut riparian forests can reduce elevated soil water nutrient concentrations, particularly N, caused by intensive forest harvesting (Binkley and Brown 1993; Feller 2005). Biogeochemical processes within buffer zones have the potential to mitigate the impact of upslope forest management on lake and stream water quality.

Throughout the Canadian boreal forest, ongoing forest management operations are undertaken utilizing a buffer strip approach, but there is considerable debate over the objectives and effectiveness of this practice (Buttle 2002; MacDonald et al. 2004). For boreal forest lakes and streams, there is a great deal of scientific ambiguity as to a suitable width or even the need for buffer zones to safeguard aquatic systems from elevated nutrient loadings caused by forest harvesting. In a clearcut harvesting study on the boreal shield without buffer zones, Nicolson et al. (1982) measured elevated stream exports of N and P up to 4 years after harvest primarily because of increased water yield from cut versus uncut catchments. Steedman (2000) reported that lake water quality changes in northwestern Ontario were similar in harvested catchments with or without shoreline buffer strips. In the same study, Steedman and Kushernick (2000) found that harvesting to shore had no impact on lake trout (*Salvelinus namaycush* Walbaum) communities. The authors concluded that buffer strips might only be required to preserve aesthetic values, since they apparently did not play a role in protecting water quality. Studies in the boreal forest of Quebec (Carignan et al. 2000; Lamontagne et al. 2000) showed that basins deforested to the lakeshore by fire had greater terrestrial exports and lake concentrations of NO_3^- and sulfate (SO_4^{2-}) compared with basins harvested with 20 m wide buffer strips. On the boreal shield in Alberta, Prepas et al. (2001) concluded that the effects of harvesting on lake water quality were not related to buffer strip width.

In the province of Ontario, timber-management guidelines (Ontario Ministry of Natural Resources 1988, 1991) provide regulations for riparian forest practices and describe the widths of shoreline reserves. In their simplest application, the slope of the surrounding terrestrial catchment determines the width of a stream or lake buffer zone, with steeper slopes requiring wider buffers. In terms of nutrient loadings, the assumption is that steep slopes are briefly saturated, have increased flow rates to the aquatic system, provide less opportunity for reaction of percolating water with soil and vegetation, and therefore, have little ability to mediate water quality. Conversely, shallow slopes are saturated longer, have lower flow rates, have longer water residence times, and have a greater ability to alter soil water quality prior to transfer to lakes and streams. The rationale for these guidelines, in terms of water-quality protection, is the assumption that steep and shallow slopes respond differently to inputs from upslope because of differences in the physical, biological, and chemical processes that regulate nutrient retention and release. Although this may apply for some forest ecosystems, it is unclear whether these processes play a significant role in nutrient-poor boreal forests with oligotrophic aquatic systems. Unharvested boreal forest soils have slow decomposition rates and low rates of inorganic-N production (Smith et al. 2000; Hazlett et al. 2007), and harvesting impacts on N production have been variable (Carmosini et al. 2003; Hazlett et al. 2007). In relation to nutrient movement from terrestrial to aquatic ecosystems, the application of buffer widths based on landscape slope implies that nutrient concentrations of drainage water in forest riparian zones will be correlated with catchment slope parameters. Digital topographic models (DTMs) are often used during the forest management planning process to estimate catchment slope angles, which are then used to prescribe buffer widths for boreal lakes and streams. Other morphological properties of watersheds derived from DTMs that could relate to processes regulating nutrient movement through soils are upslope contributing area (UCA) and the topographic index (TI) (Beven and Kirkby 1979), $\ln(\alpha/\tan\,\beta)$, where α is the upslope contributing area to a specific site and β is the local slope angle at that site. These parameters consider not only slope within the buffer zone, but also topographic properties of the entire catchment upslope from nearshore aquatic zones.

In this study, we examined N and C concentrations of riparian zone soil water at 30 cm depth and nearshore lake water in an undisturbed boreal forest landscape. Previous research at the Esker Lakes Research Area (ELRA) reported soil textures of B horizons with up to 40% clay content (Hazlett et al. 2005), and the possibility exists for the lateral movement of water to aquatic systems along this horizon contact because of lower hydraulic conductivities at depth in the mineral soil. These flowpaths would develop during periods of high water input, such as the spring snowmelt, and would be similar to those described by the transmissivity feedback mechanism that outlines the importance of shallow soil horizons within riparian zone soil profiles in relation to surface water chemistry (Bishop et al. 2004). Our primary objective was to provide evidence to assist in determining if current guidelines for the establishment of buffer zones in the boreal forest based on catchment slope are appropriate in the context of terrestrial nutrient inputs. The premise underlying our study was that, within the uncut boreal forest, shallow and steep slopes responded differently to upslope nutrient fluxes, resulting in variable riparian soil water chemistry. Specifically, we tested the hypothesis that catchment terrain attributes were related to riparian zone shallow soil water N and C concentrations. There is the possibility that other factors other than those related to watershed topography may influence the response of boreal aquatic systems to forest disturbance. We also examined the role of site vegetation (over- and under-story composition) and soil N concentrations in controlling N concentrations in forest floor and shallow mineral soil water. We hypothesized that these properties would be significantly related to soil water nutrient concentrations and, therefore, potentially have an effect on terrestrial nutrient exports and lake water chemistry.

Materials and methods

Study area

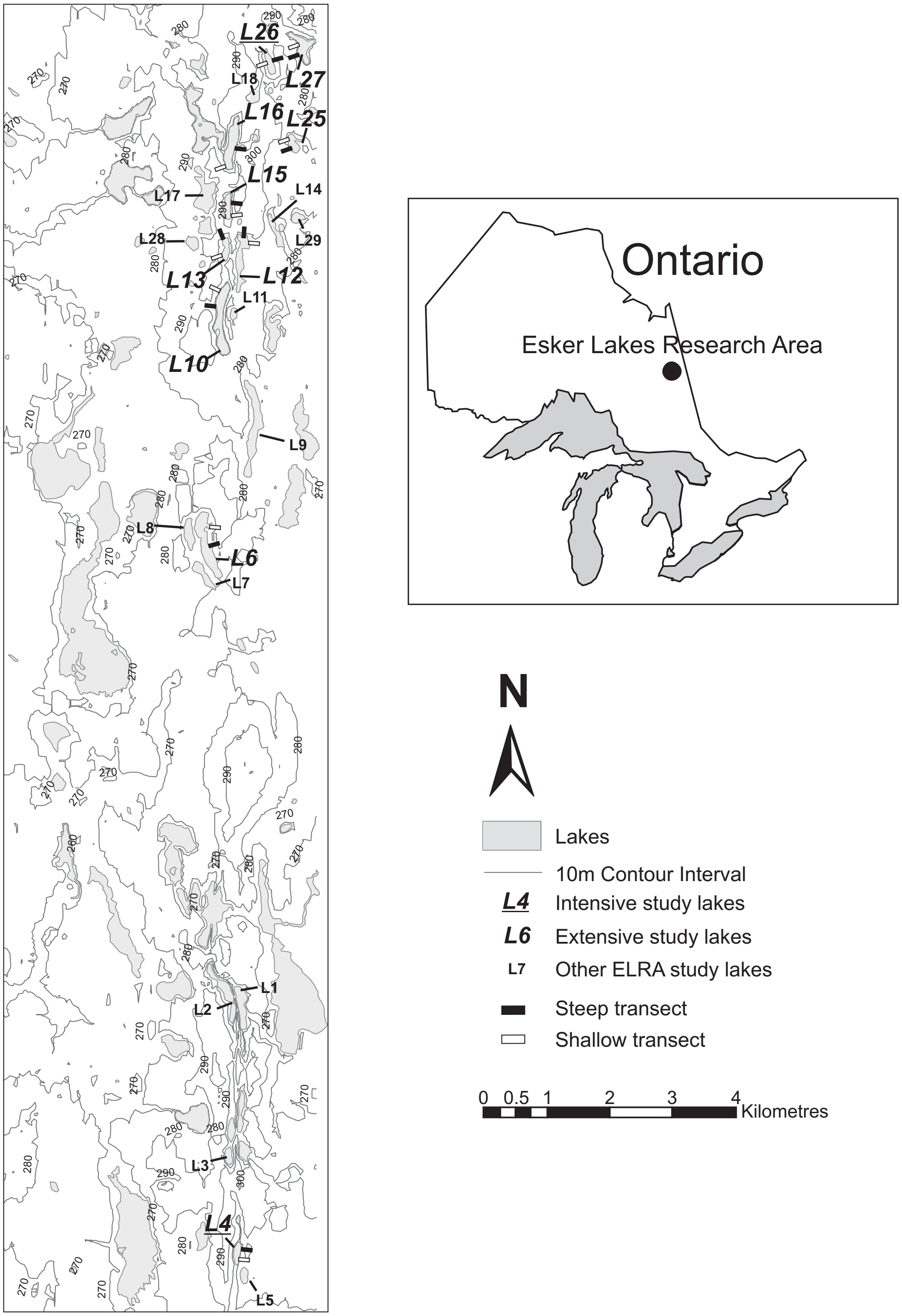
The study watersheds are located at the ELRA, approximately 75 km north of Cochrane in northeastern Ontario (49°38′N, 81°00′W) (Fig. 1). The ELRA consists of 21 study lakes spanning a north–south distance of 20 km along an esker formation in the Arctic watershed within the Northern Clay Section of the Boreal Forest Region (Rowe 1972). Study lakes are headwater lakes with no stream inputs and range in size from 2.1 to 18.0 ha. The overall research objective at the ELRA is to study the interaction of various widths of forest buffer strips and harvesting practices on water quality and ecological integrity of the nearshore zone of boreal lakes. The soil has a podzolic profile and a mean total organic horizon depth of 10 cm (Hazlett et al. 2005). Vegetation is typical fire-origin boreal forest comprised predominantly of an overstory of black spruce (*Picea mariana* (Mill.) BSP), white spruce (*Picea glauca* (Moench) Voss), balsam fir (*Abies balsamea* (L.) Mill.), and white birch (*Betula papyrifera* Marsh.) in various proportions (Hazlett et al. 2005), with a scattered distribution of other species such as eastern white cedar (*Thuja occidentalis* L.), tamarack (*Larix laricina* (Du Roi) K. Koch), balsam poplar (*Populus balsamifera* L.), and trembling aspen (*Populus tremuloides* Michx.). Dominant understory shrub species are mountain maple (*Acer spicatum* Lamb.), speckled alder (*Alnus rugosa* (Du Roi) J. Clausen), and beaked hazel (*Corylus cornuta* Marsh.). The Environment Canada CAPMoN (Canadian Air and Precipitation Monitoring Network) station at Bonner Lake (49°22′N, 82°07′W), approximately 80 km southwest of the ELRA, reported total precipitation in 2003 and 2004 of 981 and 935 mm, respectively, slightly greater than the 1995–2004 mean of 893 mm (Environment Canada 2004). Although winter snow accumulation (November of the previous year to April of the year noted) for 2003 (300 mm) and 2004 (284 mm) were comparable to the 10 year mean (299 mm), summer rainfall (May–August) was greater in 2003 (358 mm) and 2004 (403 mm) than the 1995–2004 mean of 315 mm. Mean annual maximum temperature and mean annual minimum temperature for the 10 year period from 1995 to 2004 were 7.6 °C and –5.1 °C, respectively (Environment Canada 2004).

Site selection, instrumentation, and sampling

The 10 lakes selected represented catchments where modified buffer strip width prescriptions were implemented by Tembec Inc. after this study as part of the harvesting experiment at the ELRA. At each of eight extensive study lakes, one shallow and one steep slope transect were selected by topographic map assessment and onsite slope measurements. A lower slope position plot was established within 5 m of the shoreline, and four 60 cm long porous cup tension lysimeters were installed at an angle of approximately 45° to the soil surface. Installation angle depended on the total organic layer depth, which averaged 11 cm in the nearshore zone at the ELRA (Hazlett et al. 2005), with the midpoint of the porous cup sampling point at a depth of 30 cm below the organic–mineral horizon interface. Installation in this way prevented soil disturbance immediately above the sampling point of each lysimeter and minimized channelized flow along the sides of the sampler from the soil surface. Lysimeters were constructed with 2 bar (1 bar = 100 kPa) standard ceramic cups with 1.3 µm pore size (Soil Moisture Equipment Corp., Santa Barbara, Calif.). The four lysimeters were set up in a line parallel to the lakeshore, with 2–3 m separating each instrument. Prior to field installation the ceramic cups were acid washed with 1 mol/L HCl and then rinsed with deionized water. Rinsing was completed when the pH and conductivity of solution passing through the ceramic cup had reached the value of the deionized water. Lysimeters were installed in September 2003, sampled three times with the solutions being discarded (Soil Moisture Equipment Corp., Santa Barbara, Calif.), and allowed to settle prior to initiation of soil water collections in the spring of 2004. Lake water was sampled from the littoral zone (0.5–1.0 m depth) at the base of the shallow and steep slope at each lake using an integrated water sampler during periods of ice cover and with a 2.5 m long pole sampler from the lake shoreline during the ice-free periods. Soil and lake water were sampled three times during the snowmelt period (April) and monthly (May–October) until freeze-up during 2004. Tension lysimeters were evacuated after each monthly sampling to 50 kPa suction and left to accumulate solution for the subsequent month. In the majority of cases the lysimeters were still under suction when visited for the next monthly sampling. At two intensive study lakes (Lakes 4 and 26), additional plots were established at middle and upper slope positions approximately 45 and 65 m from the lake shoreline, respectively, along both the shallow and steep transects. At each slope position, mineral soil water was collected with six tension lysimeters pretreated and installed as described above, and forest floor percolate was sampled with three 0.15 m × 0.30 m plastic tension-free lysimeters below the F horizon at a mean depth of 6 cm below the soil surface. Intensive site lysimeters were installed in October 2002; they were sampled three times during the 2003 snowmelt period and monthly until October 2003 and then in conjunction with the extensive sites during 2004.

During May 2003, species and diameter at breast height (DBH) were recorded for all trees >5 cm DBH in a 10 m × 50 m plot at each intensive site slope position. Due to the importance of various *Alnus* species with respect to forest ecosystem N cycling, the abundance of speckled alder within each plot was assessed by assigning a value representing no alder present (0), some alder present (1), or abundant alder present (2). Alder species support symbiotic N-fixing bacteria in root nodules and can provide a significant internal source of N to alder-dominated terrestrial ecosys-

Fig. 1. The Esker Lake Research Area (49°38′N, 81°00′W) showing intensive and extensive study lakes and shallow and steep transects.



tems (Wurtz 1995; Hurd et al. 2001). Depths of forest floor horizons were determined at seven locations within each plot and moss plus L, F, and H layers were sampled separately from 0.1 m^2 quadrats. Mineral soil was sampled by horizon from a soil pit in each plot by taking samples from three locations along the pit face and bulking into a single horizon sample.

Laboratory analysis

Water samples collected in the field were kept on ice and then stored at 4 °C in the laboratory. Samples were initially coarse filtered (Fisher quantitative Q8 filter paper) and then passed through 0.45 µm filter paper prior to analysis. Inorganic N (NH_4^+ and NO_3^-), total N, DOC, and dissolved inorganic carbon (DIC) concentrations of soil and lake water samples were determined by Technicon autoanalyzer IIC using sodium nitroprusside, cadmium reduction, autoclave digestion – cadmium reduction, acid – potassium persulphate and sulphuric acid – carbon dioxide methods, respectively. Dissolved organic nitrogen (DON) concentrations were determined as the difference between total N and the sum of NH_4^+ and NO_3^-. For all samples, total N concentrations were greater than inorganic N concentrations, and therefore, calculated DON values were positive. Forest floor horizon samples were oven-dried at 70 °C and analyzed for organic C and N using a NCS combustion analyzer (Model Vario EL III; Elementar Americas, Inc., Mt. Laurel, N.J.). Mineral soil horizon samples were air-dried, passed through a 2 mm sieve, and analyzed for organic C by wet combustion (Walkley–Black method) and N by NCS analyzer. Soil analyses of C and N are reported on a dry mass basis.

Terrain analysis

To determine if relationships exist between N and C concentrations in riparian zone soil water and catchment terrain characteristics, we used three different methods of measuring and calculating terrain attributes. In the field, slope was determined by Suunto clinometer, measured from the lake shoreline to 10 m (SC10), 30 m (SC30), and 50 m (SC50) upslope along each shallow and steep transect. Slope aspect was also determined for each transect by measurement in the field. Slope aspect data was transformed using a cosine function of degrees from north to enable a comparison of north- and south-facing transects. The second method involved the extraction of slope from a triangular irregular network (TIN) model using ArcMap. This model was provided by Tembec Inc. and was based on a 20 m × 20 m resolution digital elevation model (DEM) for Sustainable Forest Licences in northeastern Ontario. The TIN model is used in the forest management planning process to determine appropriate buffer zone widths for streams and lakes in this region. Slope was calculated for each triangular facet of the TIN and classified as no slope, 9°–17°, 18°–24°, and ≥25°. Lysimeter positions were assigned the midpoint of the TIN slope class category (SCTIN) in which they were geographically located. In the third method, digital terrain analyses were performed using TAPES-G, a grid-based terrain analysis program for the environmental sciences (Gallant and Wilson 1996). From TAPES-G, we computed slope and upslope contributing area for each cell of a 25 m × 25 m resolution DEM provided through the Provincial Watershed Project (Ontario Ministry of Natural Resources 2002) and derived from 1 : 20 000, 10 m digital contours using ANUDEM (Hutchinson 1997). Slope, UCA, and TI were calculated with TAPES-G for each cell and then computed for each lysimeter sampling point from locations determined using a differential global positioning system.

Statistical analysis

Relationships between modeled and measured terrain attributes for the 20 transects at the extensive and intensive study lakes were determined by correlation analysis. Initially, the influence of slope on C and N concentrations of mineral soil and lake water was analyzed using paired *t* tests. Slope type (shallow or steep) as identified in the field for each study lake was defined as the treatment variable. Residuals were tested for normality with the Shapiro–Wilk test. Homogeneity of variance between slope types was determined using Bartlett's test, and data that did not meet test requirements were transformed using a log or reciprocal function. If N and C concentrations in soil water of the riparian zone reflect physical, chemical, and biological processes linked to catchment slope, then substantial variation in the terrain attributes of the selected shallow and steep slopes on the 10 study lakes could influence the *t* test results, potentially decreasing significance. Linear regression modeling was used to establish the functional relationships between terrain attributes and annual and seasonal riparian zone mineral soil water N and C concentrations. Seasonal concentrations were determined by grouping sample date mean concentrations by season to produce spring (day of the year (DOY) 1–135), summer (DOY 136–245), and fall (DOY 246–366) mean mineral soil and lake water concentrations for 2004. Regression residuals that did not meet normality and homogeneity requirements were transformed using a log or reciprocal function. Intensive site annual forest floor and mineral soil water N and C concentrations at all slope positions were related to selected forest and soil properties using Spearman rank correlation and partial correlation analysis. As the intensive site soil water sampling was conducted on only two plots for each slope type – slope position combination, data were not analyzed using inferential statistics. Statistical analyses were performed using the GLM, REG, and CORR procedures in SAS version 9.1 (SAS Institute Inc., Cary, N.C.). Results were considered statistically significant at $\alpha < 0.05$.

Results

Terrain attributes

Terrain attributes calculated using TAPES-G, including UCA, ln UCA, and TI, were not significantly related to slope derived from either field measurements or the TIN model calculated slope class (Table 1). Mean UCA and TI values were larger for steep when compared with shallow transects; however, this difference was only significant for TI (Table 2). In contrast, SCTIN values were significantly related to the field-measured slopes SC30 and SC50 (Table 1). The TIN slope class was determined using contours up to 100 m away from the lake shorelines, so it is not surprising that this slope is most closely related to field slope measured over the longer horizontal distance transects. Mean field slopes show the greatest difference between steep and shallow slopes for SC10, with values closer but still significantly different for SC30 and SC50 (Table 2).

Terrain attributes and soil and lake water N and C concentrations

Soil water collected at 30 cm depth in riparian zone mineral soil during 2004 had mean annual DON concentrations 3.4 and 2.1 times greater than combined inorganic-N concentrations ($NH_4^+ + NO_3^-$) for shallow and steep slopes, respectively (Table 2). Mean annual soil water DOC concentrations for 2004 were significantly greater for steep slopes compared with shallow slopes. Mineral soil water mean NO_3^- concentrations on steep slopes were 2.5 times greater than those on shallow slopes; however, because of

Table 1. Correlation coefficients between digital elevation model (DEM) derived topographic attributes, triangulated irregular network (TIN) data model slope class and field-measured slopes at the Esker Lakes Research Area extensive study sites.

	ln UCA	TI	SCTIN	SC10	SC30	SC50
UCA	**0.79 ($p < 0.001$)**	**0.82 ($p < 0.001$)**	0.31 ($p < 0.186$)	0.33 ($p < 0.155$)	0.15 ($p < 0.515$)	0.06 ($p < 0.796$)
ln UCA		**0.81 ($p < 0.001$)**	0.27 ($p < 0.256$)	0.42 ($p < 0.067$)	0.31 ($p < 0.187$)	0.34 ($p < 0.144$)
TI			0.12 ($p < 0.605$)	0.41 ($p < 0.074$)	0.11 ($p < 0.653$)	–0.06 ($p < 0.797$)
SCTIN				0.35 ($p < 0.134$)	**0.46 ($p < 0.041$)**	**0.54 ($p < 0.015$)**
SC10					**0.76 ($p < 0.001$)**	**0.48 ($p < 0.031$)**
SC30						**0.87 ($p < 0.001$)**

Note: Significant ($p < 0.05$) correlation coefficients are given in boldface. UCA, upslope contributing area; TI = ln(a/tan β); SCTIN, slope class from Tembec triangulated irregular network (TIN) data model; SC10, SC30, and SC50, field-measured slope class from lake shoreline to 10, 30, and 50 m upslope, respectively.

Table 2. Terrain attributes, 2004 annual riparian zone mineral soil water (30 cm depth), and 2004 littoral zone lake concentrations for shallow and steep slopes at the Esker Lakes Research Area extensive study sites (n = 10 lakes for each slope type).

	Slope	
Attribute	Shallow	Steep
Terrain		
Aspect (° from N)	170.4 (32.3)a	170.0 (29.6)a
UCA (m^2)	3024 (521)a	22 552 (12 766)a
TI	10.9 (0.2)a	12.4 (0.6)b
SCTIN (° slope)	10.3 (1.4)a	14.3 (2.3)a
SC10 (° slope)	12.2 (1.6)a	25.3 (0.8)b
SC30 (° slope)	10.3 (1.0)a	16.8 (1.2)b
SC50 (° slope)	9.0 (0.9)a	12.1 (1.1)b
Mineral soil water at 30 cm depth		
DOC (mg·L^{-1})	7.5 (1.0)a	13.7 (2.2)b
DIC (mg·L^{-1})	33.6 (6.5)a	35.8 (5.1)a
NH_4^+ (µmol·L^{-1})	0.55 (0.10)a	0.61 (0.11)a
NO_3^- (µmol·L^{-1})	4.5 (2.8)a	12.0 (5.5)a
DON (µmol·L^{-1})	17.1 (2.2)a	26.4 (3.2)a
Lake water		
DOC (mg·L^{-1})	5.8 (0.9)a	5.9 (0.9)a
DIC (mg·L^{-1})	8.0 (0.8)a	7.9 (0.9)a
NH_4^+ (µmol·L^{-1})	2.0 (0.6)a	2.0 (0.8)a
NO_3^- (µmol·L^{-1})	3.6 (0.5)a	3.5 (0.5)a
DON (µmol·L^{-1})	19.5 (1.9)a	20.0 (1.9)a

Note: Values are means with SEs given in parentheses. Values followed by the same letter are not significantly different (paired t tests, $p > 0.05$) between shallow and steep slopes. DOC, dissolved organic carbon; DIC, dissolved inorganic carbon; DON, dissolved organic nitrogen. See Table 1 for the other abbreviations.

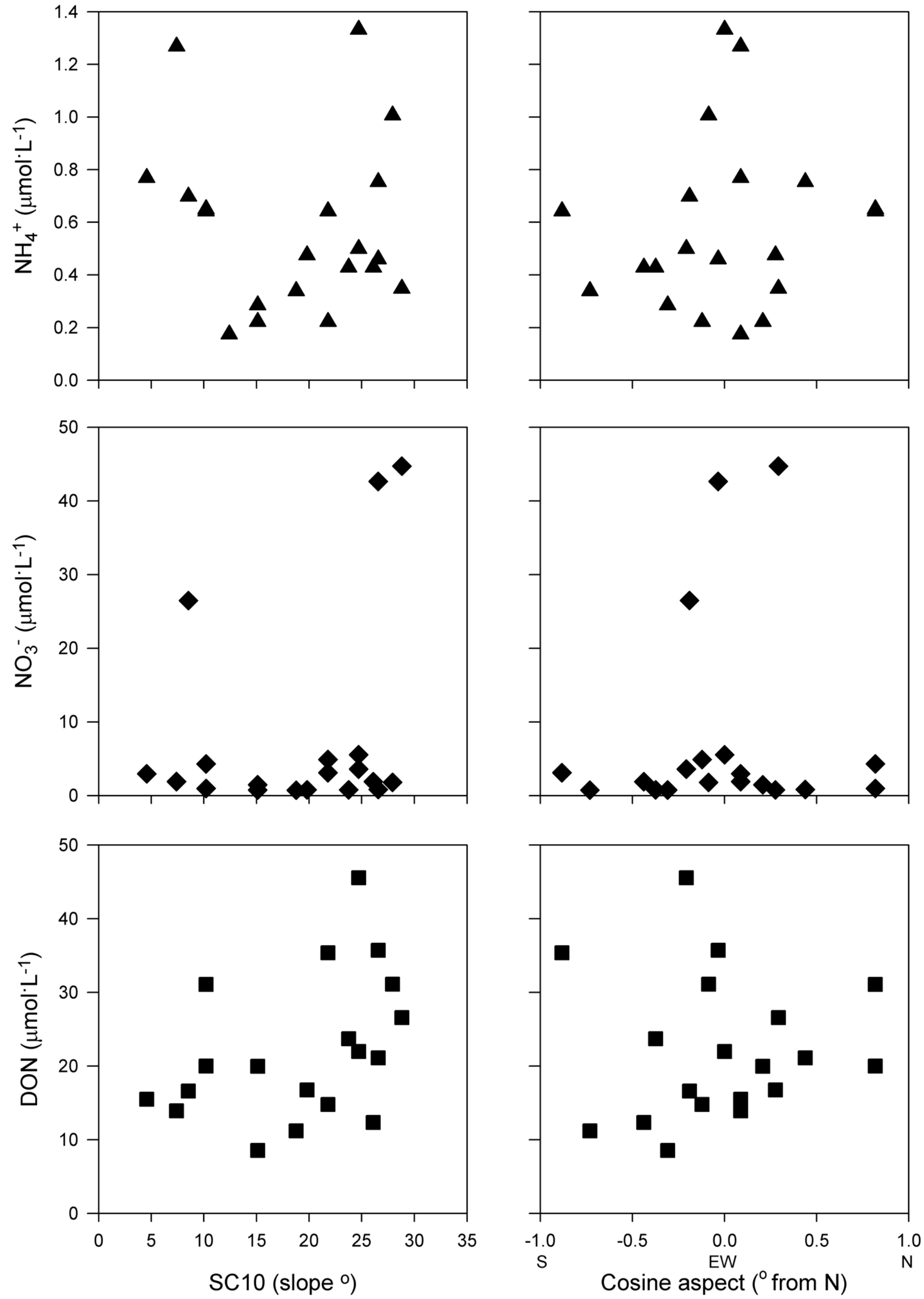
large variation within each slope type, these differences were not statistically significant. Annual inorganic-N, DON, and DIC concentrations were not significantly different between slope types. Annual DIC concentrations were 4.5 and 2.6 times greater than DOC concentrations at shallow and steep slopes, respectively. Paired t test results showed no significant differences between annual lake water N and C concentrations in the littoral zone of shallow and steep slopes of the 10 study lakes (Table 2). As was the case for mineral soil water, lake water DON concentrations were substantially greater than inorganic-N concentrations. In contrast, lake water DIC was less than soil water DIC and only 1.4 times greater than lake water DOC levels. Regression modeling of aspect, UCA, TI, SCTIN, and SC50 with annual, spring, summer, or fall N and C concentrations of the 20 riparian areas under study yielded no significant relationships (data not shown). Plots of 2004 annual mean mineral soil water concentrations with SC10 and cosine of slope aspect for the 20 riparian zones studied are shown in Figs. 2 and 3. The only significant relationship for annual N and C concentrations was between mineral soil water DOC and SC10 (log (DOC) = 0.036(SC10) + 1.56, R^2 = 0.22).

Vegetation and soil properties and soil water N and C concentrations

Annual DON and DOC concentrations, summarized for the intensive study watersheds during 2003 and 2004, decreased as water passed from the forest floor through the upper 30 cm of mineral soil (Table 3). There were no apparent trends with slope position for DON or DOC concentrations of forest floor percolate or mineral soil water. Annual DIC concentrations were higher in mineral soil water relative to forest floor percolate and were greater in the mineral soil water at lower slope positions at both shallow and steep transects. Inorganic-N levels in forest floor percolate exceeded those in mineral soil water at almost all slope positions and slope types by a large amount for NH_4^+ and to a lesser degree for NO_3^-. Greater inorganic-N and DON concentrations in forest floor percolate and mineral soil water on the steep transect, particularly at the middle and lower slope position, appear to be related to site properties at Lake 26 rather than slope position. Annual forest floor percolate concentrations of NH_4^+, NO_3^-, and DON at the middle slope location on the steep transect at Lake 26 were 157, 89, and 120 µmol·L^{-1}, respectively, which were much greater than the mean value that included the steep slope at Lake 4. This transect had abundant alder present and the highest organic horizon N concentrations across the intensive sites.

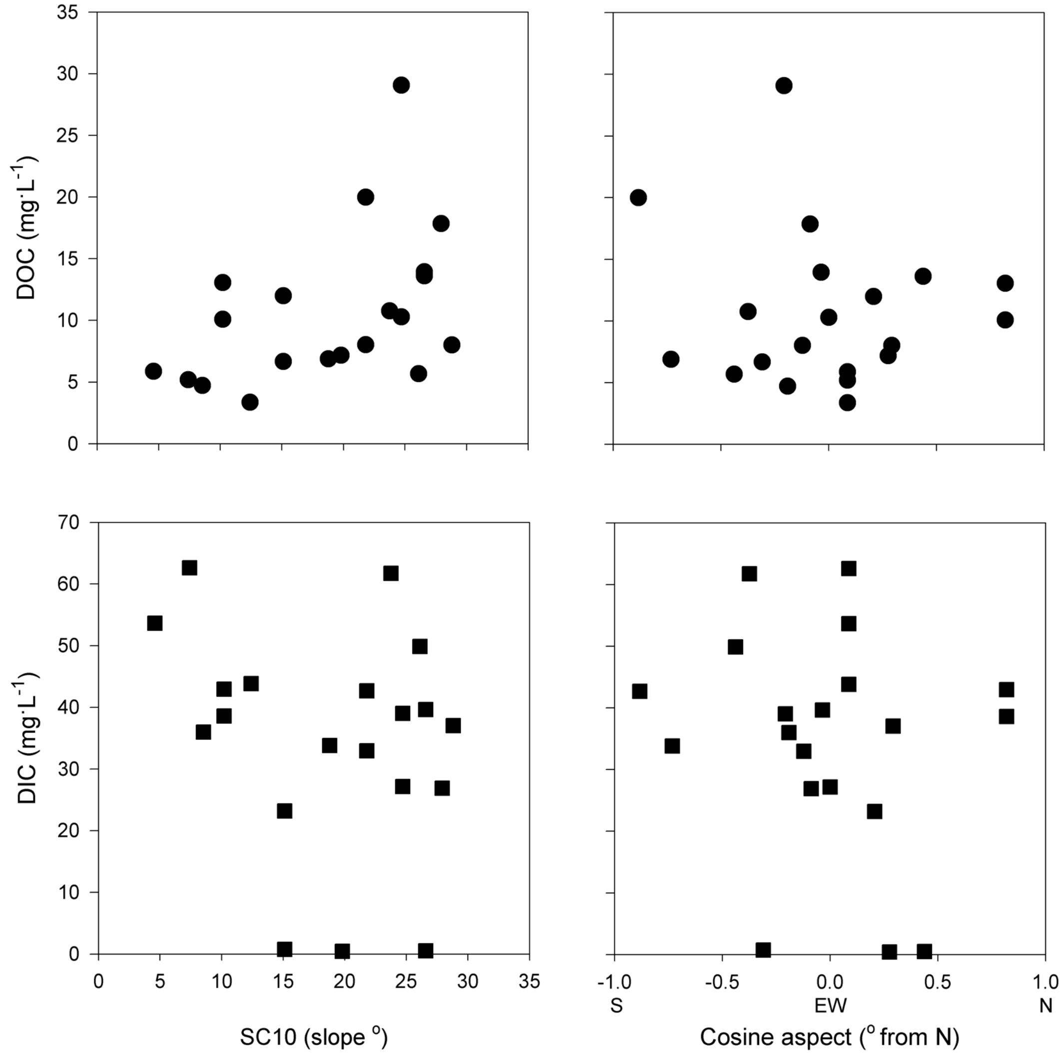
There were significant positive rank correlations between forest floor percolate N concentrations and organic horizon N concentrations, the abundance of alder in the forest understory, and the basal area of white spruce in the forest overstory (Table 4). A comparison of forest floor percolate N concentrations between two sites with contrasting soil N levels during 2003 and 2004 showed particularly high NO_3^- concentrations at the high soil N site (Fig. 4). Partialling out alder abundance and the percentage of basal area of the stand occupied by white spruce weakened, and in most cases removed, the significance of the soil N correlations to forest

Fig. 2. Relationships between SC10 (field-measured slope 0–10 m from shoreline) and cosine aspect (° from N) with inorganic (NO_3^- and NH_4^+) and DON (dissolved organic N) 2004 annual concentrations of mineral soil water sampled at 30 cm depth within the lake riparian zone at the Esker Lakes Research Area.



floor percolate N concentrations (Table 4). Mineral soil water NO_3^- concentrations were significantly correlated with organic layer and 0–10 cm depth mineral soil N concentrations (Table 5). Mineral soil water NO_3^- was higher at the higher soil N site during the spring and summer, whereas NH_4^+ and DON concentrations were comparable throughout the year (Fig. 4). As was the case for forest floor percolate, partialling out alder and white spruce abundance decreased the correlation coefficients and removed the significance of the organic horizon N concentrations. Concentrations of N species in forest floor percolate and 0–10 cm depth mineral soil N concentration maintained significant positive relationships with mineral soil water NO_3^- when controlled for alder and white spruce (Table 5). At the high N site at Lake 26, forest floor percolate NO_3^- concentrations were less than those in mineral soil water during the snowmelt period but equaled or exceeded mineral soil concentrations during the growing season (Fig. 4). There were significant positive rank correlations between over- and under-story vegetation and N concentrations in organic

Fig. 3. Relationships between SC10 (field-measured slope 0–10 m from shoreline) and cosine aspect (º from N) with DOC (dissolved organic C) and DIC (dissolved inorganic C) 2004 annual concentrations of mineral soil water sampled at 30 cm depth within the lake riparian zone at the Esker Lakes Research Area.



layers and the shallow mineral soil (Table 6). Basal area of white spruce within measurement plots was positively correlated with N levels in the F and H layers and the upper mineral soil, whereas alder abundance was associated with higher organic layer N concentrations. Concentrations of N below 10 cm depth in the mineral soil were unrelated to organic layer N levels and vegetation characteristics (Table 6).

Discussion

Controls of soil water N and C concentrations

It is impossible in the field to experimentally control many of the factors that influence the chemistry of water as it moves from the land base within the catchment to aquatic systems. As a result, there is great difficulty in discerning the relative importance of any specific factor. In spite of this limitation or perhaps in recognition of this limitation, forest-management guidelines in Ontario and elsewhere have used slope as the primary factor in determining buffer zone width. Protection of lakes and streams from nonpoint-source nutrient loading associated with forest harvesting is one of the goals of these guidelines. Our use of several different measured and modeled terrain attributes to examine the hypothesis that slope characteristics can be used to predict N and C concentrations in shallow soil water within the riparian zone of boreal forest lakes produced varied results.

For inorganic-N, DON, and DIC, we were unable to provide evidence to support our hypothesis that field-measured slope and aspect were related to shallow soil water concentrations at the ELRA. In terms of NH_4^+ and NO_3^-, the absence of a relationship is not surprising in that the annual riparian zone mineral soil water N concentrations for the extensive sites were extremely low in this boreal ecosystem when contrasted with other forest types (Van Miegroet et al. 1992; Foster et al. 2005). Low net mineralization potential, especially for NO_3^-, for the F horizon and 0–10 cm of mineral soil from unharvested stands at the ELRA has been reported by Hazlett et al. (2007). Of significant note were forest floor percolate NH_4^+ and NO_3^- concentrations and mineral soil water NO_3^- concentrations at sites with alder present that were as high or higher than concentrations determined in a N-rich tolerant sugar maple (*Acer saccharum*

Table 3. Annual forest floor and mineral soil water (30 cm depth) concentrations at the Esker Lakes Research Area intensive sites (n = 6 for forest floor and n = 12 for mineral soil for each slope type and slope position, Lakes 4 and 26).

Slope and position		UCA (m^2)	TI	DOC ($mg \cdot L^{-1}$)	DIC ($mg \cdot L^{-1}$)	NH_4^+ ($\mu mol \cdot L^{-1}$)	NO_3^- ($\mu mol \cdot L^{-1}$)	DON ($\mu mol \cdot L^{-1}$)
Shallow								
Upper	Forest floor	1292	10.1	37.8 (4.6)	0.49 (0.23)	31.5 (19.3)	8.4 (3.7)	77.2 (11.8)
	Mineral soil	1461	10.3	10.7 (2.3)	1.1 (0.4)	1.1 (0.4)	0.92 (0.40)	18.5 (4.2)
Middle	Forest floor	1344	10.0	41.3 (5.0)	0.39 (0.18)	16.8 (10.0)	2.2 (1.0)	76.6 (15.7)
	Mineral soil	1741	10.3	8.8 (3.5)	9.8 (4.9)	2.1 (1.5)	1.1 (0.3)	16.1 (2.9)
Lower	Forest floor	1935	10.4	36.8 (6.1)	0.24 (0.06)	9.2 (5.0)	1.4 (0.4)	57.2 (7.2)
	Mineral soil	2193	10.7	7.8 (4.1)	17.6 (1.7)	0.60 (0.32)	0.88 (0.41)	23.3 (17.8)
Steep								
Upper	Forest floor	2349	10.8	39.7 (8.3)	0.32 (0.08)	56.0 (32.8)	6.3 (3.3)	101.6 (24.4)
	Mineral soil	2431	10.9	15.7 (8.8)	3.4 (3.9)	1.1 (0.5)	5.5 (1.7)	29.4 (7.4)
Middle	Forest floor	2607	10.9	51.5 (12.5)	0.58 (0.19)	96.9 (49.1)	45.8 (21.2)	144.8 (39.4)
	Mineral soil	2772	11.0	11.9 (2.6)	12.5 (12.5)	1.5 (2.5)	42.3 (14.6)	28.7 (9.6)
Lower	Forest floor	2709	11.1	54.4 (12.9)	0.42 (0.18)	93.9 (48.3)	20.4 (25.4)	140.3 (34.5)
	Mineral soil	2679	11.2	14.2 (2.6)	20.4 (3.9)	1.5 (2.7)	22.7 (6.7)	28.4 (4.4)

Note: Values are means for 2003–2004 with spatial SDs given in parentheses. See Tables 1 and 2 for abbreviations.

Table 4. Spearman rank correlation and partial correlation results for relationships of forest and soil parameters with annual forest floor percolate concentrations (mean of 2003–2004) at the Esker Lakes Research Area intensive sites.

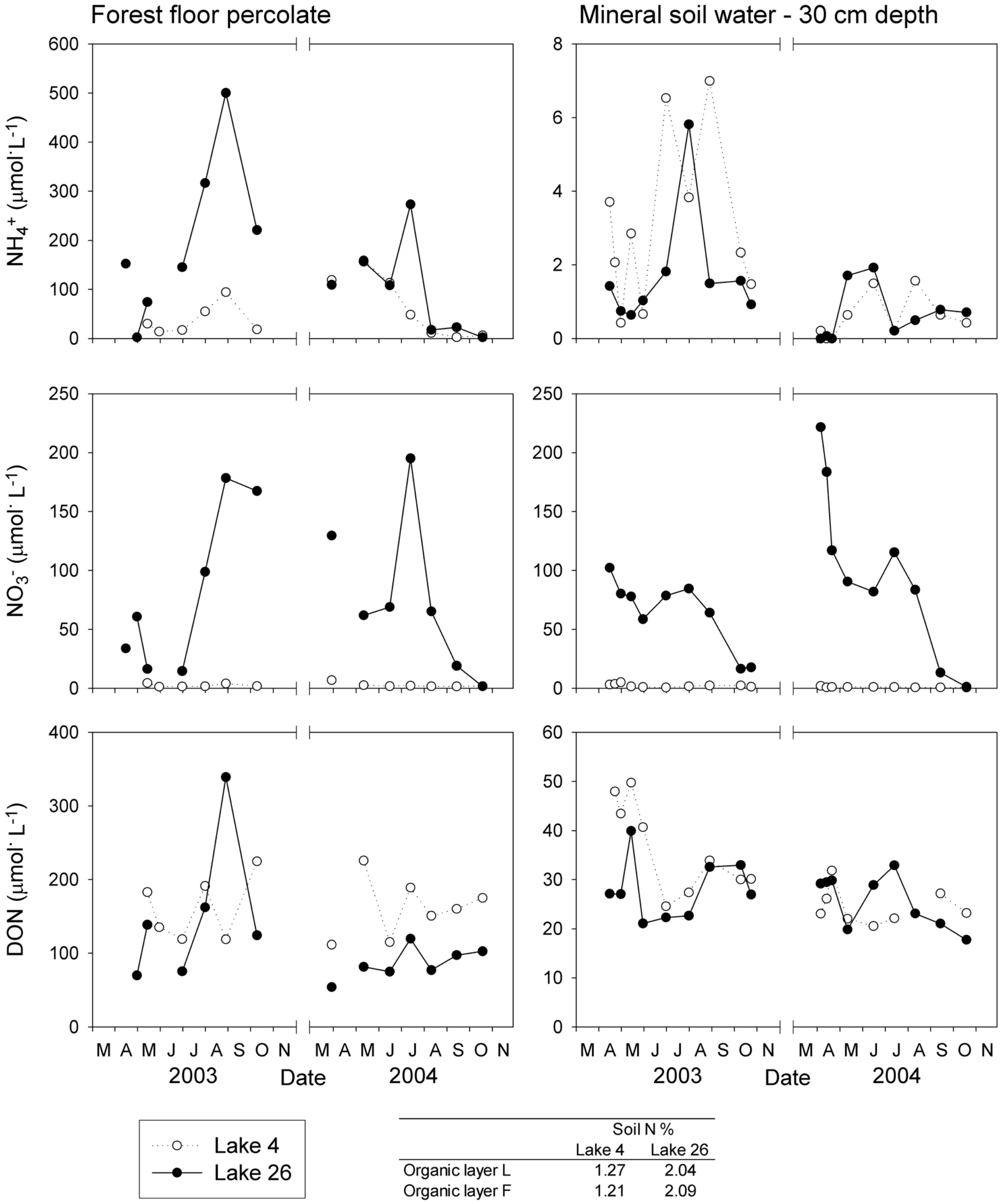
				Controlled for alder abundance		Controlled for Sw (%BA)	
Forest floor percolate		r	p	r	p	r	p
NO_3^- ($\mu mol \cdot L^{-1}$)	L-N (%)	**0.916**	**<0.001**	0.471	0.143	0.624	0.135
	F-N (%)	**0.685**	**0.014**	0.122	0.722	–0.091	0.846
	H-N (%)	**0.734**	**0.007**	–0.096	0.778	**0.796**	**0.032**
	Sw (%BA)	0.659	0.076	–0.402	0.371		
	Alder abundance	**0.867**	**<0.001**			**0.887**	**0.008**
NH_4^+ ($\mu mol \cdot L^{-1}$)	L-N (%)	**0.888**	**<0.001**	0.034	0.921	–0.022	0.963
	F-N (%)	**0.783**	**0.003**	0.369	0.264	–0.052	0.912
	H-N (%)	**0.713**	**0.009**	0.052	0.880	0.108	0.818
	Sw (%BA)	**0.922**	**0.001**	0.616	0.141		
	Alder abundance	**0.769**	**0.004**			0.519	0.232
DON ($\mu mol \cdot L^{-1}$)	L-N (%)	**0.741**	**0.006**	–0.059	0.863	–0.013	0.979
	F-N (%)	0.490	0.107	–0.028	0.934	–0.163	0.728
	H-N (%)	**0.797**	**0.002**	**0.618**	**0.043**	0.179	0.701
	Sw (%BA)	**0.922**	**0.001**	0.669	0.100		
	Alder abundance	0.552	0.063			0.546	0.205

Note: Bolded values indicate significance at $p < 0.05$. Sw (% BA), % of total stand basal area as white spruce; alder abundance: 0, no alder present; 1, some alder present; 2, abundant alder present; L-N, F-N, and H-N, N concentration of L, F, and H horizons. See Tables 1 and 2 for other abbreviations.

Marsh.) dominated forest at the Turkey Lakes Watershed (Hazlett and Foster 2002; Foster et al. 2005). The possibility for NO_3^- depletion, and therefore, variation between shallow and steep slope concentrations within the riparian zone soils of ELRA watersheds could depend to some extent on hydrologic conditions. Although some nearshore areas had high water tables and anaerobic conditions required for denitrification, much of the lake shorelines were characterized by slopes where soil profiles showed no evidence of redox features related to prolonged saturation (Hazlett et al. 2005).

When examining catchment slope as determined by field measurements close to the lake shorelines (SC10 and SC30), our field designation of shallow and steep slopes indicated that DOC concentrations were greater at steeper slopes and that there was a significant functional relationship between slope class and DOC concentrations. Similar results were reported for riparian zone seepage water collected from the soil–bedrock interface from slopes surrounding an oligotrophic lake in central Ontario. Soil water DOC concentrations in subcatchments with gentle slopes were lower (4.6–5.7 $mg \cdot L^{-1}$) when compared with those from steep slopes (9.4–13.5 $mg \cdot L^{-1}$) (McCart 1998). Increased DOC precipitation and sorption on reactive soil surfaces that could result from longer water residence times at shallow slopes may explain lower DOC concentrations in shallow soil water. Lower DOC concentrations in throughflow

Fig. 4. Temporal variation for inorganic (NO_3^- and NH_4^+) and dissolved organic N (DON) concentrations for forest floor percolate and mineral soil water sampled at 30 cm depth at two sites with contrasting soil N concentrations at the Esker Lakes Research Area. Lake 26 has abundant alder present on site, and Lake 4 has no alder present on site.



	Soil N %	
	Lake 4	Lake 26
Organic layer L	1.27	2.04
Organic layer F	1.21	2.09
Organic layer H	1.34	1.43
Mineral soil 0-10 cm	0.15	0.26
Mineral soil 10-20 cm	0.10	0.11
Mineral soil 20-30 cm	0.05	0.04

water at lower slope positions compared with upslope positions along a topographic gradient at a hardwood forest site were attributed to longer soil water residence times by Hazlett and Foster (2002).

Calculations of SCTIN from the TIN and UCA and TI from the DEM were at a spatial resolution that is currently used during the forest management planning process. It appears from the lack of association between these modeled topographic attributes and the field-measured slope data, and the absence of relationships of UCA, TI, and SCTIN with concentrations, that the processes that resulted in differences in DOC concentrations are operating on a smaller scale than was reflected in the modeled data. From these observations, we conclude that differences in soil processes between shallow and steep slopes are resulting in greater DOC concentrations in shallow soil water at the steep slopes but that they cannot be adequately detected with terrain attributes determined from DTMs at the scale used in this study.

Table 5. Spearman rank correlation and partial correlation results for relationships of forest and soil parameters with mineral soil water (30 cm depth) concentrations (mean of 2003–2004) at the Esker Lakes Research Area intensive sites.

				Controlled for alder abundance		Controlled for Sw (%BA)	
		r	*p*	*r*	*p*	*r*	*p*
Mineral soil water NO_3^- (μmol·L^{-1})	FF NH_4^+ (μmol·L^{-1})	**0.748**	**0.005**	**0.700**	**0.017**	**0.899**	**0.006**
	FF NO_3^- (μmol·L^{-1})	**0.587**	**0.045**	**0.785**	**0.004**	0.200	0.667
	FF DON (μmol·L^{-1})	**0.895**	**<0.001**	0.095	0.781	**0.900**	**0.006**
	L-N (%)	**0.664**	**0.019**	0.138	0.687	–0.280	0.543
	F-N (%)	**0.476**	**0.118**	0.136	0.690	–0.460	0.300
	H-N (%)	**0.748**	**0.005**	–0.088	0.796	0.213	0.646
	Sw (%BA)	**0.790**	**0.020**	0.458	0.302		
	Alder abundance	0.493	0.104			0.508	0.245
	N-10 (%)	**0.650**	**0.022**	**0.605**	**0.049**	0.402	0.371
	N-20 (%)	0.308	0.331	–0.025	0.942	–0.435	0.329
	N-30 (%)	0.217	0.499	–0.334	0.316	–0.016	0.973

Note: Bolded values indicate significance at $p < 0.05$. FF, forest floor percolate concentration; N-10, N-20, and N-30, N concentration at 0–10, 10–20, and 20–30 cm depth in the mineral soil. See Table 4 for other abbreviations.

Table 6. Spearman rank correlation results for relationships between forest parameters and soil N concentrations at the Esker Lakes Research Area intensive sites.

		r	*p*
L-N	F-N (%)	**0.713**	**0.009**
	H-N (%)	**0.762**	**0.004**
	Sw (%BA)	0.683	0.062
	Alder abundance	**0.847**	**<0.001**
F-N	H-N (%)	0.308	0.331
	Sw (%BA)	**0.826**	**0.011**
	Alder abundance	**0.650**	**0.022**
H-N	Sw (%BA)	**0.611**	**0.108**
	Alder abundance	**0.769**	**0.004**
N-10	L-N (%)	**0.566**	**0.055**
	F-N (%)	**0.636**	**0.026**
	H-N (%)	0.420	0.175
	Sw (%BA)	**0.707**	**0.050**
	Alder abundance	0.453	0.139
N-20	L-N (%)	0.559	0.059
	F-N (%)	0.301	0.342
	H-N (%)	0.238	0.457
	Sw (%BA)	–0.108	0.800
	Alder abundance	0.453	0.139
N-30	L-N (%)	0.301	0.342
	F-N (%)	0.210	0.513
	H-N (%)	0.182	0.572
	Sw (%BA)	0.515	0.192
	Alder abundance	0.059	0.855

Note: Bolded values indicate significance at $p < 0.05$. See Tables 4 and 5 for abbreviations.

Several other studies have demonstrated that topographic position along a catena can be an effective explanatory variable for soil physical and chemical properties and soil water quality. Sauer et al. (2005) reported increased infiltration rates in valley bottom soils compared with upland and side-slope soils in a mixed land use watershed, and Macrae et al. (2005) measured lower soil moisture levels in surface horizons and subsoils in upland positions than those in lower slope positions on the boreal plain. In terms of soil and soil water chemistry, soil P concentrations and surface soil lysimeter water P concentrations (Macrae et al. 2005) and forest floor percolate and mineral soil percolate N and C concentrations and fluxes (Hazlett and Foster 2002) were linked to topography. Jansson et al. (2007) identified lower humus layer C:N ratios in groundwater discharge zones associated with long slopes that decreased in downslope steepness for riparian zones of seventh-order rivers in northern Sweden. The authors attributed greater plant species richness in the discharge zones to increased soil N availability as a result of soil chemical differences due to the influence of upland groundwater discharge in riparian zones. However, as in our study, extension of this concept to using topographic variables calculated from DTMs as predictors has not always satisfactorily explained the variance in soil characteristics. Creed et al. 2002 used a 25 m × 25 m resolution DEM to calculate terrain attributes for modeling with soil C and N concentrations and pools in surface soils at the Turkey Lakes Watershed in central Ontario. Although terrain slope, elevation, and aspect were identified as key factors influencing C and N pools in the landscape the majority of variance was unexplained; the authors concluded that dynamic factors of soil development occurring at the hillslope or catchment scale could better assist in the explanation of soil heterogeneity. Johnson et al. (2000) came to a similar conclusion while examining the relationships between pH, exchangeable bases, and C and N concentrations in soil with terrain attributes generated from a 5 m × 5 m resolution DEM in the Winnisook watershed in southeastern New York. Microtopographic influences on forest soil properties that occur at spatial scales less than the DEM resolution and factors other than topography (such as vegetation composition) were postulated as variables that could explain soil chemical properties to a greater extent.

Results from the intensive-study transects provided strong evidence that inorganic-N and DON concentrations in forest floor percolate and NO_3^- concentrations in shallow mineral soil water were related to forest and soil characteristics in the immediate area of the lysimeter sampling. The partial correlation analysis indicated that, in most cases, organic horizon soil N levels and forest floor percolate N concentrations had a common association with alder abundance and the basal area of white spruce. There was no relationship between soil N and percolate N concentrations within one level of either of the forest characteristic parameters. In previous work at the ELRA while examining the soils of 21 lake shorelines, the dominance of white spruce was associated with litter layers of predominantly coniferous needles, which had higher organic layer N concentrations in contrast to sites with black spruce and feathermoss dominated forest floors (Hazlett et al. 2005). These relationships were confirmed with our data from the intensive sites and in addition soil N levels within the upper 10 cm of the mineral soil were also found to be positively correlated with the presence of white spruce. The overall impact of white spruce and alder vegetation was higher soil N levels; greater NO_3^-, NH_4^+, and DON concentrations in forest floor percolate; and higher NO_3^- concentrations in soil water at 30 cm depth. These results indicated that, although we did not directly determine whether alder was actively fixing N at the site, the association between greater alder abundance and higher soil N levels implied active N fixation. Our data also suggested that the influence of vegetation composition on soil N is restricted to the organic horizons and the upper 10 cm of mineral soil at the ELRA. Our results are similar to those of Binkley et al. (1992), who found elevated concentrations of inorganic and organic-N at 80 cm depth in mineral soil in conifer forests associated with alder when compared with stands without alder.

Riparian buffers

Since our study was executed preharvest, there are some limitations to our analysis, which must be considered when extending the results to a discussion of the effectiveness of riparian buffer zones in the boreal forest and the prescription of varied widths depending on catchment slope. Previous work has demonstrated that organic and mineral soils at the site have the potential to release N after harvest (Hazlett et al. 2007); however, it is uncertain to what extent this N will be microbially immobilized or taken up by regenerating vegetation within clearcut areas and, therefore, what amount will move into the riparian buffers downslope. The ability of riparian forests and soils on shallow and steep slopes to modify soil water concentrations under increased inputs from cutover areas could be dissimilar to that which was observed for the unharvested forest.

Another consideration is the extent of connectivity between terrestrial and aquatic systems and the degree to which the shallow soil zone acts as a hydrological pathway of water. During the snowmelt period and after large rainfall events, there is the potential that water could move laterally downslope above B horizons that have high clay contents (Hazlett et al. 2005). Observations in the field have identified perched water tables in soil pits intermittently during periods of high water input. Our analysis of annual and seasonal N and C concentrations yielded no support for the hypothesis that catchments with the highest riparian zone shallow soil water concentrations had the highest lake water concentrations. It is important to note that this evaluation of terrestrial and aquatic linkages assumes that in-lake processes that modify N and C concentrations through consumption or alteration are consistent everywhere within the littoral zone. However, if the distribution of aquatic organisms in a lake reflects differences in inputs of dissolved N and C, this could result in differential uptake of nutrients by aquatic communities. Consequently, a homogeneous distribution of the concentrations of residual N and C in the lake water would occur, and thus, we would not necessarily expect a correlation between soil and lake water even if there were a hydrological connection. An example of this type of shift in aquatic communities was reported by Kreutzweiser and Capell (2003), who found a response of benthic microorganisms to terrestrially derived dissolved organic matter in stream mesocosms within a tolerant hardwood forest. In their study, density estimates of microbial communities and bacteria abundance increased in response to experimentally applied flushes of dissolved organic matter that had been extracted from upper soil horizons. Phytoplankton community analysis of lakes at the ELRA exhibited heterogeneous species distribution and abundance between and within lakes in relationship to lake water DOC concentrations (Rattan 2005). It is also possible that, in the small lakes at the ELRA, in-lake hydrodynamics could largely obviate any differences that existed in the littoral zone water quality, whether because of differences in inputs or organism activity.

Our results have highlighted the potential shortcomings of using only catchment slope as a tool for prescribing riparian buffers during harvesting in the boreal forest when considering terrestrial nutrient export. Since the N and C concentrations of mineral soil water in riparian zones were not well predicted by terrain attributes, one could argue that there is little merit to establishing wider buffers on steeper catchment slopes. We recognize that there are additional ecological, social, and economic factors to consider and that our results reflect the preharvest condition. Notwithstanding these limitations, our data suggest that reducing buffer width on steep slopes in this boreal ecosystem could be undertaken without impacting riparian soil water N and C levels and seemingly lake water concentrations. We have determined that stand and soil characteristics are important factors in controlling drainage water quality in the shallow soil zone in a boreal forest ecosystem. Although this may be an expected result, it does raise the question as to whether forest-management guidelines can be modified in such a way to protect areas of the forest landscape that might be expected to have a larger impact on surface water quality after harvesting. A more useful approach for establishment of forest reserves could be the integration of vegetation or ecosite data with topographic attributes calculated from more accurate DEMs than used in this study. In particular, the presence of white spruce in the overstory and alder in the understory could be easily determined by forest managers to identify landscape units with the potential for increased N flux to aquatic systems. In theory, this approach would enable more accurate predictions of soil water quality and, perhaps, a better ability to develop management policies that would protect aquatic systems while maximizing economic use of the forest resource.

Conclusions

Our objective in this study was to examine the relationships between shallow soil water N and C concentrations and terrain attributes in an undisturbed boreal forest landscape. An ability to predict the spatial distribution of soil water nutrient concentrations from watershed topographic properties, readily computed from DEMs, would enable forest-management planning to better protect aquatic systems from broad fluctuations in nutrient inputs. We were only able to discern an association between slope and DOC concentrations, and this only applied for field-measured slope at a small scale and not for terrain attributes calculated from DEMs. With regard to forest management in the boreal forest of Ontario, our results indicate that there is a disconnect between guidelines for slope as a modifying factor for buffer width establishment and slope as a causal factor impacting riparian zone nutrient concentrations and potential impact on surface water quality. Lee et al. (2004), in a review of buffer width guidelines in Canada and the United States, describe many reasons for the establishment of buffer zones during timber harvest. Absent from their review is an indication of the protection of surface water quality, likely a reflection of the paucity of information that exists with regard to this subject area, and this is particularly true for boreal forest ecosystems. In terms of the aquatic system, most ecological literature has focused on changes in biota (e.g., invertebrate and fish communities) as a result of forest harvesting and modified riparian reserves; however, modifications to dissolved nutrients exported from the catchment utilized by aquatic organisms have often been ignored. In a sense, this approach measures water quality indirectly, although not specifically nutrient levels, because biotic community changes can occur in response to alterations in terrestrial nutrient inputs. From the perspective of shoreline forest management, an additional challenge is the fact that topographic controls that determine soil water N and C concentrations are operating at smaller scales than are routinely calculated with DTMs used during the forest management planning process. The study highlights the importance of stand characteristics, in particular the presence of white spruce and alder, as factors influencing soil N concentrations and, consequently, shallow soil water N concentrations. Improvements to the landscape prediction of terrestrial nutrient source areas could be accomplished by using both topographic attributes, such as slope, and site characteristics, such as vegetation composition. Harvesting at the ELRA was completed during the winter of 2005. Continuing work will examine the impact of full-tree harvesting on nutrient release and movement from boreal forest clearcuts, and the postharvest impact of experimentally prescribed buffer widths on riparian zone soil water quality and lake water quality. The postharvest research is addressing N and C concentration differences that are a result of biogeochemical processes and an assessment of the hydrology of ELRA watersheds, including water table depths, deep groundwater flowpaths, and soil water residence times. The calculation of total nutrient export from shallow and steep slopes to lakes will be used to assess the impact of harvesting and the effectiveness of varying widths of riparian buffers. Results from the current study draw attention to the importance of vegetation and soil properties as factors that must be considered when interpreting the response of soil and lake water quality to forest harvesting with variable-width buffers based on catchment slope. Due to the large variation in conditions across the boreal forest landscape, site-specific preharvest water quality data, as has been collected in this study, rather than a postharvest only assessment is crucial for an accurate evaluation of harvesting impacts.

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