Analytical methods for defining stand–clearcut edge effects demonstrated for N mineralization

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Abstract: Edge effects are becoming an important forest management consideration, but information regarding the influence of edges on N cycling variables has not been well documented. In addition, the quantification of edge effects can benefit from the application of complementary spatial analysis methods. Forest floor N mineralization and environmental variables were intensively measured 5 years after harvest along transects crossing the north and south edges of a 1-ha clearcut, in a high-elevation Engelmann spruce – subalpine fir forest. Wavelet analysis and depth-of-edge influence (DEI) methods were used to locate and measure the spatial extent of edge effects on N mineralization. Then variance partitioning (partial redundancy analysis) was used to examine the influence of edges on N mineralization relative to the influence of other environmental factors. Initial NO_3-N content and net nitrification markedly increased in the opening within 2–6 m of each edge. Net ammonification did not exhibit obvious edge-related spatial patterns. Spatial patterns of nitrification appeared to be more closely related to spatial changes in substrate quality than to soil temperature and moisture. Results of the wavelet and DEI analyses provided quantification of locations and functional extents of edge effects.

Résumé : On se préoccupe de plus en plus des effets de bordure en aménagement forestier mais l'influence des bordures sur le recyclage de l'azote est peu connue. De plus, l'application de méthodes complémentaires d'analyse spatiale peut être bénéfique pour quantifier les effets de bordure. La minéralisation de N dans la couverture morte et les variables environnementales ont été mesurées de façon intensive cinq ans après la récolte le long de transects traversant les bordures nord et sud d'une coupe à blanc d'un hectare dans une forêt d'épinette d'Engelmann et de sapin subalpin à haute altitude. Des méthodes basées sur l'analyse par ondelettes et l'influence de la distance à la bordure ont été utilisées pour localiser et mesurer l'étendue spatiale des effets de bordure sur la minéralisation de N. La répartition de la variance a ensuite été utilisée pour examiner l'influence des bordures sur la minéralisation de N relativement aux autres facteurs environnementaux. Le contenu initial en N-NO_3 et la nitrification nette ont augmenté de façon marquée dans l'ouverture à l'intérieur de 2–6 m de chaque bordure. L'ammonification nette n'a pas montré de variation spatiale évidente due à l'effet de bordure. La variation spatiale de la nitrification semble plus étroitement reliée aux variations de la qualité du substrat qu'à celles de la température et de l'humidité du sol. Les résultats des analyses par ondelettes et ceux de l'influence de la distance à la bordure fournissent une quantification des effets de bordure en termes de localisation et d'importance fonctionnelle.

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Introduction

At the boundary (or edge) between forest and opening, environment changes (often termed edge effects) may occur abruptly or gradually, either into the forest or into the opening (Cadenasso et al. 1997, 2003*a*, 2003*b*). For forest management, edge effects are of increasing concern as harvesting practices move toward smaller openings that have a greater length of edge per unit area harvested and that would therefore magnify any edge effects over the landscape (Franklin and Forman 1987). Forest–clearcut edge effects have been well documented for variables such as soil temperature and moisture (Saunders et al. 1999; Gray et al. 2002; Redding et al. 2003). It has been proposed that these variables may influence the spatial patterns of soil nitrogen (N) mineralization across edges (Chen et al. 1995; Edmonds et al. 2000).

The detection and quantification of edges and their functions may require the application of a range of techniques (Fagan et al. 2003), depending on the form of the boundary and the type of data available (Strayer et al. 2003). Recently, wavelet analysis has been used as an edge detection technique to allow comparison of the position of the structural edge (location of trees) and the position of the functional edge (location of transition between forest and clearcut for the variable of interest) for structure and composition of forest vegetation (Harper and Macdonald 2001) and soil tem-

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perature and moisture (Redding et al. 2003). Wavelet analysis is well suited for studying spatial patterns across forest edges, as it does not require data normality or stationarity, unlike many other spatial analysis methods used in soil and forest ecology research (Lark and Webster 1999; Csillag and Kabos 2002; Lark and McBratney 2002). To complement the wavelet analysis, the depth-of-edge influence (DEI) method (Chen et al. 1995; Saunders et al. 1999) may be employed to provide the range (functional extent of the edge effects) over which the transition between forest and clearcut occurs for different variables. In addition, variance partitioning methods (Borcard et al. 1992) may be employed to investigate the influence of the edge on selected response variables relative to the influence of various environmental and spatial variables.

At the Sicamous Creek silvicultural systems trial (Vyse 1999), edge effects have been well documented for a number of biotic and abiotic variables (Huggard and Vyse 2002), including soil temperature and moisture (Redding et al. 2003). Concurrent research at the Sicamous Creek site has also measured elevated nitrate concentrations in forest floor and mineral soil of clearcuts more than 5 years after harvest (Prescott et al. 2003). To address a shortfall in our knowledge on the spatial interactions between N mineralization and forest–clearcut edges, we have applied spatial sampling and analysis techniques to characterize changes in forest floor N mineralization across high-elevation forest–clearcut edges and have related patterns to changes in environmental variables. We hypothesized that the spatial patterns in N mineralization across edges would follow those measured for soil temperature and moisture previously reported by Redding et al. (2003).

The objectives of this research were to (*i*) describe the spatial patterns of N mineralization across north and south forest–clearcut edges, using wavelet analysis; (*ii*) investigate the spatial extent of the effect of forest–clearcut edges on N mineralization, using DEI methods; and (*iii*) investigate the importance of distance from the edge as a source of spatial variability of N mineralization relative to the influence of other environmental and spatial variables, using variance partitioning (partial redundancy analysis (RDA)).

Materials and methods

Study area

This study was conducted as part of the Sicamous Creek Silvicultural Systems Project (Vyse 1999), located near the town of Sicamous in the southern interior of British Columbia, Canada (50°50′N, 119°55′W). The study area is within the Engelmann Spruce – Subalpine Fir Wet Cold (ESSFwc2) biogeoclimatic unit (Lloyd et al. 1990). The study site has an elevation range of approximately 1550–1800 m above sea level (asl), with a north-facing aspect and slopes of 5%–40%. The average annual temperature (1993–2000) measured at the site is 1.2 °C, with a mean maximum monthly temperature of 11.5 °C in August and a mean minimum monthly temperature of –7.8 °C in December (D. Spittlehouse, B.C. Ministry of Forests, unpublished data). Deep snowpacks often last until mid-June, and average June–September rainfall is 308 mm (1993–2000; Spittlehouse, unpublished data). Soils are derived from mixed metamorphic glacial till and have sandy loam mineral soil textures, with thin discontinuous silt loam surface layers. On mesic sites, soils are classified as Orthic Humo-Ferric Podzols (Soil Classification Working Group 1998). Humus forms are predominantly Hemimors (Green et al. 1993).

The forest at Sicamous Creek is dominated by subalpine fir (*Abies lasiocarpa* (Hook.) Nutt.) and Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), with a maximum age of >300 years (Parish et al. 1999) and a mean canopy tree height of approximately 21 m. Understory vegetation on mesic sites is dominated by a shrub layer of black huckleberry (*Vaccinium membranaceum* Dougl.) and white-flowered rhododendron (*Rhododendron albiflorum* Hook.). The herb layer is dominated by oak fern (*Gymnocarpium dryopteris* (L.) Newm.) and Sitka valerian (*Valeriana sitchensis* Bong.), with red-stemmed feather moss (*Pleurozium schreberi* (Brid.) Mitt) being the dominant bryophyte.

Sampling design

Forest floor material was sampled across a single, 1-ha (100 m × 100 m) square opening. Because of previously measured high spatial variability in N mineralization within openings (G. Hope, B.C. Ministry of Forests, unpublished data), we chose to intensively sample a single opening to investigate spatial patterns. The opening elevation was 1550 m asl, sloping from south to north at approximately 5%. The site series of the opening and adjacent stand was dominantly mesic (Lloyd et al. 1990), with small wetter or drier areas. At the time of sampling, 4-year-old seedlings were approximately 50 cm tall with a ground cover of approximately 3%–5%, and there was little advanced regeneration present. The opening had been harvested during the winter of 1995, and samples were collected during July 2000.

A spatially intensive, stratified, semiregular grid sampling approach was used. Samples were collected along five parallel north–south transects, 200 m long and separated by 5 m. The edge was defined as the location of the stems of mature trees. Transects extended from 50 m south into the forest (0 m) from the south edge, across the south edge (50 m), through the centre of the opening (100 m), across the north edge (150 m), and 50 m into the forest from the north edge (200 m). Forest floor samples were collected 1 m apart within 4 m north and south of each edge, 2 m apart within 4–20 m of each edge, and 5 m apart when >20 m from the edge. Because of a wetland at the 200-m location, only 72 samples were collected along three of the transects, but 73 samples were collected along the other two. Sampling locations were stratified to ensure consistent sampling of physically undisturbed forest floor materials to allow comparison between forest and clear-cut conditions. All sample locations were within 2 m east or west of the transect lines.

All forest floor material (L, F, and H horizons) was excavated to the mineral soil surface, with a 0.15 m × 0.15 m template, for bulk density calculations. The forest floor depth was calculated as the average of eight measurements taken from the sides of each excavated sample. Subsamples were oven-dried at 70 °C for 48 h to determine oven-dry weight for bulk density calculations.

N mineralization

The buried bag method (Hart et al. 1994) was used for determining net nitrification and net ammonification at all sampling locations. Two sets of samples were collected: fresh samples for analysis of initial (preincubation) NO_3-N and NH_4-N concentrations; and field-incubated samples for analysis of postincubation NO_3-N and NH_4-N. Both initial and incubated samples were composites of three subsamples collected within 20 cm of every sampling point. Samples were incubated for 40 days (July 6 – August 14, 2000). Samples were stored at 4 °C until processed within 1 week of field collection. In the laboratory, samples were sieved (4.7-mm mesh) to remove pieces of wood and rocks. A 5-g subsample (dry mass equivalent) was extracted in 1 mol/L KCl and filtered through Whatman No. 42 equivalent Gelman glass-fibre syringe filters. Extracts were analyzed for NO_3-N and NH_4-N concentrations with the use of a Lachat QuikChem® AE autoanalyzer (Lachat Instruments, Madison, Wis.). Net nitrification and net ammonification were calculated as the difference between postincubation and initial measurements. Prior to data analysis, all concentration measures were converted to an area basis ($kg \cdot ha^{-1}$), using the bulk density values determined at each sampling location, and net nitrification and net ammonification rates were calculated ($kg \cdot ha^{-1} \cdot day^{-1}$).

Environmental and spatial variables

Environmental variables were measured at each sampling location along all five transects. Variables measured included forest floor temperature at 3-cm depth, volumetric moisture content of the forest floor (measured on preincubation samples), canopy openness, microtopography, ground cover, vegetation strata, and absence or presence of vascular plant species (Redding 2001). Forest floor type was recorded at each sampling location, with morphologic descriptions adapted from Green et al. (1993). The spatial variables measured included the northing and easting of each sampling location, the distance of each sample from the edge, and its situation (indicating whether the sample was collected in the forest or collected in the clearcut).

Wavelet analysis

Wavelet analysis was used as an edge detection method to locate high-magnitude spatial changes in N mineralization (Bradshaw and Spies 1992; Dale and Mah 1998; Harper and Macdonald 2001; Fagan et al. 2003). In this application, the definition of edge is the location of the highest rate of change in the data series (Fagan et al. 2003). Edge detection can be achieved through the use of wavelets, by dividing the data into fairly homogeneous areas that can be modeled with as many waveforms (wavelet transform coefficients) as needed to model the local pattern; homogeneous areas require few coefficients of low values, whereas contrasting locations, such as edges, require more coefficients with larger values (Csillag and Kabos 2002). Where a rapid change occurs in adjacent values along a data series, there will be a relatively large increase in the wavelet variance; in contrast data with low spatial variability will have low wavelet variance (Bradshaw and Spies 1992). The continuous wavelet transform acts similar to a moving window analysis (Dale and Mah 1998). When the shape of the wavelet function is similar to the shape of the underlying data series, the wavelet variance has a higher value (Dale and Mah 1998). The wavelet function can vary in size along both the x and the y axes to perform a multiscale analysis. The Haar wavelet was applied, as it is considered the best for detecting boundaries in a spatial data series (Bradshaw and Spies 1992). The analysis relied on a continuous wavelet transform at a maximum scale of 10% (20 m) and used PASSAGE (Rosenberg 2001).

As wavelet analysis requires regular spatial intervals, the original data set had to be modified, and the analysis was performed on two different data sets. The first data set contained data interpolated to 1-m spacing by using a cubic spline in S-Plus® (Mathsoft Corporation 2000); this interpolation increased the data set from 73 points to 201 points. The original data were reduced to those at 5-m spacing for an investigation of whether the 1-m interpolation introduced any artefacts into the wavelet analysis that would cause incorrect interpretation of edge-related patterns. This data reduction required the estimation of eight data points based on the average of the adjacent samples, which were 1 m to either side of the estimated point. The location of each peak in wavelet variance was visually compared with the original data series to determine whether a peak was related to a change at the edge or related to inherent variability in the data. Peaks in wavelet variance were classified as being a single dominant peak (clear spatial discontinuity) or multiple peaks (poorly defined spatial discontinuity).

Depth-of-edge influence

The DEI was calculated for initial and net N mineralization variables to determine the spatial extent (functional zone) over which edge effects occur in the data series (Chen et al. 1995; Saunders et al. 1999). The process followed Saunders et al. (1999), who described the method in considerable detail. The general procedure is to calculate the mean values in the forest and in the clearcut for a given variable and then calculate 5% of the absolute difference between the means. The DEI is the spatial zone (along each transect) where the values of a variable fall between the 5% difference thresholds. To calculate the forest and clearcut means, we used samples from the original noninterpolated data that were located >10 m from the edge (i.e., south forest, 0–40 m; south clearcut, 60–100 m; north clearcut, 100–140 m; and north forest, 160–200 m), as visual inspection of the data indicated that most change occurred within 10 m of the edge. We chose the 5% absolute difference parameter arbitrarily, although it is the most commonly used value in the literature (Chen et al. 1995; Saunders et al. 1999). The DEI values were also computed on the basis of a 10% difference, but this did not affect the patterns, and results are not presented.

Variance partitioning

Variance partitioning (Borcard et al. 1992) was used to examine the sources of spatial variability in forest floor net ammonification and net nitrification. This method allows the variation in response variables to be partitioned into the following classes: pure environmental (unrelated to spatial orientation), spatially structured environmental, pure spatial, and unexplained (Borcard et al. 1992). The spatially structured environmental variation is determined by environmental variables that covary with spatial variables (Borcard et al. 1992). Variance partitioning was performed with partial RDA in CANOCO™ (ter Braak 1998).

Forest floor net nitrification and net ammonification were used as separate sets of response variables in the variance partitioning. All variables were assessed for normality and transformed, as required, with square root or logarithmic transformations to most closely approximate a normal distribution. The net nitrification and net ammonification data sets were each split into three subsets: all samples, forest samples (not for net nitrification, as most locations had values below the analytical detection limits), and clear-cut samples. The inclusion of each additional insignificant explanatory variable is likely to increase the amount of variation explained by chance alone (Borcard et al. 1992; Okland and Eilertsen 1994). Therefore, the number of environmental and spatial variables measured was reduced for the analysis by removing variables with high inflation values or low explanatory power in a forward selection procedure (ter Braak 1998). For all data sets, the number of environmental variables retained was less than 10, and the maximum number of spatial variables was 4.

Results

Initial NO_3-N and NH_4-N contents and net nitrification rates all increased markedly from the forest into the opening; net ammonification changed only little across the edges (Fig. 1). Clear edge-related influences (single dominant peaks) were found by wavelet analysis for initial NO_3-N and NH_4-N and net nitrification (Fig. 1) at both the 1- and 5-m spatial resolutions (Table 1). These edges were within 3–7 m of both north and south edges (Table 1). The functional extent of the edge effects (DEI range) was small (<4 m) for nitrate variables and greater (4–7 m) for initial NH_4-N content (Table 2).

Results of the wavelet and DEI analyses for the nitrate and ammonium variables show good agreement (overlap of the wavelet-determined edge location with the DEI range) for the 1-m wavelet analysis and poor agreement for the 5-m wavelet analysis. No clear boundaries were detected for net ammonification by wavelet analysis at either the 1-m or the 5-m sample spacing (Table 1), and the functional edge zone could not be determined by DEI analysis (Table 2). In general, the 1- and 5-m wavelet analyses show similar results, with the 5-m peaks corresponding to the location closest to the 1-m peak (Table 1). The interpolation of the original data to 1-m spacing did not introduce any artefacts into the wavelet analysis results that interfered with the interpretation of edge effects. Examples of wavelet and DEI results for clear (net nitrification) and unclear (net ammonification) edge patterns for the 1-m wavelet analysis and DEI analysis are shown in Fig. 2.

In all the variance partitioning analyses, the unexplained variance component was the largest of all categories (Table 3). Spatially structured environmental variation was the primary source of explained variability for net nitrification when all samples (forest and clear-cut) were included in the

Fig. 1. The trend of forest floor initial NO_3-N and NH_4-N content, net nitrification, and net ammonification along north–south transects across a 1-ha opening. Open circles are individual measurements; solid black lines are the means of all individual measurements for the five transects at each location along the distance axis. Vertical dashed lines denote the south (50 m) and north (150 m) edges.

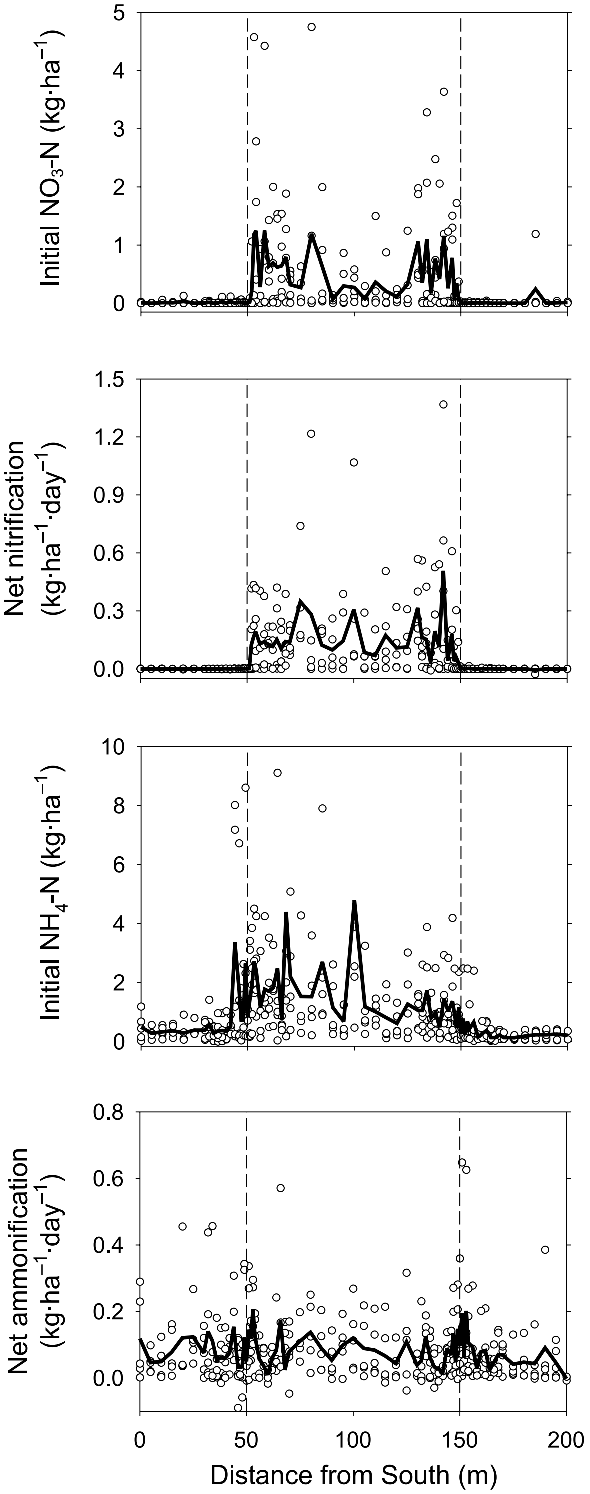

Table 1. Location of wavelet analysis detected edges for initial NO_3-N and NH_4-N, net nitrification, and net ammonification, detected by wavelet analysis using data series at 1- and 5-m spacing.

	1-m spacing		5-m spacing	
Variable	South edge (m)	North edge (m)	South edge (m)	North edge (m)
Initial NO_3-N	53 (3)*	147 (3)*	55 (5)*	150 (0)*
Net nitrification	52 (2)*	144 (6)*	55 (5)*	145 (5)*
Initial NH_4-N	43 (–7)*	147 (3)*	45 (–5)*	150 (0)*
Net ammonification	51 (1)	144 (6)	65 (15)*	145 (5)

Note: Values with asterisks signify a single dominant peak in wavelet variance near the edge. Values in parentheses are the corresponding distance from the south (50 m) and north (150 m) forest–clearcut edges at which edges were detected in the N mineralization data series. Positive values indicate that the detected edge occurs within the clearcut, whereas negative values indicate that the detected edge occurs within the forest.

Table 2. The spatial range along the transect over which the transition zone (functional extent of edge effect) occurs between forest and clearcut and the width of the transition zone.

	South edge		North edge	
Variable	Range (m)	Width (m)	Range (m)	Width (m)
Initial NO_3-N	50–53	3	146–150	4
Net nitrification	51–53	2	146–150	4
Initial NH_4-N	40–44	4	146–153	7
Net ammonification	N.D.	N.D.	N.D.	N.D.

Note: Obtained from depth-of-edge influence analysis for north and south edges at the mean ± 5% threshold, using the average of the five transects at the original spacing. N.D., the difference between forest and clear-cut threshold values is too small for a transition zone to be located.

analysis. For net nitrification in the clearcut and for all variance partitioning analyses conducted on the three net ammonification data sets, environmental factors were the predominant sources of variability and spatial influences were small.

Discussion

The application of three complementary analytical methods (wavelet analysis, DEI, and variance partitioning) indicated that initial NO_3-N content and net nitrification rate increased abruptly within the clearcut close to the edge. This does not agree with the hypothesis that N mineralization would change gradually across the edge following the patterns of soil temperature and moisture. Wavelet analysis indicated soil temperature and moisture data boundaries at 57–62 m for the south edge and 160–168 m for the north edge, depending on the variable and weather conditions (Redding et al. 2003). The DEI analysis indicated the functional zones of edge influence were 50–62 m and 150–160 m for soil temperature and moisture, depending on the variable and weather conditions (Redding 2001). Although changes in initial NO_3-N content and net nitrification occur within the temperature and moisture transition zones for the south edge, they do not at the north edge, where changes in temperature and moisture occur within the forest. These results are confirmed by the variance partitioning of net nitrification, which shows that the difference between forest and clearcut overwhelms any more gradual edge gradients, such as those for temperature and moisture.

The spatial pattern in net nitrification may be related to differences in substrate. In a concurrent study at Sicamous Creek, Prescott et al. (2003) examined the relative influences of soil temperature and substrate quality on net nitrification in buried bags. They found evidence that differences between forest and clearcut substrates, rather than differences in soil temperature, were driving the difference in net nitrification. The abrupt changes in initial NO_3-N content and net nitrification correspond spatially to the boundary of the canopy drip line approximately 2 m into the opening from the tree stems (G. Hope, B.C. Ministry of Forests, unpublished data), a decrease in recent conifer litter within 4 m of the edge (Redding 2001), a large decrease in fine root abundance (Welke et al. 2003), and a decrease in fungal diversity and abundance (Hagerman et al. 1999). The absence of litter, conifer fine roots, and hyphae may indicate a loss of labile carbon sources (Stark 1994) and reduced fungal immobilization (Stark and Hart 1997), resulting in greater accumulation of NO_3-N in the forest floor during incubation. Our results for net ammonification, although not explainable by substrate differences, agree with those of Prescott et al. (2003), who found no difference between postincubation NH_4-N concentration in 1-ha clearcuts and that in forests 5 years after harvest at Sicamous Creek.

Wavelet analysis allowed comparison of the position of the forest edge (50 and 150 m) with the location of the transition between forest and clearcut for N mineralization and comparison between different variables. Wavelet analysis provides a robust tool for quantifying edge effects, as it does not require data normality or stationarity, unlike many other spatial analysis methods commonly used in ecology and soil science (Bradshaw and Spies 1992; Lark and Webster 1999; Csillag and Kabos 2002). However, wavelet analysis, as with most other edge detection methods, works best for well-defined boundaries (Fagan et al. 2003). When patterns in the data are not clear, the interpretation of what is and what is not a boundary is subjective. As a boundary detection method, the usefulness of wavelet analysis is only as clear as the data series on which it is performed. For some data sets, it might be possible to increase the maximum scale (kernel size) of the wavelet to provide a smoothing effect and a larger scale interpretation of the spatial pattern; however, long data series are required so that boundaries are not obscured by distortion at the ends of the series (end effects) (Lark and McBratney 2002).

Although the DEI results confirmed, for the most part, the results of the wavelet analysis, this method also requires subjectivity in application and interpretation. A problem with all edge detection methods is that when boundaries are not clearly defined, they can produce results that might be misinterpreted as a well-defined boundary (Fagan et al. 2003). We have shown that for our data set, the interpolation of the data to 1-m spacing did not introduce artefacts into the results of the wavelet analysis. This might be due to the fact that the original sample spacing was only 1–2 m within the zone in which all edge influences occurred in the N min-

Fig. 2. Examples of wavelet transforms and depth-of-edge influence (DEI) analysis along north–south transects across a 1-ha opening. Standardized wavelet transforms computed for the data at 1-m spacing (thick line) and the original mean values (thin lines) of net nitrification (*a*) and net ammonification (*c*). The wavelet transforms have been standardized where the mean equals 1. DEI analysis is shown for the south edge only (with subsequent change in distance axis scale) and was performed on the average of measured data for net nitrification (*b*) and net ammonification (*d*). Horizontal dashed lines are the DEI thresholds calculated from the original data. Vertical dashed lines denote the south (50 m) and north (150 m) edges.

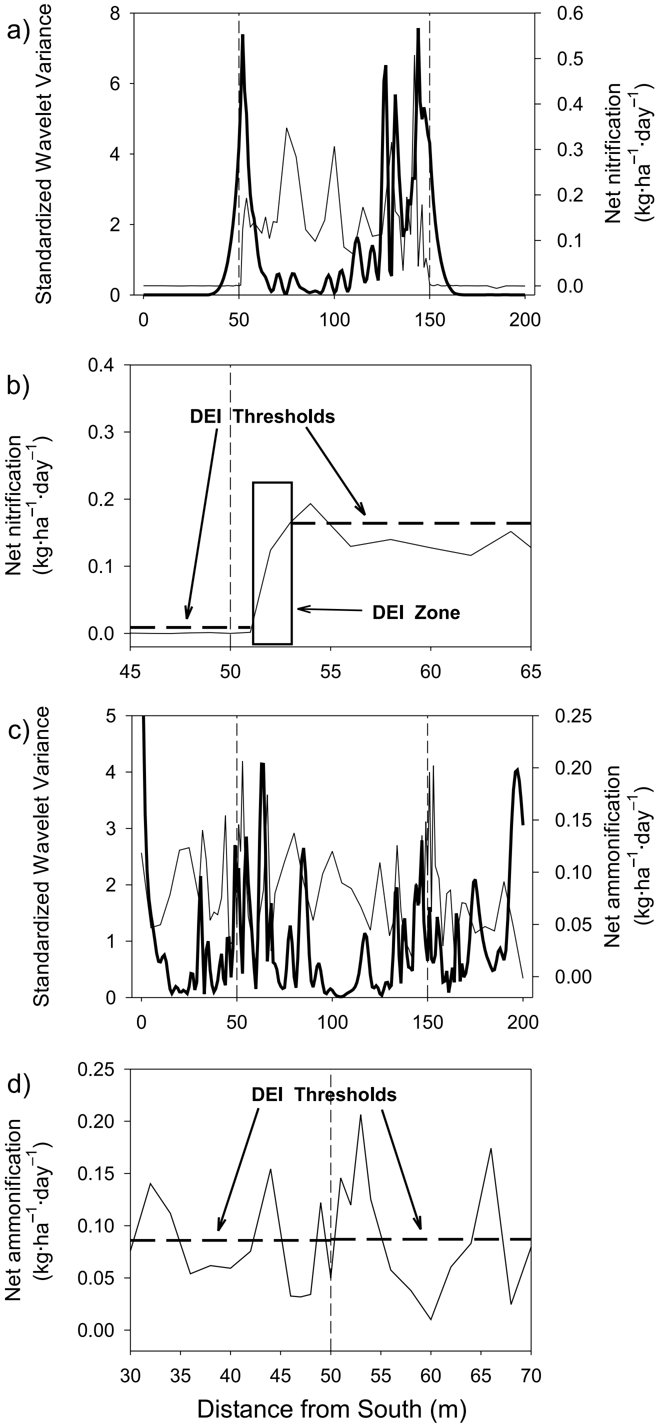

Table 3. The percentage variance accounted for within each variance category obtained from variance partitioning analysis (partial redundancy analysis) for net ammonification and net nitrification.

	Percentage of total variance within each category				
	Net ammonification			Net nitrification	
	All	Forest	Clearcut	All	Clearcut
Environment	23.8	29.1	37.4	7.0	26.5
Environment + space	10.2	8.4	3.5	44.4	18.1
Space	2.3	4.2	1.9	1.5	2.5
Unexplained	63.7	58.3	57.2	47.1	52.9

Note: Results are displayed for the data sets, including all locations in the forest and clearcut (all), for forest locations only (forest), and for clear-cut locations only (clearcut). No variance partitioning analysis was performed for net nitrification in the forest, as most values were below the analytical detection limit.

eralization data, and therefore potential distortions due to interpolation for this data set were likely minor. The use of the 1-m interpolated data provided greater resolution in delineation of edge effects relative to the results of the 5-m data. However, on the basis of our experience, we recommend that wherever possible, a regular sampling interval be used when wavelet analysis (or most other edge-detection methods) is to be applied, to avoid any potential complications introduced by interpolation to a regular interval.

The variance partitioning provided a useful tool for examining the role of multiple spatial and environmental influences on net nitrification and net ammonification. For net nitrification, the primary source of explained variability was related to differences between forest and clearcut and not the more gradual edge effects measured for soil temperature and moisture (Redding et al. 2003). As net ammonification did not show a strong forest–clearcut contrast, the primary source of explained variation was from environmental variables, rather than spatial influences. Although the unexplained variance component was large, this is consistent with most other applications of this technique (Borcard et al. 1992; Okland and Eilertsen 1994).

From this examination of boundary detection and quantification, it is clear that a careful visual inspection of the data is necessary to confirm that wavelet peaks and DEI-determined zones are related to edge effects. However, the advantage of these techniques over purely visual inspection is that they provide a boundary location or extent of edge effects that can be compared consistently between variables or sites. This approach has allowed us to infer that patterns in initial NO_3-N content and net nitrification are likely related to spatial changes in substrate properties, rather than the hypothesized influence of soil temperature and moisture. This result has implications for sampling regimes and highlights the need to consider spatial patterns of treatment and edge effects when locating a sampling plot.

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References

Borcard, D., Legendre, P., and Drapeau, P. 1992. Partialling out the spatial component of ecological variation. Ecology, **73**: 1045–1055.

Bradshaw, G.A., and Spies, T.A. 1992. Characterizing canopy gap structure in forests using wavelet analysis. J. Ecol. **80**: 205–215.

Cadenasso, M.L., Traynor, M.M., and Pickett, S.T.A. 1997. Functional location of forest edges: gradients of multiple physical factors. Can. J. For. Res. **27**: 774–782.

Cadenasso, M.L., Pickett, S.T.A., Weathers, K.C., Bell, S.S., Benning, T.L., Carreiro, M.M., and Dawson. T.E. 2003*a*. An interdisciplinary and synthetic approach to ecological boundaries. BioScience, **53**: 717–722.

Cadenasso, M.L., Pickett, S.T.A., Weathers, K.C., and Jones, C.G. 2003*b*. A framework for a theory of ecological boundaries. BioScience, **53**: 750–758.

Chen, J., Franklin, J.F., and Spies, T.A. 1995. Growing season microclimatic gradients from clearcut edges into old-growth Douglas-fir forests. Ecol. Appl. **5**: 74–86.

Csillag, F., and Kabos, S. 2002. Wavelets, boundaries, and the spatial analysis of landscape pattern. Ecoscience, **9**: 177–190.

Dale, M.R.T., and Mah, M.H. 1998. The use of wavelets for spatial pattern analysis in ecology. J. Veg. Sci. **9**: 805–814.

Edmonds, R.L., Marra, J.L., Barg, A.K., and Sparks, G.B. 2000. Influence of forest harvesting on soil organisms and decomposition in western Washington. *In* Proceedings of the California Forest Soils Council Conference on Forest Soils Biology and Forest Management. *Edited by* R.F. Powers, D.L. Hauxwell. and G.M. Nakamura. USDA For. Serv. Gen. Tech. Rep. PSW-GTR-178. pp. 53–72.

Fagan, W.F., Fortin, M.-J., and Soykan, C. 2003. Integrating edge detection and dynamic modeling in quantitative analyses of ecological boundaries. BioScience, **53**: 730–738.

Franklin, J.F., and Forman, R.T.T. 1987. Creating landscape patterns by forest cutting: ecological consequences and principles. Landscape Ecol. **1**: 5–18.

Gray, A.N., Spies, T.A., and Easter, M.J. 2002. Microclimatic and soil moisture responses to gap formation in coastal Douglas-fir forests. Can. J. For. Res. **32**: 332–343.

Green, R.N., Trowbridge, R.L., and Klinka, K. 1993. Towards a taxonomic classification of humus forms. Society of American Foresters, Bethesda, Md., For. Sci. Monogr. 29.

Hagerman, S.M., Jones, M.D., Bradfield, G.E., Gillespie, M., and Durall, D.M. 1999. Effects of clearcut logging on the diversity and persistence of ectomycorrhizae at a subalpine forest. Can. J. For. Res. **29**: 124–134.

Harper, K.A., and Macdonald, S.E. 2001. Structure and composition of riparian boreal forest: new methods for analyzing edge influence. Ecology, **82**: 649–659.

Hart, S.C., Stark, J.M., Davidson, E.A., and Firestone, M.K. 1994. Nitrogen mineralization, immobilization and nitrification. *In* Methods of soil analysis. Part 2: Microbiological and biochemical properties. *Edited by* R.F. Weaver, J.S. Angle, and P.S. Bottomley. Soil Science Society of America, Madison, Wis., Book Series No. 5. pp. 985–1018.

Huggard, D.J., and Vyse, A. 2002. Edge effects in high-elevation forests at Sicamous Creek. B.C. Ministry of Forests, Victoria, B.C. Extension Note 62. Available from http://www.for.gov.bc.ca/hfd/pubs/Docs/En/En62.htm [updated July 2002; cited 15 October 2003].

Lark, R.M., and McBratney, A.B. 2002. Wavelet analysis. *In* Methods of soil analysis. Part 4: Physical methods. *Edited by* J.H. Dane and G.C. Topp. Soil Science Society of America, Madison, Wis., Book Series No. 5. pp. 184–195.

Lark, R.M., and Webster, R. 1999. Analysis and elucidation of soil variation using wavelets. Eur. J. Soil Sci. **50**: 185–206

Lloyd, D., Angove, K., Hope, G., and Thompson, C. 1990. A guide to site identification and interpretation for the Kamloops forest region. B.C. Ministry of Forests, Victoria, B.C., Land Manage. Handb. 23.

Okland, R.H., and Eilertsen, O. 1994. Canonical correspondence analysis with variance partitioning: some comments and an application. J. Veg. Sci. **5**: 117–126.

Parish, R., Antos, J.A., and Fortin, M.-J. 1999. Stand development in an old-growth subalpine forest in southern interior British Columbia. Can. J. For. Res. **29**: 1347–1356.

Prescott, C.E., Hope, G.D., and Blevins, L.L. 2003. Effect of gap size on litter decomposition and soil nitrate concentrations in a high-elevation spruce–fir forest. Can. J. For. Res. **33**: 2210–2220.

Redding, T.E. 2001. Spatial patterns of soil properties across forest–clearcut edges. M.Sc. thesis, Department of Geography, Simon Fraser University, Burnaby, B.C.

Redding, T.E., Hope, G.D., Fortin, M.-J., Schmidt, M.G., and Bailey, W.G. 2003. Spatial patterns of soil temperature and moisture across subalpine forest–clearcut edges in the southern interior of British Columbia. Can. J. Soil Sci. **83**: 121–130.

Rosenberg, M.S. 2001. PASSAGE: pattern analysis, spatial statistics and geographic exigesis. Version 1.0 [computer program]. Department of Biology, Arizona State University. Tempe, Ariz.

Saunders, S.C., Chen, J., Drummer, T.D., and Crow, T.R. 1999. Modeling temperature gradients across edges over time in a managed landscape. For. Ecol. Manage. **117**: 17–31.

Soil Classification Working Group. 1998. The Canadian system of soil classification, 3rd ed. Agriculture and Agri-Food Canada Publ. 1646.

Stark, J.M. 1994. Causes of soil nutrient heterogeneity. *In* Exploitation of environmental heterogeneity by plants. *Edited by* M.M. Caldwell and R.W. Pearcy. Academic Press, New York. pp. 255–284.

Stark, J.M., and Hart S.C. 1997. High rates of nitrification and nitrate turnover in undisturbed coniferous forests. Nature (London), **385**: 61–64.

Strayer, D.L., Power, M.E., Fagan, W.F., Pickett, S.T.A., and Belnap, J. 2003. A classification of ecological boundaries. BioScience, **53**: 723–729.

ter Braak, C.J.F. 1998. CANOCO: a program for canonical community ordination by (partial) (detrended) (canonical) correspondence analysis, principal components analysis, and redundancy analysis. Version 4.0 [computer program]. Agricultural Mathematics Group, Ministry of Agriculture and Fisheries, Wageningen, Netherlands. 351 pp.

Vyse, A. 1999. Is everything all right up there? A long-term interdisciplinary silvicultural systems project in a high-elevation spruce–fir forest at Sicamous Creek, BC. For. Chron. **75**: 467–472.

Welke, S.E., Hope, G.D., and Hunt, G. 2003. Effects of harvesting on fine root biomass and decomposition in an Engelmann spruce – subalpine fir forest. Can. J. For. Res. **33**: 847–853.