Characterization of nutrient regimes in some continental subalpine boreal forest soils

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Chen, H. Y. H., Klinka, K., Fons, J. and Krestov, P. V. 1998. **Characterization of nutrient regimes in some continental subalpine boreal forest soils.** Can. J. Soil Sci. **78**: 467–475. To determine whether field-identified **soil nutrient regimes (SNRs)** can be characterized and segregated by direct soil nutrient measures, we collected samples of forest floor and mineral soil (0 to 30 cm) from a wide range of forest sites throughout the **Engelmann Spruce — Subalpine Fir (ESSF)** zone of British Columbia. The samples were analyzed for acidity, total C, total N, mineralizable N, and extractable Ca, Mg, K, P, and SO_4-S. The study sites were stratified according to an a priori field classification (SNRs) and an a posteriori classification derived from quantitative classification (groups) using all direct measures of nutrients as discriminating variables. The two classification methods had 72% agreement. Regardless of the classification, nitrogen-related variables (C:N ratio, total N, and mineralizable N) in the mineral soil segregated best among SNRs or groups indicating the presence of a steep, N-driven regional soil nutrient gradient. Multiple regression models using SNRs, groups, or direct measures of nutrients together with surrogates of climate (elevation, latitude, and/or longitude) as predictors had the similar accountability for the variation in subalpine fir and Engelmann spruce site index ($0.41 \le R^2 \le 0.65$). The similarity in the accountability for site index justifies the use of the a priori classification in estimating site quality. Comparison of mineralizable-N values for field-identified SNRs between different climatic regions showed similarities between boreal climates and discrepancies between boreal and cool mesothermal climates. The study gave further evidence that indices of plant-available nitrogen in the upper mineral soil provide useful measures for field-identified SNRs, but indicated that it may be necessary to expand the existing five-class a priori classification to accommodate differences in regional soil nutrient gradients.

Key words: Classification, Engelmann spruce, subalpine fir, nitrogen, site index, soil nutrient regime

Chen, H. Y. H., Klinka, K., Fons, J. et Krestov, P. V. 1998. **Caractères des régimes de fertilité de certains sols de la forêt boréale subalpine intérieure en Colombie-Britannique.** Can. J. Soil Sci. **78**: 467–475. Pour établir la possibilité de caractériser et de distinguer par analyse chimique directe les régimes nutritionnels du sol (RNS) identifiés sur le terrain, nous avons prélevé des échantillons de la couche organique et du sol minéral (0–30 cm) dans un large écart de stations forestières de la zone de l'épinette d'Engelmann — sapin subalpin en ColombieBritannique. Les échantillons étaient analysés sur l'acidité, C et N totaux, N minéralisable et Ca, Mg, K, P et S-SO_4 extractibles. Les placettes étaient rangées selon une classification a priori sur le terrain (RNS) et selon une classification quantitative a posteriori utilisant toutes les mesures directes des éléments nutritifs comme variables discriminantes. Les deux méthodes de classification concordaient à 72 %. Quelle que soit la classification adoptée, ce sont les variables du sol minéral reliées à l'azote, soit le rapport C:N, N total et N minéralisable, qui se différenciaient le mieux parmi les régimes qualitatifs ou les groupes quantitatifs, suggérant ainsi la présence d'un fort gradient de fertilité régional lié à l'azote. Des modèles de régression multiple utilisant les régimes de fertilité, les groupes quantitatifs ou les analyses directes des élments nutritifs ainsi que les indicateurs du climat (altitude, latitude, longitude) comme prédicteurs, produisaient une même intensité de relation avec les variables affectant les indices de fertilité des stations à sapin subalpin et à épinette d'Engelmann (R^2 = 0,41 à 0,65). Cette correspondance vient conforter l'utilité de la classification a priori pour l'estimation de la qualité d'une station. La comparaison entre différentes régions climatiques des valeurs de N minéralisable mesurées selon les régimes nutritionnels fait ressortir des similarités parmi les climats boréaux, mais des discordances parmi les zones à climat boréal et à climat mésotherme frais. Nos observations viennent confirmer que les quantités de N assimilables dans le haut de la couche minérale donnent une bonne mesure de la fertilité des régimes nutritionnels (qualitatifs) identifiés sur le terrain, encore qu'il puisse être nécessaire d'élargir la classification a priori actuelle à cinq classes pour tenir compte des différences affectant les gradients de fertilité régionaux.

Mots clés: Classification, épinette d'Engelmann, sapin subalpin, azote, indice de fertilité stationnel, régime nutritionnel du sol

Qualitative or quantitative, consistent estimates of the levels of plant-available nutrients in forest soils are required for ecological studies and applications. Qualitative a priori estimates of SNR together with climatic, soil moisture, and soil aeration regimes have been used as the ecological determinants of site quality to facilitate the application of site-specific forest management in British Columbia (Pojar et al. 1987). SNR is a class of a presumed regional soil nutrient gradient, and thus represents a similar level of soil nutrient availability for a population of soils that is distinguished from other soils by difference in nutrient availability. For a given soil, SNR can be identified in the field using easily observable soil morphological properties as criteria, aided

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by indicator plants — a priori field classification (Green and Klinka 1994; Klinka et al. 1989, 1994); it can also be assigned according to a quantitative classification derived from direct measures of plant-available nutrients — posteriori classification (Klinka et al. 1994; Wang 1997).

Recent research efforts in British Columbia have focussed on (1) characterizing regional soil nutrient gradients, (2) developing regional, quantitative SNR classifications using direct measures of soil nutrients, (3) examining the relationship between qualitative and quantitative SNR classifications, and (4) testing the ecological significance of qualitative and quantitative SNR classifications (Kabzems and Klinka 1987; Courtin et al. 1988; Klinka and Carter 1990; Qian et al. 1993; Green and Klinka 1994; Klinka et al. 1994; Wang et al. 1994; Kayahara et al. 1997; Wang 1997; Carter et al.1998). Subsequent studies examined the influence of direct measures of soil nutrients or SNRs on vegetation patterns (Klinka et al. 1996a) and plant diversity (Qian et al. 1997).

Further studies are needed to determine whether the nutrient properties selected for the characterization of a soil nutrient gradient and the limiting values used to define SNRs in one climatic region are portable to the soils in other climatic regions. Thus this study (a sequel to that of Klinka et al. [1994]) investigates soils of the subalpine boreal ESSF biogeoclimatic zone, which represents a large area of the high-elevation forest in central and southern British Columbia (Krajina 1969; Meidinger and Pojar 1991).

The objectives of the present study were: (1) to characterize plant-available nutrients stratified according to field-identified SNRs, (2) to examine the agreement between qualitatively and quantitatively derived SNRs, (3) to examine relations of site index of subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.) and Engelmann spruce (*Picea engelmannii* Parry ex Engelmann) to (i) categorical measures (qualitative and qualitatively derived SNRs) and (ii) continuous direct measures of soil nutrients, and (4) to compare SNR classifications developed for cool mesothermal, montane boreal, and subalpine boreal soils. These objectives were achieved by examining soil and forest productivity data of 155 study sites using analysis of variance, cluster analysis, discriminant analysis, and regression analysis.

MATERIALS AND METHODS

Study Sites

All 155 study sites were located throughout the ESSF zone. This continental subalpine boreal zone is the uppermost, forested zone in central and southern interior BC. It extends from 49° to approximately 57° N latitude and from approximately 900 to 1700 m in the north, from 1200 to 2100 m in the central part, and from 1500 to 2300 m in the south (Krajina 1969; Meidinger and Pojar 1991). Similar to subalpine vegetation zones in Alberta and in the Pacific Northwest and Rocky Mountain States, the ESSF zone includes closed-canopy forests in lower elevations and parkland forests in upper elevations.

The sites selected for the study supported naturally regenerated (after wildfires), unmanaged stands, ranging in age from 40 to 200 years at breast height. The stands were dominated either by subalpine fir or Engelmann spruce or both species. Most the selected stands were even-aged, i.e., the differences in age at breast height of dominant and codominant trees was ≤20 years. However, some stands were uneven-aged and these stands were excluded from determination of site index. The associated soils were typically loamy-skeletal Brunisols or Podzols (Canadian Soil Survey Committee 1987); humus forms ranged from Mors to Moders to Mulls (Green et al. 1993).

Table 1. Number of study plots in each field-identified combination of soil moisture and nutrient regime

Soil moisture regime	Soil nutrient regime					Total
	Very poor	Poor	Medium	Rich	Very rich	
Moderately dry	1	5	1			7
Slightly dry	3	8	3	1		15
Fresh	1	28	39	12	3	73
Moist		5	7	18	7	37
Very moist			2	8	2	12
Total	10	45	52	42	6	155

The study sites were deliberately located to represent the widest possible range of soil climatic, moisture and nutrient conditions across the zone (Table 1). Wet sites (with growing-season groundwater table at a depth from 0 to 30 cm) were avoided due to the difficulties in determining the nutrient inputs and the influence of stagnant or laterally moving groundwater on nutrient availability (e.g., Brooke et al. 1970; Wali and Krajina 1973).

Measures of Plant-available Nutrients

On each study site, a 20 × 20 m (0.04 ha) sample plot was subjectively located to represent an ecosystem relatively uniform in soil and vegetation. The SNR and **soil moisture regime (SMR)** for each plot were identified in the field using soil morphological properties, indicator plants and the methods described by Green and Klinka (1994). The identification was based on a key (see Klinka et al. 1994) that integrates the effect of several selected, easily observable, soil morphological properties on the level of plant-available nutrients.

In each sample plot, forest floor and mineral soils were sampled at five random sampling points. At each sampling point, samples of entire forest floor and of the 0- to 30-cm mineral soil layer were taken from three points of an equilateral triangle (2 m on a side) located over each sampling point, with a total of 15 subsamples taken from each plot. The subsamples from each plot were composited into two samples (forest floor and mineral soil) for chemical analysis. All samples were air-dried to constant mass. Forest floor samples were then ground in a Wiley mill to pass 2-mm sieve size; mineral soil samples were passed through a 2-mm sieve to separate coarse fragments.

Each composite sample was analyzed for acidity (pH), total carbon (tC), total N (tN), mineralizable-N (min-N), extractable P (eP), extractable SO_4-S (eSO_4-S), and extractable Ca, Mg, and K (eCa, eMG, and eK) using the

Table 2. Means ± standard errors of the means for measured nutrient properties of the forest floor and mineral soil (0–30 cm) according to quantitatively classified groups[z]

	A	B	C	D	E
n	18	47	48	36	6
Forest floor					
pH	4.2±0.1*c*	4.4±0.1*bc*	4.5±0.1*b*	4.9±0.1*a*	5.1±0.3*a*
Total C (%)	47.3±2.0	44.1±1.2	45.7±0.9	42.9±1.1	43.1±2.5
Total N (%)	1.08±0.05*c*	1.28±0.04*b*	1.47±0.05*ab*	1.47±0.06*ab*	1.57±0.09*a*
C:N ratio	44.4±1.7*a*	34.5±0.5*b*	31.9±0.8*c*	30.2±1.0*cd*	28.1±3.2*d*
Min-N (mg kg^{-1})	289±54*c*	448±43*b*	603±43*a*	512±40*ab*	553±49*ab*
Min-N:total N ratio (%)	2.6±0.3*c*	3.3±0.3*b*	3.9±0.2*a*	3.4±0.2*ab*	3.5±0.3*ab*
Extractable P (mg kg^{-1})	158±17*ab*	210±15*a*	121±12*b*	88±9*c*	92±33*bc*
Extractable S (mg kg^{-1})	36.1±7.4	32.6±2.1	42.0±4.2	38.7±2.8	44.2±4.0
Sum of extractable Ca, Mg, and K (g kg^{-1})	4.1±0.8*c*	4.5±0.3*c*	5.7±0.4*b*	8.6±0.8*a*	9.3±1.8*a*
Mineral soil					
pH	4.9±0.1*b*	4.9±0.1*b*	5.2±0.1*ab*	5.7±0.1*a*	5.5±0.1*a*
Total C (%)	3.0±0.5*c*	3.0±0.2*c*	3.3±0.2*c*	4.5±0.5*b*	6.5±0.7*a*
Total N (%)	0.08±0.01*d*	0.12±0.01*cd*	0.17±0.01*c*	0.29±0.02*b*	0.41±0.04*a*
C:N ratio	27.0±1.2*a*	22.8±0.6*b*	20.2±0.5*c*	18.3±0.9*c*	16.2±1.2*c*
Min-N (mg kg^{-1})	3.8±1.2*d*	9.5±0.9*d*	18.9±1.4*c*	54.1±3.2*b*	115±15.3*a*
Min-N:total N ratio (%)	0.5±0.1*e*	0.8±0.1*d*	1.2±0.1*c*	2.0±0.1*b*	2.9±0.4*a*
Extractable P (mg kg^{-1})	45.4±5.9*a*	47.4±5.4*a*	18.3±3.4*b*	8.4±2.2*c*	4.8±1.1*c*
Extractable S (mg kg^{-1})	8.5±1.6*ab*	7.4±0.9*b*	14.0±2.0*a*	8.4±1.3*ab*	7.2±1.4*ab*
Sum of extractable Ca, Mg, and K (g kg^{-1})	0.3±0.1*c*	0.4±0.1*c*	0.9±0.2*b*	4.4±1.4*a*	3.1±0.7*a*

*a–c*Values in the same row with the same letter are not significantly different ($P \leq 0.05$); variables without letters are not significantly different.

analytical procedure described by Klinka et al. (1994). Chemical analysis was done by the BC Ministry of Forests Research Laboratory, Victoria, BC.

Measures of Site Productivity

In each sample plot, three dominant trees of subalpine and/or Engelmann spruce with no visible evidence of growth abnormalities and damage were felled for stem analysis. Height over age curves of the sampled trees were plotted for each study species and plot and examined for uniformity and the presence of suppression. An average height growth curve was computed for site trees using Richard's (1959) three-parameter model (Chen et al. 1998). Site index for each study species and plot was calculated from the fitted height growth curve as the height at 50 yr at breast height.

Data Analysis

Prior to statistical analysis, normality of all soil nutrients and site index variables was assessed by probability plots (Chambers et al. 1983); homogeneity of variance was tested using Bartlett's procedure (Zar 1984). Two new variables — C:N ratio and min-N:tN ratios — were used as indices of organic matter and N qualities, with min-N:tN ratio as an indicator of the portion of total N that could be readily mineralized and made available to plants. These kinds of variables reduce a bivariate space to an uni-dimensional space while retaining the information.

Differences in soil nutrient properties among field-identified SNRs were examined by one-way analysis of variance followed by Bonferonni's test for multiple comparisons (Zar 1984). **Discriminant analysis (DA)** was employed using all forest floor and mineral soil properties as discriminating variables to obtain a five-class quantitative (a posteriori) classification. The field-identified SNRs were submitted to DA. The agreement between the field-identified SNRs (a priori classification) and groups of the a posteriori classification according to all soil nutrient properties was determined after the first run. The misclassified plots by the field-identified procedure were reassigned according to the discriminant functions after each run of DA. The final quantitative classification was obtained after the analysis was repeated until no further misclassifications occurred. The differences in soil nutrient properties among the quantitatively classified groups were also examined by one-way analysis of variance followed by Bonferonni's test for multiple comparisons.

Site index (SNR relationships were examined by multiple regression analysis using both categorical and continuous variables (Chatterjee and Price 1991). To limit the number of independent variables when direct measures of soil properties were used as predictors, backward stepwise procedure was employed using critical $\alpha = 0.05$. Considering the wide geographical range and steep local climatic gradient, regressions included elevation, longitude, and latitude as independent variables. The residuals of regression models were graphically examined for normality and homoscedasticity (Zar 1984).

RESULTS

Stratification according to field-identified SMRs and SNRs showed that the study plots occurred in 19 combinations; however, some combinations, such as those related to water-deficient and nutrient-rich sites or nutrient very poor sites, were poorly represented due to their apparent absence or rare occurrence (Table 1). The distribution pattern was diagonal, i.e., it extended from drier and poorer sites to wetter and richer sites.

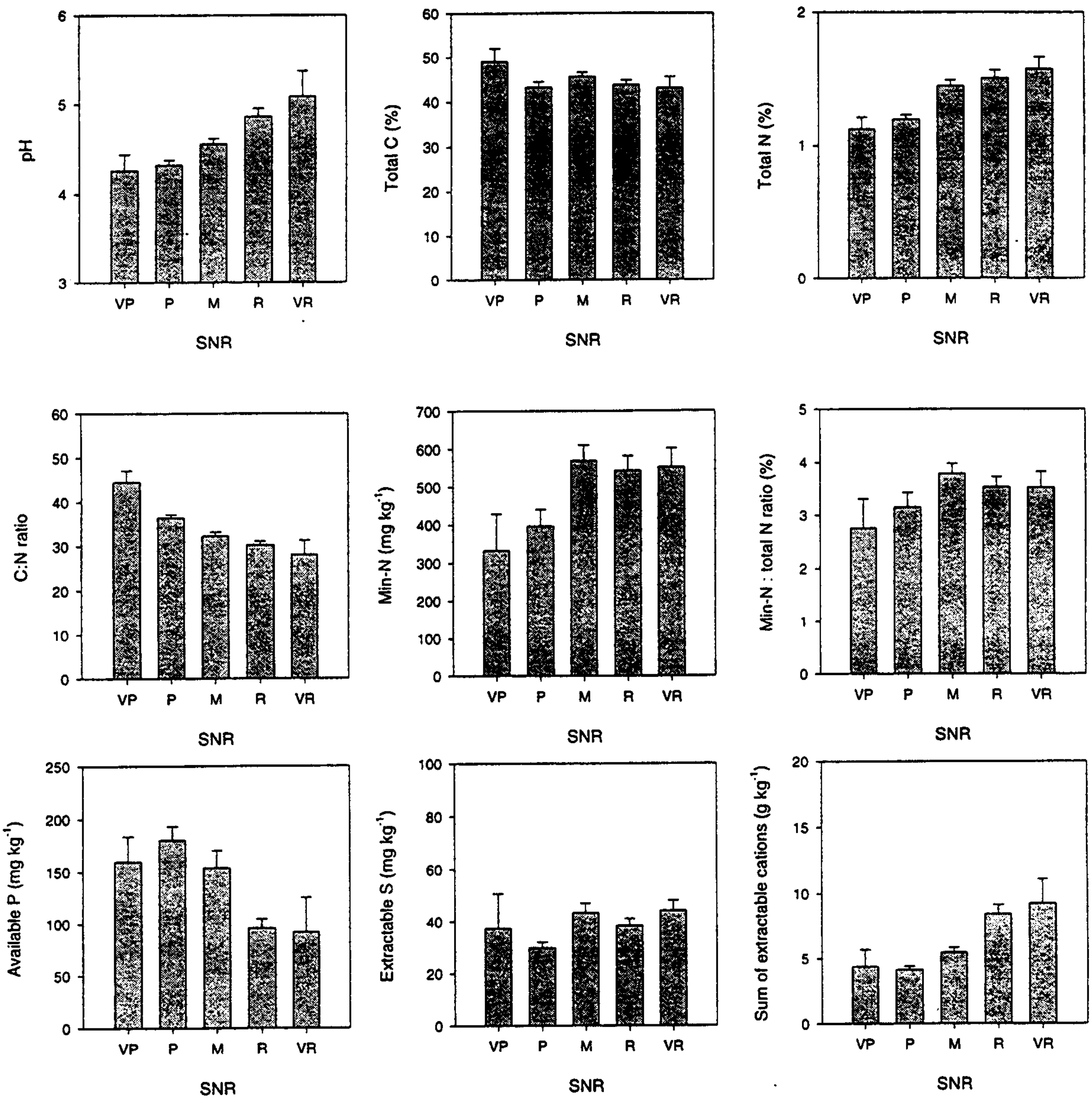

Fig. 1. Direct measures of forest floor properties stratified according to field-identified SNR. Error bar is one standard error for the mean. VP, P, M, R, and VR are very poor, poor, medium, rich, and very rich SNR, respectively.

Characterization of Nutrient Regimes

In view of the mean concentrations of the direct soil nutrient measures, the five qualitative SNRs were more or less equivalent to the five quantitatively derived groups (Table 2, Figs. 1 and 2). Stratification according to field-identified SNRs (a priori qualitative classification) resulted in a regional soil nutrient gradient in most nutrient properties (Figs. 1 and 2). The differences of nutrient properties among SNRs were more pronounced in the mineral soil than in the forest floor (Figs. 1 and 2). In the forest floor, pH, total N, min-N, min-N:tN, and sum of extractable Ca, Mg, and K increased and C:N ratio decreased significantly from very poor to very rich sites (Fig. 1, $P < 0.05$); other properties, however, did not show any consistent increase or decrease with the field-identified SNR. In the mineral soil, total N, min-N, and min-N:total N ratio pronouncedly increased and C:N ratio decreased from very poor through very rich sites, indicating the presence of a steep, N-driven nutrient gradient (Fig. 2, $P < 0.05$). pH, tC, and sum of eCa, eMg, and eK also increased while eP significantly decreased from poor through rich sites ($P < 0.05$).

Stratification according to the five groups derived from the a posteriori quantitative classification produced results

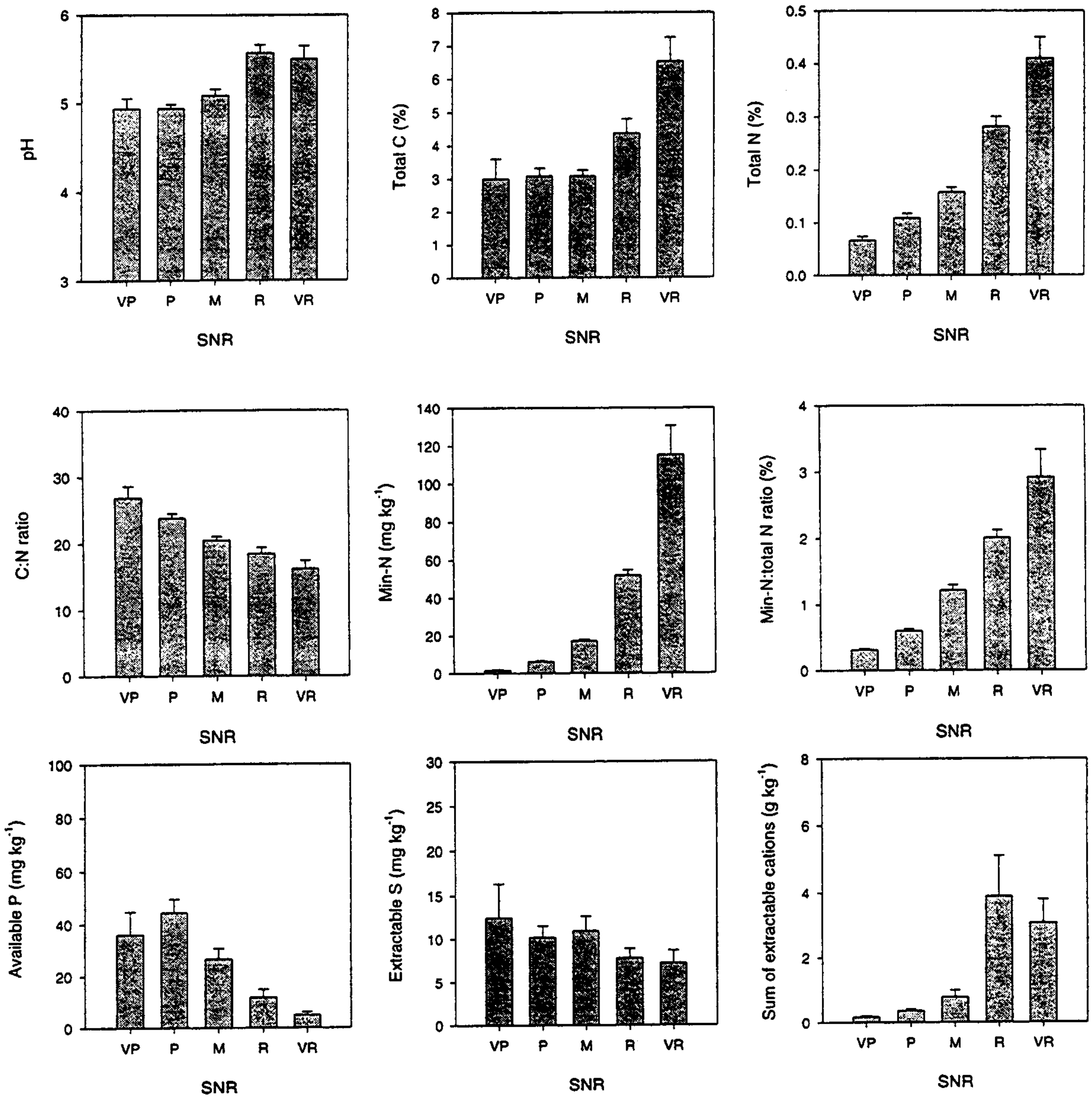

Fig. 2. Direct measures of mineral soil properties stratified according to field-identified SNR. Error bar is one standard error for the mean. VP, P, M, R, and VR are very poor, poor, medium, rich, and very rich SNR, respectively.

similar to those for field-identified SNRs (Table 2). Again, differences among the groups were stronger for the mineral soil than forest floor. Except for eSO_4-S, there were significant differences among the groups for all other forest floor properties ($P < 0.05$). Acidity and C:N ratio of the forest floor and the mineral soil showed consistent trends of change along the regional soil nutrient gradient from group A (relatively poorest sites) through group E (relatively richest sites). All mineral properties were significantly different among the five groups, with nitrogen-related properties — C:N ratio, tN, min-N, and min-N:tN — showing the largest variation.

Comparison of Qualitative and Quantitative Classifications

When the a priori and a posteriori classifications were compared, 111 (71.6%) study sites fell into the same SNR/group, 40 (25.8%) sites fell to the adjacent SNRs/groups, and 4 (2.6%) sites were apart two or more SNRs/groups (Table 3). There was no discrepancy between very rich SNRs and group E; however, there were discrepancies between the other SNRs and groups (A–D). For example, from 52 study sites that were field-identified as having medium SNRs, about 40% were placed by multivariate analysis into poorer (A or B) or richer (D) groups;

Table 3. Comparison of two soil nutrient regime classifications: (1) qualitative (based on field observable soil morphological properties (rows), and (2) quantitative (based on direct soil nutrient measures and multivariate analysis (columns)[z]

	A (Very poor)	B (Poor)	C (Medium)	D (Rich)	E (Very rich)	Total	Agreement (%)
Very poor	**8**	1	1			10	80
Poor	8	**30**	7			45	67
Medium	2	15	**33**	2		52	63
Rich		1	7	**34**		42	81
Very rich					**6**	6	100
Total	18	47	48	36	6	155	72

[z]Values in bold print indicate agreement and underlined values indicate disagreement by two or more classes.

indicating disagreement between qualitative with quantitative classification. From 48 study sites that were classified by multivariate analysis into C (medium) group about 30% were estimated in the field as having very poor, poor, or rich SNRs, indicating disagreement between the two classifications.

Relations of Site Index to Different Measures of Nutrients

Three types of linear regression models were developed to estimate site index for each study species: (1) the SNR model using field-identified SNRs as dummy variables (Eqs. 1 and 4), (2) the model using groups derived from multivariate analysis as dummy variables (Eqs. 2 and 5), and (3) the analytical model using direct measures of soil nutrient properties as continuous variables (Eqs. 3 and 6) (Table 4). Each model included elevation and latitude and/or longitude as surrogates for climate to account for its strong influence on tree growth (Klinka et al. 1996b).

All models were significant ($P < 0.001$) and indicated the presence of strong relationships between site index and climatic and soil nutrient variables. As expected, site index decreased with increasing elevation, latitude, and longitude, and increased with increasing levels of plant-available soil nutrients. The models for Engelmann spruce accounted for a larger proportion of the variation in site index than those for subalpine fir — adjusted R^2 ranged from 0.47 to 0.65 for Engelmann spruce compared with 0.41 to 0.47 for subalpine fir (Table 4). Regardless of study species, the strength of relationships between site index and independent variables determined by each model was quite similar. The analytical models tended to have better relationships compared with the SNR and Group models (adjusted R^2 ranged from 0.47 to 0.65) (Table 4).

SNR Classifications Developed from Different Climates

Mineral soil min-N has been considered the best measure to differentiate between field-identified SNRs in two previous studies (Klinka and Carter 1990; Klinka et al. 1994) (Table 5). The min-N values determined for very poor, poor, medium, and rich SNRs were very similar for continental subalpine and continental montane boreal climate, except for the very rich SNR, which had a considerably higher min-N value in the montane than subalpine boreal region. The min-N values for poor, medium, and rich SNR in the boreal climates were similar to those in the mesothermal climate; however the min-N values for the very poor SNRs were higher and for the very rich SNR were lower in the boreal than mesothermal region.

DISCUSSION

The intent of the SNR concept is to organize forest soils into a uni-dimensional space that best reflects the differences in the levels of plant-available soil nutrients. Nutrient availability is the result of a balance between different physical and chemical processes, but very often a few elements or processes dominate or regulate the system. SNR classification tends to focus on the relevant processes or elements. The previous SNR studies (Klinka and Carter 1990; Klinka et al. 1994; Wang 1997) and numerous forest fertilization studies (Ballard and Carter 1986; Heilman 1979; Carter et al. 1998) suggest that nitrogen is the most growth-limiting nutrient in the Pacific Northwest. Therefore, we focused on nitrogen, specifically on min-N that has been considered to be a useful index of plant available nitrogen (e.g., Timmer 1987; Carter and Klinka 1990). SNRs should be viewed as N-driven indices of plant-available soil nutrients.

Characterization of study sites, stratified according to field-identified SNRs or groups derived from multivariate analysis, produced similar results (Tables 3 and 4). Nitrogen-related properties (C:N ratio, tN, min-N, and min-N:tN ratio) in the mineral soil were the most useful discriminating properties in this study as well as previous studies of SNR (Klinka et al. 1994; Wang 1997). Other macronutrients such as Ca, Mg, K, P, and S appeared to be correlated with nitrogen. This nutrient profile indicates that the soil nutrient gradient in boreal and other climatic regions is well represented by nitrogen-related variables, particularly indices of plant-available soil N.

The smaller differences among field-identified SNRs for the forest floor properties is likely due to the presence of similar humus forms — Hemimors (Green et al. 1993) — in most of the study sites. Regardless of the stand development stage, decomposition of forest floor materials in the ESSF zone is slow, due to the cool and short growing season, and results in the development of acidic and a compacted Mors over wide range of sites (Krajina 1969).

Discrepancies encountered in assignments of study plots into SNRs and groups are the consequence of the differences in criteria between qualitative and quantitative classification. While multivariate analysis was based entirely on the direct measures of selected soil nutrient properties, the heuristic procedure used to identify SNRs in the field was

Table 4. Models for the regression of subalpine fir and Engelmann spruce site index (SI) on categorical and continuous soil nutrient variables[z]

Subalpine fir				
(1)	SI = 145.9 – 0.013(ELE) – 0.858(LAT) – 0.705(LONG) + 1.6(P) + 3.7(M) + 2.6(R) + 5.1(VR)			
	Adjusted R^2 = 0.41	SEE = 3.44 m	P <0.001	n = 101
(2)	SI = 145.9 – 0.013(ELE) – 0.858(LAT) – 0.705(LONG) + 1.6(B) + 3.7(C) + 2.6(D) + 5.1(E)			
	Adjusted R^2 = 0.41	SEE = 3.44 m	P <0.001	n = 101
(3)	SI = 125.2 (0.011(ELE) (0.927(LONG) + 4.88(tNff) (0.06(eSO_4-Sms) + 2.2(pHms) (0.21(SEBms)			
	Adjusted R^2 = 0.47	SEE = 3.26 m	P <0.001	n = 101
Engelmann spruce				
(1)	SI = 183. 8 – 0.019(ELE) – 1.147(LAT) – 0.705(LONG) + 3.3(M) + 0.7(R) + 1.9(VR)			
	Adjusted R^2 = 0.52	SEE = 3.04 m	P <0.001	n = 52
(2)	SI = 174.0 – 0.018(ELE) – 1.205(LAT) – 0.629(LONG) + 4.3(B) + 4.6(C) + 2.5(D) + 3.9(E)			
	Adjusted R^2 = 0.47	SEE = 3.19 m	P <0.001	n = 52
(3)	SI =249.9 – 0.02(ELE) – 1.06(LAT) – 1.18(LONG) (0.37(C/Nff) + 0.21(C/Nms) (0.08(eSO_4-Sms) (0.5(SEBms)			
	Adjusted R^2 = 0.65	SEE = 2.58 m	P <0.001	n = 52

[z]Abbreviations used are: ELE, elevation (m); LAT, N latitude (degrees and minutes in metric); LONG, W longitude (degrees and minutes in metric); P, poor; M, medium, R, rich, and VR, very rich are qualitative SNRs (based on field observable soil morphological properties); A, group A; B, group B; C, group C; D, group D; and E, group E are quantitative SNRs (based on direct soil nutrient measures and multivariate analysis); ff, forest floor property; ms, mineral soil property; tN, total N (%); eSO_4-S, extractable SO_4-S (mg kg^{-1}); pH, acidity; C/N, C:N ratio; SEB, sum of extractable Ca, Mg, and K (mg kg^{-1}).

Table 5. Means and standard deviations (in parentheses) of mineral soil (0–30 cm) mineralizable-N (mg kg^{-1}) for soil nutrient regimes as determined in four independent studies conducted in different climatic regions

	Soil nutrient regime				
Climate/study	Very poor	Poor	Medium	Rich	Very rich
			Continental subalpine boreal		
This study (SNRs)	1.6 (1.4)	6.2 (3.8)	17.3 (5.8)	51.9 (18.4)	115.3 (37.5)
This study (Groups)	3.8 (5.3)	9.5 (6.0)	18.9 (9.9)	54.1 (19.2)	115.3 (37.5)
			Continental montane boreal		
Klinka et al. (1994)	0.8 (0.9)	5.0 (2.4)	17.0 (7.5)	47.0 (23.0)	181.0 (67.0)
			Cool mesothermal		
Klinka and Carter (1990)	7.0 (2.8)	9.5 (4.5)	17.5 (13.5)	31.1 (11.4)	49.6 (37.9)
Varga and Klinka (unpublished manuscript)	15 (6)	41 (13)	85 (26)	173 (29)	322 (74)

based on soil morphological properties (such as humus form quality, rooting depth, soil texture, soil colour, content of coarse fragments, and the presence of seepage) and was aided by indicator plant analysis. Thus, compared with groups, field-identified SNR accounted, to some extent, for nutrient content and possible nutrient inputs. Nevertheless, the SNR and the groups from the quantitative classification had a high percentage of agreement. The value of using plants as indicators of plant-available soil N in characterizing SNRs was demonstrated by Courtin et al. (1988) and Wang (1997).

Indirect and direct measures of soil nutrients provided a similar accountability for the variation in site index of subalpine fir and Engelmann spruce over a large geographical area (Table 5). This indicates (i) that the usefulness of the qualitative SNRs (field-identified by the heuristic procedure) is similar to quantitative SNRs (groups derived from discriminant analysis) and (ii) that the indirect measure provides good estimates of the direct soil nutrient measures. We suggest that stronger relationships between site index and soil nutrients cannot be expected considering (i) a strong influence of subalpine boreal climate on tree growth, which could be accounted for by elevation, latitude, and longitude, (ii) limitations of chemical analysis in providing accurate measures of plant-available nutrients, especially for the dynamics of nutrients in natural environments and nutrient inputs by myccorhizal fungi and seepage, (iii) the use of a portion of the available rooting space and nutrient concentrations instead of contents, and (iv) ignoring soil moisture, aeration, and temperature conditions of the soil.

Similarities in min-N values for field-identified SNRs between different studies support the use of the existing heuristic procedure in different climatic regions; however, the comparison also indicates differences in soil nutrient gradients among regions (Table 4). The differences may be a result of different soils and processes in different regions as well as differences in sampling. Podzols that are characteristic of humid coastal and subalpine soils had higher carbon and nitrogen concentration than Brunisols and Luvisols that were frequent in the sub-humid montane boreal region (Valentine et al. 1978; Carter et al. 1985). Compared with the other studies, the highest mean min-N concentrations for any particular SNR came from West Vancouver Island (Varga and Klinka, unpublished manuscript). It appears that when the values from this perhumid region are shifted to the right they correspond better to the other studies, e.g., the values for the very poor and medium SNRs more or less agree with those for medium and rich SNRs of the other studies, however, the values for the medium, rich, and very rich SNRs agree poorly with those determined by the other studies (Table 5).

Sampling in the montane boreal region was done in lodgepole pine and interior spruce (*Picea engelmannii* Parry *ex* Engelm. × *P. glauca* [Moench] Voss) stands; the former species growing on the driest and poorest sites, such as coarse-skeletal fluvial soils, and both occurring on high-organic matter soils, such as Humic Gleysols with a fluctuating water table. Such soils were not sampled in the subalpine region because they typically support non-forest ecosystems. A possible explanation for the poor agreement between the very poor and very rich SNRs of Klinka and Carter (1990) and the studies conducted in the boreal region is that an incomplete range of the regional soil nutrient gradient was sampled by Klinka and Carter (1990). They sampled Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) stands in a summer-dry, coastal region. Douglas-fir occurs very infrequently on the driest and poorest and wettest and richest sites (Krajina 1969; Krajina et al. 1982), and the soils in this climatic region are typically low in C and N (Carter et al. 1985). Future SNR studies should be carried out in stands along the entire soil nutrient gradient regardless of tree species composition. However, to accommodate regional differences, it may be necessary to consider additional SNRs to the existing five classes.

CONCLUSIONS

Nitrogen related variables (C:N ratio, total N, mineralizable N, and mineralizable N:total N ratio) in the mineral soil were the best nutrient properties to segregate soil nutrient regimes for both qualitative (a priori) and quantitative (a posteriori) classifications. The two classification methods had 72% agreement. Regardless of the difference in assigning the study sites into one of the five soil nutrient regimes between the classifications, both qualitatively and quantitatively derived soil nutrient regimes had a similar accountability for the variation in site index of subalpine fir and Engelmann spruce. This similarity justifies the use of the a priori classification in estimating ecological quality of forest sites.

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