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Spatial variability of humus forms in some coastal forest ecosystems of British Columbia

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Summary — The spatial variability of 5 humus form properties (thickness, acidity, total C, total N and mineralizable-N) was examined in 3 coastal forest sites of different tree species composition (western hemlock, Douglas-fir and western redcedar), humus forms, and ecological site quality using variogram and kriging. Humus form properties were found spatially dependent and the kriging interpolation between sample locations unbiased for all 5 properties and in all 3 sites. The overall range of spatial dependence ranged from 46 to 1 251 cm, but varied with property and site. The average range for the humus form properties increased from 109 cm (total N) to 704 cm (mineralizable-N), and that for the sites increased from 275 cm (western hemlock) to 581 cm (Douglas-fir). It appears that humus forms in each site occur in polygons with the lateral dimension ranging from 100 to 700 cm. The spatial pattern of each property in each site was portrayed in contour maps.

humus form / spatial variability / variogram / kriging

Résumé — Variabilité spatiale des types d'humus dans quelques écosystèmes forestiers côtiers de Colombie britannique. *La variabilité spatiale de 5 caractéristiques de l'humus (épaisseur, acidité, carbone total, azote total et minéralisable) a été étudiée dans 3 sites forestiers côtiers, différant par l'espèce dominante (pruche de l'Ouest, douglas et thuya géant), le type d'humus et le type de station. Elle est analysée par variogramme et krigeage. Ces propriétés des types d'humus sont dépendantes spatialement, et l'interpolation par krigeage entre les points d'échantillonnage est non biaisée pour les 5 propriétés et les 3 sites. La portée globale de dépendance spatiale varie de 46 à 1 251 cm, mais dépend de la propriété considérée et du site. La portée moyenne pour les propriétés de l'humus varie entre 109 cm (pour l'azote total) à 704 cm (pour l'azote minéralisable), et cella des sites varie entre 275 cm (sous pruche de l'Ouest) à 581 cm (sous douglas). Il apparaît que les types d'humus dans chaque site sont groupés en polygones dont la dimension varie entre 100 et 700 cm. La variabilité spatiale de chaque propriété dans chaque site est illustrée par des cartes obtenues par krigeage.*

type d'humus / variabilité spatiale / variogramme / krigeage

INTRODUCTION

Humus form is a group of soil horizons located at or near the surface of a pedon, which have formed from organic residues, either separate from, or intermixed with, mineral materials (Green *et al,* 1993). In consequence, humus forms may be comprised of entirely organic or both organic and mineral (melanized A) horizons. Due to the difficulties in combining organic and mineral horizons in chemical and data analyses (Lowe and Klinka, 1981), this study examined only the organic or the forest floor portion of humus forms.

As the product of biologically mediated decomposition processes, the humus form that has developed on a particular site depends on the biota and environment of that site. Both biota and environment may change over a short distance, yielding a variety of microsites which support the development of different humus forms. The nature of spatial variability in humus forms is itself scale-dependent because the factors and processes of humus formation interact over many different spatial scales. It seems reasonable to assume that, on average, the closer humus forms are to each other, whether in space or time, the more likely it is their properties will be similar. This assumption calls for an inquiry into the nature and degree of spatial dependence between the humus forms, particularly in the sample plots chosen to represent individual ecosystems, *ie* segments of landscape relatively uniform in climate, soil and vegetation (Pojar *et al,* 1987).

Classical statistical techniques are unable to treat adequately the spatial aspect of data in which neighboring samples may not be independent of each other; furthermore, they do not consistently provide unbiased estimates for unsampled points, or estimate optimal variances for the interpolated values (Matheron, 1963; Journel and Huijbregts, 1978; Yost *et al,* 1982a; Robertson, 1987; Rossi *et al,* 1992). Geostatistics can be used to quantify the spatial dependence between sampling locations and to provide optimal estimates for unsampled locations (Matheron, 1963, 1971; Burgess and Webster, 1980a; Vieira *et al,* 1981; Yost *et al,* 1982b). Central to geostatistics is the variogram, which models the average degree of similarity between the values as a function of their separation distance, and kriging, which estimates values for unsampled locations without bias and with minimum variance.

Geostatistics has been extensively used in mining (*eg* Matheron, 1963, 1971; Krige, 1966; David, 1977; Clark, 1979; Journel and Huijbregts, 1978) and, more recently applied in soil science (*eg* Nielsen *et al,* 1973; Biggar and Nielsen,1976; Campbell, 1978; Burgess and Webster, 1980a, b; Vieira *et al,* 1981; Yost *et al,* 1982a, b; Xu and Webster, 1984), hydrology (*eg* McCullagh, 1975; Delhomme, 1976, 1978, 1979; Hajrasuliha *et al,* 1980; Kitandis, 1983), ecology (*eg* Robertson, 1987; Kemp *et al,* 1989), vegetation science (*eg* Palmer, 1988; Fortin *et al,* 1989), but no systematic effort has yet been made to apply it to humus form studies.

The objective of this study was to examine the spatial variation of 5 selected humus form properties – thickness, acidity, total C, total N and mineralizable-N – in disturbed and undisturbed coastal forest ecosystems. This objective was accomplished by employing variogram and kriging for the analysis of spatial variability of these properties. The thickness was thought the most variable morphological property, reflecting difference in the deposition and decomposition of organic residues in both space and time. The significance of the 4 selected chemical properties has been long recognized in humus form classification (Green *et al,* 1993).

MATERIALS AND METHODS

All study sites were located near Vancouver, British Columbia, and were within the Coastal Western Hemlock (CWH) zone, which delineates the sphere of influence a cool mesothermal climate (Klinka *et al,* 1991). The soils in the area are typically coarse-textured humo-ferric podzols (Canada Soil Survey Committee, 1978) derived from granitic morainal deposits.

The study sites were deliberately chosen to represent forest ecosystems with different vegetation, humus forms, ecological site quality and history of disturbance (table I). The first site (Hw) was dominated by western hemlock (*Tsuga heterophylla* [Raf] Sarg), the second (Fd) by Douglas-fir (*Pseudotsuga menziesii* [Mirbel] Franco), and the third (Cw) by western redcedar (*Thuja plicata* Donn ex D Don). The western hemlock site had a well-developed moss layer dominated by *Plagiothecium undulatum* (Hedw) BSG, and Mors (Hemimors and Lignomors) (Green *et al,* 1993) were the prevailing humus forms; the Douglas-fir site had a well-developed herb layer with abundant *Polystichum munitum* (Kaulf) Presl and *Dryopteris expansa* (K Presl) Fraser-Jenkins & Jermy, and Mormoders were the prevailing humus forms; and the western redcedar site had well-developed shrub and herb layers dominated by *Athyrium filix-femina* (L) Roth, *Rubus spectabilis* Pursh and *Tiarella trifoliata* L, and Leptomoders and Mullmoders were the prevailing humus forms (table III). Using the methods described by Klinka *et al* (1984, 1989), the western hemlock site was considered slightly dry and nitrogen-poor; the Douglas-fir site, fresh and nitrogen-rich and the western redcedar site, moist and nitrogen-very rich.

At each study site, a 20 x 20 m (0.04 ha) sample plot was located to represent an individual ecosystem. Within each plot, a 10 x 10 grid, 1 x 1 m, and a 7 x 7 grid, 15 x 15 cm, were laid out for sampling humus forms. One-hundred discontinuous samples were collected from the large, 10 x 10 grid at the center of each 1 x 1 m quadrant, and 49 contiguous samples were taken from the small, 7 x 7 grid – a total of 149 humus form samples per site. The small grid provided data for the analysis of a small-scale pattern (the sampling interval of 15 cm), while the large grid provided data for the analysis of a large-scale pattern (the sampling interval of 1 m).

Each humus form sample was a composite of all of its organic horizons (except recently shed litter), and represented a uniform, 15 x 15 cm column cut by knife from the ground surface to the boundary with mineral soil. Each sample was

Table I. General characteristics of the study sites.

Site	*Dominant tree species*	*Climate*	*Soil moisture regime*	*Soil nutrient regime*	*History*	*Stand description*
Hw	Western hemlock	Humid mesothermal	Slightly dry	Poor	Cut in 1910	Naturally established, unmanaged even-aged, 80-year-old, mid-seral stage
Fd	Douglas fir	Humid mesothermal	Fresh	Rich	Cut in 1910 Fire in 1919	Naturally established, unmanaged even-aged, 75-year-old, mid-seral stage
Cw	Western redcedar	Perhumid mesothermal	Moist	Very rich	Undisturbed	Unmanaged, uneven-aged (mean age of tree layer ≈ 450 years), edaphic climax ?

described and identified according to Green *et al* (1993), its grid location recorded and its thickness determined by taking 4 measurements at each cardinal direction with a steel ruler.

All samples were air-dried to constant mass and ground in a Wiley mill to pass through a 2-mm sieve. The chemical analysis was done by Pacific Soil Analysis Inc (Vancouver, BC) and the results were expressed per unit of mass (tables II and III). Humus form pH was measured with a pH meter and glass electrode in water using a 1:5 suspension. Total C (tC) was determined using a Leco Induction Furnace (Bremner and Tabatabai, 1971). Total N (tN) was determined by semimicro-kjeldahl digestion followed by determination of NH_4-N using a Technicon Autoanalyzer (Anonymous, 1976). Mineralizable-N (min-N) was determined by an anaerobic incubation procedure of Powers (1980) with released NH_4 determined colorimetrically using a Technicon Analyzer.

For the geostatistical analyses, we used the GS+ geostatistical package (Gamma Design Software, 1992) following the theory and principles given by Matheron (1963, 1971), Journel and Huijbregts (1978), David (1977), Delhomme (1978), Vieira *et al* (1981, 1983), Vauclin *et al* (1983), Webster (1985), Trangmar *et al* (1985) and Isaaks and Srivastava (1989). Consider that a humus form property is a regionalized variable $Z(x)$ and that its measurements at places x_i, $i = 1, 2, 3, \ldots, n$, constitute n discrete points in space, where x_i denotes a set of spatial coordinates in 2 dimensions. The measurements give a set of values $z(x_i)$, and the semivariance that summarizes the spatial variation for all possible pairing of data is calculated by:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2 \qquad [1]$$

where the value $\gamma(h)$ is the estimated half- or semivariance for h, which is a vector known as the lag, with both distance and direction, and $N(h)$ is the number of pairs of points separated by h. A plot of the estimated $\gamma(h)$ values against h is called a *semivariogram* or *variogram*.

By definition, the variogram value at zero lag should be zero, but in practice it usually intercepts the ordinate at a positive value known as the *nugget variance* (c_0). The nugget represents measurement error and unexplained or random spa-

Table II. Means, coefficients of variation (CV), variances and skewness of 5 humus form properties in 3 study sites ($n = 149$ for each site).

Property	*Site*	*Mean*	*CV (%)*	*Variance*	*Skewness*
Thickness (cm)	Hw	6.5	53.2	11.9	1.81
	Fd	7.0	57.5	16.2	1.75
	Cw	6.4	44.7	8.2	0.40
pH	Hw	3.6	6.2	0.05	−1.13
	Fd	4.0	6.8	0.08	1.50
	Cw	3.9	8.7	0.12	1.15
tC(%)	Hw	51.0	4.6	5.46	−0.94
	Fd	50.0	5.2	6.84	−0.48
	Cw	43.2	21.6	87.4	−0.67
tN (%)	Hw	1.34	17.0	0.05	−1.12
	Fd	1.53	14.3	0.05	−1.54
	Cw	1.43	21.1	0.09	−0.16
min-N (ppm)	Hw	104	41.2	1 824	0.11
	Fd	189	52.1	9 722	1.10
	Cw	414	29.7	15 118	0.50

Table III. Means and coefficients of variation (in parentheses) of 5 humus form properties in 3 study sites stratified according to humus form taxa (n = 149 for each site).

Site	*Humus form taxon*	*No of samples*	*Thickness (cm)*	*pH*	*tC (%)*	*tN (%)*	*min-N (ppm)*
Hw	Hemimor	83	5.6	3.6	50.5	1.41	116
			(48)	(6.0)	(4.6)	(6.5)	(33)
	Lignomor	48	8.2	3.5	51.9	1.15	77
			(52)	(5.6)	(4.1)	(21)	(50)
	Mormoder	13	5.0	3.7	49.6	1.59	133
			(33)	(7.5)	(3.5)	(15)	(26)
	Ligmomoder	5	9.2	3.5	52.9	1.20	85
			(29)	(4.7)	(2.6)	(29)	(35)
Fd	Hemimor	10	10.0	4.0	50.7	1.57	130
			(58.7)	(6.8)	(4.5)	(7.5)	(56)
	Lignomor	12	13.8	3.8	53.9	1.08	77
			(37.2)	(7.0)	(3.4)	(29)	(54)
	Mormoder	73	6.3	4.0	49.6	1.62	178
			(38)	(5.0)	(4.7)	(7.3)	(39)
	Leptomoder	37	4.7	4.2	49.0	1.59	292
			(39)	(7.6)	(5.1)	(8.8)	(34)
	Lignomoder	17	8.1	3.8	50.6	1.31	125
			(51)	(4.1)	(4.3)	(9.3)	(35)
Cw	Leptomoder	123	5.8	3.9	42.1	1.47	426
	(Mullmoder)		(43)	(8.5)	(22)	(20)	(28)
	Lignomoder	26	9.2	3.7	48.3	1.22	355
			(32)	(6.6)	(16)	(21)	(36)

tial variability at distances smaller than the smallest sampling interval. The variogram value at which the plotted points level off is known as the *sill*, which is the sum of *nugget variance* (c_0) and *structural variance* (c), and the *lag distance* (a) at which the variogram levels off is known as the *range* (or the zone of influence) beyond which there is no longer spatial correlation and, hence, no longer spatial dependence.

Local estimation by kriging required fitting a continuous function to the computed experimental semivariance values. The most commonly used models are: linear, linear with sill, spherical, exponential and gaussian (Journel and Huijbregts, 1978; Tabor *et al*, 1984; McBratney and Webster, 1986; Oliver and Webster, 1986). Experimental variogram values for each humus form property were fitted to each model by least square approximation. Using Akaike's (1973) information criterion (AIC), the spherical (eq [2]) and exponential (eq [3]) isotropic models were found best fitting the data:

$$\gamma(h) = c_0 + c\{1.5\,(h/a) - 0.5\,(h/a)^3\} \text{ for } 0 < h \leq a$$
$$\gamma(h) = c_0 + c \quad \text{for } h > a \qquad [2]$$
$$\gamma(0) = 0$$

$$\gamma(h) = c_0 + c\{1 - \exp(-h/a_0)\} \quad \text{for } 0 < h \qquad [3]$$
$$\gamma(0) = 0$$

where c_0, c, a and a_0 are nugget variance, structural variance, range and range parameter, respectively. Because the semivariance from an exponential isotropic model approaches the sill asymptotically, there is no absolute range. A working range of $a = 3\,a_0$, a lag at which the semivariance is 95% of the sill values, was estimated for practical purposes (Oliver and Webster, 1986).

With appropriate variogram models defined, kriging was used to interpolate between sample points and to estimate the values for unsampled locations. Kriging is a weighted moving average with an estimator:

$$\hat{z}(x_0) = \sum_{i=1}^{n} \lambda_i z(x_i) \qquad [4]$$

where n is the number of values $z(x_i)$ for the sampled locations involved in the estimation of the unsampled location x_0, and λ_i are the weights associated with each sampled location value.

Kriging is considered an optimal estimation method as it estimates values for unsampled locations without bias and with minimum variance. No estimation method is without estimation errors, thus there is an error associated with kriging. The magnitude of this error will be a measure of the validity of estimation. The goodness of estimation can be determined by comparing the difference between the measured value at a given location with its kriged value at the same location, using neighborhood values but not the measured value itself. Thus, if for each location with a measured value $z(x_i)$, where $i = 1, 2, 3, \ldots, n$, the estimated value is $\hat{z}(x_i)$, where $i = 1, 2, 3, \ldots, n$, then the calculated set of estimated errors is $\varepsilon_i = \hat{z}(x_i) - \hat{z}(x_i)$, where $i = 1, 2, 3, \ldots, n$. The goodness of estimation is expressed by 2 conditions on the estimated error: 1) a mean error, $m_{\hat{\varepsilon}}$, close to zero – this property of the estimator is known as unbiasedness, and 2) dispersion of the errors was to be concentrated around m_ε – this being expressed by a small value of the estimated variance σ_ε^2 (table VI).

For statistical analyses, we used the SYSTAT (Wilkinson, 1990a, b). Prior to geostatistical analysis, humus form variables for each study stand were examined for normality, using probability distribution diagrams (Wilkinson, 1990a). The thickness values in the western hemlock and Douglas-fir sites and the acidity and min-N values in the Douglas-fir site were log-transformed as they were found log-normally distributed.

RESULTS AND DISCUSSION

A univariate summary of humus form data according to study sites suggested the presence of comparable mean values for the 5 properties but dissimilar distributions, except for mineralizable-N (table II). The values of coefficient of variation and variance implied trends of a low variability around mean acidity and total C (except in the western redcedar site), a moderate variability around mean total N and a high variability around mean thickness and mineralizable-N. Skewness values indicated an asymmetric distribution for each property in 1 or 2 study sites (table II). When considering the skewness values (table II) and the univariate summary of data stratified according to both humus form taxa and study sites (table III), the acidity data for the Douglas-fir site were strongly skewed to the right, reflecting the presence of relatively less-acid Leptomoders occupying mineral mounds. The acidity and carbon data for the western redcedar site were skewed to the right and left, respectively, attesting to the presence of more-acid and carbon-richer Lignomoders relative to dominant Leptomoders. The total N data for both Douglas-fir and western hemlock sites were strongly skewed to the left, indicating the presence of nitrogen-richer Mormoders relative to the other humus forms on these sites. In the Douglas-fir site, the distribution of mineralizable-N was skewed to the right, manifesting the presence of Lignomors – the humus form with the lowest concentration of available N. The distribution of thickness data in both Douglas-fir and western hemlock sites was highly asymmetric and strongly skewed to the right, indicating the presence of disturbed microsites (mineral mounds) with thin forest floors.

Although univariate measures provided useful summaries, they did not describe spatial continuity of the data, *ie* the relationship between the value for a property in one location and the values for the same property at another location. The spatial continuity of each humus form property and study site was examined by the variograms computed as an average overall direction using equation [1] and assuming isotropy – similar spatial continuity with direction. The data collected from the small, 7 x 7 grids were used for the lag distance (h) $\leq$ 100 cm, and those collected from the large 10 x 10 grid were used for the lag distance > 100 cm. Although the maximum lag distance could have been 1 000 cm, the maximum h of 800 cm was used in order to have each lag class adequately represented by a sufficient number of data.

The parameters of the models fitted to experimental variograms are given in table IV, and the fitted regression lines are shown in figure 1. The models used for fitting produced transitive variograms, which are forms of second-order stationarity with finite variances represented by the sill; the spherical models represent the variograms with fixed range, the exponential models the variograms without fixed range.

The computed and plotted variograms showed that the distribution of each of the 5 humus properties is not random but spatially-dependent as their estimated variogram values increase with increasing lags to their sills, at a finite lag or approaching the sill asymptotically (table IV, fig 1). Overall, the variograms were generically similar, reflecting relatively small differences in spatial continuity of their properties, and implying a small-scale spatial pattern of humus form variability. Despite the overall similarity, the variograms varied with property and site.This suggested that each property has a somewhat different spatial pattern imposed by the property itself, the factors controlling humus form development in each site, and the history of site disturbance.

The average range values for the humus form properties increased from 109 cm for total N to 708 cm for mineralizable-N, and those for the study sites increased from 275 cm in the western hemlock site to 581 cm in the Douglas-fir site. Thus, the ranges beyond which humus forms are no longer spatially dependant were short for both the properties and sites. It appears that in all study sites humus forms have developed in polygons with the lateral dimension ranging from about 100 to 700 cm, and that their spatial continuity increases somewhat from disturbed to undisturbed sites.

The property with the absolutely shortest range (46 cm) was total N in the disturbed western hemlock site (table IV, fig 1). This feature manifests a nearly random spatial pattern of Hemimors and Mormoders *versus* Lignomors and Lignomoders, each pair with strongly contrasting N concentrations (table III). The property with the absolutely longest range (1 251 cm) was mineralizable-N in the Douglas-fir site (table IV). This feature indicates a low spatial variability, which might be related to a uniform forest floor cover resulting from disturbance.

To compare the nugget effect within- and between-site, relative nugget variances, *ie* (real) nugget variances out of sills in percentage, were calculated (table IV). These variances also varied with property and site (fig 1). The relative nuggets for easily measured thickness and acidity were clearly smaller than those for total C, total N and mineralizable-N (table IV), *ie* the properties with a greater likelihood of analytical error. The low relative nuggets for thickness and acidity, ranging from 0.2 to 14.0%, indicated that their structural variances account for more than 85% of their sill variances and approach their overall sample variances. The high relative nuggets for total C, total N and mineralizable-N, ranging from 32 to 70%, indicated that their nuggets represent a large proportion of their total variance that can be modelled as spatial dependence from the available sampling scheme.

Using the variogram models (table IV) with kriging algorithm (eq [4]), the values for each of the 5 humus form properties were estimated for a total of 1 581 unsampled locations in each large (10 x 10 m) grid. Since the configuration of sampling locations had the regular, 100 cm sampling inter-

Table IV. Parameters of the models fitted to experimental variograms for 5 humus form properties in 3 study sites.

Property	*Site*	*Model*	*Nugget variance*		*Structural variance*	*Sill*	*Range (cm)*	*Residual sum of squares*	*Correlation coefficient*
			Real	*Relative*					
			c_o		c		a		
Thickness	Hw*	Eq [2]	0.03	12.4	0.213	0.243	141	1.4×10^{-1}	0.60
	Fd*	Eq [3]	0.019	5.0	0.362	0.381	906	1.74×10^{-1}	0.81
	Cw	Eq [2]	0.66	7.4	8.23	8.89	331	4.82×10	0.90
pH	Hw	Eq [2]	0.0001	0.2	0.0589	0.059	252	9×10^{-3}	0.72
	Fd*	Eq [3]	0.0006	14.0	0.0037	0.0043	225	9×10^{-6}	0.82
	Cw	Eq [2]	0.004	4.2	0.091	0.095	581	2.4×10^{-2}	0.75
tC	Hw	Eq [2]	3.11	55.0	2.55	5.66	312	4.51×10	0.53
	Fd	Eq [2]	2.88	37.1	4.88	7.76	414	1.25×10^{2}	0.62
	Cw	Eq [2]	53.5	68.4	24.7	78.2	438	7.7×10^{3}	0.46
tN	Hw	Eq [2]	0.016	32.0	0.034	0.05	46	6.8×10^{-3}	0.23
	Fd	Eq [2]	0.0353	70.0	0.0151	0.0504	110	3.3×10^{-3}	0.26
	Cw	Eq [2]	0.058	65.2	0.031	0.089	172	1.4×10^{-2}	0.32
min-N	Hw	Eq [3]	1 063	55.3	859	1 922	624	3.7×10^{6}	0.57
	Fd*	Eq [3]	0.139	36.3	0.244	0.383	1 251	1.3×10^{-1}	0.72
	Cw	Eq [2]	5 390	32.4	11 240	16 630	248	4.42×10^{8}	0.63

* Data log-transformed.

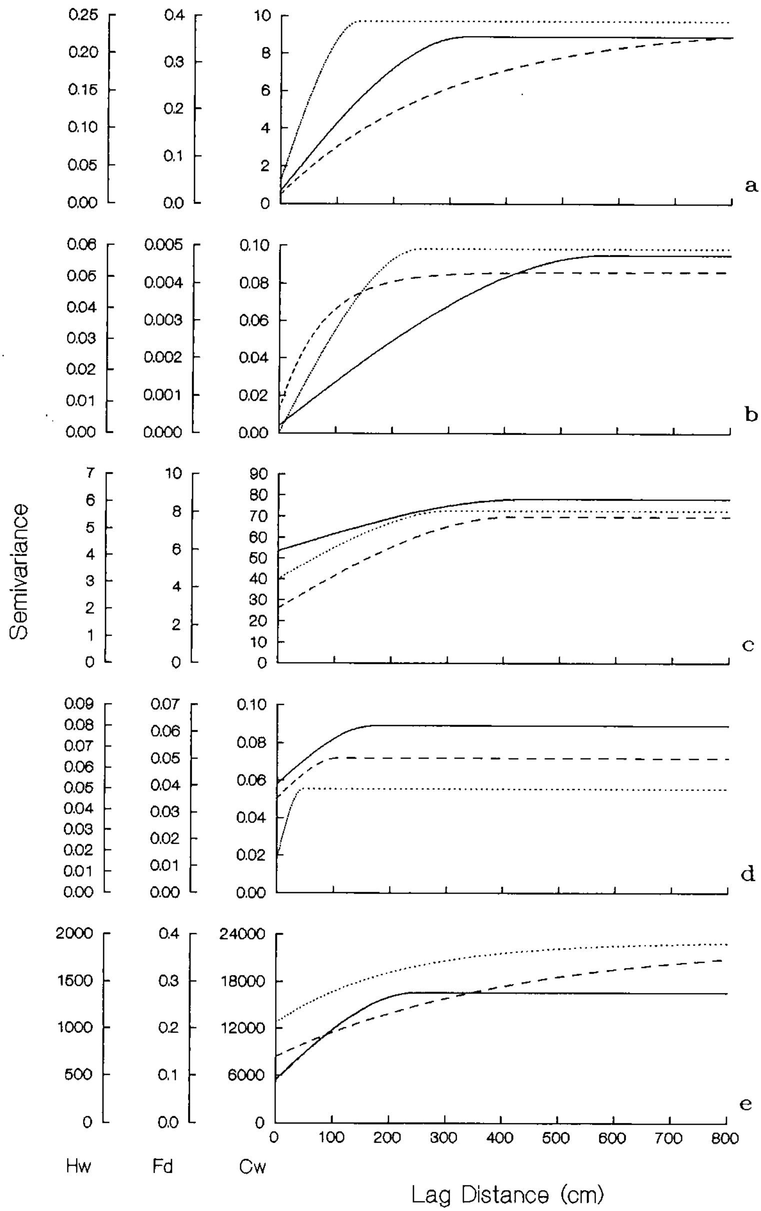

Fig 1. Fitted regression curves of omnidirectional variograms of humus form (**a**) thickness [$\gamma(h)/(\mathrm{cm}^2)$], (**b**) acidity [$\gamma(h)/(\mathrm{pH}^2)$], (**c**) total C [$\gamma(h)/(\mathrm{percent}^2)$], (**d**) total N [$\gamma(h)/(\mathrm{percent}^2)$] and (**e**) mineralizable-N [$\gamma(h)/(\mathrm{ppm}^2)$] in the western hemlock (Hw, dotted lines), Douglas-fir (Fd, dashed lines) and western red-cedar (Cw, solid lines) sites using the models in table IV. The estimated semivariances of thickness, acidity and min-N for the Douglas-fir site and thickness for the western hemlock site are in logarithmic scale.

val and the interval for kriging was 25 cm, each of the 1 681 measured-plus-kriged points was located at the nodes of the 25 x 25 cm grid. Each kriged point was estimated using 16 measured points around it. The means and standard deviations for the measured values (n = 100) and the measured-plus-kriged values (n = 1 681) are given in table V.

The mean estimated errors were submitted to t-test (Zar, 1984; table VI). Compared to the value of 1.984 for $t_{0.05\ (2),\ 99}$, all the mean estimated errors were significantly equal to zero, except for mineralizable-N in the Douglas-fir site with mean estimated error close to 1.984. The verification of the low variance also showed that the percentages of the observed estimation errors were within $m_\varepsilon \pm 2\sigma_\varepsilon$, except a few cases where the errors were slightly smaller than 95%.

As a supplement to the spatial analysis, the contour maps based on the measured-plus-kriged values were produced for each of the 5 humus form properties in each of the 3 10 x 10 m study sites (fig 2). We consider these maps more precise (with the precision definable in terms of the kriging variance) than those which would be produced from the original samples, as 16.81 times more values were used to construe a picture of spatial continuity. The maps illustrate the interpretations made earlier from variograms, *ie* the distribution of all 5 humus form properties is spatially-dependent and generically similar, and that the 5 humus form properties measured in the 3

Table V. Means and standard deviations (SD) of the measured and measured-plus-kriged values for 5 humus form properties in 3 study sites.

Property	*Site*	*Measured value*		*Measured + kriged value*	
		Mean	*SD*	*Mean*	*SD*
		(n = 100)		*(n = 1 681)*	
Thickness (cm)	Hw	6.560	3.947	6.070	2.352
	Fd	7.268	4.711	6.739	3.477
	Cw	5.838	3.163	5.807	2.282
pH	Hw	3.512	0.194	3.511	0.173
	Fd	4.076	0.292	4.060	0.165
	Cw	3.975	0.386	3.979	0.341
tC (%)	Hw	51.278	2.375	51.232	1.660
	Fd	50.152	2.794	50.117	1.930
	Cw	41.776	9.948	42.027	4.762
tN (%)	Hw	1.337	0.216	1.342	0.080
	Fd	1.564	0.212	1.552	0.073
	Cw	1.323	0.263	1.342	0.108
min-N (ppm)	Hw	91.987	39.794	91.517	19.566
	Fd	190.477	109.478	172.580	58.440
	Cw	426.170	135.585	427.797	73.281

Table VI. The means and variances of estimated errors for the measured values of 5 humus form properties and the tests for the goodness of estimation (n = 100).

Property	*Site*	*Mean of estimated error*	*t-value for error mean*	*Variance of estimated error*	*Percentage* [a]
Thickness (cm)	Hw	–0.654	–1.760	14.267	96
	Fd	–0.568	–1.553	13.705	92
	Cw	–0.000	–0.000	9.553	96
pH	Hw	0.002	0.102	0.038	97
	Fd	–0.018	–0.621	0.085	97
	Cw	–0.007	–0.262	0.071	94
tC (%)	Hw	0.022	0.093	5.539	92
	Fd	0.014	0.053	6.844	95
	Cw	–0.338	–0.358	89.236	97
tN (%)	Hw	–0.003	–0.139	0.046	95
	Fd	0.016	0.722	0.050	94
	Cw	–0.024	–0.859	0.078	96
min-N (ppm)	Hw	0.873	0.241	1308.604	94
	Fd	–17.918	–2.010	8261.100	94
	Cw	–1.933	–0.135	20518.840	96

[a] The percentage indicates a relative number of observations for which estimate errors were within $m_\varepsilon \pm 2\sigma_\varepsilon$.

study sites are spatially continuous over a short distance. Furthermore, the maps illustrate an aspect which was not examined in this study – a joint spatial dependence between humus form properties. For example, the right center and lower right regions of the 10 x 10 m grid for the Douglas-fir site (fig 2, center) shows relatively thicker humus forms. Relative to other regions of the grid, the same area is also shown to have a higher acidity, higher total C concentration and lower total N and mineralizable-N concentrations, *ie* the characteristics of Lignomors and Lignomoders, which, in fact, were the prevailing humus forms in these 2 regions.

CONCLUSION

The spatial analysis of 5 humus form properties in 3 sites showed the presence of a distinct pattern that reflected spatial dependence. The structural spatial dependence ranged from 46 to 1 251 cm, and varied somewhat with property and site. The most spatially continuous property was mineralizable-N, and the most spatially discontinuous property was total N. The results suggest a relatively low spatial continuity and small-scale pattern of humus form development which appears to occur in polygons with the lateral dimension ranging from about 100 to 700 cm.

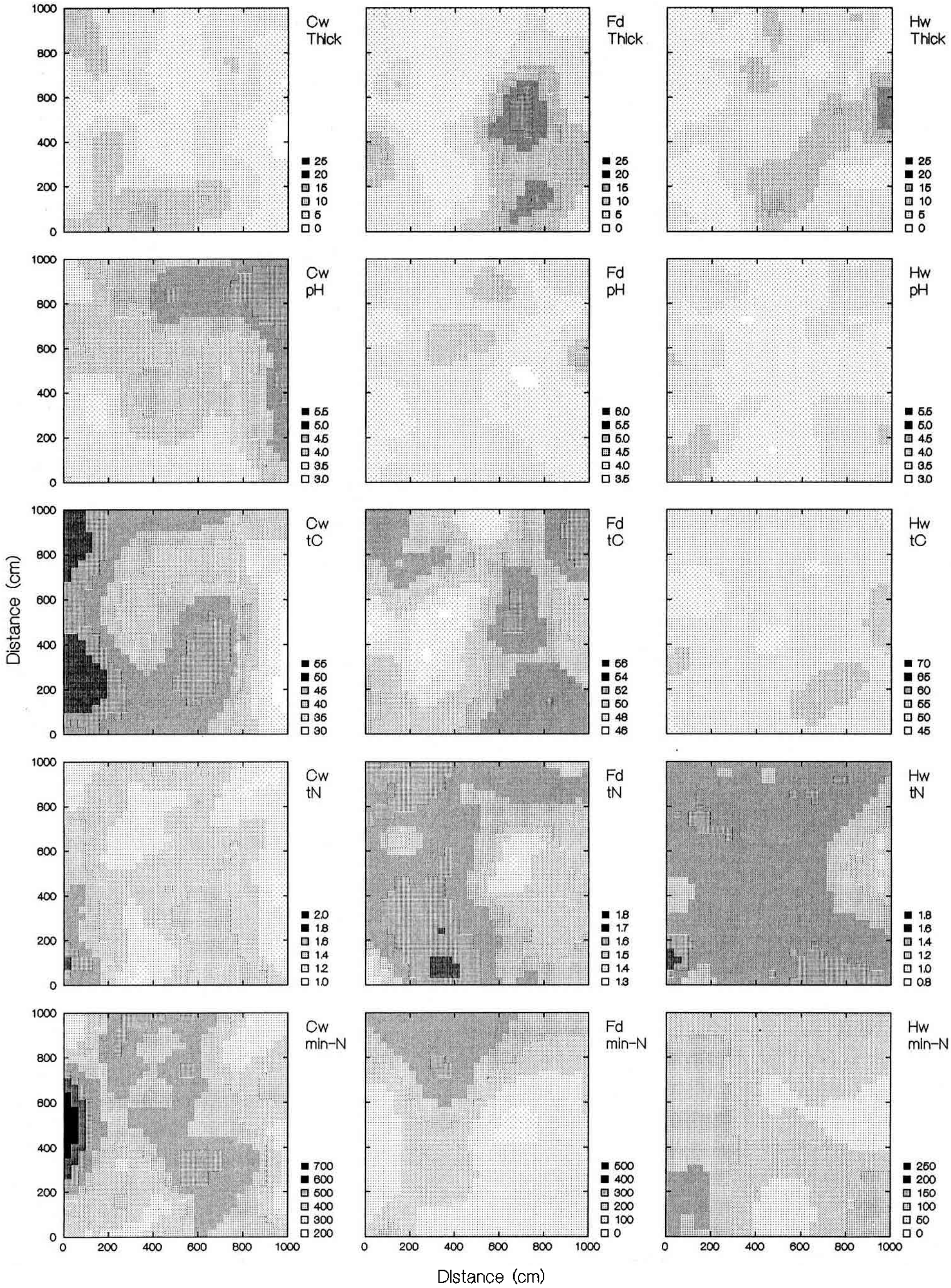

Fig 2. Contour maps of humus form thickness (Thick), acidity (pH), total C (tC), total N (tN) and mineralizable-N (min-N) in the western redcedar (Cw), Douglas-fir (Fd) and western hemlock (Hw) sites using the values for both measured and kriged locations.

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