HYDROLOGICAL PROCESSES
Hydrol. Process. **18**, 41–52 (2004)
Published online 7 November 2003 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/hyp.1309

Statistical characterization of the spatial variability of soil moisture in a cutover peatland

Richard M. Petrone,[1]* J. S. Price,[2] S. K. Carey[3] and J. M. Waddington[4]

[1] *Department of Geography and Cold Regions Research Centre, Wilfrid Laurier University, 75 University Ave West, Waterloo, Ontario, Canada, N2L 3C5*
[2] *Wetlands Research Centre, Department of Geography, University of Waterloo, 200 University Ave West, Waterloo, Ontario, Canada, N2L 3G1*
[3] *Department of Geography, University of Saskatchewan, Saskatoon, Saskatchewan, Canada, S7N 5A5*
[4] *School of Geography and Geology, McMaster University, 1280 Main St. W, Hamilton, Ontanio, Canada, L85 4Kl*

Abstract:

Soil moisture is a significant variable in its importance to the validation of hydrological models, but it is also the one defining variable that ties in all components of the surface energy balance and as such is of major importance to climate models and their surface schemes. Changing the scale of representation (e.g. from the observation to modelling scale) can further complicate the description of the spatial variability in any hydrological system. We examine this issue using soil moisture and vegetation cover data collected at two contrasting spatial scales and at three different times in the snow-free season from a cutover peat bog in Cacouna, Québec. Soil moisture was measured using Time Domain Reflectometry (TDR) over 90 000 m^2 and 1200 m^2 grids, at intervals of 30 and 2 m respectively. Analyses of statistical structure, variance and spatial autocorrelation were conducted on the soil moisture data at different sampling resolutions and over different grid sizes to determine the optimal spatial scale and sampling density at which these data should be represented. Increasing the scale of interest without adequate resolution in the measurement can lead to significant inconsistency in the representation of these variables. Furthermore, a lack of understanding of the nature of the variability of soil moisture at different scales may produce spurious representation in a modelling context. The analysis suggests that in terms of the distribution of soil moisture, the extent of sampling within a grid is not as significant as the density, or spacing, of the measurements. Both the scale and resolution of the sampling scheme have an impact on the mean of the distribution. Only approximately 60% of the spatial pattern in soil moisture of both the large and small grid is persistent over time, suggesting that the pattern of moisture differs for wetting and drying cycles. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS spatial variability; soil moisture; ecohydrology; time-series stability

INTRODUCTION

In Canada and around the world, the drainage and harvesting of peatlands for horticultural and agricultural purposes has increased over the past 50 years, altering their local hydroclimatology and greenhouse gas exchange (Armentano and Menges, 1986; Keys, 1992; Price, 1996; Waddington *et al*., 2002). Peat harvesting destroys the typical diplotelmic structure of the peat (Ingram, 1978) and the natural hydrological function of the system is lost. Therefore, processes affecting the exchange of moisture and carbon become much more temporally variable (Price, 1996; Schlotzhauer and Price, 1999). This switches the peatland to a large net source of atmospheric CO_2 (Waddington and Price, 2000). Thus, restoring the hydrology of these systems is required to return these peatlands to functioning, carbon accumulating ecosystems.

When cutover peatlands are rewetted, soil moisture conditions within the peat are dominated by evaporation over the summer period (Price, 1996; Van Seters and Price, 2001), leading to a strong coupling between

* Correspondence to: Richard M. Petrone, Department of Geography, Wilfrid Laurier University, 75 University Avenue West, Waterloo, Ontario, Canada, N2L 3C5. E-mail: rpetrone@wlu.ca

Received 28 June 2002
Accepted 17 January 2003

the moisture regime and both carbon dynamics (Waddington and Price, 2000) and ecological patterns and processes. An understanding of this coupling is essential to the development of appropriate restoration plans for cutover peatlands.

The important coupling of soil moisture conditions and vegetation re-emergence in ecosystems is well established (Rodriguez-Iturbe *et al.*, 1999) and recently many studies have focused on the representation of hydrological parameters such as soil moisture at different spatial scales. However, there have been few equivalent studies on such variables in organic soils, despite the significance of soil moisture variability to the restoration of natural vegetation species on harvested cutover peatlands.

Soil moisture is the key defining variable that integrates all components of the surface energy balance and as such is of major importance to climate models and their surface schemes (Rodriguez-Iturbe and Rinaldo, 1997). Furthermore, it is highly variable in space (Western and Blöschl, 1999). An understanding of the soil moisture balance and its variability (spatial and temporal) is instrumental in quantifying the linkage between a region's hydrology, ecology and physiography (geology). That is, the spatial patterns and temporal variability of soil moisture will be a consequence (and to some extent a controlling factor) of the area's vegetation and physiography (Rodriguez-Iturbe, 2000).

Systematic and reliable soil moisture observations are scarce for larger systems, owing to the labour intensive nature of most ground-based measurement techniques (Anctil *et al.*, 2002). Given the important coupling behaviour of soil moisture, the ability to characterize its spatial variability is crucial to the efficient monitoring and modelling of that particular area. However, the nature of spatial variations in soil moisture, and hydrological behaviour may change with scale. Within an ecosystem the spatial variability of soil moisture can be influenced by larger scale watershed features such as slope and aspect, or smaller scale variations in microtopography. Thus, increasing the scale of interest without considering the nature of the variability at that scale will lead to an inappropriate sampling scheme and inconsistency in the representation of the soil moisture field.

In cutover (or restored) peatland ecosystems, where water is the controlling factor on vegetation regrowth, the interaction (spatially and temporally) between climate, soil and vegetation is manifest through the soil moisture dynamics. An understanding of the nature of variability in soil moisture at the ecosystem scale is required to understand the restoration process. For example, in a harvested peatland much of the variability in soil moisture may be controlled by microscale variations in surface topography. Therefore, if the moisture is not sampled at fine enough resolution accurate quantification of the true statistical nature of the soil moisture field may be compromised. This paper, although not focusing on the actual processes at work, examines the nature of soil moisture variability in an organic soil, and how it changes with the scale of measurement. The objectives of this analysis are to characterize the spatial variability (variogram analysis), determine what the controlling factors are on this distribution and the scales at which they operate (correlogram), and to examine whether these factors, and the resulting distribution, change seasonally (time-series stability). Thus, this research is intended to serve as a baseline on which to base future, and ongoing, detailed process studies in this catchment.

STUDY AREA

This study was conducted at the cutover and partially restored sections of the 200 ha Bois-des-Bel peatland near Rivière-du-Loup (47°53'N, 69°27'W), Québec, Canada (Figure 1). The mean annual temperature and total precipitation for the region are 3 °C and 926 mm (27% falling as snow), respectively (Environment Canada, 1993). In 1972 11·5 ha of the bog was drained, and peat was removed by vacuum harvesting from 1973 to 1980. The area harvested comprises eleven 30 × 300 m fields separated by parallel drainage ditches that drain to the south (Figure 1). In 1980 the site was abandoned and the peatland remained abandoned until the autumn of 1999 when restoration measures were undertaken. Fields numbered one through to eight were restored; 10 and 11 were left as a comparison site (control); and field nine was tilled, but not restored, to serve as a buffer between the experimental zone and the control section. The restoration measures included blocking of the drainage ditches, constructing surface bunds to retain spring meltwater, surface tilling to remove wood, the application of *Sphagnum diasporas* at a ratio equivalent to 1/10 the coverage of an undisturbed system, and finally the spreading of 3000 kg/ha of straw mulch (Rochefort, 2000).

FIELD METHODOLOGY

Soil moisture was measured using a Hydrosense Portable Time Domain Reflectometry (TDR) system (Campbell Scientific, Utah) over a 1200 m^2 grid at an interval of 2 m (hereafter referred to as the 'small grid'), and over the entire restored portion of the 200 ha peatland at an interval of approximately 30 m (hereafter referred to as the 'large grid') (Figure 1). The Hydrosense TDR has an accuracy of $\pm 3\%$ and an integration volume of approximately 650 cm^3. The TDR unit measured the mean volumetric soil moisture in the upper 12 cm of the peat profile. Along with the sampling of soil moisture, visual observations of the presence (or non-presence) of moss and vascular plant species and straw mulch were noted at each sampling point within a 25×25 cm area. Sampling was undertaken at the two grids within a 5 h period on 10 June, 17 July and 20 August 2001.

Within the large grid, 57 soil moisture measurements were made over the entire eight fields of the restored portion of the peatland along transects running down the centre of each field (15 m away from their respective drainage ditches) (Figure 1). Within the small grid, 336 soil moisture measurements were made over the 30×40 m grid that was placed between fields four and five, encompassing one of the blocked drainage ditches. The position and resolution of this grid was chosen to examine the microscale effects of topography (e.g. ditches, bunds, etc.) and vegetation cover on the soil moisture distribution (Figure 1).

There were insufficient points in the large grid to construct a variogram. Thus, a 254 m transect running from the south-east to the north-west corner of the restored portion of the peatland (Figure 1) was sampled on 11 July and 11 August. On these occasions, soil moisture was measured every 0·5 m using the 12 cm Hydrosense probe yielding 508 data points that will be used to analyse large-scale variability over the large grid.

RESULTS

Mean soil moisture was greater for the larger grid and a larger decrease in the mean over the three measurement periods was observed for the smaller grid (Table I). Histograms of the distribution of soil moisture (Figure 2) for both grids were left skewed, with the highest frequencies occurring towards the wetter portion of the distribution. This skew was due to the predominance of wet conditions and high porosity of the peat soil, and the truncation limit of soil moisture (1·0). This predominance of values around 90% (Petrone *et al.*, 2003), especially in June and July, may represent saturation soil moisture values or capillary saturation of the cutover peat. Higher values may be supersaturated (high water table), disturbed peat or saturated mosses that have larger volumetric moisture contents. This is less evident as the mean soil moisture content decreases (e.g. in August).

Table I. Descriptive statistics for the two study grids during the three study periods. Shown are means (μ), standard deviations (σ), range and sample size (n) for the soil moisture measurements

Statistic	Large grid			Small grid		
	June	July	August	June	July	August
μ	0·77	0·80	0·76	0·78	0·77	0·69
σ	0·06	0·11	0·12	0·07	0·12	0·14
Range	0·31	0·47	0·39	0·51	0·74	0·91
n	57	57	57	336	336	336

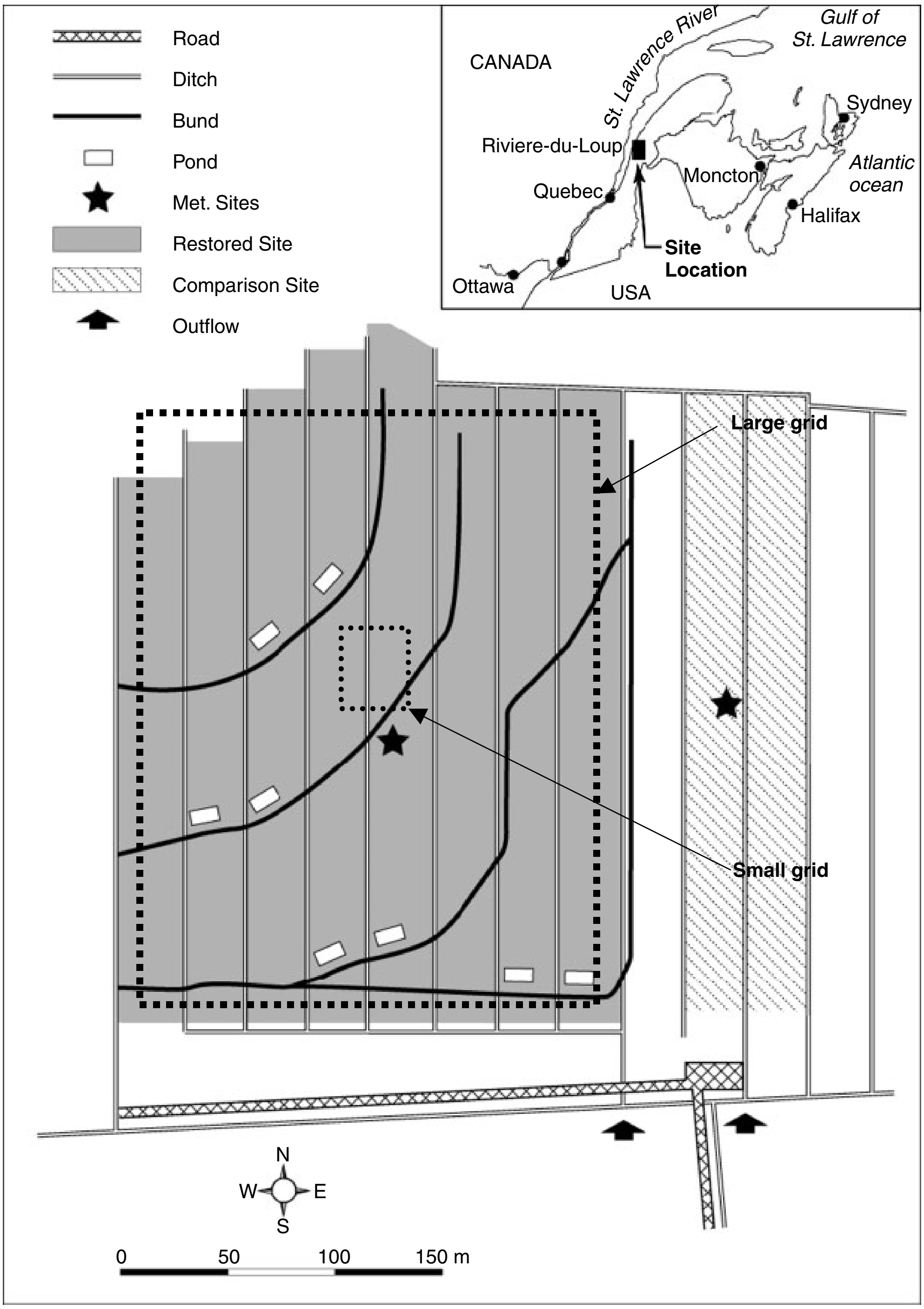

Figure 1. Location and schematic plan of the study site showing the restored plot

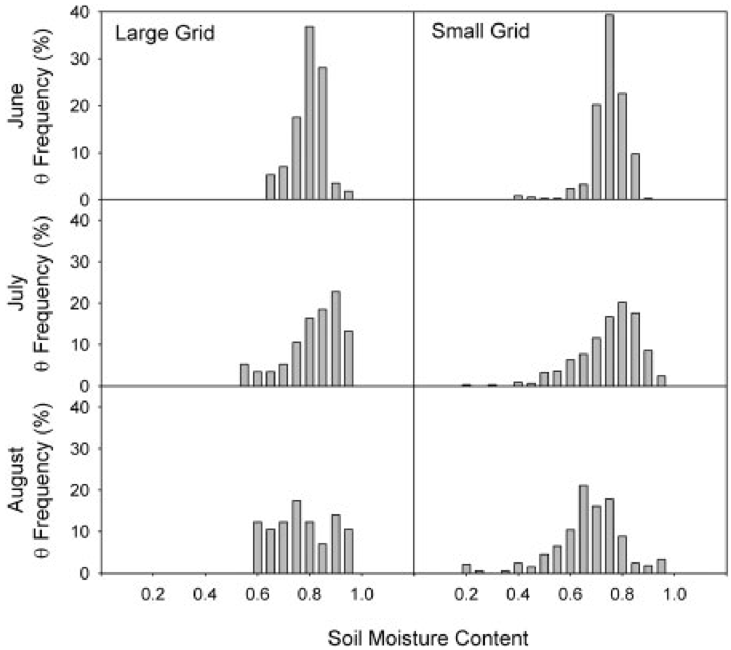

Figure 2. Frequency histograms of both the large and small grid for each of the three sampling periods (June, July and August 2001)

Table II. Pearson correlation coefficients for moisture conditions (θ), surface cover type (mosses, vascular plants, and straw mulch), for the entire peatland in June and July, 2001

		Mosses	Vascular	Straw
Wet period	θ	0·37	−0·16	0·47
	Moss	—	0·11	0·29
Dry period	θ	0·45	0·06	0·58
	Moss	—	0·63	0·23

Field observations suggest a predominance of mosses in wetter areas, with some vascular vegetation and mulch cover. Pearson correlation coefficients demonstrate that the largest soil moisture values are frequently associated with the greatest densities of straw and moss cover (Table II). Soil moisture was greatest under the mulch cover during both the wetter (June) and drier periods (July). During the wetter period, soil moisture was weakly negatively correlated with the presence of vascular plants, but uncorrelated during the drier part of the season (Table II). Furthermore, the presence of moss species was correlated with the presence of vascular plant species during the drier period, but only weakly correlated when conditions were wet. During this wetter period, the presence of mosses was slightly more correlated with the presence of straw mulch than during the dry period (Table II).

Vegetation is a function of temperature and moisture conditions, both of which are interrelated (Eissenstant and Van Rees, 1994). The system's temperature will have an impact on the vegetation's metabolic activity and rates of evapotranspiration, and soil moisture conditions will have an impact on all of the physiological processes of the vegetation (Rodriguez-Iturbe *et al.*, 1999). Therefore, within and between year environmental fluctuations may be important for vegetation dynamics. The mosses are seen to be strongly correlated with spatial patterns in soil moisture. Furthermore, the moss cover was strongly correlated with vascular plant cover, especially during the drier period (Table III). McNeil and Waddington (2003, 2002) have shown that

Table III. The effects of changing spacing on the mean (μ) of the June sampling period, standard deviation (σ), range, Moran's I (I) and standard normal deviant (z). A standard normal deviant value greater than 1·96 suggests a significance level greater than 95%

	10 m	4 m	2 m
μ	0·78	0·78	0·78
σ	0·06	0·06	0·07
Range	0·29	0·41	0·51
I	−0·06	0·02	0·14
z	−0·07	0·48	3·7

the growth of *Sphagnum* moss species are strongly dependent on the presence of vascular plants (especially ericaceous shrubs), as suggested by the correlation coefficients in this study. As the vascular shrubs emerge before any significant moss cover, the observed spatial patterns can be explained by the tendency of the moss diaspores to prefer germination adjacent to, or underneath, vascular shrub cover (McNeil and Waddington, 2003, 2002).

ANALYSES AND DISCUSSION

To further explore the nature of soil moisture variability several analyses were undertaken. First, the scale of natural variability of the peatland's soil moisture can be obtained by determining the soil moisture field's correlation length, which is derived from the variogram of the data set (Journel and Huijbregts, 1978; Western and Blöschl, 1999). This analysis is useful to determine if the soil moisture distribution is spatially erratic or continuous. A variogram is a plot of the average of the square of the differences between data values as a function of separation distance (i.e. distance between sample points). The range in a variogram is the distance at which the variogram reaches the sill, which is the plateau that is reached when no further increase in variability occurs as separation distance increases. This approximates the 'range of influence' or 'range of correlation' and can be identified on a variogram as the region of the plot where the slope changes to approximately zero. Thus, if a data set is very continuous over short distances, then the difference between closely spaced data values would be small. If a data set is less continuous the difference increases as the distance increases between compared pairs. Beyond this range, a sample is no longer correlated with other values.

Figure 3 illustrates the variogram for the sample set, which shows that the range of soil moisture variability is around 10 m for the large grid and 4 m for the small grid. This suggests that the factors controlling the distribution of soil moisture at these two scales are different. The nugget effect in a variogram is the vertical height of the discontinuity at the origin. This effect is a combination of variations that occur at scales smaller than the closest sample spacing, and sampling error. The large grid shows very little nugget effect (Figure 3b), whereas the small grid demonstrates a small nugget effect that decreases over the course of the season, as conditions become drier. However, the spacing over the larger area (254 m transect used to construct the variogram) is actually smaller and as such the variogram is better defined near the origin. A short range and high nugget effect suggest a data set that is spatially erratic or discontinuous. Thus, the ratio of the nugget effect to the total semivariance will provide an indication of the degree of spatial variability. If this ratio is less than 25% there is strong spatial dependence; for 25 to 75% there is moderate spatial dependence; and greater than 75% there is weak spatial dependence. The ratio in the large and small data set is approximately 10 and 25%, respectively. Therefore, there is stronger spatial dependence within the larger area than the small area, and this spatial dependence does not really vary over the course of the season as moisture conditions change. However, as suggested by these ratios, there is some degree of stationarity and spatial dependence in soil moisture at both sample sizes and resolutions.

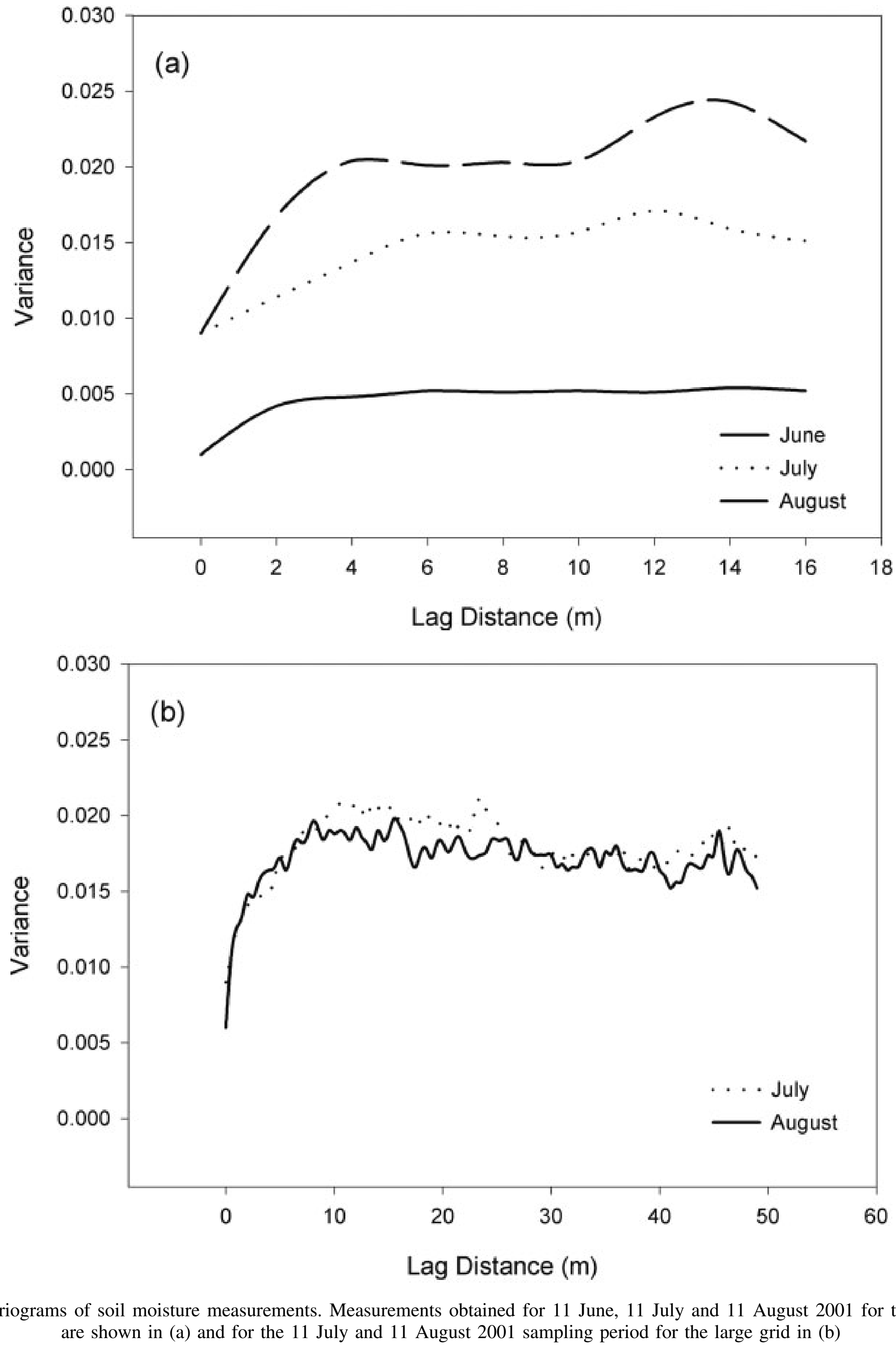

Figure 3. Variograms of soil moisture measurements. Measurements obtained for 11 June, 11 July and 11 August 2001 for the small grid are shown in (a) and for the 11 July and 11 August 2001 sampling period for the large grid in (b)

The variograms (Figure 3) show that the variability increases with lag distance. If there is spatial autocorrelation, one should be able to determine what the optimal sampling strategy might be to capture the natural statistical properties of the soil moisture field. For example, accurate representation of the soil moisture distribution may be obtained by some optimal areal coverage and sampling density. Thus, the effects of resolution and grid size on spatial autocorrelation should be examined.

Resolution and variability

Intuitively, soil moisture can be thought of as being spatially organized. It is often organized by topography (slope, depressions, etc.), land use, vegetation, soil and geological patterns (Western and Blöschl, 1999). As this spatial organization will have an impact on the representation of the system's variability, the degree of this organization must also be investigated.

A correlogram is, in a sense, a mirror image of a variogram with the exception that the correlogram assumes a stationary mean (Srivastava, 1996). As a variogram gradually rises to a plateau, a correlogram gradually drops and levels out. A measure of the degree of correlation between samples at different separation distances will provide a measure of dissimilarity of the soil moisture field. That is, a high correlation coefficient will show that data values are similar, which should decrease as the separation distance increases (Srivastava, 1996). Moran's I method of local spatial autocorrelation analysis was used in addition to the variogram to determine if there was any organization in the measured soil moisture field. The computation of Moran's I is achieved by dividing the spatial covariation by the total variation. The resulting values are in the range of approximately -1 to 1, with positive values suggesting positive spatial autocorrelation, and vice versa.

Moran's analysis on the data set at different spacings (resolutions) provides insight on whether there is more than one factor controlling the natural organization of the soil moisture field. For example, a data set may demonstrate significant spatial autocorrelations at more than one resolution, or scale. This could be the result of different external factors controlling the distribution at different scales. In the case of soil moisture, microtopography or vegetation may control the distribution at smaller spatial scales, whereas, at larger scales slope, geology or basin topography may be responsible for the observed variance.

Table III shows statistical information from the small grid at different levels of aggregation. That is, the original sample spacing of 2 m was increased such that increasingly larger subgrid areas are used to contribute the statistical properties of the small grid. The seasonal mean soil moisture value does not vary significantly with spacing (Table III). However, the standard deviation increases slightly as the sample spacing becomes more coarse (Table III). Similarly, the range in seasonal soil moisture values decreases as increasingly larger subgrids are aggregated. That is, as measurements become more coarse (greater than approximately 10 m) the spatial dependence decreases. As spacing increases, the potential to not sample wetter areas may cause the range to decrease.

As mentioned earlier, an extent or spacing that shows a high positive Moran's I value suggests clustering and strong spatial dependence. Therefore, if such a scale can be identified in the data set, the sample size could probably be decreased without compromising the reliability of the field's representation. Table III illustrates that I is greatest at the finer resolutions (smaller spacings). The Z values also show a higher significance in this range. Thus, to accurately represent this soil moisture field sampling does not need to be done at too fine a resolution. As the mean will not change significantly the sampling should be done over a larger extent to really capture the variability of the whole site. This leads to the question as to how this larger areal sampling should be conducted (randomly or in a regular gridded fashion?) and if there is an effect of seasonality on this distribution?

Time-series stability

Perhaps just as significant as the degree of spatial variability, especially from a modelling point of view, is the degree of variability in the soil moisture field over time and whether this degree of temporal variability is the same across the soil moisture field. That is, will certain portions of the peatland have different drying and wetting responses? The concept of *time-series stability* is useful in addressing these questions. Time-series stability assumes that there is some time invariant association between spatial location and classic parametric values of soil properties (Vachoud *et al*., 1985). Soil variability may be viewed as the product of soil-forming processes operating and interacting over a continuum of spatial and temporal scales (Trangmar *et al*., 1985).

Vachoud *et al*. (1985) demonstrate that the relative deviation ($\delta_t(j)$) at a horizontal spatial location (j) from the mean soil moisture ($\mu[\theta_t(j)]$) at the same time across the spatial domain can be expressed as

$$\delta_t(j) = \frac{\theta_t(j) - \mu[\theta_t(j)]}{\mu[\theta_t(j)]} \tag{1}$$

Figure 4 illustrates the relative deviation for every sample point on both grids during the three measurement periods. Positive (light) contours indicate sample areas that are wetter than the grid's mean for that period, whereas negative (dark) contours represent drier areas. The large grid yields some apparent trends to the wetting and drying patterns over the course of the season. On average, the small grid shows more variability in its wetting and drying trends than the large grid. Furthermore, at the finer resolution of the small grid drier

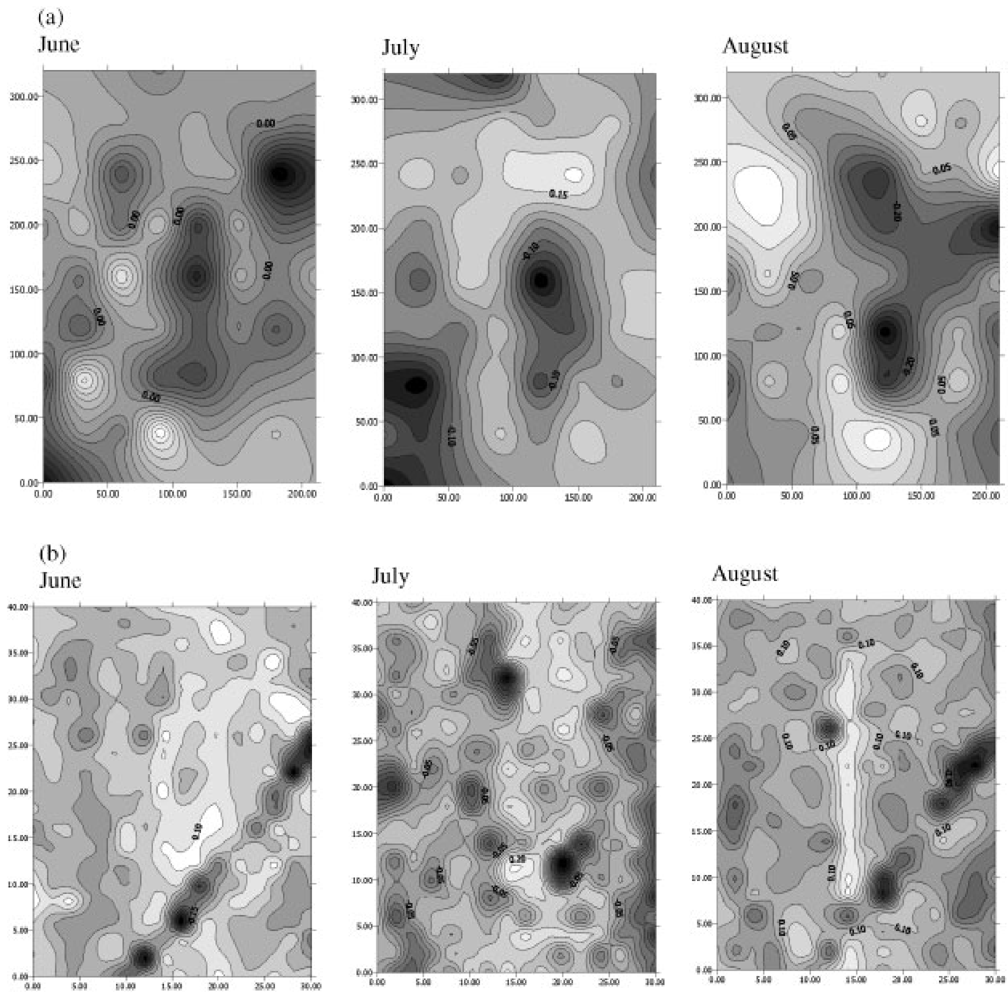

Figure 4. Contour plots of the relative difference in soil moisture of each grid point and the mean of the entire grid. Plots are shown for the large grid (a) and small grid (b) for the three sampling periods (June, July and August 2001)

features such as the surface bunds are much clearer than at the coarser resolution of the larger grid (Figure 4). Whereas, larger scale dry features such as topographical highs are much more prevalent in the large grid. Conditions in the restored side of the peatland (Figure 4a) appear to be less transient, with fairly persistent drier features apparent in all periods. The small grid encompasses a blocked ditch and surface bund, which is evident in all three plots, especially in the wetter June and August periods (Figure 4b). In addition, there is slightly more deviation from the mean, in either direction, than that observed for the large grid.

If the relationship above is expanded over two different measurement times (t_1 and t_2), and assuming a linear relationship between soil moisture at times t_1 and t_2 across all spatial locations, the following is obtained to describe the variation between the successive plots in Figure 4

$$\theta_{t_2}(j) \approx \frac{\mu[\theta_{t_2}(j)]}{\mu[\theta_{t_1}(j)]}\theta_{t_1} \tag{2}$$

Thus, a useful test for time stability is a simple correlation between soil moisture measured at consecutive times

$$\theta_{t_2}(j) = a_{t_2} - t_1\theta_{t_1}(j) + b_{t_2} - t_1 \tag{3}$$

where $a_{t_2} - t_1$ is the regression slope, and $b_{t_2} - t_1$ is the regression intercept (Kachanoski and De Jong, 1988). Tables IV and V show the temporal stability of soil moisture by correlating the point measurement values for the three successive measurement dates for both grids. There is obvious temporal persistence of the spatial patterns of $\delta_t(j)$ for much of the sampled grids (Figure 4), which suggests that the slopes of the regression equations should remain relatively constant over the course of the season. However, the slope and intercept (Tables IV and V) are quite different (probability $< 0{\cdot}0001$) from the expected values if the relative difference was constant. Only about 60% of the spatial pattern persisted over the time period, with most of the variability in the relative difference observed for the small grid, especially during the drying period (i.e. July to August). By examining the patterns of these differences in soil moisture over the course of the season at the two sampling scales and resolutions it appears as though different processes control the distribution at different scales and during wetting or drying periods. Soil drying appears to be correlated with small-scale surface variations as observed in the more obvious change in the distribution from the June to July period for the small grid (Figure 4). Drying did not appear to alter the spatial pattern of soil moisture as much for the large grid. Thus, the stability of soil moisture distribution over time appears to be scale dependent.

Table IV. Regression parameters for the relative difference in soil moisture ($\delta_t(j)$) for the large grid

Measurement date	Regression slope (intercept)		
	June	July	August
June	1(0)	0·212 (60)	0·085 (71)
July		1 (0)	0·078 (74)
August			1 (0)

Table V. Regression parameters for the relative difference in soil moisture ($\delta_t(j)$) for the small grid

Measurement date	Regression slope (intercept)		
	June	July	August
June	1(0)	0·37 (49)	0·92 (−1·82)
July		1 (0)	−30 (46)
August			1 (0)

CONCLUSIONS

When comparing the descriptive statistics of the soil moisture distribution at the two sampling scales (extents) more change in the mean soil moisture was observed on the larger grid. Similarly, the standard deviation was greater on the smaller grid. Evidence of this was observed in the contours of relative differences from the mean soil moisture for both grids. Individual sample points across the larger grid were, on average, closer to the mean soil moisture over the season and less transient. There was some persistence in the soil moisture patterns (especially over the large grid). However, regression analysis indicated that the slopes between successive measurement periods changed and that approximately 60% of the spatial pattern persisted over the time period. This suggests that the soil moisture pattern was different for wetting and drying periods.

Hydrologists have long recognized that vegetation may be a significant control on subsurface hydrological processes (Whitehead and Price, 2001; Gurnell *et al*., 2000). This interaction is very significant in restoration hydrology. The interaction of spatial vegetation dynamics and soil hydrology must be quantified at scales pertinent to that of the restoration of an entire ecosystem. Thus, if one is attempting to restore a peatland ecosystem, knowledge of the distribution at the ecosystem scale is required.

Furthermore, variability in soil moisture and vegetation will influence soil respiration by altering the soil microclimate and structure, the quantity and quality of detritus supplied, and the overall rate of root and soil respiration (Raich and Tufekcioglu, 2000). Therefore, there is an important linkage between the spatial patterns in soil moisture and vegetation cover, and that of the carbon dynamics of the system (Gates, 1980). Knowing the nature of the spatial and temporal interactions among surface vegetation and soil moisture will facilitate a better understanding of the carbon exchange processes under a changing surface cover.

Quantifying the feedbacks between vegetation regrowth and the ecosystem's microclimate is crucial to really understand the restoration effects and processes. In harvested/restored peatlands, where water is the controlling factor, the interaction (spatially and temporally) between climate, soil and vegetation is manifest through the space–time dynamics of the soil moisture field. Thus, the accurate characterization of the true state of moisture in the ecosystem, important from both an experimental and modelling view point, will require the proper sampling approach specific to the system. As illustrated in this study, to quantify the effects of soil moisture conditions on vegetation re-emergence on the cutover Bois-des-Bel Peatland high-resolution sampling is not as important as larger areal coverage.

ACKNOWLEDGEMENTS

This research was made possible by grants from NSERC Canada to JSP and JMW, with the assistance of our industrial partners. Suzanne Campeau and Dr Line Rochefort (University of Laval) provided invaluable assistance in the interpretation of vegetation survey results and processes, and Dr Mike Stone (University of Waterloo) offered much appreciated insight into the data analysis. Sarah Day, Amanda Sills and Mike Shantz are thanked for their help in the collection of the survey data. The authors also thank the anonymous reviewers of this manuscript for their helpful and insightful comments.

REFERENCES

Anctil F, Mathieu R, Parent LE, Viau AA, Sbih M, Hessami M. 2002. Geostatistics of near-surface moisture in bare cultivated organic soils. *Journal of Hydrology* **260**: 30–37.

Armentano TV, Menges ES. 1986. Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. *Journal of Ecology* **74**: 755–774.

Environment Canada. 1993. *Canadian Climate Normals, 1961–1990*. Québec. Atmospheric Environment Service, Canadian Climate Program, Environment Canada: Ottawa, Canada.

Gates DM. 1980. *Biophysical Ecology*. Springer-Verlag: New York.

Gurnell AM, Hupp CR, Gregory SV. 2000. Linking hydrology and ecology. *Hydrological Processes* **14**: 2813–2815.

Ingram HAP. 1978. Soil layers in mires: function and terminology. *Journal of Soil Science* **29**: 224–227.

Kachanoski RG, De Jong E. 1988. Scale dependence and the temporal persistence of spatial patterns of soil water storage. *Water Resources Research* **24**(1): 85–91.

Keys D. 1992. *Canadian Peat Harvesting and the Environment*. North American Wetlands Conservation Council Report No. 1992–93: Ottawa, Canada.

Journel AG, Huijbregts CJ. 1978. *Mining Geostatistics*. Academic Press: London.

McNeil P, Waddington JM. 2002. Influence of moisture on *Sphagnum* growth and CO_2 exchange on a cutover bog. *Journal of Applied Ecology* **40**(2): 354–367.

Petrone RM, Price JS, Waddington JM. 2003. The microclimate of a restored vacuum harvested peatland: the effects of a surface mulch cover on the moisture and thermal dynamics of a peat soil. *Journal of Hydrology*.

Price JS. 1996. Hydrology and microclimate of a partly restored cutover bog, Québec. *Hydrological Processes* **10**: 1263–1272.

Raich JW, Tufekcioglu A. 2000. Vegetation and soil respiration: correlations and controls. *Biogeochemistry* **48**: 71–90.

Rochefort L. 2000. *Sphagnum*—a keystone genus in habitat restoration. *The Bryologist* **103**: 503–508.

Rodriguez-Iturbe I. 2000. Ecohydrology: a hydrologic perspective of climate-soil-vegetation dynamics. *Water Resources Research* **36**(1): 3–9.

Rodriguez-Iturbe I, Rinaldo A. 1997. On the spatial organization of soil moisture fields. In *Fractal River Basins: Chance and Self-Organization*. Cambridge University Press: New York.

Rodriguez-Iturbe I, D'Odorico P, Porporato A, Ridolfi L. 1999. On the spatial and temporal links between vegetation, climate, and soil moisture. *Water Resources Research* **35**(12): 3709–3722.

Schlotzhauer S, Price JS. 1999. Soil water flow dynamics in a managed cutover peat field, Quebec: Field and laboratory investigations. *Water Resources Research* **35**: 3675–3684.

Srivastava RM. 1996. Describing spatial variability using geostatistical simulation. In *Geostatistics for Environmental and Geotechnical Applications*, Rouhani S, Srivastava RM, Desbarats AJ, Cromer MV, Johnson AI (eds). American Society for Testing and Material: Ann Arbor, MI; 13–19.

Stanley HE. 1986. Form: an introduction to self-similarity and fractal behaviour. In *On Growth and Form. Fractal and Non-Fractal Patterns in Physics*, Stanley HE, Ostrowsky N (eds). Martinus Nijhoff Publishers: Boston; 21–53.

Trangmar BB, Yost RS, Uehara G. 1985. Application of geostatistics to spatial studies of soil properties. *Advances in Agronomy* **38**: 45–93.

Vachoud G, Passerat De Silane A, Balabanis P, Vauclin M. 1985. Temporal stability of spatially measured soil water probability density function. *Soil Science Society of America Journal* **49**: 822–827.

Van Seters TE, Price JS. 2001. The impact of peat harvesting and natural regeneration on the water balance of an abandoned cutover bog, Québec. *Hydrological Processes* **15**: 233–248.

Waddington JM, Price JS. 2000. Effect of peatland drainage, harvesting, and restoration on atmospheric water and carbon exchange. *Physical Geography* **21**(5): 433–451.

Waddington JM, Warner KD, Kennedy GW. 2002. Cutover peatlands: a persistent source of atmospheric CO_2. *Global Biogeochemical Cycles* **16**(1): 1–7.

Western AW, Blöschl G. 1999. On the spatial scaling of soil moisture. *Journal of Hydrology* **217**: 203–224.

Whitehead GS, Price JS. 2001. Developing hydrologic thresholds for *Sphagnum* recolonization on an abandoned cutover bog. *Wetlands* **21**(1): 32–40.

