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Soil Spatial Dependence in Three Arctic Ecosystems

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We examined the spatial variability of 13 soil physicochemical attributes and their correlation with soil gravimetric moisture content (θ_g) in 279 soil samples collected from three high arctic ecosystems. The observed correlations between θ_g and pH, NH_4, NO_3, total organic C, dissolved organic C, and dissolved organic N contents in the Arctic are considerably higher than temperate agricultural and tropical grassland soils, which suggests that θ_g plays a critical role in arctic soil ecosystems. We found that, despite the climatic extremities, arctic soil attributes are spatially well structured and their spatial dependency is consistent within and between the studied ecosystems. The range of spatial dependency, however, is considerably smaller, which can be ascribed to the environmental extremities and other periglacial features. Based on the results, we recommend that, to obtain independent samples, the minimum distance between samples should be 10 m in Haplorthels or Haploturbels and 45 m in Histels.

Abbreviations: DOC, dissolved organic carbon; DON, dissolved organic nitrogen; TOC, total organic carbon.

Soil spatial dependency is the correlation of values of a variable at one point related to its values at nearby points as a function of the distance separating these two points. Understanding spatial dependencies allows inferences to be made about the long-term ecological and physical processes that define an ecosystem. Spatial dependency has been extensively studied for physical (Iqbal et al., 2005), chemical (Cerri et al., 2004; Mzuku et al., 2005; Ruth and Lennartz, 2008), and biological properties (Saetre and Baath, 2000; Bengtson et al., 2007) of tropical and temperate soils; however, studies examining spatial heterogeneity in permafrost soils are limited. Permafrost soil ecosystems dominate about one-fifth of the world's and the majority (40%) of the Canadian landscape (Beer, 2008; Bockheim and Tarnocai, 1998). Efforts are underway to map the soil organic matter (SOM) present in permafrost soils, as are efforts to understand SOM dynamics and its spatial variability in these soils (Beer, 2008). Characterizing the spatial dependency of these soils will help us extrapolate from single-point estimates to a larger spatial scale. Furthermore, soil moisture content (θ_g) is well known for its considerable spatial variability (Petrone et al., 2004). Information on the spatial heterogeneity of θ_g plays a critical role in soil survey, land surface hydrologic modeling, and the assessment of ecophysiographic patterns (Choi et al., 2007). The relationships between θ_g and other physicochemical attributes, including SOM, have not been quantified in arctic soils. In this study, we used three sites in the Canadian Arctic to examine: (i) the minimum sampling distance for obtaining independent samples in organic (Histel) vs. mineral (Orthel and Turbel) soils; (ii) the spatial relationships between θ_g and other physicochemical attributes; and (iii) whether the spatial dependency is consistent across all three sites.

MATERIALS AND METHODS

Three high arctic ecosystems were selected for this study: Truelove Lowland, Simpson Lake, and Ross Point. Truelove Lowland (75°40′ N, 84°35′ W) has been the subject

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Table 1. Mean values of soil physicochemical attributes at three sites and Pearson correlation between soil gravimetric moisture content (θ_g) and other soil attributes.

Soil attributes	Truelove Lowland	Simpson Lake	Ross Point
θ_g	24.7 (1.66) a†	20.4 (1.36) a	60.6 (5.62) b
pH	7.54 (0.0130) a	5.54 (0.0294) b	7.57 (0.0396) a
NO_3^-, mg kg^{-1} dry soil	0.889 (0.0485) a	1.38 (0.126) b	4.49 (0.667) c
NH_4^+, mg kg^{-1} dry soil	0.744 (0.0462) a	0.348 (0.0244) b	5.28 (0.452) c
Dissolved organic C, mg kg^{-1} dry soil	7.45 (0.242) a	381 (41.6) b	1890 (159) c
Dissolved organic N, mg kg^{-1} dry soil	1.61 (0.137) a	53.7 (4.51) b	187 (18.3) c
Total organic C, % (w/w)	3.32 (0.270) a	1.25 (0.157) a	15.8 (1.12) b
Total inorganic C, % (w/w)	2.15 (0.121) a	0.221 (0.0149) b	1.29 (0.142) a
Total N, % (w/w)	0.370 (0.0235) a	0.0991 (0.0120) b	1.068 (0.0682) c
C/N ratio	15.4 (0.430) a	14.6 (0.669) a	16.1 (0.867) a
Sand, %	90.8 (0.525) a	51.2 (1.42) b	86.0 (1.045) a
Silt, %	7.95 (0.397) a	37.2 (0.895) b	13.2 (0.883) c
Clay, %	1.20 (0.140) a	11.5 (0.688) b	0.666 (0.229) c
Correlation between θ_g and other soil attributes			
pH	−0.247*	0.0131	−0.753**
NO_3^-, mg kg^{-1} dry soil	0.713**	0.207*	0.225*
NH_4^+, mg kg^{-1} dry soil	0.765**	0.583**	0.790**
Dissolved organic C, mg kg^{-1} dry soil	0.819**	0.777**	0.906**
Dissolved organic N, mg kg^{-1} dry soil	0.402**	0.791**	0.930**
Total organic C, % (w/w)	0.843**	0.755**	0.923**
Total inorganic C, % (w/w)	0.0531	−0.0423	−0.191
Total N, % (w/w)	0.920**	0.554**	0.806**
C/N ratio	−0.414**	−0.277**	−0.240*
Sand, %	−0.251*	0.0645	0.435**
Silt, %	−0.276**	−0.0612	−0.448**
Clay, %	0.163	−0.0491	−0.248*

* Relationships are significant at $P < 0.05$.

** Relationships are significant at $P < 0.01$.

† Mean values ($n = 93$) of different variables for three sites. Standard errors are shown in parentheses. Different letters indicate a significant difference ($P < 0.05$) between sites as tested by ANOVA with sites as factors.

of extensive scientific expeditions (Bliss, 1977; Chapin, 1996; Lev and King, 1999); the soils at the study site are predominantly Aquic Haplorthels and Typic Aquiturbels. Simpson Lake (68°35′ N, 91°57′ W) is situated in the middle of the Boothia Peninsula and is dominated by Typic Haplorthels and Aquic Haploturbels. Ross Point (68°31′ N, 111°10′ W) is situated in the south port of Victoria Island and the soils are dominated by Histels. At all three sites, a slope with a southern aspect was selected and three parallel transects (2-m lateral distance) were laid out along a 300-m section. Soil samples were collected at 31 points (0, 0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50, 100, 100.1, 100.2, 100.5, 101, 102, 105, 110, 120, 150, 200, 200.1, 200.2, 200.5, 201, 202, 205, 210, 220, 250, and 300 m) along each transect. In the laboratory, we measured θ_g, pH, particle size distribution, total organic C (TOC), dissolved organic C (DOC), total C, total inorganic C, exchangeable NH_4^+ and NO_3^-, dissolved organic N (DON), and total N contents.

Before one-way ANOVA and geostatistical analyses, normality and homoscedasticity of the variables were checked using Anderson–Darling and Levene's test in Minitab 11 (Minitab Inc., State College, PA). The degree of spatial heterogeneity was assessed by semivariance analysis (Goovaerts, 1998) in GS+ version 9.0 (Gamma Design Software, Plainwell, MI).

RESULTS AND DISCUSSION

Arctic soils are historically known to be N limited (Chapin et al., 1993). Therefore, it is not surprising that the exchangeable NH_4^+ and NO_3^- content found at Truelove Lowland and Simpson Lake were significantly lower than agricultural (Robertson et al., 1997) and grassland (Jackson and Caldwell, 1993) soils (Table 1). These two sites were dominated by mineral soils, however, while Ross Point had much higher organic matter contents (Histels), which explains the difference in DOC, DON, and TOC contents. In arctic ecosystems, DOC and DON pools have been found to play a significant role in soil ecological processes (Bardgett et al., 2007; Buckeridge et al., 2010). Soil DOC and DON pools and fluxes offer substrates for microbial populations and serve as a link between terrestrial and aquatic ecosystems (Wickland et al., 2007). There have been few studies examining the spatial variability of DOC and DON contents. Rover and Kaiser (1999) found that the DOC content of agricultural soils has moderate spatial dependency (16–44%) and, similarly, Rodriguez et al. (2009) reported moderate spatial dependency (46–62%) for DON in forest soils. Our study demonstrates, however, that the DOC and DON content of arctic soils are highly spatially dependent (61–99%) (Table 2). The spatial range of arctic soil physicochemical attributes was considerably smaller than that of other ecosystems (Cerri et al., 2004; Ruth and Lennartz, 2008). Moreover, the spatial range of the soil properties was comparatively larger in Histels than Haplorthels or Haploturbels (Fig. 1). It should be noted that Histels are more homogeneous, with a similar vegetation type and moisture content and fewer hummocks than Haplorthels or Haploturbels. Therefore, Histels are spatially more consistent and their spatial nature and patterns extend across a larger distance. For researchers interested in obtaining independent samples, the recommended minimum distance between samples is 45 m in Histels and 10 m in Haplorthels or Haploturbels.

Soil moisture content plays a central role in regulating soluble nutrient pools and the structure and composition of microbial and plant communities (Bardgett et al., 2007; Chen et al., 2007). Soil moisture content is known to be highly variable across short temporal scales in most ecosystems, including the high arctic (Bardgett et al., 2007); however, the impact of θ_g on microbial communities and nutrient pools is functionally stable. Thus, strong correlations between θ_g and soil properties can be seen even when the θ_g is temporally variable. The spatial variability of θ_g affects and is affected by vegetation and physiography (Petrone et al., 2004). The role of θ_g in arctic regions is particularly significant because of the short-term active layer dynamics and long-term permafrost dynamics, and this role is further emphasized by the uptake of dissolved N by high arctic plants (Chapin et al., 1993). We found that θ_g was correlated to other soil attributes at all three sites (Table 1). The correlation between θ_g and TOC found in this study is similar to that of tropical forest soil (r = 0.86; Wang et al., 2002) but higher than that of temperate agricultural soil (r = 0.44; Yanai et al., 2005), temperate grassland soil (r = 0.73; Zhao et al., 2007), or tropical grassland soil (r = 0.32; Jackson and Caldwell, 1993). Similarly, the correlation between θ_g and pH, DOC, DON, and exchangeable NO_3^- and NH_4^+ contents in Gelisols is considerably higher than in temperate agricultural (Rover and Kaiser, 1999) or tropical grassland soils, which reconfirms the critical role of soil moisture in high arctic ecosystems (Bardgett et al., 2007).

In summary, we found that, despite the climatic uniqueness of arctic ecosystems, soil properties displayed strong spatial dependency. In general, the observed range of spatial dependency was smaller than in non-arctic ecosystems, which may be attributed to various periglacial features of arctic ecosystems such as cryoturbation, gelifluction, and thermokarst. Due to increasing concern over the impact of climate change on arctic ecosystems, arctic research is going through a phase of rapid development that will probably continue. The spatial variability information found in this study would be helpful to arctic soil researchers when designing sampling schemes for arctic soils.

Table 2. Spatial parameters of gravimetric moisture content (θ_g) and other soil properties.

Property	Truelove Lowland			Simpson Lake			Ross Point		
	Range†	SPD‡	r^2	Range	SPD	r^2	Range	SPD	r^2
	m			m			m		
θ_g	1.68	0.902	0.600	0.720	0.595	0.135	1.57	0.821	0.958
pH	0.420	0.819	0.438	0.848	0.885	0.520	15.0	0.903	0.906
NO_3^-	7.96	0.732	0.728	0.751	0.999	0.490	NS§	NS	NS
NH_4^+	6.58	0.829	0.689	0.930	0.698	0.197	27.6	0.500	0.706
Dissolved organic C	7.44	0.712	0.813	0.625	0.999	0.339	42.6	0.684	0.728
Dissolved organic N	8.48	0.611	0.466	0.782	0.999	0.312	42.0	0.711	0.783
Total organic C	7.96	0.758	0.817	NS	NS	NS	41.2	0.587	0.727
Total inorganic C	NS	NS	NS	1.52	0.999	0.155	NS	NS	NS
Total N	8.31	0.730	0.798	9.03	0.870	0.788	6.70	0.756	0.956
C/N ratio	10.5	0.818	0.972	0.766	0.998	0.797	70.6	0.967	0.977
Sand	NS	NS	NS	NS	NS	NS	NS	NS	NS
Silt	NS	NS	NS	0.775	0.616	0.208	8.00	0.872	0.961
Clay	9.00	0.500	0.467	NS	NS	NS	26.7	0.999	0.993

† Range indicates the zone of spatial dependence.

‡ SPD, spatial dependency, calculated as $C/(C + C_0)$, where C is .

§ NS, not significant (r^2 < 0.1).

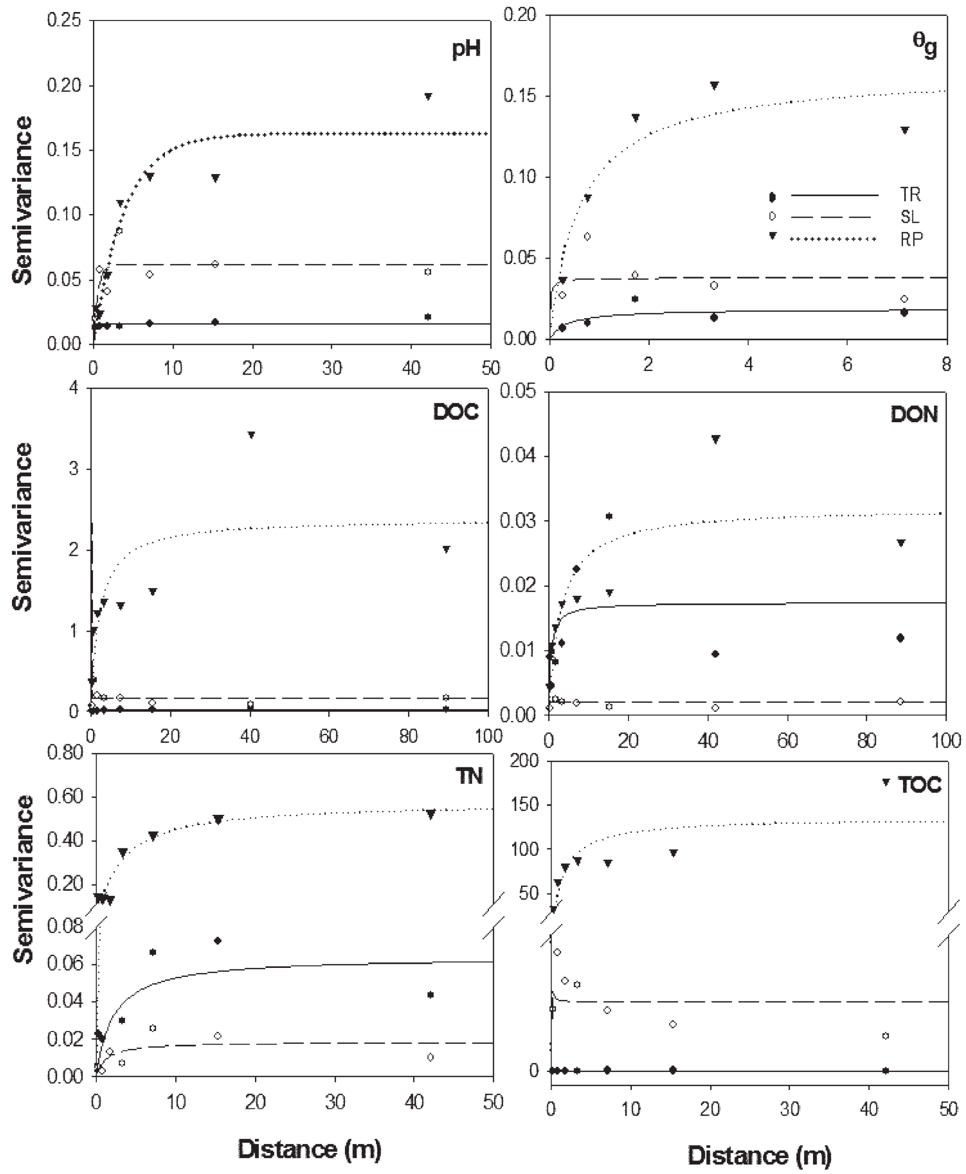

Fig. 1. Experimental semivariograms of selected soil pH, gravimetric moisture content (θ_g), dissolved organic C (DOC), dissolved organic N (DON), total N (TN), and total organic C (TOC) in three arctic ecosystems: Truelove Lowland (TR), Simpson Lake (SL), and Ross Point (RP).

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