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Characteristics of organic soil in black spruce forests: Implications for the application of land surface and ecosystem models in cold regions

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[1] Soil organic layers (OL) play an important role in land-atmosphere exchanges of water, energy and carbon in cold environments. The proper implementation of OL in land surface and ecosystem models is important for predicting dynamic responses to climate warming. Based on the analysis of OL samples of black spruce (*Picea mariana*), we recommend that implementation of OL for cold regions modeling: (1) use three general organic horizon types (live, fibrous, and amorphous) to represent vertical soil heterogeneity; (2) implement dynamics of OL over the course of disturbance, as there are significant differences of OL thickness between young and mature stands; and (3) use two broad drainage classes to characterize spatial heterogeneity, as there are significant differences in OL thickness between dry and wet sites. Implementation of these suggestions into models has the potential to substantially improve how OL dynamics influence variability in surface temperature and soil moisture in cold regions. **Citation:** Yi, S., K. Manies, J. Harden, and A. D. McGuire (2009), Characteristics of organic soil in black spruce forests: Implications for the application of land surface and ecosystem models in cold regions, *Geophys. Res. Lett.*, *36*, L05501, doi:10.1029/2008GL037014.

1. Introduction

[2] Organic soils play an important role in the function of boreal forest ecosystems. The thickness of the organic layer (OL) directly affects the soil thermal regime and indirectly affects permafrost stability, soil hydrology, soil carbon (C) decomposition, and other ecological processes. OL thickness is heterogeneous across landscapes (e.g. north-facing slopes have thicker OLs than south-facing slopes [*Kane et al.*, 2007]), as well as within a soil profile (e.g., deeper OLs are usually more decomposed and have higher bulk densities than shallow OLs [*Boelter*, 1969; *Bauer et al.*, 2006]). OLs are also dynamic over time; they can be combusted by fire and subsequently recover [*Harden et al.*, 2000]. Due to these complexities, OL dynamics have generally been neglected in most land surface and ecosystem models. Static OLs have been implemented in models to represent soil thermal dynamics in cold regions [*Lawrence and Slater*, 2007; *Yi et al.*, 2007; *Zhang et al.*, 2008]. Several other studies have considered the dynamics of OLs on the basis of limited datasets [*Carrasco et al.*, 2006; *Fan et al.*, 2008], but have used static soil temperature and moisture fields as drivers of OL dynamics. Due to the prominent role OLs play in ecosystem function there is a need to characterize their properties and determine how these layers vary across landscapes and within soil profiles. This study examines how organic soil properties vary within soil vertical profiles as well as between two different age classes (young versus mature) and between moisture conditions (dry versus wet) for black spruce (*Picea mariana*) forests, one of the most common ecosystem types in the North American boreal forest [*Viereck and Johnston*, 1990]. To demonstrate the utility of these findings, we incorporated this understanding into a terrestrial ecosystem model to simulate the dynamics of OLs and associated variations in the soil environment for black spruce stands on dry and wet soils.

2. Methods

[3] In this study we use the term OL to generally refer to organic soil overlying mineral soil. OL data analyzed in this study were collected from a variety of black spruce sites near Thompson, Manitoba, Canada (55.8°N 97.9°W). There are 17 young (<70 years) and 10 mature (≥ 70 years) black spruce stands represented in this dataset (Data Set S1 and Figure S1 of the auxiliary material).[1] Soil profiles were classified into two broad categories: dry and wet (see auxiliary material for more detail). Samples within each soil profile had been analyzed for porosity, bulk density, C fraction, and thickness as well as identified as one of four field horizon types. The field horizon type describes the general decomposition state of the sample (Data Set S2). For this study, field horizons were classified as live surface material (“live”), slightly decomposed fibric organics (“fibrous”), moderately to very decomposed organics with amorphous material (“amorphous”), and mineral soil. Horizon type is defined as a property of a sample within a soil profile. For some of the analyses in this study, we aggregated samples of a soil profile with the same horizon type to represent the properties of that horizon. More detailed information about these data is provided in the auxiliary material section.

[4] We performed (1) a three-way unbalanced analysis of variance (ANOVA) with three factors (horizon type, stand age, and drainage) for five independent variables (C fraction, bulk density, porosity, thickness, and C content) using SAS, with data aggregated to the horizon level for each soil profile,

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[1] Auxiliary materials are available in the HTML. doi:10.1029/2008GL037014.

Table 1. Porosity, Bulk Density, and Carbon Fraction for Different Organic Horizon Types in Soil Profiles of Black Spruce Stands[a]

		Live	Fibrous	Amorphous
Porosity (%)	Mean	98.26	96.16	90.05
	STD (n)	1.39 (77)	3.16 (113)	6.10 (56)
Bulk density (g/cm^3)	Mean	0.028	0.070	0.179
	STD (n)	0.023 (78)	0.088 (114)	0.135 (58)
Carbon Fraction (%)	Mean	44.14	41.52	32.78
	STD (n)	4.28 (82)	7.20 (113)	10.36 (59)

[a] Results are aggregated across stand age classes (young and mature) and soil drainage classes (dry and wet). The mean, standard deviation (STD), and number of profiles (n) are indicated. Porosity, bulk density and carbon fraction are significantly different among horizon types at the 0.05 level.

and (2) a two-way unbalanced analysis with two factors (stand age and drainage) for total thickness and total C content for horizons aggregated within each soil profile. A posteriori comparisons of means were performed using Tukey-Kramer tests.

[5] The sample data were used to determine fitted parameters for the exponential relationship between C density and height above the mineral-organic boundary:

$$c_{den} = ae^{bh} + c_{\min} \tag{1}$$

where h is height (cm), a and b are fitted parameters, and $c_{\min}$ is the minimum C density (gC/cm^3); $c_{\min}$ was assumed to be 0.0025 gC/cm^3 based on the minimum C density among samples in the dataset.

[6] To develop relationships between C content and thickness of particular organic horizon type, the C content and thickness of the live, fibrous, or amorphous horizons were summed for each profile, and the relationships between the summed C content and summed thickness were expressed as:

$$C_{sum} = ax_{sum}^{b} \tag{2}$$

where C_{sum} and x_{sum} are summed C content (gC/cm^2) and summed OL thickness (cm) of live, fibrous or amorphous horizons of a profile, respectively, and a and b are fitted parameters. The value of b was constrained to be greater than or equal to 1, so that the C content would increase at least linearly with an increase in horizon thicknesses.

[7] In this study, a dynamic OL version of Terrestrial Ecosystem Model (TEM) was used to demonstrate the effects of OL dynamics and drainages on the soil environment. To demonstrate how a dynamic OL influences active layer depth and water table depth, we analyzed the output from two TEM simulations over a 900 year period, one with a dynamic OL (DOL) and the other with a static OL (SOL) for black spruce stands on dry and wet soils. More detailed information about implementation of dynamic OLs in TEM and the simulation procedures is provided in the auxiliary material section.

3. Results

[8] Porosity, bulk density and C fraction are best characterized by generalized horizon type (live, fibrous, and amorphous; Table 1). All three variables vary significantly among horizon types ($p < 0.0001$; Data Sets S3, S4, and S5), and do not vary by other main effects or interactions among main effects, with the exception that bulk density also varies by drainage class ($p = 0.0075$) and C fraction varies by stand age ($p = 0.0020$). For both dry and wet soils, the mean porosity and C fraction of the live horizon are generally greater than those of the fibrous horizon, which are greater than those of the amorphous horizon (Data Sets S8, S9 and S10). For both dry and wet soils, the mean bulk density of the live horizon is less than that of the fibrous horizon, which is less than that of the amorphous horizon (Data Sets S8, S9 and S10).

[9] OL thickness varies among horizon types, between stand ages, and between drainage classes ($p < 0.0001$; Data Set S6). There are also interactions among main effects ($p < 0.0001$), with the exception of stand age and drainage. At the 0.05 significance level, there is no significant difference between stand ages or between drainage classes for the live horizon (Table 2). For the fibrous horizon, there is a significant difference between young and mature stands in both dry and wet drainage classes. The amorphous horizon thickness in the dry soils is significantly less than the thickness in wet soils, regardless of stand ages. The live thickness is always significantly less than that of the fibrous horizon, regardless of stand age and drainage class.

[10] The total OL thickness in a profile (i.e., the sum of the live, fibrous and amorphous horizons) varies by stand age and drainage ($p < 0.001$), with no interactions. The average (standard deviation) of OLs in dry and wet soils of mature stands are 17 (6) and 34 (14) cm thick, respectively; and OLs in dry and wet soils of young stands are 8 (11) and 23 (13) cm thick, respectively.

[11] OL C content varies by horizon type, stand age, and drainage ($p < 0.001$; Data Set S7). There is also an interaction between stand age * horizon type ($p = 0.0084$). The total organic C in the organic horizons of a soil profile (the sum of live, fibrous and amorphous horizons) varies by stand age and drainage with no interactions ($p < 0.001$). The average (standard deviation) of total organic C in dry and wet organic soils of mature stands are 0.50 (0.27) and 0.89 (0.55) gC/cm^2, respectively; and the average (standard deviation) of total organic C in dry and wet organic soils of young stands are 0.23 (0.49) and 0.68 (0.36) g/cm^2, respectively.

Table 2. Mean, Standard Deviation, and Number of Profiles for Organic Layer Thickness (cm)[a]

		Live		Fibrous		Amorphous	
		Dry	Wet	Dry	Wet	Dry	Wet
Young	Mean	1.35^{f}	1.48^{fa}	$\underline{5.68}^{l}$	$\underline{9.26}^{l}$	**2.90**	**13.03**^{l}
	STD (n)	2.19 (110)	1.76 (36)	5.87 (107)	8.70 (36)	7.23 (98)	9.83 (25)
Mature	Mean	3.5^{f}	3.27^{fa}	$\underline{\mathbf{11.23}}^{l}$	$\underline{\mathbf{22.62}}^{la}$	**7.62**	**12.69**^{lf}
	STD (n)	1.49 (47)	2.64 (49)	5.29 (46)	10.02 (47)	10.05 (45)	11.02 (35)

[a] The superscript of the horizon type (e.g., l - Live, f - Fibrous, a - Amorphous) indicates that the thickness of that horizon is significantly different from the noted horizon. Bold values identify cases for which the thickness of dry soil is significantly different from wet soil. Underlined values identify cases for which the thickness of young stands is significantly different from that of mature stands.

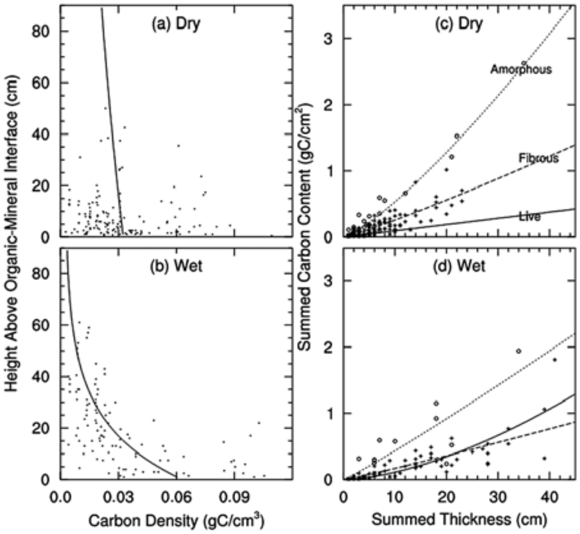

Figure 1. Relationships between carbon density and (a and b) height above the mineral-organic boundary for black spruce stands analyzed in the data set. Dots represent samples. Lines represent regression lines for dry (Figure 1a) and wet (Figure 1b) soils, respectively; and (c and d) relationships between summed carbon content and summed organic layer thickness for three general horizons. Stars, pluses, and circles represent measured values for live, fibrous, and amorphous horizons, respectively, and solid, dashed, and dotted lines represent regression lines for live, fibrous, and amorphous horizons, respectively.

[12] In black spruce stands, C density is generally at a maximum near the boundary between the mineral and organic soil horizons, and decreases exponentially upward from that boundary (Figures 1a and 1b). The relationship between C density and height (equation (1)) had the poorest fit for organic horizons of dry soils ($r = 0.06$; Table 3). The relationship was much stronger for organic horizons of wet soils ($r \geq 0.60$; Table 3).

[13] Total C content of each horizon type is well predicted by summed OL thickness (Figures 1c and 1d and Table 4). Equation (2) and the thicknesses provided in Table 2 predict about 0.72 and 0.99 gC/cm^2 in the total OL of dry and wet soil of the mature stands, respectively. These equations predict 0.27 and 0.74 gC/cm^2 in the total OL of dry and wet soil of the young stands, respectively.

[14] In the static SOL simulation of TEM for dry soil (Figure 2a), the active layer depth (ALD) and water table depth (WTD) had little variability during the 900 years of simulation (Figures 2b and 2c). In contrast, the OL varied from 0.06 to 0.15 m in the DOL application of TEM, with the minimum OL immediately after fire and recovery of the OL occurring until the next fire (Figure 2a). In the DOL simulation for dry soil, ALD increased to about 1.5 m immediately after fire and gradually decreased to 0.8 m in response to OL dynamics (Figure 2b). WTD responded in a different fashion to OL dynamics (Figure 2c) as increases in ALD caused enhanced subsurface drainage to cause an increase in WTD. Once WTD increased, it was not able to recover to the previous wetter condition. In contrast, in the SOL simulation the soil stayed very wet and WTD remained close to soil surface. For wet soil, the OL, ALD and WTD of the SOL simulation were similar to that of dry soil, except that OL and ALD of wet soil were thicker and shallower than that of dry soil, respectively (Figures 2d, 2e, and 2f). In contrast to the simulation for dry soil, the WTD simulated for wet soil were similar between the SOL and DOL simulations (Figure 2f).

Table 3. Coefficients a and b, Correlation Coefficient (r), and Number of Samples (n) Used for Fitting Equations Between Carbon Density and Height Above Organic-Mineral Interface for Black Spruce Stands With Dry and Wet Soils

	a	b	r	n
Dry	0.029	−0.005	0.06	145
Wet	0.061	−0.047	0.60	105

Table 4. Coefficients a and b, Correlation Coefficient (r), and Number of Profiles (n) Used for Fitting Equations Between Summed Carbon Content and Summed Thickness of Generalized Horizons for Black Spruce Stands With Dry and Wet Soils

		a	b	r	n
Dry	Live	0.009	1.000	0.79	108
	Fibrous	0.019	1.125	0.87	93
	Amorphous	0.029	1.262	0.98	106
Wet	Live	0.003	1.621	0.87	48
	Fibrous	0.014	1.088	0.72	44
	Amorphous	0.036	1.080	0.89	21

4. Discussion

4.1. Implementation of Vertical Heterogeneity of Organic Layer in Models

[15] Our analysis in this paper identifies that the carbon density is lowest at the top of the organic layer and highest near the interface between the organic and mineral soil layers.

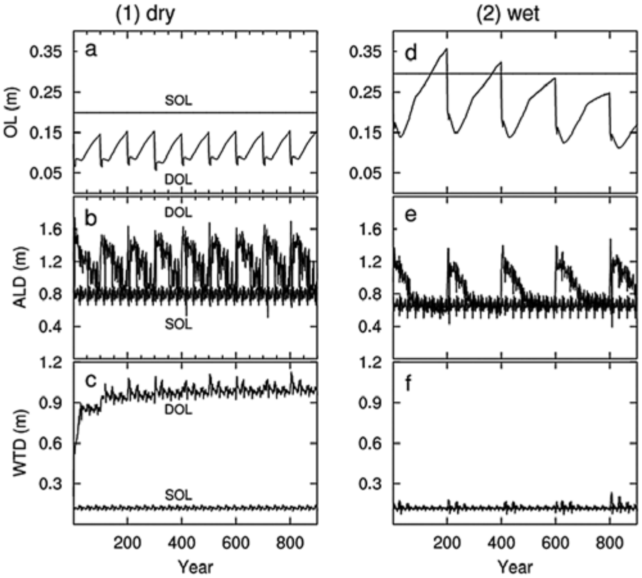

Figure 2. Comparisons of (a and d) organic layer thickness (OL), (b and e) Active layer depths (ALD), and (c and f) water table depths (WTD) between simulations with a dynamic organic layer (thick line; DOL) and a static organic layer (thin line; SOL) for black spruce stands with (left) dry and (right) wet soils.

In addition, the OL properties (porosity, bulk density, and C fraction) differ significantly among the three different horizon types. Porosity is an important factor that affects soil thermal and hydrological properties, e.g., thermal conductivity, matric potential, and hydraulic conductivity. The differences between the porosity of the fibrous and amorphous OLs indicate that modeling efforts should use at least two types of OLs [see *Letts et al.*, 2000], rather than one type [see *Beringer et al.*, 2001]. We also suggest the inclusion of a live moss surface horizon within land surface and ecosystem models due to its distinct physical and ecological properties (e.g., the live horizon has higher porosity and can photosynthesize). The mean values of porosity of different horizon types in Table 1 can be used in models, since there are no significant differences in porosity between stand ages or between drainage classes. However, differences in live moss properties between wet and dry soils need to be considered when simulating soil water dynamics. These differences are likely due, in part, to differences in species composition between drier and wetter soils. Wet sites tend to be dominated by different moss species, including *Sphagnum sp.*, whereas dry sites tend to be dominated by species other than *Sphagnum* [*Manies et al.*, 2006].

[16] In comparison to thermal properties of organic horizons (e.g., thermal conductivity and thermal capacity), there are more uncertainties in hydraulic properties (e.g., hydraulic conductivity and matric potential) [*Letts et al.*, 2000]. More accurate and precise measurements of hydraulic properties of organic horizons are needed to improve modeling of organic layer dynamics.

4.2. Implementation of Spatial Heterogeneity of Organic Layer in Models

[17] The total OL thickness of dry soils is significantly less than that of wet soils, regardless of stand age. The amorphous layer is also thinner in dry soils, regardless of stand age. As discussed by *Harden et al.* [2006] and *Kane et al.* [2007], this difference is likely related to two factors: (1) increased decomposition of these layers in drier soils, which inhibits the accumulation of this horizon, and (2) more frequent and deeper burning fires in dry soils. After fire disturbance, a new OL with low C density forms directly over a high C density layer, as shown in Figure 1. The thickness of the fibrous horizon of wet soils in mature stands is significantly greater than that of dry soils, while the same pattern does not apply to young stands. This suggests that there are distinct differences in the burning and development of the fibrous horizon between drainage classes, which might be caused by different moss types and soil environments in the different drainage classes.

[18] Spatial variability was also found in the vertical distributions of C density. For black spruce stands on dry soils, equation (1) provided a poor fit of C density with height above the mineral-organic soil boundary. This is partly caused by fire disturbance, which can burn deeply into the amorphous horizon of dry soils. Ecological succession after fire causes the accumulation of a fibrous horizon with low C density over a higher density amorphous horizon. Thus, in dry soils there is generally a large difference between the C density at the depth of burning and the newly accumulating organic matter in the soil. Wetter soils, with their thicker fibrous horizon, prevent wildfire from burning into the amorphous horizon. *Carrasco et al.* [2006] used a relationship that was similar to our equation (1) for organic horizons of wet soils to calculate the thickness of OL, based on simulated vertical soil C. The results of this study indicate that the relationship should only be used for black spruce stands with wet soils, but approaches based on equation (2) can be used for all drainage classes.

[19] Because there are distinct differences in fire disturbance and processes controlling organic soil development of black spruce stands across landscapes, the heterogeneity of OLs across landscapes needs to be considered in modeling studies. *Ju and Chen* [2005] implemented six drainage classes to simulate the soil carbon stocks of Canada. While it might be unrealistic to implement this many drainage classes, we recommend using at least two broad drainage classes, as in this study.

4.3. Implementation of Temporal Dynamics of Organic Layer in Models

[20] The total OL thickness and total organic C content of a young stand is significantly less than that of a mature stand, regardless of drainage. With respect to the thermal buffering role of the organic horizons, we suggest that the successional development of organic horizons after fire needs to be considered for simulating the soil environment in cold regions. Here we suggest using the relationships between cumulative C content and cumulative thickness of different organic horizons (equation (2); see Figures 1c and 1d) to simulate the change of thickness of each generalized horizon, based on simulated organic C in that horizon. Our simulations with the DOL version of TEM indicates that the OL dynamics can (1) be simulated in an implementation that is based on equation (2), and (2) can substantially affect ALD and WTD of organic soils. Correctly predicting the dynamics of ALD and WTD of organic soils is important for properly modeling soil C dynamics.

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