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Generalized models to estimate carbon and nitrogen stocks of organic soil layers in Interior Alaska

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Abstract

Boreal ecosystems comprise about one tenth of the world's land surface and contain over 20 % of the global soil carbon (C) stocks. Boreal soils are unique in that the mineral soil is covered by what can be quite thick layers of organic soil. These organic soil layers, or horizons, can differ in their state of decomposition, source vegetation, and disturbance history. These differences result in varying soil properties (bulk density, C content, and nitrogen (N) content) among soil horizons. Here we summarize these soil properties, as represented by over 3000 samples from Interior Alaska, and examine how soil drainage and stand age affect these attributes. The summary values presented here can be used to gap-fill large datasets when important soil properties were not measured, provide data to initialize process-based models, and validate model results. These data are available at https://doi.org/10.5066/P960N1F9 (Manies, 2019).

1 Introduction

Boreal soils play an important role in the global carbon (C) budget and are estimated to store between 375 - 690 Pg of C (Hugelius et al., 2014; Bradshaw and Warkentin, 2015; Khvorostyanov et al., 2008), which is over 20 % of the global soil C stock (Jackson et al., 2017). These soils are unique in that for many boreal ecosystems a large portion of this C can be found within the organic soil layer (Jorgenson et al., 2013). This organic soil layer results from the relatively high input rates, through plant matter, that result from the high summer solar radiation this region receives. In addition, C losses from the soil are low, as cool and/or freezing soil temperatures result in low rates of decomposition. The imbalance between C inputs and losses results in thick organic soils that store large amounts of C (Jorgenson et al., 2013). There is also considerable C found in the mineral soil of these systems, especially where protected by permafrost (O'Donnell et al., 2011; Jorgenson et al., 2013).

Nitrogen (N) also plays an important role in boreal ecosystems due to N limitations on plant growth. One of the main determinants of N availability is decomposition rates. Disturbances that increase

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Open Access Earth System Science Data Discussions

decomposition can also increase N availability which, in turn, increases plant growth, offsetting some of the C losses due to increased decomposition (Finger et al., 2016).

Boreal organic soils are unique when compared to soils from other regions. First, these organic soils are thick, ranging from several centimeters to several meters (Ping et al., 2006). They are also comprised of layers which vary in their degree of decomposition. These layers can also be formed from different types of vegetation. Both factors result in soil layers of varying density. The density and thickness of these organic soil layers also vary depending on the amount of time since the last disturbance (Deluca and Boisvenue, 2012). In addition, C and N concentrations vary between layers, again depending on the degree of decomposition, source vegetation, and disturbance history.

The main disturbances of the boreal region that affect both C/N dynamics and physical soil properties are fire and permafrost thaw. Fire affects boreal soils in several ways (Harden et al., 2000). First, some portion of the organic soil is combusted during the fire, the amount of which varies depending on fire severity (Turetsky et al., 2011). Loss of insulating organic soil and the resulting darkened soil surface warms these soils post-fire, increasing decomposition rates (Genet et al., 2013). Fire severity also influences post-fire vegetation, which in turn affects the amount and chemistry of C and N inputs to the soil (Johnstone et al., 2010; Johnstone et al., 2008). Permafrost thaw, including thermokarst as well as gradual active-layer deepening, influences temperature and moisture regimes. With landscape subsidence and inundation, thermokarst wetlands occur (Schuur et al., 2015). These wetlands differ from the forested permafrost plateaus in both C and N inputs, due to differences in vegetation, and loss, due to differences in soil temperatures (Osterkamp et al., 2009), which in turn affects rates of decomposition (Mu et al., 2016; Schadel et al., 2016). Gradual active layer deepening also results in enhanced soil temperatures and rates of decomposition.

Boreal organic soils have not been adequately characterized. Instead, much of the work regarding these soils has focused on predicting C and N stocks for combined organic and mineral soil horizons to a predetermined depth (Johnson et al., 2011; Bauer et al., 2006). There is currently no source of summarized data of these important soil properties by organic soil layer. To fill this gap, we summarized different soil properties from a large database (>3000 observations) of observations from Interior Alaska (Figure 1). These properties were examined by degree of decomposition (via classification into distinct organic soil horizons), soil drainage, and stand age. Our results can be used to: 1) gap fill when an important soil property was not measured, 2) serve as baseline values to initialize boreal soil models, and 3) validate model results.

2 Methods

2.1 Field methodology

Soil cores were taken using one or more of four different methods. The first method, most often used with surface layers, involved cutting soil blocks to a known volume. Another method often used to sample these soils uses a coring device inserted into a hand drill (4.8 cm diameter; Nalder and Wein, 1998). Wetter sites were sometimes sampled while frozen using a Snow, Ice, and Permafrost Research Establishment (SIPRE) corer (7.6-cm diameter; Rand and Mellor, 1985). Alternatively, if wetter sites were sampled unfrozen we used a 'frozen finger'. This coring method uses a thin-walled, hollow tube (~6.5 cm diameter), sealed at one end, which is inserted into the ground until it hits mineral soil. A slurry of dry ice and alcohol is then poured into the corer, freezing the unfrozen material surrounding the corer to the outside. The corer is removed and the exterior of the core is scraped to remove any large roots or material that stuck to the sample during removal. For some cores, two coring methods were combined to create continuous samples from the surface to the mineral soil.

Cores were subdivided into subsections representing soil horizons based on visual factors such as level of decomposition, color, and root abundance. These horizon samples provided the basis for our analyses and are based on Canadian (Soil Classification Working Group, 1998) and U.S. Department of Agriculture's Natural Resource Conservation Service (Staff, 1998) soil survey techniques. A description of the horizons and the codes we used to represent them are:

https://doi.org/10.5194/essd-2019-114
Preprint. Discussion started: 6 August 2019

Live moss (L)	Live moss, which is usually green. This layer generally also contains a small amount of plant litter.
Dead moss (D)	Moss that is dead and either undecomposed or slightly decomposed. This horizon would be considered an O_i horizon in the U.S. soil system.
Fibric (F)	Fibrous plant material that varies in the degree of decomposition (somewhat intact to very small plant pieces), but there is no amorphous organic material present. Very fine roots often make up a large fraction of this horizon. This horizon would be considered an O_i horizon in the U.S. soil system.
Mesic (M)	This horizon is comprised of moderately decomposed material, with few, if any, recognizable plant parts other than roots. There is amorphous present within this layer to varying degrees, but it is not smeary. This horizon is generally considered an O_e horizon (U.S. soil system).
Humic (H)	This organic horizon is highly decomposed. The soil in this horizon smears when rubbed and contains little to no recognizable plant parts. The H horizon is generally considered an O_a horizon (U.S. soil system).
Mineral (Min)	Classified as an A, B, or C mineral soil (U.S. soil system), it contains less than 20-volume-percent organic matter, as judged in the field.

Because modeling so many different organic layers is difficult, we also combined layers as done in Yi et al. (2009). The fibrous horizon combined the dead moss (D) and fibric (F) horizon, while the amorphous horizon combined the mesic (M) and humic (H) horizon. These combinations were based on similarities in decomposition state and depth. We also present data for several types of horizons that are only found at a subset of sites: ash and burned organics are only found on the surface of recently burned sites, while lichen and litter layers are only found on the surface of ~16 % of profiles. Our field studies also found several horizon types (buried wood, grass, etc.) for which we did not have enough observations (5 or less).

We examined the effect of disturbance on soil properties by categorizing each of the soil profiles in relation to time since the last disturbance, which we divided into three age classes: new (<5 yrs old), young (5 – 50 yrs old), and mature (> 50 yrs old). All 'new' sites had recently burned and lost some portion of their surface organic layers (Harden et al., 2000), which in turn effects soil moisture and temperature (O'Donnell et al., 2010). Young sites had recently experienced fire or permafrost thaw. Both fire and thaw change the dominant vegetation, thus influencing C inputs into the soil. They also influence soil temperature and moisture, which in turn affects soil C stocks.

Although classifications of soil drainage have been established for many soil types (Staff, 1993), the presence of permafrost necessitates modifications of this system (Survey, 1982). Although generally described (Harden et al., 2003; Johnstone et al., 2008), a soil drainage classification for permafrost landscapes is lacking. Here we present such a classification, developed over the past two decades, for areas of discontinuous permafrost (Figure 2). Well drained sites are similar to traditional drainage classifications, in that water moves through the soil rapidly. However, moderately well drained drainage sites have permafrost between 75 – 150 cm, which increases soil moisture of surface organics. Somewhat poorly, poorly, and very poorly drained sites have some factor (permafrost, soil texture, or landscape position) that inhibits drainage and causes redoximorephic features such as blue-grey colors in the mineral soil to appear. Somewhat poorly drained sites have a shallow active layer (often around 50 cm), which affects soil moisture and surface vegetation. Poorly drained sites experience saturated surface conditions only while seasonal ice is present (usually May through early July). In contrast, very poorly drained sites have saturated surface soils during the entire growing season. When sites are located on a slope >5 %, which helps promote drainage (Woo, 1986; Carey and Woo, 1999), drainage class is increased by one step; we call this the hillslope modifier. In addition, because burning increases active layer thickness, recently burned sites may have deeper or no permafrost; therefore, we ascribed their soil drainage using nearby unburned sites.

2.2 Laboratory methodology

We air-dried soils at room temperature (20 °C to 30 °C) to constant mass, then oven-dried the samples for 24-48 hours in a forced-draft oven. Organic soils were oven-dried at 65 °C to avoid the alteration of organic matter chemistry. Mineral soils were oven-dried at 105 °C. Samples were then processed in one of two ways, depending on the horizon code. Mineral soil samples were gently crushed using a mortar and pestle, with care to break only aggregates, and then sieved through a 2-mm screen. Soil particles that did not pass through the screen were removed, weighed, and saved separately; soil that passed through the screen was then ground by using a mortar and pestle to pass through a 60-mesh (0.246-mm) screen. The ground material was mixed and placed in a labeled glass sample bottle for subsequent analyses.

https://doi.org/10.5194/essd-2019-114
Preprint. Discussion started: 6 August 2019

Organic samples were weighed, and roots wider than 1 cm in diameter were removed, weighed, and saved separately. The remaining sample material was then milled in an Udy Corp. Cyclone Sample Mill to pass through a 0.25-mm screen and placed in a labeled glass vial.

We analyzed soil samples for total C and N using a Carlo Erba NA1500 elemental analyzer (Fisons Instruments). In summary, samples were combusted in the presence of excess oxygen. The resulting sample gases were carried by a continuous flow of helium through an oxidation furnace, followed by a reduction furnace, to yield CO_2, N_2, and water vapor. Water was removed by a chemical trap and CO_2 and N_2 were chromatographically separated before the quantification of C and N (Pella, 1990a,b). For organic horizon samples, where inorganic carbon (IC) is largely absent, total C represents total organic C. For mineral-soil horizons were IC was present, we removed carbonates using the acid fumigation technique (Komada et al., 2008) prior to running samples. Briefly, we preweighed samples in silver capsules and transferred them to a small desiccator. Samples were wetted with 50 µL of deionized water and then exposed to vaporous hydrochloric acid (1 N) for 6 hours, during which carbonates degassed from samples as carbon dioxide.

2.3 Data quality and statistical methodology

Often the soil descriptions at the interface of the organic and mineral soil included notations indicating that these horizons consisted of mixed organics and mineral soil. In the field the best call was made to if it was mineral (<20 % C) or organic (≥20 % C). However, chemistry data often shows these horizons were mislabeled (for example, a mineral soil with 22 % C). We used C chemistry to remove organic soils with < 20 % C from our analyses.

All statistical analyses were run using the R program (Team, 2017). We first checked the data for normality. Much of the data needed transformation (Table S1). The effects of drainage and age class, for all soil horizons with the exception of the fibrous and amorphous horizons, was tested using the mixed-effects model command *lmer* (lme4; Bates et al., 2015), using profile (or soil core) as the random effect. When significant, differences among drainage types or age class were determined using the *difflsmeans* command (lmerTest; Kuznetsova et al., 2017), which produces a Differences of Least Squares Means table with p-values. For the evaluation of drainage and age class on thickness for the fibrous and amorphous horizons, because all applicable samples within a soil profile were combined, we used an analysis of variance model (*aov*) with the *TukeyHSD* function.

3. Dataset Review

3.1 Bulk density

Bulk density varied by depth and was significantly different ($p < 0.05$) among all horizon types (live moss, dead moss, fibric, mesic, humic, and mineral soil; Table 1), including the two combined horizon codes (fibrous and amorphous). Surprisingly, as they are comprised of very similar material, even the live and dead moss layers had significantly different bulk densities. Bulk density increases ~10-fold from one layer to the next as one progress down the soil profile (from 0.021 g/cm^3 for live moss to 0.215 g/cm^3 for humics). These differences are likely related to the length of time each soil layer has had to decompose. As soil layers become older, plant fibers break down physically and biologically, becoming smaller and more compressible.

Bulk density also varied by drainage class: well drained sites tended to have higher bulk densities than other soil drainage classes (Table S1). While this pattern was not always significant it was consistent for all horizons except for the dead moss horizon, where it was the 2nd highest. The higher bulk densities of well-drained sites are likely related to two factors: 1) the influence of lichens and litters, which are more often found within well drained sites and have higher bulk densities than moss (Table 3), and 2) the influence of mineral soil, which, due to shallower organic soils, is more likely to be incorporated into fibric (F) and mesic (M) horizons. This last reason is supported by the lower %C values also found within well-drained F and M horizons (Table S2). New (< 5 yr old) sites tended to have slightly higher bulk densities than the young and mature age classes (all horizons except for the humic horizon; Table S1). However, the differences weren't usually significant.

3.2 Carbon

Upper soil layers (live moss, dead moss, and fibric horizons) are consistently higher in % C than lower layers (mesic, humic, and mineral horizons; Table 1). Bulk density values also increase with depth for these horizons, so that C storage values increase dramatically with depth (Figure 3).

C content varied by drainage class for the fibric and mesic layers (Table S3), which had lower % C values in well drained as compared to more poorly drained sites. Lower C values for the fibric and mesic well-drained sites are likely due to the inclusion of mineral soil material into these horizons, likely due in large part to natural process such as cryoturbation or aeolian contributions. Somewhat poorly drained sites also have lower C values for all organic soil horizons as compared to other non-well drained classes.

C content increased with age class for the fibric and mesic horizons (Table S2). Since all sites classified as 'new' were recently disturbed by fire, this increase could be due to both the inclusion of more live roots and the loss of ash, which has a lower C content and is a component of recently burned soil's surface layers, within these two horizons as stands recover.

3.3 Nitrogen

All horizons had significantly different N concentrations from each other (Table 1). The amount of N within the organic layers increased with depth. N was 2-3 times higher in the organic horizons as compared to mineral soil. There was significant variability in N by drainage class for each horizon type (Table S3). The poorly and very poorly drained sites had greater concentrations of N than then other drainage classes for the fibric (F), mesic (M), and humic (H) horizons. These higher concentrations may be due to the number of these observations (~40 %) from bogs and fens, which have been shown to have higher litterfall N concentrations (Finger et al., 2016). There was also a trend of higher N in the new and younger stands for the live and dead moss horizons (Table S3), which may be related to N quality of early succession litterfall.

3.4 C:N ratio

All horizon types had significantly different C:N ratio from one another (Table 4), with these ratios tending to decrease as the horizons deepen and become more decomposed. There were no trends in C:N ratio by drainage class. Age class played a role in C:N ratios for the less decomposed horizons, where C:N ratio increase as stands aged. These trends are more influenced by changes in N by age class, than changes in C.

3.5 Thickness

The factor that varied the most by horizon was the thickness of each horizon type (Table 1). There was a very strong effect of drainage on thickness, with the well-drained sites having much thinner soil horizons (and no humic horizon) than the other drainage classes and the very poorly drained sites having much thicker soil horizons that the other drainage classes (Table 2). Age class also plays a role in horizon thickness: new sites (<5 yrs old) had much thinner organic soil horizons than young or mature sites (Table 3). Since new sites recently burned, these thin soil horizons are the result of the loss of organics due to combustion. Both fire return interval and fire severity impact the amount of legacy soil remaining (Harden et al., 2012), therefore fire history likely plays a large role in horizon thickness.

Vegetation could also influence horizon thickness. An examination of these data that included current surface vegetation found greater thicknesses for sites with *Sphagnum* sp. and sedges, although this factor usually wasn't statistically significant. Historical vegetation could also influence horizon thickness. For instance, if a site was *Sphagnum* dominated in the past, even if it's not the current surface vegetation, the soil profile is more likely to have thicker soil layers due to the slow decomposition rate of *Sphagnum* (Turetsky et al., 2008). Because such historical factors are difficult to measure and predict, we recommend that users of these data include the natural variability in thickness estimates in their analyses.

https://doi.org/10.5194/essd-2019-114
Preprint. Discussion started: 6 August 2019

3.6 How well do these values represent the data?

To test how well the values in Table 1 – 3 estimate C and N stocks we compared predicted versus measured stocks for two locations. Our first test was for 142 samples taken from two chronosequences (time since fire) located near Thompson, Manitoba (Manies et al., 2006). Each chronosequence represents a different drainage class: moderately well drained versus somewhat poorly drained. These data were taken using the same methods of sampling and describing soil horizons. We used the bulk density, C, and N values based on horizon only (Table 1) and thickness based on horizon and drainage (Table 2). For those profiles with high C or N stocks (> 5 gC/m^2 and > 0.01 gN/m^2, respectively) our predicted stocks were consistently higher than measured stocks. This result is mostly due to greater predicted than observed thicknesses, most dramatically for the mesic (M) horizons. In addition, our predicted bulk density values tended to be slightly higher than measured values especially for the fibric (F) and humic (H) horizons. We found that most the observations with large differences in predicted versus observed stocks had anomalously low measured bulk densities. For example, there were some thick fibric horizons with a bulk density of 0.01 g/cm^2 (versus the predicted value of 0.06 g/cm^2) and mesic horizons with a bulk density of 0.05 g/cm^2 (versus the predicted value of 0.15 g/cm^2). These results could be because a) our data, from Interior Alaska, does not well represent other black spruce, boreal regions, or b) our average values, especially thickness, tend to overestimate stocks.

To determine if our previous results were due to regional differences, we also compared predicted versus measured C stocks for a second study, this one located within Alaska (Kane and Ping, 2004). They measured horizon thickness (all samples), C (all samples), and bulk density (one sample per site) for soil profiles along a continuum of tree productivity. This work used the US Soil System to describe their soils, dividing the organic horizons into O_i and O_e/O_a horizons. We chose to represent their O_i data, which they described as slightly decomposed moss, with our dead moss (D) horizon and their O_e/O_a data, which they described as intermediately decomposed moss with rare saprics, as our fibric (F) horizon. For this dataset our predicted stocks were much less than measured stocks. This result is due to underestimating thicknesses (both the O_i and O_e/O_a horizons) and bulk density (O_e/O_a horizon). The discrepancy in bulk density values may be because the bulk density samples taken by Kane and Ping (2004) were 5.08 cm in diameter, while the actual thickness of these horizons they were measuring ranged between 1 and 25 cm. Therefore, their measurements likely did not accurately characterize their soil horizons. These results also point out potential issues that could arise with data described in a different manner (here the US Soil System). While we made our best guess as to which of our horizons best fit their data, the measured O_e/O_a bulk density ranged between 0.06 and 0.12 g/cm^2, implying that their samples were likely a combination of fibric (F) and mesic (M) horizons (which have average bulk densities of 0.07 and 0.15 g/cm^2, respectively, Table 1).

3.7 Caveats

It is important to include mineral soil in soil C stock evaluations, as the mineral soil of this region contains large amounts of C, especially within Yedoma deposits (Hugelius et al., 2014; O'Donnell et al., 2011). However, the mineral soil data presented here do not represent full mineral soil profiles, since our sampling often stopped 5-10 cm into mineral soil. Additional examinations into bulk density and C concentrations of Alaskan mineral soil can be found in Ping et al. (2010), Michaelson et al. (2013), and Ebel et al. (2019).

Our analysis includes Alaska data from >3,000 soil samples and >290 soil profiles, with samples dominated by soil profiles from somewhat poorly, poorly, and very poorly drainages. Age classes were also not equally distributed, as almost 50 % of our soil profiles were from mature stands. This unbalanced design means that our results may not adequately represent all drainages and age classes, particularly well-drained sites. Deciduous stands are not well represented. In addition, we have few sites from shrub dominated ecosystems. Our data best represents black spruce dominated forests and thermokarst wetlands in Alaska.

4 Data Access

All data used in this manuscript is available from https://doi.org/10.5066/P960N1F9 (Manies, 2019). In addition, many additional soil attributes, such as volumetric water content, von Post decomposition index, and additional chemistry, can be found for the majority of these data through various USGS Open-File Reports (Manies et al., 2017; Manies et al., 2016; Manies et al., 2014; O'Donnell et al., 2013; O'Donnell et al., 2012; Manies et al., 2004).

5 Conclusions

Boreal ecosystems are especially sensitive and vulnerable due to climate change. Unfortunately, most models do not do a good job recreating high latitude biogeochemical processes (Flato et al., 2013). One reason for the discrepancies between model results and data is that many large scale models do a poor job at recreating soil thermal dynamics, which is necessary for recreating permafrost dynamics (Koven et al., 2013; Khvorostyanov et al., 2008). While these processes are starting to be incorporated into land surface and regional models (see, for example, Genet et al., 2013; Koven et al., 2011), currently few models include the "distinct properties of organic soils" that are found in the boreal region (Flato et al., 2013). The data presented in this paper provide a needed dataset for initializing and validating models related to boreal organic soils. In addition, these data can be used by scientists to gap-fill in instances when an important soil property was not measured.

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Author contribution

KM prepared the manuscript with the help of MW and JH. All authors were involved in supporting the collection of these data.

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Preprint. Discussion started: 6 August 2019

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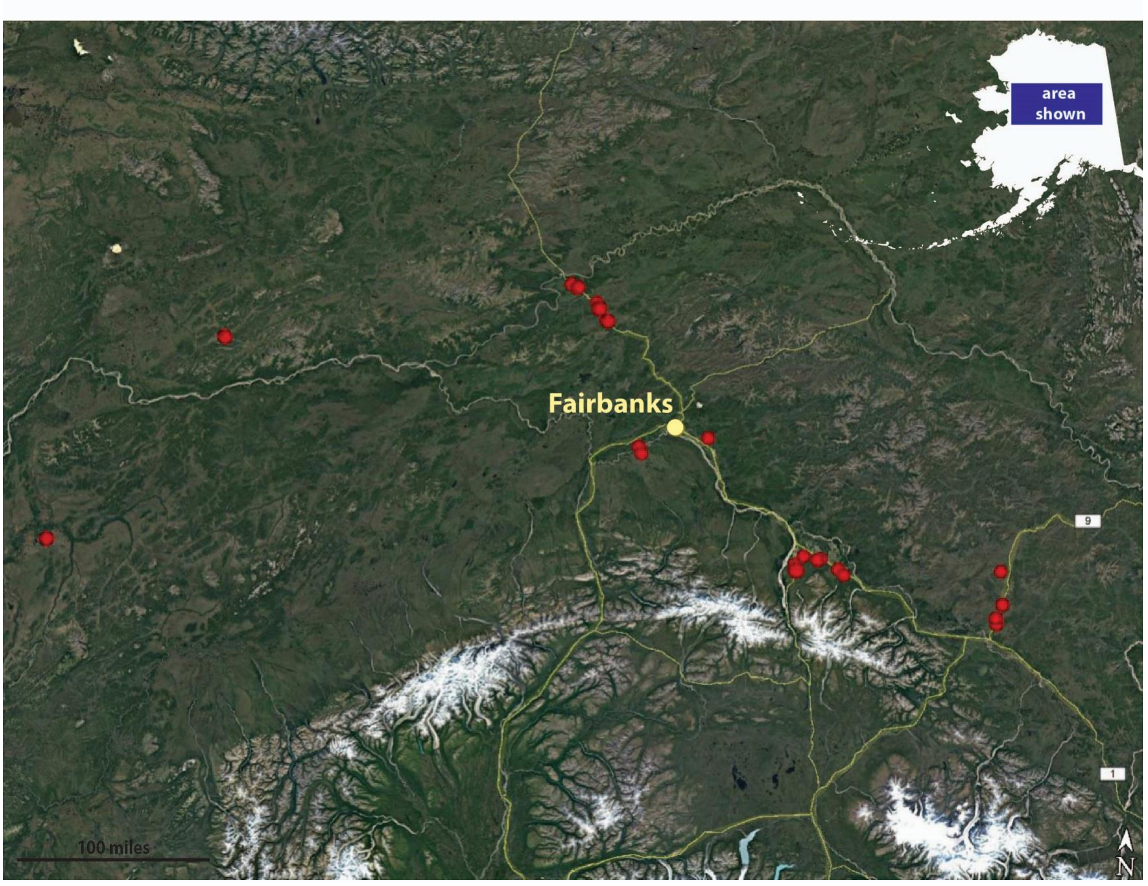
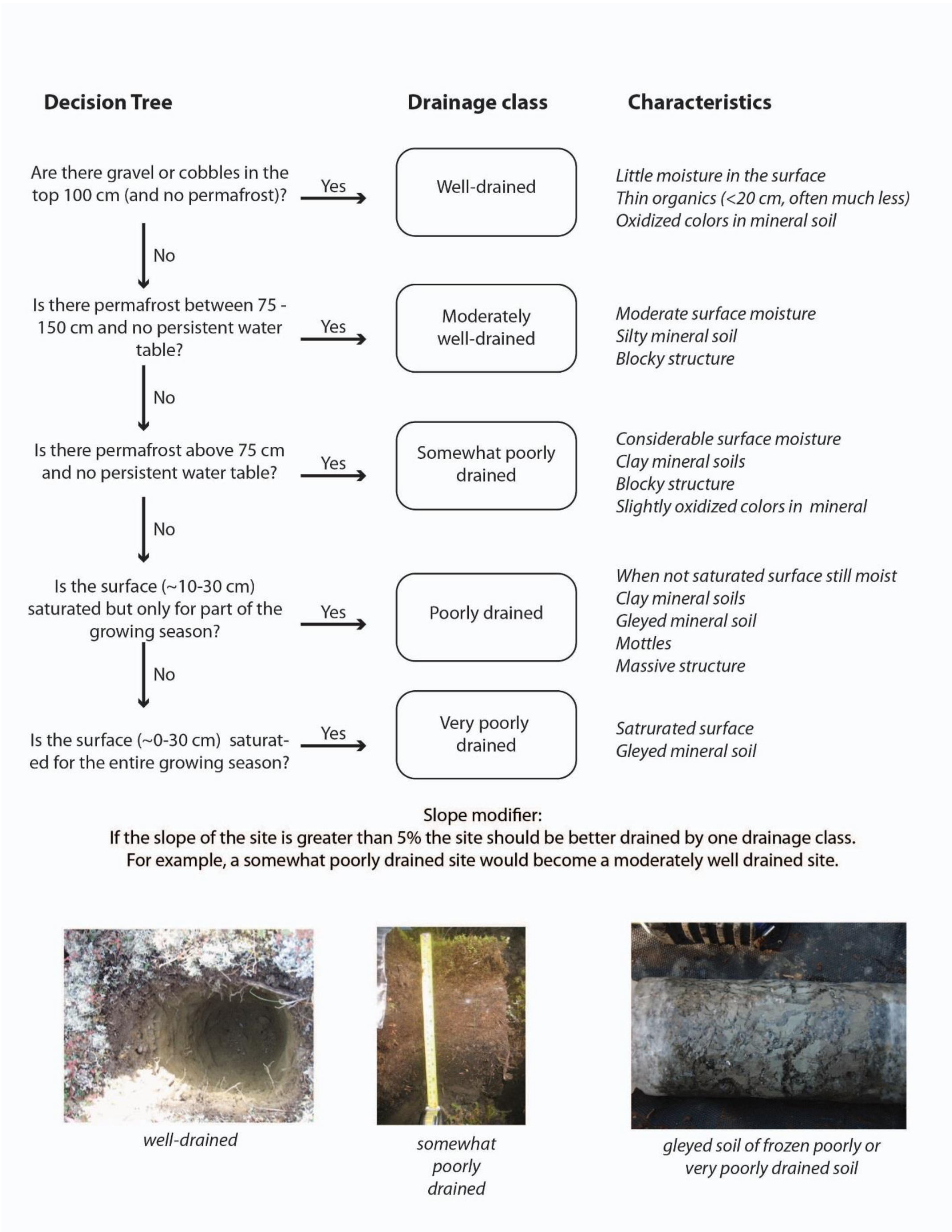
Preprint. Discussion started: 6 August 2019

Figure 1. Location of the sites used in this study within Interior Alaska. (Map data: © Google, 2018.)



https://doi.org/10.5194/essd-2019-114
Preprint. Discussion started: 6 August 2019

Figure 2. Soil drainage class decision tree.



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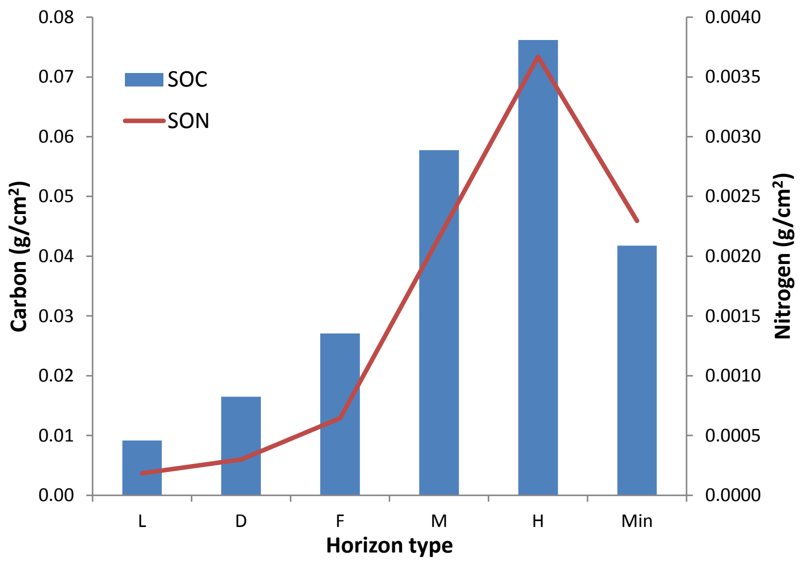
Preprint. Discussion started: 6 August 2019

Figure 3. Trends in carbon and nitrogen storage (g/cm[2]) by horizon type using average values for bulk density, carbon, and nitrogen (see Table 1). Horizon designations: L = live moss, D = dead moss, F = fibric, M = mesic, H = humic, Min = mineral.



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Preprint. Discussion started: 6 August 2019

Table 1. Bulk density (g/cm^2), C (%), N (%), C:N ratio, and thickness (cm) for the main horizon codes. Values in parenthesis are standard deviations. Significant differences ($p < 0.05$) among the main horizon codes are indicated with different letters. There are no thickness values for mineral soil because these results would reflect the thickness sampled, not the actual thickness of this horizon.

Horizon Code	**Bulk Density (g/cm^2)**	**Carbon (%)**	**Nitrogen (%)**	**C:N**	**Thickness (cm)**
live moss (L)	0.022[a] (0.018) n=138	41.7[a] (3.8) n=145	0.84[a] (0.25) n=145	54[a] (16) n=141	2.5[a] (1.6) n=138
dead moss (D)	0.039[b] (0.026) n=540	42.6[a] (3.8) n=538	0.77[b] (0.27) n=537	62[b] (23) n=541	14.3[b] (26.0) n=161
fibrics (F)	0.065[c] (0.041) n=552	41.0[a] (5.6) n=566	0.98[c] (0.42) n=564	48[c] (17) n=552	12.8[c]* (17.8) n=225
mesics (M)	0.149[d] (0.077) n=634	38.2[b] (6.8) n=650	1.42[d] (0.54) n=651	31[d] (13) n=634	20.4[d]* (40.3) n=208
humics (H)	0.215[e] (0.096) n=160	32.1[c] (6.6) n=164	1.53[e] (0.44) n=164	22[e] (6) n=160	10.0[bc] (11.5) n=77
mineral (Min)	0.731[f] (0.380) n=584	6.5[d] (6.2) n=674	0.34[f] (0.32) n=673	18[f] (7) n=603	n/a
fibrous (D&F)	0.052 (0.037) n=1092	41.8 (4.8) n=1104	0.88 (0.37) n=1101	29 (12) n=794	22.8 (41.1) n=220
amorphous (M&H)	0.162 (0.085) n=794	36.9 (7.2) n=814	1.44 (0.52) n=815	55 (21) n=1093	19.7 (27.7) n=263

*p-value very close to 0.05 (thickness F vs M = 0.044). These values are so close to our threshold of 0.05 we would like to recognize that there is a chance that the bulk density values are not significantly different from each other.

https://doi.org/10.5194/essd-2019-114
Preprint. Discussion started: 6 August 2019

Table 2. Thickness (cm) of the main horizon codes by soil drainage and age class. The mineral soil horizon was not included in this table because the way in which we sampled the mineral soil led to arbitrary thicknesses. Data presented are means, standard deviations (in parentheses), and number of observations. Significant differences ($p < 0.05$) for horizon codes, among either drainage or age class, are indicated with different letters.

Horizon	**Drainage**					**Age class**		
	Well-drained	**Moderately well-drained**	**Somewhat poorly drained**	**Poorly drained**	**Very poorly**	**New**	**Young**	**Mature**
live moss (L)	2.2 (1.0) n=6	2.5 (1.1) n=13	2.1 (1.1) n=75	1.5 (0.7) n=18	4.3 (2.1) n=26	1.0 (-) n=2	2.6 (2.1) n=43	2.4 (1.2) n=93
dead moss (D)	3.3^{a} (1.6) n=20	8.1^{a} (7.2) n=20	7.5^{a} (10.7) n=78	6.5^{a} (6.5) n=21	38.8^{b} (44.5) n=36	6.3^{a} (4.5) n=17	16.4^{b} (19.7) n=45	14.7^{b} (30.2) n=99
fibrics (F)	3.1^{a} (3.0) n=11	10.0^{abd} (5.2) n=18	8.0^{b} (5.2) n=123	13.6^{cd} (11.0) n=46	39.1^{bd} (38.5) n=27	6.6^{a} (5.9) n=65	19.1^{b} (31.2) n=41	14.0^{c} (14.6) n=119
mesics (M)	2.8^{a} (1.3) n=5	12.4^{abc} (16.7) n=17	13.2^{b} (37.9) n=113	15.2^{c} (23.0) n=39	57.0^{d} (53.8) n=34	6.5^{ab} (4.1) n=54	20.9^{a} (32.6) n=53	27.6^{b} (51.4) n=101
humics (H)	none	10.0^{ab} (14.0) n=9	6.2^{a} (8.3) n=38	7.4^{b} (3.4) n=13	20.7^{b} (14.3) n=17	4.3^{a} (3.2) n=24	13.4^{ab} (12.7) n=19	12.3^{b} (13.2) n=34
fibrous (D&F)	4.5^{a} (4.4) n=12	15.5^{b} (8.9) n=22	11.6^{b} (10.0) n=136	14.6^{b} (11.3) n=52	59.8^{c} (50.0) n=41	7.3^{a} (6.4) n=73	26.7 (36.1) n=47	23.5 (28.8) n=133
amorphous (M&H)	2.8^{a} (1.3) n=5	15.8^{a} (24.5) n=19	14.5^{a} (38.3) n=119	16.8^{a} (22.3) n=41	63.6^{b} (51.5) n=36	8.0 (5.3)^{a} n=57	23.5^{a} (33.2) n=58	30.5^{b} (52.5) n=105

https://doi.org/10.5194/essd-2019-114
Preprint. Discussion started: 6 August 2019

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Table 3. Number of observations, bulk density (g/cm2), C (%), N (%), C:N ratio, and thickness (cm) of non-main horizon codes. Values in parenthesis are standard deviations.

Horizon	**N**	**Bulk density (g/cm2)**	**Carbon (%)**	**Nitrogen (%)**	**C:N**	**Thickness (cm)**
ash	14	0.183 (0.155)	38.0 (14.4)	0.84 (0.34)	49 (20)	0.1 (-)
burned organics	99	0.122 (0.142)	38.6 (8.9)	1.07 (0.32)	99 (38)	1.6 (0.9)
lichen	31	0.034 (0.019)	40.3 (5.9)	0.76 (0.41)	69 (37)	3.6 (2.2)
litter	16	0.044 (0.018)	41.2 (3.1)	1.55 (0.52)	29 (10)	1.6 (0.9)