Soil Organic Carbon at Lake Hovsgol, Mongolia: The Role of Grazing and Permafrost

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Abstract

Approximately 15% of global soil carbon is in permafrost and permafrost-underlain soils. Climate change and land-use change could both cause the release of large quantities of this soil C, creating feedbacks in the global C cycle. I studied the amount, vertical distribution, and potential mineralization of soil organic carbon in four sites at the Hovsgol Global Environmental Facility, Mongolia. Two sits were lightly grazed and two heavily grazed, and one in each grazing level was underlain by permafrost. In the site without permafrost, soil C (0-110 cm) was 7.4±0.8 kg m^{-2} and there was no difference between the lightly and heavily grazed sites without permafrost. In sites with permafrost, the permafrost table was deeper where there was heavy grazing than where there was light grazing, and C storage was more than four times greater (30±15 kg m^{-2}) in soil above the permafrost at the light grazing site than to 110 cm at the heavy grazing site (7.1±0.7 kg m^{-2}). Grazing may lead to the loss of large amounts of soil C through erosion of peat layers and indirectly by soil warming due to the loss of the insulating peat layer, and consequent lowering of the permafrost table. However, the limited extent of lightly grazed grasslands underlain by permafrost suggest that any positive feedback from global warming will be limited. Except for the permafrost underlain, lightly grazed site, C mineralization from soils in 90 day incubations was not statistically different among sites. The lightly grazed permafrost site had the greatest total mineralized C per unit area, but less than the other sites as a fraction of total soil C. The observed patterns of C distribution and mineralized C among sites suggests a relationship between grazing, permafrost, and C cycling that requires further research.

Introduction

The largest terrestrial pool of carbon is in soils. In tundra systems underlain by permafrost, soil organic carbon (SOC) in the upper layers of permafrost has been found to contain 50-400% as much C as soil above the permafrost (Michaelson et al. 1996), and globally, permafrost soils contain approximately 400 Pg of organic C, or 15% of global soil C (Davidson and Janssens 2006). Climate models have predicted that human-induced climate change will cause the greatest warming at high latitudes (IPCC 2001), the site of permafrost soils. A warmer climate will likely cause a lowering or elimination of the permafrost table, and a greater portion of SOC will be likely to enter the active zone, potentially increasing decomposition rates and creating a positive feedback in the C cycle. Microbial respiration occurs in frozen soils, though slowly (Michaelson et al. 2002, Mikan et al. 2002), and total respiration from SOC in deep soils can be sensitive to soil thaw (Goulden et al. 1997, Mikan et al. 2002). However, models predicting release of C from frozen soils from climate warming are extremely sensitive to assumptions of the quantity and quality of SOM in permafrost and little is known about the quantity and characteristics of SOM in the permafrost pool (Hobbie et al. 2000)

Soil temperature effects on decomposition rate are not the only climatic control of C mineralization. Flooding and subsequent anoxia reduce decomposition rates (Davidson and Janssens 2006). In areas of shallow permafrost, permafrost impedes drainage, creating waterlogged, anaerobic soil conditions. Such conditions can lead to C accumulation due to very slow decomposition rates. In arctic tundra, the greatest accumulation of C occurs in poorly drained areas with shallow permafrost (Giblin et al.1991). Drainage of such areas leads to increases in CO_2 respiration (Hobbie et al.

2000). Melting of permafrost could potentially cause large amounts of SOC to decompose quickly due to changes in temperature, moisture, and oxygen availability.

Land use change can also affect soil C storage. It has been clearly established that conversion of native soils to cultivated land leads to significant losses of soil C (Davidson and Ackerman 1993, Burke et al. 1997). It is less clear, however, what effect grazing has on soil C. In overgrazed systems, grazing can reduce soil C through reduction of inputs (Conant 2001). However, ecosystem response to moderate grazing varies widely and is dependent on the productivity of the system and whether the system evolved under grazing pressures (Milchunas and Lauenroth 1993). In some semi-arid systems, grazing has been shown to increase soil C (Reeder and Shuman 2002).

Permafrost depth may also be affected by land-use. Vegetation, moss, and litter act as a thermally insulating layer above soils. Permafrost depth changes dramatically with the removal of this insulation (Dyrness 1982). Grazing can reduce the thickness of the insulating layer by removing or plant matter that would otherwise become litter, and lead to lead to higher soil temperatures through both herbivory and trampling. Changes in the plant community due to grazing may also affect the amount of energy absorbed by the canopy rather than warming the soil. Such a mechanism, in reverse, has been suggested to have contributed to the conversion of northern Russia to tundra from steppe at the end of the Pleistocene, when many large grazing mammals were hunted to near-extinction (Zimov et al. 1995). In the Western U.S., grazing has been shown to increase soil temperatures in riparian zones through the removal of insulating vegetation (Fleischner 1994). Van der Wal and others (2001) showed that excluding herbivores from plots in arctic tundra for seven years caused a thickening of the moss layer and reduced summer soil temperatures at the surface of the mineral soil by 0.9ºC in Spitsbergen, Norway; change in soil temperatures also induced a change in plant community structure. On the Tibetan Plateau, sites with a history of heavy grazing had soil temperatures an average of 2.0ºC warmer than sites with little history of grazing (Klein et al. 2005). Long-term grazing exclosures in Barrow, Alaska, showed both shallower permafrost and increased moss thickness over time (Miller et al. 1980). Grazing, thus, can affect soil C through the indirect mechanisms of changing soil temperatures and permafrost depth in addition to directly reducing litter inputs from plants.

Both climate and land-use changes are likely to affect Central Asia. Mongolia is experiencing rapid warming, with surface air temperatures increasing 0.7ºC in the past 50 years (IPCC 2001). The southernmost extent of permafrost is in Mongolia and Northern China and is likely to shift northwards due to warming (IPCC 2001). While the region has a long history of grazing livestock (Chuluun and Ojima 2002), the 20th century saw a rapid increase in the area of rangelands. Rangelands comprise 82% of the grassland in Central Asia (China, Mongolia, Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan and Tajikistan), and 60-70% of these grasslands are now over-grazed or over-cropped (Chuluun and Ojima 2002). In Mongolia, approximately 80% of the land area is grazed, and one-third of it has been overgrazed (IPCC 2001). This widespread land-use contrasts with other permafrost-underlain areas.

I investigated the amount and distribution of soil C across sites with differing grazing intensities and in the presence and absence of permafrost in Northern Mongolia. Given a limited scope, I sought to identify patterns associated with these factors that could inform a study to examine specific effects in the future. To examine the processes generating relationships between site and soil C, I also examined the lability of soil C in the system.

Methods

Field Site

I performed my study in two river valleys at the Hovsgol Long Term Ecological Research (LTER) Site in Mongolia, in June-August 2005. The Hovsgol LTER spans six river valleys on the eastern shore of Lake Hovsgol. Mean annual air temperature at the south end of the lake basin, (Hatgal, 88 km south of the field site), is -4.5º, with June and January average temperatures of 11ºC and -21ºC (Banzragch et al. 2006). Mean annual temperature has risen 1.8ºC during in the past 40 years. Mean annual precipitation is 300-350 mm (Banzragch et al. 2006). Most rain falls during the summer months, peaking at an average of 100 mm in July (Banzragch et al. 2006).

River valleys at Hovsgol LTER run east-west. Valleys have gentle north-facing slopes, slightly steeper south-facing slopes and a flat valley floors with meandering rivers that drain into the lake. Near the river mouth (where study sites were), it is 3-4 km between ridge tops and the valley floors are approximately 0.5 km wide. Most soils are sandy loams with alluvial origins, although patches of aeolian sands occur. Bedrock at the site consists of Cenozoic volcanic deposits (Batkhishig 2006).

I established four plots – two in Turag Valley(51º1' N, 100º46' E) and two in Dalbay Valley (51º17' N, 100º49' E). In each valley one plot was on a north-facing slope and the other on a south-facing slopes. Plots were 60 x 60 m. All plots were on toeslopes 10-15 m above the valley bottom. Slopes ranged from 0 to 15º. Permafrost was absent on south-facing slopes and the depth to frozen soil on the north-facing slopes was measured in early August. On the Dalbay north slope, frozen soil was 0.6 m below the surface, as measured by a sounding rod at six points within the plot. In Turag Valley, permafrost depth was 2.5 m, as measured by temperature soundings from a borehole in the plot (Sharkuu et al. 2005).

To the north of the field site is the town of Khankh, a border depot, and to the south is the strictly protected area of Hovsgol Lake National Park. As a result, there is a population gradient running north-south, with areas of greater population to the north. Almost all families in the study area are nomadic pastoralists, raising goats, sheep, yak, and horses, so the livestock density gradient follows population. Over the four years 2002-2005, the Dalbay Valley had an average of 0.076 livestock units/ha (sheep equivalents) of non-forest land cover in the watershed, and the Turag valley had 0.15 livestock units/ha. The livestock density for Turag Valley may be an underestimate, as livestock are counted only during the summer and the valley is more heavily occupied in the winter. As herders are nomadic, these values are indicative of long-term, average grazing intensities since herds move among and within the valleys on a seasonal basis. Within a single season, a herd occupies a pasture area at a stocking rate of 0.3-4.3 animals/ha, with an average of 2.3 animals/ha (Bayasgalan 2005). Another measure of short-term grazing intensity is the percent cover of dung, which was 0% in the Dalbay valley study sites and 6% in the Turag Valley sites in 2005. It is believed that the relative grazing intensities in the two study valleys had been similar for the period 1960-1990, with grazing intensity increasing in both since the economic transformations of the early 1990s.

In both Turag plots and the Dalbay-south facing plots, vegetation consisted of short-stature sedges and forbs. In Turag-south facing, the dominant species are *Carex duriuscula* and *Artemisia frigida*. In Turag-north facing, the dominant species are *Koeleria macrantha*, *Artemisia commutate,* and *Poa attenuate*. In Dalbay-south facing, dominant species are *Thymus gobicus and Carex pediformis.* In Dalbay north-facing, 75% of ground cover is moss; the primary other plant species are the grass *Carex dichroa* and the shrub *Salix glauca.* Live plant biomass in mid-summer is much greater at Dalbay-north facing (600 g/m^2) than at the other sites (100-200 g/m^2). (Ariuntsetseg et al. 2006).

Soil Pits

Within each 60 x 60 m plot, I excavated three soil pits. The pits were randomly located in three strata in each of two spatial dimensions, north-South and east-west. Pit sites were rejected where soil had clearly been recently disturbed, e.g. from recent vehicle passage, and moved 5 m in a random cardinal direction. Two sampling points had to be moved based on this criterion. At each sampling point, slope, aspect, and local microtopography were recorded.

I dug soil pits using the “quantitative method”, modified from Hamburg (1984). A 0.5 m^2 square reference frame was secured to the ground using rebar. I recorded percent cover of plant species, bare ground, and rock in the frame. I collected soil in six layers (0-10 cm, 10-30 cm, 30-50 cm, 50-70 cm, 70-90 cm, and 90-110 cm). I measured depth relative to the reference frame at 25 points on a grid in order to precisely determine the layer volume.

All coarse material from each 0.5 m^2 layer was separated using a 12 mm sieve. I weighed coarse fragments, > 12 mm, and < 12 mm. Density of a sub-sample of coarse fragments from each pit was measured by displacement in water. A ~300 g subsample of <12 mm soil was weighed, collected, and air dried, and re-weighed for moisture determination.

At one site, the Dalbay north-facing plot, peat layers were present above the mineral soil. I excavated peat in 10 cm layers until mineral soil was reached. Due to difficulty in sieving peat, all material in these layers was weighed, and 3 10×10×10 cm subsamples were separated using a 12 cm sieve. The entirety of the <12 mm and >12 mm fractions were weighed, and a ~300 g sub-sample of the <12 mm material was weighed, collected, air-dried, and re-weighed. Soil layers were removed until frozen ground impeded further digging.

Laboratory Analysis and Calculations

I passed subsamples of <12 mm air-dry mineral soil through a 2 mm sieve. Less than 2 mm and 2-12 mm fractions were weighed to calculate total coarse fragment content. Organic peat subsamples were not sieved beyond 12 mm. Approximately 10 g subsamples of all soils were weighed and dried at 105ºC for 24 hr to determine an oven-dry to air-dry weight conversion. Oven-dry subsamples were pulverized in a ball-mill (5300 Mixer/Mill, Spex Industries, Edison, NJ), re-dried, and total C of a 10 mg subsample was measured in a CHN elemental analyzer (Carlo Erba NC2100, Milan, Italy). Acetanilide, cyclohexane, Mag1 Marine Sediment, and Montana Soil SRM2711 were used as calibration standards and reference material. (Standard Reference Materials Program, NIST, Gaithersburg, MD). Minimum detectable C was 0.02% on a per-mass basis.

Several deep soil layers were suspected of containing carbonate rock. However, all of these soil samples had C values at or near the limit of detectability. Thus, all soil C was assumed to be organic.

Total C per unit area was calculated by multiplying the ratio of <2mm oven-dry weight to <12 mm wet weight of the soil subsample by the wet weight of all <12 mm soil in the pit layer area by percent C content. Values for peat were calculated by summing values for all peat layers in a pit.

I measured potentially mineralizable C of soils as C respired as CO_2 at near-optimal conditions in 90 day incubations, following Robertson and others (1999). Approximately 10 g subsamples of air-dry soil were placed in 20-ml scintillation vials. Nano-pure water was added to mineral soils (<2 mm) to bring them to 60% water-filled pore space. Peat soils (<12 mm) were brought to field capacity, measured by saturating ~50 g samples and then allowing them to drain for 24h. I placed scintillation vials in 250-ml glass jars with Teflon©-silicone septa in the lids and 2 ml nano-pure water on the bottom to maintain a saturated atmosphere. These jars were capped loosely and placed in a dark growth chamber at 25ºC and 85-95% humidity for 90 days.

I measured rates of soil respiration at days 1, 8, 13, 37, 56, and 90 of the incubation. To measure respiration, incubation jars were capped tightly and 0.2 ml headspace samples were taken using 1 ml-syringes through the septa in the jar lids at the start and end of the measurement period. Measurement periods varied from 3 to 16 hours. I measured CO_2 concentrations from these headspace samples using a gas chromatograph with a thermal conductivity detector (Varian CP-3800, Palo Alto, CA) using a Porapak Q80/100 column (Alltech Associates, Deerfield, IL).   I calculated total C mineralized over the incubation period was calculated by a intergrating respiration rates numerically. This value was converted to both total mineralized C (g m^{-2}) and fraction of soil C mineralized (‰). The minimum detectable change in headspace CO_2 concentration was 65 ppm. In calculating total C respired, I rejected any sample that did not have at least this change in headspace CO_2 concentration at one or more time points during incubation. This had the effect of rejecting nearly all soil samples with less that 0.5% total C by weight. However, in calculating total C respired for samples not rejected, I used all values for respiration rates, including those near 65 ppm.

Humidity control in the growth chambers failed between days 8 and 13, and samples dried out considerably. Control was restored on day 17 and water was added to bring samples back to their intended water content. Due to this failure, the value of mineralized C may not be comparable to other studies with the same incubation times and conditions. However, since the change in environmental conditions affected all samples, values remain comparable within this study.

Data analysis

The sampling scheme was not sufficient to explicitly test for effects of grazing and permafrost presence as independent variables, so I only analyzed differences between the sites. While this approach prevents me from drawing general conclusions, it allowed me to highlight differences between sites that merit further exploration.

I fit a standard least-squares model to test the effect of site on total C, C in each individual soil layer, and mineralized C (absolute and as a fraction of total C) in total and in each layer. Site was tested as a fixed, categorical effect nested within soil depth layer. Total soil C values were log-transformed, with zero values changed to limit of detectability (0.05 kg m^{-2}, which was the value for samples whose C on a per-mass basis was 0.02%, the limit of detectability for the elemental analyzer.)

Results

Total Soil C and Vertical Distribution

In both Turag Valley sites and at the Dalbay South-facing site, parent material, defined as light olive brown soil (2.5Y 5/4, Munsell Color, 1998) by was reached by 110 cm in all pits except one pit at the Turag north-facing site. The two permafrost-free sites had very similar total C to 110 cm despite differences in grazing intensity (Figure 1): 7.1±0.7 kg m^{-2} at the Dalbay south-facing site, and 7.7±1.7 kg m^{-2} at the Turag south-facing site. In the permafrost-underlain sites, the lightly grazed and heavily grazed sites had very different total C: 7.6±2.3 kg m^{-2} to 110 cm at the Turag north-facing site and 35±15 kg m^{-2} to frozen soil in the Dalbay north-facing site. (Figure 1). At the Dalbay north-facing site, frozen soil was encountered in the peat layer at one pit, 30 cm into the mineral soil in another pit, and 50 cm into the mineral soil at the last pit. Total C was only significantly different from average in the Dalbay-north facing site ($P < 0.01$); total C was indistinguishable among the other sites.

The two permafrost-free sites had indistinguishable soil C vertical distributions: at the Dalbay and Turag south-facing and sites, soil C decreased with depth, with more than half of the total C in the pit in top 30 cm of soil.

The permafrost underlain sites were qualitatively different from one another: at the Turag-north facing site, soil C generally followed the same distribution as the permafrost-free sites, but was 41% lower than average in the 10-30 cm layer ($P < 0.01$), Inclusions of organic material were observed at depths of 50-90 cm at in two pits at the Turag north-facing site, but not in any at either south-facing site. The Dalbay north-facing site had a peat layer with high C content. The peat layer thickness was highly variable, varying between 14 and 37 cm. C in the peat layer ranged from 6.8 to 18.9 kg m^{-2}, with an average of 11.7 kg m^{-2}. In the mineral layers, C content increased with depth, with the greatest C content just above frozen soil. C in the 30-50 cm layer was 240% greater than at other sites ($P < 0.01$). Much of the C in the mineral layers consisted of inclusions of pure organic material embedded in mineral material.

Mineralized C

My technique for measuring mineralized C proved only sensitive enough to measure values in soils of >0.5% C by mass, so results are only presented for peat soils and mineral soils to 30 cm, which all had concentrations above 0.5% C

Total mineralized C from soil 30 cm at the permafrost-free sites was 77±16 g m^{-2} at Dalbay south-facing and 58±2.8 at Turag north-facing (Figure 2). The permafrost-underlain sites, Dalbay-north facing and Turag-north facing, had 103±39 and 42±10 g m^{-2}, respectively. . Differences among sites were not significant, except for the Dalbay north-facing site, which had significantly greater mineralized C at the $P < 0.1$ level relative to the other sites. This greater mineralized C was largely due to the C in the peat layer, 61±11 g C m^{-2}, more than any at any single soil layer at any site ($P < 0.05$).

As a fraction of total C in the top 30 cm of soil (Figure 3), the permafrost-free sites had 13±1.8‰ in Dalbay-south facing and 12±3.1‰ in Turag-south facing. Among, the permafrost-underlain sites, the Dalbay north-facing site 6.2±2.1‰ and the Turag north-facing site had 8.3±1.5‰. Among all the sites, only the Dalbay north-facing sites had a mineralized fraction lower than the mean ($P < 0.1$) This site also had less mineralized C as a fraction of total in the top 10 cm of mineral soil ($P < 0.1$). The Dalbay south-facing site had a greater fraction of C mineralized in the 10-30 cm layer than at other pits. ($P < 0.1$).

Discussion

Total soil C found in heavily grazed sites and lightly grazed, permafrost-free sites was 7-8 kg m^{-2}, which is comparable to similar grassland sites. Schimel and others (1985), found 7.98±0.63 kg C m^{-2} in soils to parent material on toe slopes in shortgrass steppe at the Central Plains Experimental Range, which has similar precipitation (310 mm y^{-1}) but warmer mean annual temperatures. Soil C also had a similar depth distribution. Jobbagy and Jackson (2000) report that grasslands worldwide contain on average 11.7±6.6 kg C m^{-2} soil organic C to 1 m depth, also with similar vertical distribution.

Soils at the ungrazed, permafrost underlain site appear both qualitatively and quantitatively more similar to tundra than grassland. Michaelson and others (1996) reported that tundra soil pedons in the coastal plain near Barrow, Alaska had 10-47 kg C

m^{-2} to frozen soil, with an average of 27 kg C m^{-2}, and that many soils had accumulation of organic matter near the top of the permafrost. Soil in the permafrost to 1 m had an approximately equal amount of C as in soil above the permafrost. If the same applied to the site in this study, C in the topmost 1 m of soil would be approximately 70 kg m^{-2}. Since the peat layer had the largest store of C at the site where it where it was present, peat thickness appears to be the most important determinant of soil C at this site.

There were no differences in SOC amount or distribution between the heavily and lightly grazed sites that lacked permafrost. This is unsurprising. Grazing has not been shown to have consistent effects on SOC (Milchunaus and Lauenroth 1993). Burke and others (1997) proposed that, since most biomass in steppe systems was underground, and since a very small fraction of SOC was biologically active, an above-ground disturbance such as grazing would have little effect on total SOC.

Both total SOC and vertical distribution were very different between lightly and heavily grazed sites where permafrost was present. Differences in SOC between these sites could be due to both reduced litter and root inputs at the heavily grazed site or increased decomposition. Grazing may reduce input rates directly through removal of plant material or increase decomposition through disturbance.

Grazing could affect both inputs and outputs indirectly by affecting permafrost depth. Permafrost depth was greater in the heavily grazed site than the lightly grazed site. As the sites had similar slope, aspect, and landscape position, and climate does not vary between the valleys (Banzragch 2005), grazing is the most likely cause of the difference in permafrost depth. Both permafrost depth and soil temperatures have been shown to increase with grazing (Miller et al. 1980, Van der Wal et al. 2001). Harte and others (2005) found that while open-top warming chambers and simulated grazing both affected soil temperatures, interaction effects between the two raised soil temperatures more than would be predicted if effects were additive.

Recession of permafrost from grazing could potentially alter temperature and hydrological regimes, leading decreased inputs to and increased decomposition of SOC. A high permafrost table impedes drainage, increasing moisture available to plants. With recession of permafrost, less moisture is available and plant production could decrease. While NPP has not been measured at these sites, the large difference in biomass suggests that production is much greater at the lightly grazed site, which has shallower permafrost.

As soil decomposition rates are sensitive to soil temperatures (Davidson 2006), greater decomposition rates may occur at sites where permafrost has receded and soil temperatures increased due to grazing. In temperate zones, peat can also decompose rapidly following drainage. In New Zealand, peatlands that had been drained and used as pasture lost 0.10-0.37 kg C m^{-2} yr^{-1} through decomposition and grazing (Nieveen et al. 2005). At these rates, C in the peat layers similar to those of the ungrazed, permafrost underlain site could be entirely lost in decades. Peat soils are also particularly susceptible to erosion from grazing. In Britain and Ireland, wet peat soils have been shown to be easily scarred at stocking rates of 0.5 animals/ha, well within the range for herds at Hovsgol, and grazing damage appears to have caused decline of *Sphagnum* species, altering hydrological regimes. (Evans 1998) Grazing has the potential to reduce SOC stores through increased soil respiration and erosion.

While the permafrost underlain, heavily grazed site had similar total C to permafrost-free sites, vertical distribution was slightly different. Roots provide most of the input to soil organic C in grasslands (Burke et al. 1997), and the balance between root inputs and decomposition rates controls the vertical distribution of SOC (Gill and Burke 2002). In permafrost-underlain tundra, where peat contains much of the C, vertical distribution is affected by cryoturbation, which mixes surface-accumulated C throughout the profile, often accumulating large amounts at the top of the permafrost table (Michaelson 1996). The different distribution of SOC at the permafrost, grazed site compared to ungrazed site suggests that either a) input or decomposition rates differ, b) a mix of tundra-like and steppe-like processes are occurring, or c) the dominant processes controlling SOC inputs and outputs have changed over time.

Greater mineralized C at the ungrazed, permafrost-underlain site indicates greater potential for C loss than at other sites, particularly in peat layers. However, this site had less mineralized C as a fraction of total C, which would indicate that the accumulations of peat in the C and mineral soil are less labile than at other sites. This should be interpreted with caution, as the fraction of C that is mineralized is highly dependent on incubation time and conditions. SOC is often thought of as being composed of several pools with different intrinsic turnover rates that decompose following first-order kinetics (Wander 2004). In such a model, C mineralized in short-term incubation largely represents the most labile pools of organic C, thought to be fresh plant residues, microbial biomass, and simple, easily oxidizable organic compounds (Wander 2004). In grasslands, these typically compose a small fraction of SOC (Kelly et al. 1996). However, Weintraub and others (2003) found that decomposition of peat did not follow first-order decomposition dynamics, but rather was constant over the course of a year-long incubation. Water-soluble (very labile) carbohydrate concentration is the best predictor of short-term mineralization rates (24-48 hr) in incubated peat samples (Turetsky et al. 2003), but over longer periods, these components are regenerated through decomposition of lignins and other recalcitrant material which make up most of peat, and most decomposition in peats may be due to breakdown of lignins. Peat decomposition may be thus be relatively constant for long periods of time, perhaps limited by factors other than substrate quality (Weintraub 2003).

Among all sites and soil layers, only the 10-30 cm layer in the heavily grazed, permafrost-free site showed slowing of respiration rates during the course of incubation (Figure 4). This suggests that, in most soils tested, the active pool was not been exhausted during the 90-day course of the incubation. If these soils behave as other grassland soils do, we would expect more of them to slow during the course of longer incubations. Peats (and peat-enriched mineral soils) though, may not slow for long periods of time. Longer incubation periods are required to understand differences in the dynamics of decomposition between sites and between peat and mineral soils..

Weintraub and other (2003) report potential C mineralizations from tundra peats 3-10 times greater than found here, likely due to different protocols: peat was wetted to half of water-holding capacity as opposed to full water-holding capacity in this study. This suggests it may take even longer in the case of this study to see a drop in decomposition rate. Another way to characterize longer-term mineralizable C would be to measure decomposable C by a physical fractionation technique that is applicable to both organic and mineral soils. Acid-soluble C is one such measure which may be more useful for comparing peats and mineral soils than other measures, such as such as organic C fractionated by particle size or density.

Differing SOC stores and mineralization between these sites suggests the possibility that grazing has the potential to change SOC storage in permafrost underlain sites by improving the conditions of decomposition for large pools of labile organic matter. The effect may be similar to increased decomposition due to climate change, as both involve increased soil temperatures and recession of permafrost. However, as SOC in the heavily grazed, permafrost-underlain site resembled permafrost-free sites in both quantity, vertical distribution and lability, permafrost soils that are heavily grazed may not have large pools of labile organic matter that would rapidly decompose with further warming. Grazing, in a sense, may have a similar effect that warming would have, but has already occurred or could occur much faster As the most of the permafrost-underlain area in Asia south of the boreal zone has been in use as rangelands for long periods of time, there may not be large feedbacks to the global C cycle from the warming of these soils.

Conclusion

Two Permafrost-free steppe sites at Hovsgol GEF contain 7.4±0.8 kg C m^{-2} to 110 cm with more than 50% of C in the top 30 cm of soil. Soil C content and distribution is not different between two permafrost-free sites with different grazing intensities . Where permafrost is present, C storage is very different between two sites of different livestock grazing intensity, from a value similar to permafrost-free sites where there is heavy grazing to 35±15 kg C m^{-2} where there is light grazing. Much of the difference in C is due to a peat layer that is present only at the permafrost-underlain site with low grazing intensity. This difference may be due to differences at permafrost depth between sites, which in turn may be affected by grazing. In this mechanism, livestock grazing causes higher soil temperatures through removal of insulating plants and litter and trampling and erosion of peat, in turn causing a lowering of the permafrost table, better drainage, less plant production and better conditions for decomposition. There is a large pool of mineralizable C at the permafrost underlain, lightly grazed site, but it composes a smaller fraction of overall C than at other sites. The composition of soil C and potential for decomposition require further study, including approaches for comparing C lability across peats and mineral soils.

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Figures

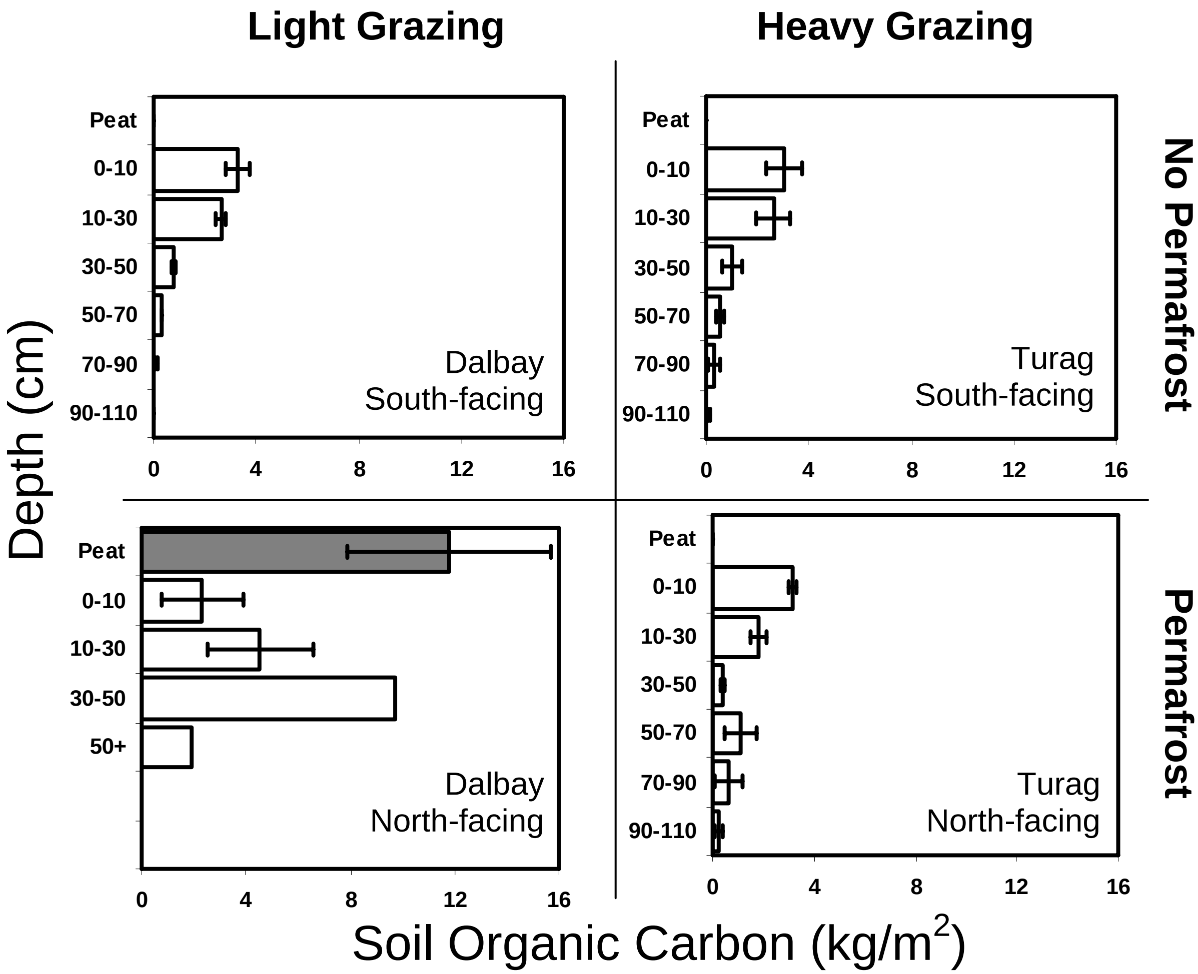

Figure 1 – Soil carbon at four sites at Hovsgol LTER, Mongolia, by depth. Error bars are ± 1 standard error. Where only one sample was taken, no error bars are shown.

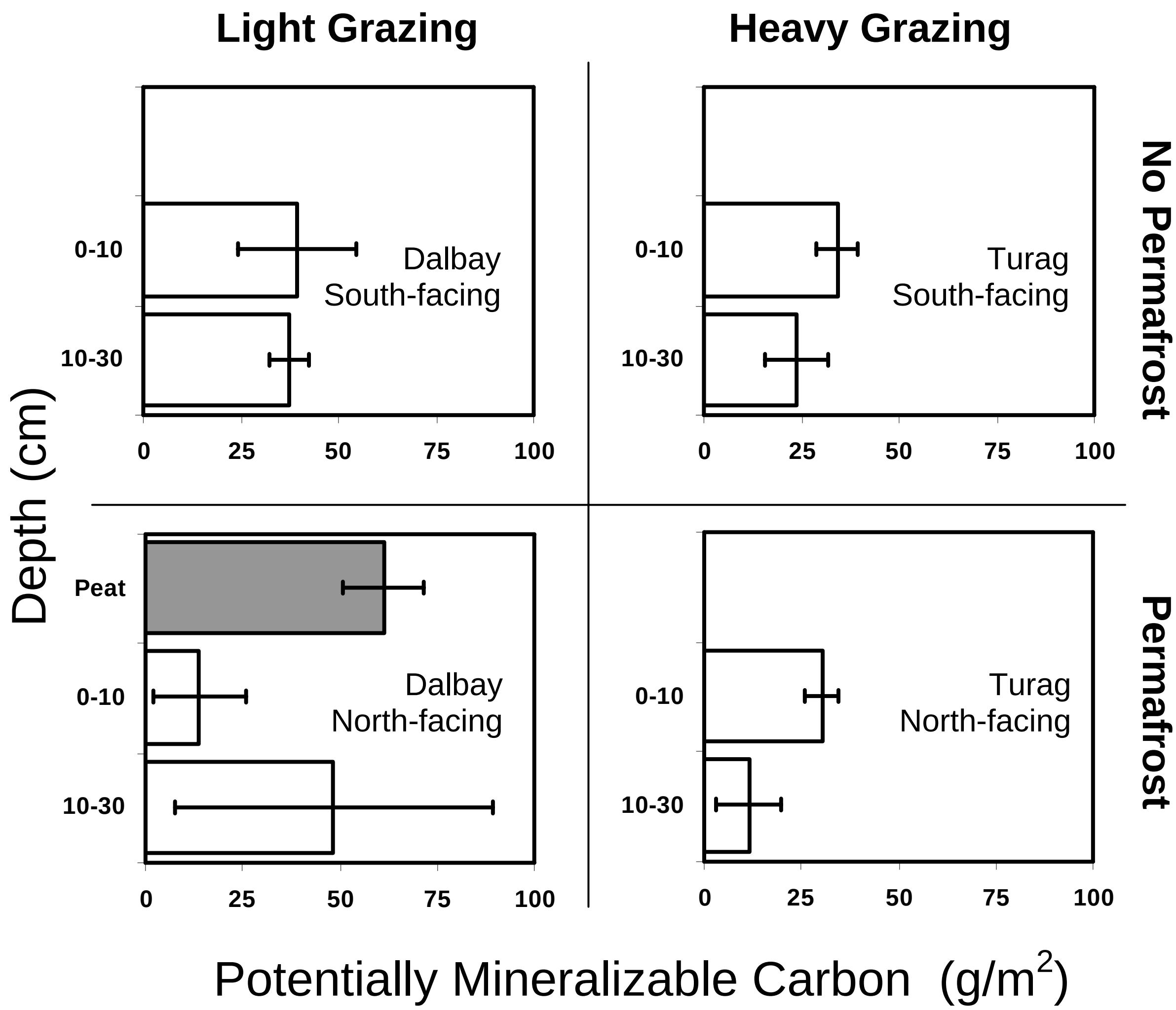

Figure 2 – Potentially mineralizable carbon by layer at four sites at Hovsgol LTER, Mongolia. Error bars are ± 1 standard error.

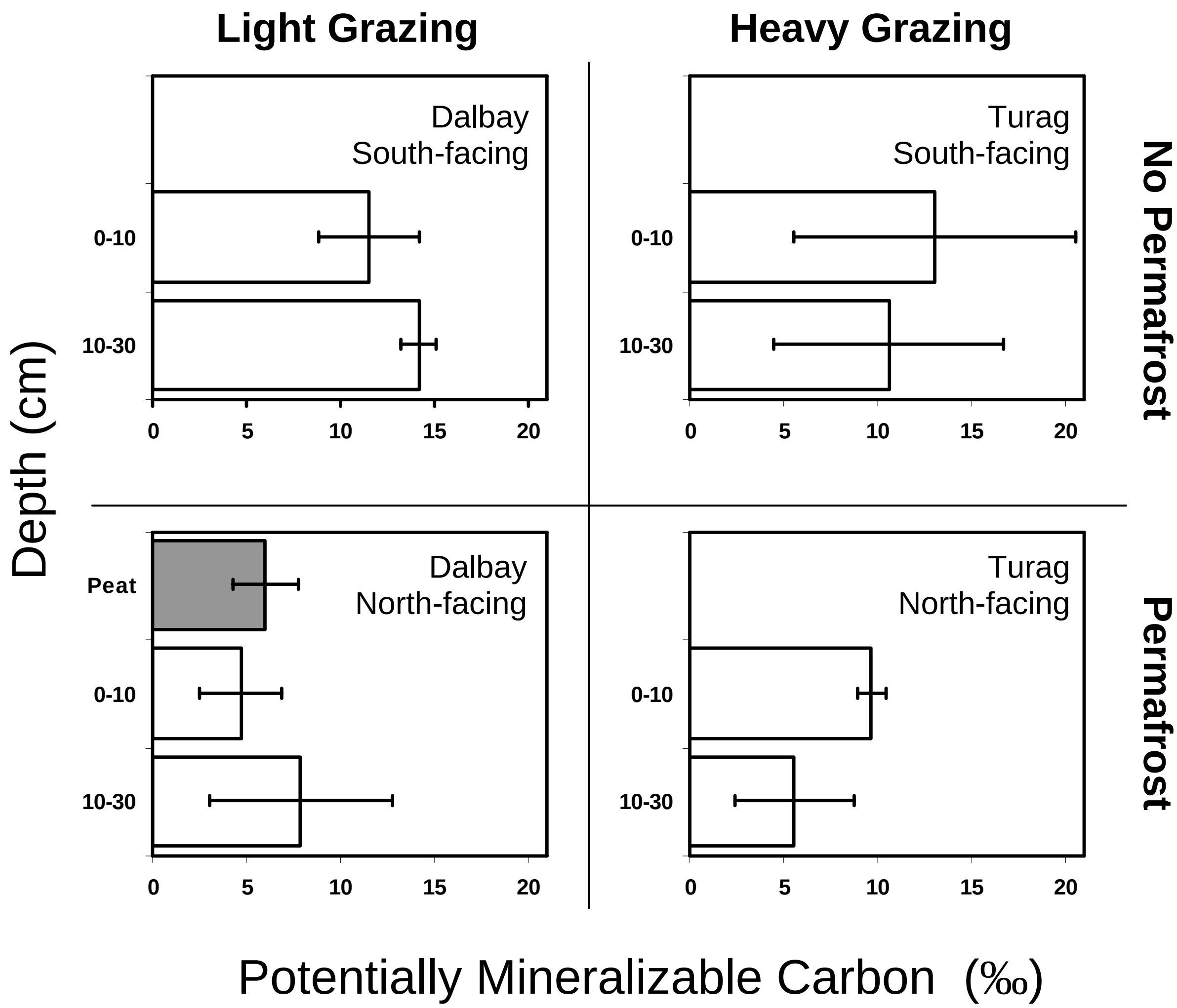

Figure 3 – Potentially mineralizable carbon as a fraction of the overall C pool by layer at four sites at Hovsgol LTER, Mongolia. Error bars are ± 1 standard error.

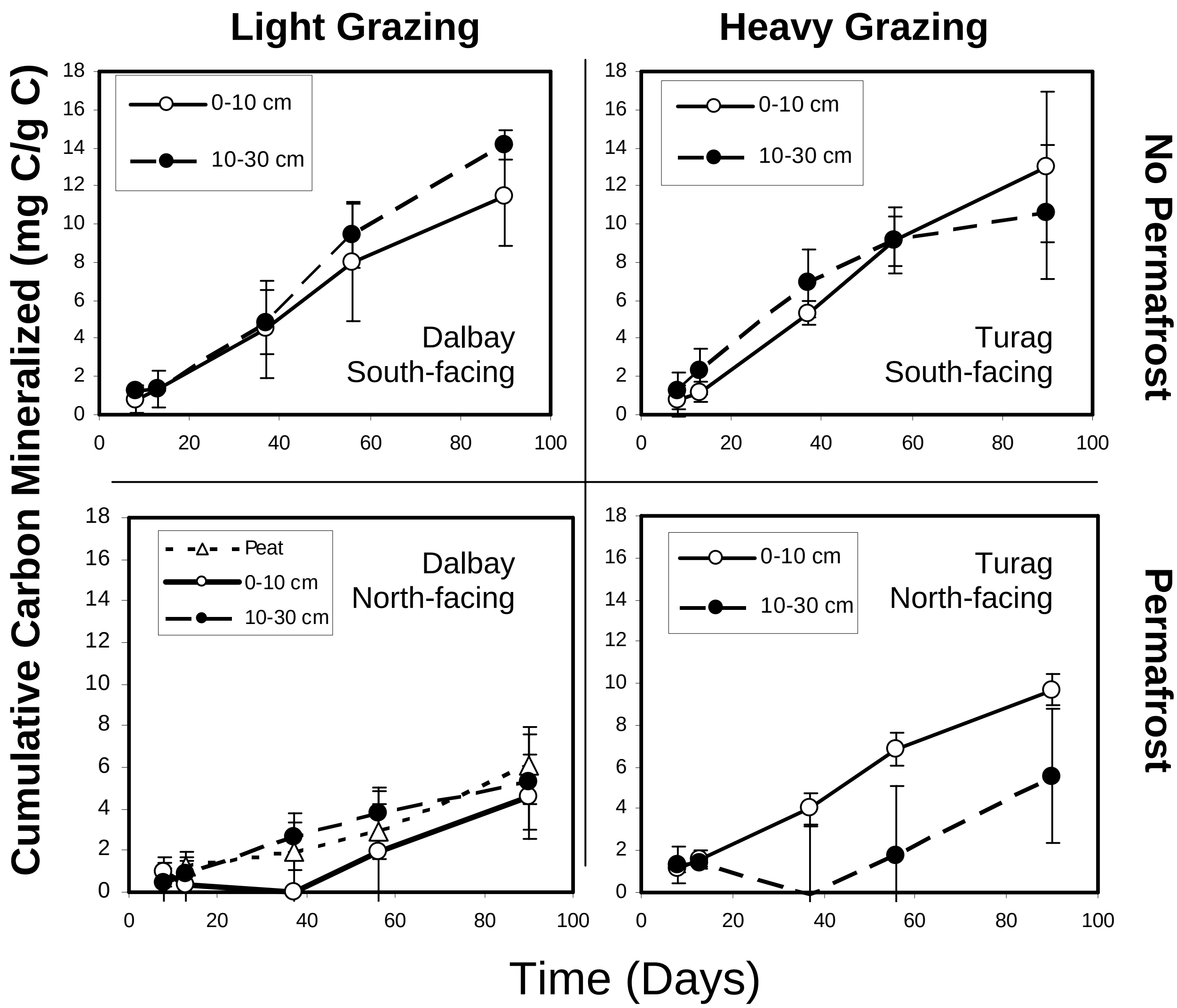

Figure 4 – Cumulative carbon mineralized during the incubations of soils from surface soils (to 30 cm of mineral soil). Only TRG-SL 10-30 showed slowing of decomposition during the 90-day incubation. Error bars are ± 1 standard error.

Appendix A: Notes on Methods

Soil Pits

I built the pit frame was built using 1.5”×1.5” lengths of cedar, with tounge-in-groove joints at the corners fasted by bolts and wing nuts, allowing it to be disassembled for transport. The inside edge of the frame was 0.707 × 0.707 m. I drilled eight ½” holes in the frame to accommodate securing rods. Tick marks were drawn on the frame every 14.14 cm starting 7.07 from the edge. I used four 50-cm lengths of rebar to secure the frame to the ground, driving them through the holes and into the ground with a metal mallet, and fixing them by driving small wooden shims in the space between the rebar and the hole in the frame.

The sieve was rectangular, approximately 40 cm × 100 cm, with legs to hold it at a 45º from the ground, and was built of larch boughs harvested on-site and nailed together. I used bent nails to attach ½” (12 mm) galvanized hardware cloth to the frame. A piece of plastic tarp was duct-taped to the bottom edge to catch the >12 mm material rolling off the sieve. The sieve was placed on a large plastic tarp to catch the >12 mm material.

Prior to a put being dug, the frame was first secured to the ground and plant species cover was estimated by identifying cover at each cross-point on the grid created by tick marks on the frame. Then all plant cover was removed by using garden clippers. Height of the soil surface relative to the frame at every point on the grid was measured by laying a 1.5”×1.5” length of cedar across the frame and holding a meter stick normal to it.

All soil was removed from the area under the frame until depth at every point in the grid was either 10 cm below the surface (for the first layer) or 20 cm below the previous layer (for all other layers). Generally, I was able to dig accurately to within 1 cm of the intended depth. I ensured the sides of the pit remained parallel by checking the width of the pit with a 0.707 length of cedar. Generally, large shovels were used to start digging a layer but small trowels were used in the end stages. In deep layers, it was generally necessary to get in the pit, fill buckets with soil and pass them up to the surface.

All material removed was passed over the sieve. Large soil aggregates were rubbed vigorously against the sieve to break them up. Roots, though often fine, generally did not pass through the sieve, but rather gathered in clumps on top of it. After all material had been removed and sieved, I used an Ohaus ES Series portable bench scale with 30 kg capacity and 0.01 kg precision. (Ohaus Corporation, Pine Brook, NJ) to weigh the <12 mm soil and >12mm rocks. I weighed both in a bucket that I pre-weighed. To representatively subsample soils, each shovelful of soil from the layer had a small trowelful taken from it to contribute to the ~300g subsample.

Soil samples were dried in cotton bags laid on an outdoor rack built of scrap wood and ½" hardware cloth. The rack was covered with plastic tarp at night and when rain threatened. I tested soils for dryness by placing them in a plastic bag, sealing the bag, and laying them in the bright sun. If no condensate formed on the inside of the bag over the course of the day, the soils were considered air-dry. Soils typically took ~1 week to dry. Once, a hole in the tarp caused four soil samples to be re-wetted.

I tried several strategies to sample frozen soils. First, I attempted to take cores using a 3" diameter diamond-edged concrete coring bit, driven by a 28-volt cordless hammer-drill (Milwaukee Electric Tool Corporation, Brookfield, WI). I was able to extract one 10-cm deep core. However, the bit had the effect of melting the soil immediately below it, causing the soil-water mix to bind the bit, overheat the drill, and strip the bit in the chuck. I attempted to sample permafrost with a variety of hand tools, including axes, rock bars, hammers and chisels. These all failed. In part, this is because the topmost surface (a few mm) would always melt quickly, making it difficult to impart force to the brittle frozen soil below.

Failing to sample permafrost soils mechanically, I attempted to melt them. After digging to frozen ground, I stretched clear plastic tarps across the pits and weighed down the edges with rocks, trapping sun-warmed air in the pit. This caused the to ~20 cm of soil to melt over the course of a few days. However, since this caused a local depression in the ice layer that was centered in the pit but extended beyond it, adjacent melting ice pit filled the pit itself with water in two out of three cases. Whether this occurs seems to be a function of permafrost microtopography.

Coring using a drill with a concrete coring bit may still be a viable strategy if using more powerful driver, such as powerful corded drill connected to a generator, or a gasoline-powered drill. In either case, it is probably best to use a spline-type bit and chuck that cannot be stripped.

Two other options that I explored, but was not able to attempt, for sampling permafrost, include using a SIPRE-style auger powered by a posthole-digger engine to drill cores, (Bockheim 2004), and a using gasoline-powered jackhammer (Michaelson 1996) to dig pits.

Soil Carbon

To measure total soil carbon, I measured out approximately ~10 g of soil from each sieved subsample and oven-dried them for 48 h at 105ºC. Oven-dry samples were re-weighed to determine the water content of each air-dry sample,then ground to a fine powder with a ball mill (5300 Mixer/Mill, Spex Industries, Edison, NJ). Soil samples were prepared in D1013 tin boats and flash combusted in a Carlo Erba NC2100 (Carlo Erba, Milan, Italy) elemental analyzer. Acetanilide, Cyclohexane, Mag1 Marine Sediment, and Montana Soil SRM2711 were used as calibration standards and reference material. (Standard Reference Materials Program, NIST, Gaithersburg, MD) .

Peat material often contained <12 mm rocks. Large subsamples were needed to ensure that representative sub-samples were homogenized.

In a few pit layers I found carbonate accumulations under rocks in deep layers, and suspected that soil would contain inorganic C. However, all of these soils had total C values near or below the detectable limit. Therefore, I did not attempt to separate SIC from SOC.

Mineralizable Carbon

Mineralizable carbon was measured as carbon respired under near-optimal decomposition conditions over 90 days. I added nano-pure water to air-dry mineral soils to bring them to 60% water-filled pore space and to peat soils to bring them to water-holding capacity. For mineral soils, I measured the volume of 10 g of soil in a graduated cylinder and, assuming a particle density of 2.65 g cm^{-3}, used this to calculate pore space volume in the incubated sample. To calculate water-holding capacity for peats, I placed weighed ~100 g of air-dry soil into a tub with a perforated bottom, saturated the sample with water and placed it in a filter jar with 10 ml of water on the bottom to maintain 100% humidity. Water content was measured gravimetrically after 24 hours.

I incubated samples in a growth chamber (GCW-15, Environmental Growth Chambers, Inc., Chagrin Falls, Ohio). Particularly on cold, dry winter days, the growth chambers were unable to maintain high humidity concentrations. To counter this, I placed four basins of water in the chamber, and later added a standard room humidifier with a 5 L tank capacity. The tank had to refilled approximately once per week. I lowered the rate of air exchange in the chamber, as well. With these modifications >85% humidity was maintained at all times.

When measuring respiration rates, I incubated samples for three hours at the first three dates, then extended the incubation time for to 10-16 hours for later time points, in order to improve sensitivity. I limited incubation time in the later dates to ensure that headspace CO_2 did not rise above 1% in order to prevent CO_2 inhibition, assuming that respiration rates would not increase with time.

When sampling, I sealed jar lids, and then at the beginning and end the measurement period, I removed 1 ml headspace gas using 1 ml plastic syringes with 2”, 28-guage needles. I loosened lids again afterwards. To store gas until time of analysis, I capped needles with rubber stoppers. This arrangement was not suitable for storing gas for periods longer than 1 week. When longer sample storage times were needed between sampling time measurement on the gas chromatograph, I stored air in 2 ml air storage vials with rubber septa and aluminum crimp seals. Vials were allowed to equilibriate with lab air for 10+ hours, then capped and sealed. I used a 5 ml syringe with a non-coring needle to remove 5 ml of air from the vial, then injected 1 ml of sample air. I stored samples of 1000ppm CO_2 standards and samples of lab air (400-430 ppm CO_2) in the same manner. Using these standards, I was able to calculate that the mixed air contained 31% sample and 69% lab air, and from this back-calculate the actual concentration of CO_2 of samples stored in mixed vials.

CO_2 concentrations from these headspace samples were measured on a gas chromatograph with a thermal conductivity detector (Varian CP-3800, Palo Alto, CA) and using a Porapak Q80/100 column (Alltech Associates, Deerfield, IL). . Helium was used as a carrier gas. Pressure was set at 28.5 psi and column temperature was 80ºC. This ensured suitable separation of nitrogen and carbon dioxide peaks. 1000 ppm CO_2 in helium was used for calibration.

There was limited sensitivity in detecting differences in concentrations of CO_2 before and after the incubation. A number of times the difference detected was negative. The negative values had a mean of -28 ppm and an inter-quartile range of -43 to -42 ppm. I rejected outliers 1.5×IQR below the lower quartile, and took the lowest non-outlier value, -65 ppm, to be the limit of sensitivity. I rejected data from samples in which none of the before-and-after differences in any incubation period were over 65 ppm. After rejecting these data, only in peat, 0-10 cm and 10-30 cm layers were there usable values across all pits and sites.

Appendix B: Linear Model Fits

Table 1: Linear Model Fit - Effect of Site on Total Carbon (kg/m^2)

Summary of Fit

R-Squared	0.708026
Adjusted R-Squared	0.598536
Root Mean Square Error	4.149408
Mean of Response	10.45798
Observations (or Sum Wgts)	12

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	334.01660	111.339	6.4666
Error	8	137.74068	17.218	Prob > F
C. Total	11	471.75728		0.0156

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	10.457978	1.197831	8.73	<.0001
Site[DLB-NL]	9.1325201	2.074704	4.40	0.0023
Site[DLB-SL]	-3.279264	2.074704	-1.58	0.1526
Site[TRG-NL]	-3.087976	2.074704	-1.49	0.1750

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Site	3	3	334.01660	6.4666	0.0156

Table 2: Linear Model Fit - Effect of Site within Layer on Log of Carbon (kg/m^2)

Summary of Fit

R-Squared	0.806818
Adjusted R-Squared	0.719885
Root Mean Square Error	0.344424
Mean of Response	-0.18117
Observations (or Sum Wgts)	59

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	18	19.817752	1.10099	9.2810
Error	40	4.745115	0.11863	Prob > F
C. Total	58	24.562867		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-0.26413	0.069903	-3.78	0.0005
Layer[0-10 cm]	0.6853805	0.110908	6.18	<.0001
Layer[10-30 cm]	0.6800499	0.110908	6.13	<.0001
Layer[30-50 cm]	0.3593172	0.12154	2.96	0.0052
Layer[50-70 cm]	-0.072956	0.116934	-0.62	0.5362
Layer[70-90 cm]	-0.614891	0.097841	-6.28	<.0001
Layer[0-10 cm]:Site[DLB-NL]	-0.185807	0.201936	-0.92	0.3630
Layer[0-10 cm]:Site[DLB-SL]	0.0814659	0.175763	0.46	0.6455
Layer[0-10 cm]:Site[TRG-NL]	0.0732971	0.175763	0.42	0.6789
Layer[10-30 cm]:Site[DLB-NL]	0.1942691	0.201936	0.96	0.3418
Layer[10-30 cm]:Site[DLB-SL]	0.0012999	0.175763	0.01	0.9941
Layer[10-30 cm]:Site[TRG-NL]	-0.167715	0.175763	-0.95	0.3457
Layer[30-50 cm]:Site[DLB-NL]	0.8921386	0.272291	3.28	0.0022
Layer[30-50 cm]:Site[DLB-SL]	-0.191282	0.18601	-1.03	0.3100
Layer[30-50 cm]:Site[TRG-NL]	-0.52489	0.18601	-2.82	0.0074
Layer[50-70 cm]:Site[DLB-SL]	-0.167464	0.162363	-1.03	0.3085
Layer[50-70 cm]:Site[TRG-NL]	0.1071485	0.162363	0.66	0.5131
Layer[70-90 cm]:Site[DLB-SL]	-0.221147	0.122222	-1.81	0.0779
Layer[70-90 cm]:Site[TRG-NL]	0.1898852	0.116706	1.63	0.1116

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Layer	5	5	17.966935	30.2913	<.0001
Site[Layer]	13	13	2.363676	1.5327	0.1480

Table 3: Linear Model - Effect of Site within Layer on Total Mineralizable Carbon (g/m^2)

Summary of Fit

RSquare	0.404448
RSquare Adj	0.181116
Root Mean Square Error	36.53084
Mean of Response	71.19361
Observations (or Sum Wgts)	12

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	7250.240	2416.75	1.8110
Error	8	10676.018	1334.50	Prob > F
C. Total	11	17926.258		0.2231

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	71.193611	10.54554	6.75	0.0001
Site[DLB-NL]	36.814682	18.26542	2.02	0.0786
Site[DLB-SL]	5.6850079	18.26542	0.31	0.7636
Site[TRG-NL]	-29.18693	18.26542	-1.60	0.1487

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Site	3	3	7250.2403	1.8110	0.2231

Table 4: Linear Model - Effect of Site within Layer on Mineralizable Carbon (g/m^2)

Summary of Fit

R-Squared	0.473493
Adjusted R-Squared	0.21024
Root Mean Square Error	19.4161
Mean of Response	33.52669
Observations (or Sum Wgts)	25

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	8	5424.428	678.054	1.7986
Error	16	6031.762	376.985	Prob > F
C. Total	24	11456.190		0.1512

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	40.303213	4.670789	8.63	<.0001
layer[0-10 cm]:site[DLB-NL]	-15.67193	11.3837	-1.38	0.1876
layer[0-10 cm]:site[DLB-SL]	10.079649	9.908239	1.02	0.3241
layer[0-10 cm]:site[TRG-NL]	0.9566652	9.908239	0.10	0.9243
layer[10-30 cm]:site[DLB-NL]	18.109122	11.3837	1.59	0.1312
layer[10-30 cm]:site[DLB-SL]	7.0645234	9.908239	0.71	0.4861
layer[10-30 cm]:site[TRG-NL]	-18.68443	9.908239	-1.89	0.0776
layer[0-10 cm]	-10.84255	5.796297	-1.87	0.0798
layer[10-30 cm]	-10.02943	5.796297	-1.73	0.1028

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
site[layer]	6	6	2790.3455	1.2336	0.3405
Layer	2	2	2581.5572	3.4240	0.0578

Table 5: Linear Model - Effect of Site on Whole-Pit Total Mineralizable Carbon (‰)

Summary of Fit

R-Squared	0.415558
Adjusted R-Squared	0.196393
Root Mean Square Error	3.833483
Mean of Response	9.740449
Observations (or Sum Wgts)	12

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	83.59258	27.8642	1.8961
Error	8	117.56475	14.6956	Prob > F
C. Total	11	201.15733		0.2087

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	9.7404485	1.106631	8.80	<.0001
Site[DLB-NL]	-3.565918	1.916742	-1.86	0.0999
Site[DLB-SL]	3.0678243	1.916742	1.60	0.1481
Site[TRG-NL]	-1.426188	1.916742	-0.74	0.4781

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Site	3	3	83.592578	1.8961	0.2087

Table 6: Linear Model - Effect of Site within Layer on Total Mineralizable Carbon (‰)

Summary of Fit

RSquare	0.410699
RSquare Adj	0.116048
Root Mean Square Error	4.762584
Mean of Response	9.498661
Observations (or Sum Wgts)	25

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	8	252.92466	31.6156	1.3938
Error	16	362.91530	22.6822	Prob > F
C. Total	24	615.83996		0.2716

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	8.4592294	1.1457	7.38	<.0001
layer[0-10 cm]	1.2333573	1.421776	0.87	0.3985
layer[10-30 cm]	1.2029645	1.421776	0.85	0.4100
layer[0-10 cm]:site[DLB-NL]	-5.123669	2.792312	-1.83	0.0852
layer[0-10 cm]:site[DLB-SL]	1.8043996	2.430396	0.74	0.4686
layer[0-10 cm]:site[TRG-NL]	-0.016817	2.430396	-0.01	0.9946
layer[10-30 cm]:site[DLB-NL]	-1.371544	2.792312	-0.49	0.6300
layer[10-30 cm]:site[DLB-SL]	4.5088373	2.430396	1.86	0.0821
layer[10-30 cm]:site[TRG-NL]	-4.097236	2.430396	-1.69	0.1112

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Layer	2	2	35.13105	0.7744	0.4775
Site[layer]	6	6	210.98086	1.5503	0.2252

Appendix C: Pit-Level Data

Dalbay - North Lower - Pit #1

	Volume of Excavated Layer (L)	Volume of >12 mm rocks excavated (L)	Volume of 2-12 cm rocks (L) (calculated from subsample)	Soil Volume (L)	Actual Layer Thickness (cm)	Total Soil Oven Dry Weight (kg) (calculated from subsample)	Soil Bulk Density (g/cc)	Areal soil density (kg/m^2)	Soil carbon/soil mass (%)	Areal Soil Carbon (kg C/m^2)	Mineralizable Carbon (g/m^2)	Mineralizable Carbon (‰)
Peat Layer	70.5	0.0	N/A[1]	70.5	14.1	28.3	0.40	56.7	11.92%	6.76	64.3	9.5
0-10 cm	50.5	0.3	0.2	50.0	10.1	68.7	1.37	137.4	2.82%	3.88	25.7	6.6
10-30 cm	105.2	6.3	1.7	97.2	21.0	124.7	1.28	249.3	2.63%	6.57	89.2	13.6
30-50 cm	102.4	1.5	3.6	97.2	20.5	123.1	1.27	246.3	3.94%	9.71		
50+ cm	43.8	1.3	3.8	38.7	8.8	63.4	1.64	126.7	1.53%	1.94		
Latitude/Longitude/Elevation	51º0.894' N / 100º45.585 E / 1662 m								**Total/Average:**	**35.61**	**179.1**	**10.4**
Plant Cover	Sphagnum 8%, Salix 20%, Carex 20%, Polygonum 24%, Litter 8%, Unknown 8%											

Dalbay - North Lower - Pit #2

	Volume of Excavated Layer (L)	Volume of >12 mm rocks excavated (L)	Volume of 2-12 cm rocks (L) (calculated from subsample)	Soil Volume (L)	Actual Layer Thickness (cm)	Total Soil Oven Dry Weight (kg) (calculated from subsample)	Soil Bulk Density (g/cc)	Areal soil density (kg/m^2)	Soil carbon/soil mass (%)	Areal Soil Carbon (kg C/m^2)	Mineralizable Carbon (g/m^2)	Mineralizable Carbon (‰)
Peat Layer	116.7	16.6	N/A	100.1	23.3	61.9	0.62	123.8	7.33%	9.08	41.4	4.6
0-10 cm	46.8	5.1	3.4	38.4	9.4	59.4	1.55	118.8	0.64%	0.76	1.9	2.5
10-30 cm	108.9	14.4	8.7	85.9	21.8	136.8	1.59	273.6	0.92%	2.53	7.6	3.0
Latitude/Longitude/Elevation	51º0.865' N / 100º45.588 E / 1660 m								**Total/Average:**	**21.45**	**50.9**	**2.4**
Plant Cover	Sphagnum 4%, Salix 24%, Carex 36%, Litter 24%, Unknown 4%											

Dalbay - North Lower - Pit #3

	Volume of Excavated Layer (L)	Volume of >12 mm rocks excavated (L)	Volume of 2-12 cm rocks (L) (calculated from subsample)	Soil Volume (L)	Actual Layer Thickness (cm)	Total Soil Oven Dry Weight (kg) (calculated from subsample)	Soil Bulk Density (g/cc)	Areal soil density (kg/m^2)	Soil carbon/soil mass (%)	Areal Soil Carbon (kg C/m^2)	Mineralizable Carbon (g/m^2)	Mineralizable Carbon (‰)
Peat Layer	176.4	38.3	N/A	138.1	35.3	100.3	0.73	200.5	9.44%	19.49	77.8	4.0

Latitude/Longitude/Elevation 51º0.879' N / 100º45.607 E / 1658 m **Total/Average: 19.49 77.8 4.0**

Plant Cover Sphagnum 4%, Carex 24%, Litter 8%, Unknown 4%

Dalbay - South Lower - Pit #1

0-10 cm	50.0	0.0	0.8	49.2	10.0	57.0	1.16	114.1	3.09%	3.53	56.2	15.9
10-30 cm	101.9	0.8	3.3	97.8	20.4	147.2	1.50	294.4	0.82%	2.42	37.8	15.6
30-50 cm	100.4	6.8	9.1	84.5	20.1	134.3	1.59	268.5	0.28%	0.76		
50-70 cm	110.1	13.6	21.4	75.1	22.0	139.7	1.86	279.3	0.10%	0.28		
70-90 cm	96.6	3.1	16.5	77.1	19.3	134.8	1.75	269.6	0.02%	0.07		
90-110 cm	100.1	3.3	11.8	84.9	20.0	133.4	1.57	266.8	0.00%	0.00		

Latitude/Longitude/Elevation 51º1.321' N / 100º45.778 E / 1671 m **Total/Average: 7.06 94.0 15.8**

Plant Cover Koeleria 40%, Carex 8%, Leymus 4%, Aster Alfinus 4%, Litter 24%, Bare 16%, Unknown 4%

Dalbay - South Lower - Pit #2

0-10 cm	51.9	0.1	0.7	51.1	10.4	52.3	1.02	104.7	3.78%	3.96	47.0	11.9
10-30 cm	96.0	0.3	2.2	93.5	19.2	141.1	1.51	282.2	1.08%	3.05	44.3	14.5
30-50 cm	99.9	1.7	6.3	91.9	20.0	163.6	1.78	327.1	0.29%	0.94		
50-70 cm	105.9	14.6	16.9	74.4	21.2	131.1	1.76	262.2	0.12%	0.32		
70-90 cm	102.6	28.7	16.6	57.3	20.5	123.4	2.15	246.9	0.06%	0.14		
90-110 cm	114.0	6.0	7.8	100.3	22.8	201.8	2.01	403.7	0.00%	0.00		

Latitude/Longitude/Elevation 51º1.310' N / 100º45.805 E / 1674 m **Total/Average: 8.40 91.3 13.0**

Plant Cover Koeleria 12%, Carex 40%, Thalictrium minus 4%, Aster Alfinus 4%, Litter 40%

Dalbay - South Lower - Pit #3

0-10 cm	48.9	0.7	2.1	46.1	9.8	49.5	1.07	99.0	2.33%	2.31	15.4	6.7
10-30 cm	107.2	5.3	4.7	97.2	21.4	148.7	1.53	297.3	0.81%	2.42	29.9	12.4
30-50 cm	95.1	5.5	7.9	81.7	19.0	130.1	1.59	260.3	0.28%	0.72		
50-70 cm	96.5	6.7	14.7	75.1	19.3	123.2	1.64	246.5	0.14%	0.35		
70-90 cm	106.9	23.1	12.0	71.8	21.4	133.8	1.86	267.6	0.05%	0.13		
90-110 cm	101.4	4.8	5.2	91.4	20.3	208.4	2.28	416.8	0.00%	0.00		

Latitude/Longitude/Elevation 51º1.301' N / 100º45.835 E / 1671 m **Total/Average: 5.93 45.3 9.6**

Plant Cover Koeleria 16%, Artemesia 16%, Potentilla 8%, Aster Alfinus 4%, Litter 40%

Turag - North Lower – Pit #1

0-10 cm	52.8	0.0	0.9	51.9	10.6	65.9	1.27	131.8	2.15%	2.84	27.5	9.7
10-30 cm	99.3	11.7	6.9	80.7	19.9	120.6	1.49	241.3	0.50%	1.21	0.9	0.8
30-50 cm	103.8	12.1	10.5	81.3	20.8	143.7	1.77	287.4	0.11%	0.31		
50-70 cm	89.6	8.2	7.2	74.2	17.9	134.9	1.82	269.8	0.04%	0.10		
70-90 cm	105.6	7.7	7.2	90.7	21.1	161.1	1.78	322.2	0.03%	0.09		
90-110 cm	125.4	8.9	10.1	106.4	25.1	203.3	1.91	406.5	0.00%	0.00		
Latitude/Longitude/Elevation	51º17.135' N / 100º49.636 E / 1671 m								**Total/Average:**	**4.55**	**28.4**	**7.0**

Plant Cover: Artemesia 8%, Xanthoparmelium 8%, Stipia kryovii 8%, Ranunculus 4%, Moss 4%, Thymus gobicus 4%, Carex 4%, Bare 4%, Unknown 8%

Turag - North Lower – Pit #2

0-10 cm	57.8	0.9	1.9	55.0	11.6	65.5	1.19	130.9	2.61%	3.41	37.5	11.0
10-30 cm	107.4	5.0	9.7	92.7	21.5	133.3	1.44	266.7	0.79%	2.11	24.5	11.6
30-50 cm	104.4	4.9	10.3	89.2	20.9	131.1	1.47	262.3	0.19%	0.51		
50-70 cm	79.6	4.3	6.5	68.8	15.9	140.8	2.05	281.6	0.31%	0.86		
70-90 cm	99.7	6.1	5.6	88.0	19.9	172.9	1.97	345.8	0.51%	1.77		
90-110 cm	99.7	9.0	5.9	84.9	19.9	247.9	2.92	495.8	0.12%	0.60		
110-130 cm	102.5	6.4	5.6	90.4	20.5	165.4	1.83	330.9	0.25%	0.84		
Latitude/Longitude/Elevation	51º17.153' N / 100º49.557 E / 1661 m								**Total/Average:**	**10.10**	**62.0**	**11.2**

Plant Cover: Carex 8%, Xanthoparmelium 8%, Festca 4%, Artemesia 4%, Koeleria 4%, Litter 40%, Bare 20%, Unknown 12%

Turag - North Lower – Pit #3

0-10 cm	54.6	8.5	2.8	43.3	10.9	53.6	1.24	107.2	2.94%	3.15	26.3	8.4
10-30 cm	120.3	20.1	15.2	84.9	24.1	144.7	1.71	289.5	0.75%	2.17	9.3	4.3
30-50 cm	75.1	22.2	12.3	40.6	15.0	68.3	1.68	136.6	0.24%	0.33		
50-70 cm	102.8	34.7	16.8	51.4	20.6	128.7	2.50	257.4	0.91%	2.35		
70-90 cm	98.4	20.1	15.9	62.5	19.7	141.1	2.26	282.2	0.04%	0.10		
90-110 cm	99.5	15.9	12.0	71.6	19.9	137.5	1.92	274.9	0.05%	0.15		
Latitude/Longitude/Elevation	51º17.121' N / 100º49.690 E / 1668 m								**Total/Average:**	**8.25**	**35.7**	**6.7**

Plant Cover: Thymus gobicus 4%, Artemsia 12%, Pedicolaris multiflora 4%, Festuca 8%, Stipa 8%, Taraxacum 4%, Rock 8%, Bare 4%, Dung 8%, Unknown 8%

Turag - South Lower – Pit #1

0-10 cm	57.4	0.2	1.6	55.6	11.5	67.3	1.21	134.6	2.91%	3.91	27.4	7.0
10-30 cm	93.9	6.2	5.2	82.5	18.8	115.8	1.40	231.6	1.17%	2.71	36.1	13.3

30-50 cm	97.6	29.6	16.6	51.4	19.5	64.2	1.25	128.4	0.70%	0.90		
50-70 cm	106.1	32.0	20.3	53.8	21.2	66.8	1.24	133.5	0.27%	0.36		
70-90 cm	99.5	28.7	18.7	52.1	19.9	96.6	1.86	193.3	0.38%	0.73		
90-110 cm	95.7	35.9	15.3	44.5	19.1	85.9	1.93	171.9	0.11%	0.20		
Latitude/Longitude/Elevation	51º17.456' N / 100º49.279 E / 1675 m								**Total/Average:**	**8.80**	**63.6**	**9.6**
Plant Cover	Potentilla 4%, Stipa 8%, Artemesia 8%, Potentilla 4%, Litter 35%, Bare 35%, Dung 4%											

Turag - South Lower – Pit #2

0-10 cm	53.0	0.4	1.7	51.0	10.6	60.4	1.18	120.8	3.00%	3.63	42.0	11.6
10-30 cm	101.5	0.5	3.5	97.5	20.3	125.4	1.29	250.7	1.48%	3.71	13.7	3.7
30-50 cm	96.3	4.3	9.1	82.9	19.3	122.4	1.48	244.8	0.73%	1.79		
50-70 cm	104.0	24.2	19.1	60.7	20.8	97.8	1.61	195.6	0.24%	0.47		
70-90 cm	100.1	15.0	19.2	65.9	20.0	131.6	2.00	263.2	0.06%	0.17		
90-110 cm	100.3	28.1	21.0	51.3	20.1	102.6	2.00	205.2	0.06%	0.12		
Latitude/Longitude/Elevation	51º17.462' N / 100º49.310 E / 1672 m								**Total/Average:**	**9.88**	**55.7**	**7.6**
Plant Cover	Potentilla 4%, Stipa 16%, Litter 48%, Bare 32%											

Turag - South Lower – Pit #3

0-10 cm	53.8	0.1	0.8	52.9	10.8	77.5	1.47	155.0	1.03%	1.60	32.9	20.5
10-30 cm	96.2	0.3	1.3	94.6	19.2	125.8	1.33	251.7	0.58%	1.45	21.6	14.8
30-50 cm	106.1	0.4	3.1	102.7	21.2	171.4	1.67	342.8	0.10%	0.36		
50-70 cm	97.9	0.6	3.4	94.0	19.6	148.6	1.58	297.2	0.29%	0.87		
70-90 cm	102.5	0.6	4.3	97.6	20.5	180.0	1.84	359.9	0.02%	0.06		
90-110 cm	98.1	0.2	2.2	95.6	19.6	173.3	1.81	346.6	0.00%	0.00		
Latitude/Longitude/Elevation	51º17.494' N / 100º49.276 E / 1686 m								**Total/Average:**	**4.34**	**54.4**	**17.8**
Plant Cover	Stipa 12%, Xanthoparmelium 4%, Potentilla 8%, Litter 40%, Bare 36%											

1 - Note that all calculations for peat layers count soil as <12 mm. In remaining (mineral soils), soil is defined as <2 mm.