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SYSTEMATIC ANALYSIS OF TERRESTRIAL CARBON STOCKS IN A SMALL CATCHMENT OF THE KOLYMA WATERSHED

By:

Kathryn Heard

Accepted in Partial Completion
of the Requirements for the Degree
Master of Science

Kathleen L. Kitto, Dean of the Graduate School

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MASTER’S THESIS

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Kathryn Heard
May 28, 2014
SYSTEMATIC ANALYSIS OF TERRESTRIAL CARBON STOCKS IN A SMALL CATCHMENT OF THE KOLYMA WATERSHED

A thesis
Presented to
The Faculty of
Western Washington University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

By Kathryn E. Heard
May 2014
ABSTRACT

With the strongest climate warming occurring and predicted in the high-latitudes, understanding arctic carbon (C) cycling and the feedback of terrestrial C pools is increasingly important. Arctic terrestrial ecosystems comprise about one-third of the global terrestrial ecosystem C total with most of the C stored in soils, making the response of arctic systems to accelerated warming an issue of global concern. For this research, above- and belowground C stocks were quantified in a small catchment of the Kolyma River watershed in northeastern Siberia, with the primary goal of contributing to a more precise estimate of arctic C pools. Eighteen sites were chosen based on four categories of tree density. We assessed the correlation between soil C, vegetation C, and four environmental correlates — slope, solar insolation, canopy density, and leaf area index. Carbon in the surface O horizon (2414 ± 391 g C m\(^{-2}\), mean +/- SE) and underlying mineral soil layer to a depth of 10 cm or to the bottom of the active layer, whichever was less, (2231 ± 432 g C m\(^{-2}\) ) were, together, approximately four times that of the aboveground C pools (1128 ± 273 g C m\(^{-2}\)). Of the environmental correlates considered, canopy cover had the most robust association with aboveground C pools (p < 0.001; r = 0.812), while no environmental variables correlated significantly with soil C pools (p > 0.05). Greater quantities of belowground C storage are consistent with previous studies in arctic terrestrial ecosystems, but a high degree of variability existed in both above- and belowground C pools. High variability will make it more difficult to accurately quantify C pools at larger spatial scales. Additionally, the identification of canopy cover as a robust biotic correlate presents alternatives to directly measuring C stocks, but this
relationship needs to be verified elsewhere in the Arctic before using it in lieu of field data collection.

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1. INTRODUCTION

1.1. Carbon, Climate, and Northern High-latitudes

Arctic ecosystems stand to play a substantial role in both the magnitude and rate of global climate warming through energy partitioning and C storage [Chapin et al., 2000, 2005; Kimball et al., 2006; Loranty and Goetz, 2012]. The arctic and boreal biomes cover 22% of the terrestrial surface and account for approximately 12% of annual vegetation productivity [Chapin et al., 2000, 2005; Kimball et al., 2006]. In the Arctic, studies have indicated that the ocean, terrestrial, and riverine areas have historically been a sink for atmospheric CO$_2$ of between 0 and 0.8 petagrams of carbon per year (Pg C yr$^{-1}$), with the terrestrial sink estimated to be between 0.3 and 0.6 Pg C yr$^{-1}$ [McGuire et al., 2010]. Factors contributing to the uncertainty in the terrestrial arctic sink include a paucity of measurements that characterize the region due to the vast landscape and remoteness of the northern latitudes [Chapin et al., 2000], as well as an imperfect understanding of the processes responsible for both photosynthesis and respiration [Houghton et al., 2007]. Because a dominant pathway of C return from the terrestrial ecosystems to the atmosphere is through the thawing of permafrost and the concomitant enhanced microbial decomposition of soil organic matter [Schuur et al., 2008], determining if arctic terrestrial ecosystems will be a future source or sink to the atmosphere requires intimate knowledge of these pathways. Additionally, accurate predictions of C-cycling dynamics necessitate a greater understanding of the shifting vegetation dynamics in the Arctic [McGuire et al., 2009].
Arctic ecosystems are strongly influenced by subtle changes in climate [Chapin et al., 2000]. One powerful driver that influences the earth’s climate system is carbon dioxide (CO₂) concentration in the atmosphere [Chapin et al., 2000]. Atmospheric CO₂ is produced from both naturally occurring processes as well as anthropogenic causes, and is the single most important greenhouse gas contributing to radiative forcing. Notably, CO₂ contributes 80% to the 7.5% increase in radiative forcing from greenhouse gases from 2005 to 2011 [IPCC, 2013]. Since the beginning of the industrial era, emissions from burning fossil fuel and changing land use have been the primary contributors to the 40% increase in CO₂ concentrations [IPCC, 2013]. Atmospheric CO₂ concentrations have exceeded the range recorded in ice cores during the past 800,000 years, evidenced by the increase from 278 ppm in 1750 to 390 ppm in 2011 [IPCC, 2013].

Arctic air temperatures are now at levels higher than any experienced in the past two millenia [Kaufman et al. 2009], with the Arctic surface air temperature warming over 2°C since the mid-1960’s [Overland et al., 2013] compared to 0.72°C (0.49-0.89) increase in global mean surface temperature over the period 1951-2012 [IPCC, 2013]. Elevated arctic air temperatures compared to the more southerly latitudes is indicative of a phenomenon termed arctic amplification [Manabe and Stouffer, 1980]. This pattern of intensified increases in arctic temperatures relative to the rest of the globe has been predicted in models and confirmed in recent data [Overland et al., 2011], and paleoclimate records [Axford et al., 2009; Fitzpatrick et al, 2010]. A multitude of intertwined processes contribute to this poleward temperature increase including an ice-albedo reduction [Manabe and Stouffer, 1980], changes in atmospheric and oceanic circulation [Serreze and Barry, 2011], longwave
emissivity changes [Garrett and Zhao, 2006], increased ocean heat storage [Gascard et al., 2008], and changes in atmospheric aerosols [Mauritsen et al., 2011]. As a result, the Arctic is unrivaled in its temperature response to both anthropogenic and natural forcings [Lesins et al., 2012].

In the high-latitudes of the Arctic, permafrost, or perenniably frozen ground [Zimov et al., 2006], protects large pools of soil organic matter belowground. While the extent of the permafrost can range from 26°N to 84° N, 70% of permafrost exists between 45° and 67° N [Zhang et al., 2008]. Permafrost occupies 22% of the land surface in the arctic and boreal regions of the Northern Hemisphere [Zhang et al., 2008] and its depth can vary considerably [Schuur et al., 2008]. In the continuous permafrost zone (≥90-100% of land area underlain by permafrost) of the Northern Hemisphere [Tarnocai et al., 2009], permafrost depth generally ranges from 350 to 650 meters, but it can extend to 1450 meters in the unglaciated reaches of Siberia [Schuur et al., 2008].

As the high-latitude warming trend continues, a broad spectrum of ecological and physical systems are being affected [Chapin et al., 2000; McGuire et al., 2009]. In 2012, arctic sea ice reached its minimum extent at 3.41 million km², a 49% decrease below the 1979-2000 average minimum of 6.71 million km² [Perovich et al., 2012]. Concomitant with the decreasing sea ice is the ice-albedo positive feedback, which results in warming of the earth due to less sea ice, and subsequently, increased absorption of solar radiation. Snow cover extent was the lowest on record in June of 2012 in the Northern Hemisphere [Derksen and Brown, 2012], while permafrost temperatures were up to 2°C warmer in 2007-2009 than they were for the previous two to three decades [Romanovsky et al., 2010a]. In 2007-2009,
Russian air temperatures were 1.5°C greater than in the 10 years preceding this period, leading to a prevalence of permafrost thawing within the discontinuous permafrost zone, and in some areas of the continuous permafrost zone [Romanovsky et al., 2010b].

1.2. **Carbon Quantification**

Predicting changes to arctic C-cycling dynamics first necessitates a more precise quantification of current terrestrial C storage. Existing estimates suggest that arctic terrestrial ecosystems in northern high-latitudes comprise about one-third of the global terrestrial ecosystem C total with most of the C stored in soils [McGuire et al., 1995], but the precise magnitude of these stocks remains elusive [McGuire et al., 2009]. The C in biomass, soils, and permafrost in high-latitude ecosystems has considerable uncertainty associated with estimates. In the Arctic, the uncertainty in vegetation C storage estimates is 10 Pg C [McGuire et al., 2009]. While this range is relatively narrow compared to soil C estimates, the true uncertainty in vegetation is likely larger because of difficulties in estimating belowground biomass [Li et al., 2003]. The difference between the lowest and highest soil C estimates in high-latitude ecosystems is 450 Pg C [McGuire et al., 2009], which is approximately half of what is estimated to be in the atmosphere [Houghton et al., 2007]. Arctic soil C estimates vary considerably because of inconsistent soil depth measurements and the poor quantification of C in peatlands [McGuire et al., 2009].

Soil C stocks in high-latitudes have been slowly accumulating since the last glacial maximum [Zimov et al., 2006], presumably due to the inhibition of decomposition in cold and wet soils [McGuire et al., 2009]. Estimates of soil C storage in high-latitude terrestrial
ecosystems range from 1400 -1850 Pg C, with much of the C stored in peatlands and the permafrost soils in Siberia [McGuire et al., 2009]. Of these estimates, approximately a quarter (> 400 Pg C) of northern permafrost organic C resides in Siberian yedoma deposits [Zimov et al., 2006]. Frozen loess, termed yedoma in Siberia, was deposited during the glacial age and represents the accumulation of windblown materials [Zimov et al., 2006]. These materials settled atop the original soil surface, fostering the development of grasses and grazing by mammoths, as the bottom of the soil layer was eventually incorporated into the permafrost layer [Zimov et al., 2006]. In Siberia, yedoma has an average depth of 25 m [Tarnocai et al., 2009], a volume of 50-90% ice, and average “C contents of 2% to 5% - roughly 10 to 30 times the amount of C generally found in deep, nonpermafrost mineral soils” [Zimov et al., 2006].

As the Arctic warms, the yedoma in Siberia, and the permafrost elsewhere in the Arctic, is susceptible to degradation. With warming, thermokarsting –the melting of subsurface ice wedges [Walter et al., 2006] – is likely to increase in prevalence [Zhang et al., 2005]. Less abrupt responses to elevated temperatures include deepening of the ground surface layer that annually thaws and refreezes (active layer), as well as concurrent talik formation. Taliks are unfrozen soil layers ripe for decomposition that are formed by an incomplete refreezing of the active layer [Schuur et al., 2008]. All three methods of permafrost degradation will likely assist in the predicted 7-11% decrease in the permafrost C pool by 2100 [Schuur et al., 2013]. Further estimates suggest that if the highest warming scenario of a 7.5°C arctic temperature increase by 2100 occurs, the top 3 meters of permafrost will by degraded by 47-61% [Schuur et al., 2013]. As permafrost thaws, a flux of carbon to the atmosphere will subsequently occur.
In the terrestrial landscape, C is further sequestered in vegetation. Arctic vegetation currently represents about 10% of the global land sink [IPCC, 2013]. Vegetation in the northern high-latitudes stores 60-70 Pg C [McGuire et al., 2009] and can fix about 100 Pg C yr\(^{-1}\) through photosynthesis [McGuire et al., 1997]. Approximately half of the fixed C will be released via autotrophic respiration and about half in the decomposition of soil organic matter (heterotrophic respiration) [McGuire et al., 1997]. In high-latitude terrestrial ecosystems, evidence of a vegetation shift is currently underway, but northern high-latitude ecosystems are not responding in a simple linear fashion to increasing temperatures [Bunn et al., 2007]. One factor contributing to the non-linearities observed in Arctic ecosystems is variable photosynthetic response between the forest and tundra vegetation [Bunn et al., 2007]. In Alaska, repeat aerial photography [Sturm et al., 2001, Stow et al., 2004], plot studies [Tape et al., 2006], and satellite remote sensing [Goetz et al., 2005; Verbyla 2008] reveal an increase in the abundance and extent of shrubs in the tundra [Tape et al., 2006], whereas in other parts of the world, a circumpolar shrub shift is indicated by one or more of the following: growth rings [Forbes et al., 2010], NDVI [Xu et al., 2013], photographs [Tape et al., 2006], and plot and remote sensing studies [Tape et al., 2006]. In the northern latitudes, advances in tree line are occurring [Lloyd, 2005], while concurrent browning (negative trend in gross primary production, GPP) [Berner et al., 2011] and increased moisture stress [Bunn et al., 2007] are occurring in boreal forests. Simulations indicate a weakening of the high-latitude boreal forest terrestrial sink in recent decades due to greater heterotrophic respiration and disturbance [Hayes et al., 2011], and in Russia and Canada, trends across 22 sites show an equal distribution of greening (positive trend in GPP), browning, and non-trending when using space-based measurements [Berner et al., 2011]. Of
the three tree taxa examined in Russia and Canada, greening was most apparent in sparse larch stands whereas browning was evident in spruce and pine stands [Berner et al., 2011]. These findings suggest that a corollary to the projected warming in northeastern Siberia [Sazonova et al., 2004] will be changes in the large stores of terrestrial C in the Arctic. Understanding and quantifying these terrestrial stocks is critical as any change in the ability of terrestrial ecosystems to act as a sink for atmospheric carbon dioxide will greatly influence the earth’s response to global warming [Billet et al., 2004].

As arctic responses show large spatial and temporal variability [Bunn et al., 2007], demand has arisen for more integrated regional studies that consider the full range of processes that may influence C-cycling [McGuire et al., 2009]. As the deciduous shrub response to changing climatic conditions gains recognition in climate analyses [McGuire et al., 2009] and browning in boreal forests becomes evident, there is a call to rectify the error associated with vegetation estimates. The quantification of both above- and belowground biomass (mass of live and dead organisms) is pressing because much of the error in vegetation is attributed to the difficulty in estimating belowground biomass, primarily coarse and fine roots [Li et al., 2003]. Refining vegetation estimates is essential to reduce the disparity in regional energy projections, as well as to understand the positive feedback that can prevail through the expansion of vegetation and the subsequent enhanced evapotranspiration [Swann et al., 2010]. Similarly, as frozen soils are likely to release large amounts of C to the atmosphere in response to elevated temperatures [Schuur et al., 2013], refining belowground C pool estimates is imperative. C analyses of both the soils and vegetation will contribute to the notable absence of literature addressing the yedoma-
dominated soils in Siberia and will provide more information about C pools in arctic terrestrial ecosystems.

1.3. **Environmental Correlates of Carbon Pools**

Both abiotic and biotic variables influence C pools. In arctic and boreal regions, one abiotic factor that controls C storage is topography [Hobbie et al., 2000]. Topographic features, such as slope and aspect, can influence patterns of water and soil moisture, nutrient availability, and the flow of energy through a landscape [Swanson et al., 1988]. Steeper slopes are often associated with heightened erosion, deeper active layer depths [Zyryanova et al., 2010a] and a decreased accumulation of nutrients. Southern aspects are characterized by greater availability of nutrients [Koike et al., 2010], and warmer soils due to increased solar insolation [Koike et al., 2010]. Solar insolation is affected by both slope and aspect, and is one factor that can control the distribution of vegetation [Osawa et al., 2010]. Slope can affect processes independently of solar insolation, but both can influence the distribution of C pools.

Biotic factors, such as forest canopy structure, can also affect C pools. Forest canopies control plant light capture [Asner et al., 2003], growth, and respiration [Song, 2012]. Canopy foliage can also strongly influence the exchanges of water, C, and energy between the forest and the atmosphere [Kobayashi et al., 2010] and elucidates how much C is accumulated in the ecosystem over a period of time [Song, 2012]. Reliable estimates of foliage are essential in understanding vegetation growth [Asner et al., 2003], abundance, and
distribution [Gray and Song, 2012], as well as ecosystem response to global change [Chen et al., 1997].

Both abiotic and biotic variables may correlate with above- and belowground C pools. If so, these correlates would help develop associations between C stocks and more wide-ranging measures of ecosystem properties, as measureable by remote sensing. Such associations would present alternatives to directly measuring C stocks, and provide information useful for modeling C-cycling dynamics.

1.4. **Scope of Research**

The goal of this research was to quantify terrestrial C stocks, and elucidate relationships between environmental correlates and these stocks, in a small catchment of the Kolyma watershed in northeastern Siberia. These data contributed to the paucity of information in northern high-latitude terrestrial ecosystems and also provided insight into the biotic and abiotic factors that mediate C pools. We collected data as part of the Polaris Project (Appendix 1) in an effort to provide context on carbon stocks as a baseline for future research. The chosen catchment, termed Y4, was selected as a model watershed where the scientists of the Polaris Project aim to complete a full accounting of C stocks and fluxes in the terrestrial and aquatic environments to better understand the dynamic of C as it is transported and transformed.

Our objectives were to:

1. Quantify aboveground biomass, O horizon, and mineral soil C pools in the terrestrial uplands of the Y4 catchment (Figure 1).
a. Determine if aboveground C pools differ among sites.

b. Determine if belowground C pools differ among sites.

c. Assess if belowground C pools are related to aboveground C pools.

d. Evaluate if there is a relationship between coarse-root and aboveground C pools.

2. Assess the variation of C pools in the terrestrial uplands of the Y4 catchment.

   a. Determine if the within-site variance differs among sites for aboveground C pools.

   b. Determine if the within-site variance differs among sites for belowground C pools.

   c. Assess if the within-site coefficient of variation compares to the among-site coefficient of variation.

3. Examine environmental correlates for C pools that can be used to characterize variation among sites.

   a. Test for correlation between abiotic environmental variables (solar insolation and slope) and C pools among sites.

   b. Test for correlation between biotic environmental variables (LAI and canopy density) and C pools among sites.
Figure 1. Conceptual diagram of within- vs. among sites. Transects D, E, and F are considered within-site, whereas among-site is distinguished by the letters A, B, and C.
2. DATA AND METHODS

2.1. Site Selection

In the summers of 2012 and 2013, 18 sites were established in a small catchment of the Kolyma watershed near the Northeast Science Station in Cherskiy, Sakha Republic, Russia (Figure 2; Appendix 2). The 18 sites were randomly chosen based on four quartiles of tree density. The Kolyma River, which eventually drains into the East Siberian Sea in the Arctic Ocean, pervades the region. The catchment was chosen as it is in proximity to the Northeast Science Station and thus conferred logistical ease for ongoing measurements done as part of the Polaris Project. It is located approximately 2000 km east of Yakutsk, 130 km south of the Arctic Ocean, has an area of approximately 3 km$^2$, and is completely underlain by continuous permafrost. The larch-dominated (*Larix gmelinii*) catchment is spatially representative of eastern Siberia as larch stands prevail in the region due to severe climatic conditions and shallow rooting depths imposed by permafrost [Krestov, 2003]. Interspersed below the larch canopy in the gently undulating landscape lies a mixture of evergreen and deciduous shrubs, herbs, lichen, and mosses. Dwarf birch (*Betula nana*) is the dominant understory deciduous shrub; however, willow (*Salix spp.*) and alder (*Alnus viridis* spp. *fruticosa*) are also common. The dominant evergreen shrubs include Labrador tea (*Ledum sp.*) and bog cranberry (*Vaccinium vitis-idaea*).
Figure 2. Map of Cherskiy and the lower part of the Kolyma watershed in northeastern Siberia. Courtesy of Greg Fiske (Woods Hole Research Center).
2.2. **2013 Polaris Terrestrial Sampling Protocol**

Vegetation and soil data were collected as part of the Polaris Project terrestrial survey. Complete details on the sampling protocol (which is part of a larger data collection effort involving over a dozen researchers) are available in Appendix 1. Hereafter, the protocol is summarized.

**Plot set up**

Field measurements were conducted over the course of 2012 and 2013 at 18 sites in the Y4 catchment (Figure 3). At each site, we established three plots with a 20 m long transect in each plot. Each plot had a width of 4 m (2 m on either side of the transect; Figure 4). All transects ran parallel to each other and slope contours, and in the absence of a slope, the transects had a N-S orientation. All transects were separated by a distance of 10 m.
Figure 3. Map of 18 sites in the Y4 catchment of the Kolyma watershed
Figure 4. Transect and plot layout within each site. Each site had three plots with a 20 m long transects running the length of it.

Trees/Snags

Within each plot, we measured the diameter at breast height (DBH) for all trees and snags (standing dead tree) tall enough to have a DBH, and the basal diameter (BD) for any tree shorter than DBH height. Dry weight was calculated using allometric equations for larch aboveground components (Appendix 1). We converted live larch biomass values to C pools
using 46% C for foliage, 47% C for stemwood and stembark, and 48% C for branches. Snag biomass was converted to C pools using 47% C for stemwood and stembark, and 48% C for branches. The decay stage was estimated for snags (Appendix 1).

**Understory**

**Percent cover**

We estimated understory percent cover in a 1 m$^2$ plot located 1 m away from the 0 m and 20 m ends of the transect. If the plot location landed on a tree taller than breast height, the plot was moved farther away from the transect. If the plot was moved, this did not influence the determination of C values within the site. The 1 m$^2$ plots were separated into four quadrats. In each quadrat, we estimated percent cover to the nearest percentage for each functional type using the top-down perspective. Functional types included shrubs (evergreen and deciduous were combined), herbs, moss, lichen, and other. Woody debris and bare ground constituted the functional type “other”. All percent cover estimates summed to 100%. Thaw depth was also recorded in the center of each quadrat.

**Biomass**

Aboveground understory biomass was harvested from within a 0.25 m$^2$ quadrat located within the percent cover plot (Appendix 1). In this quadrat, we removed biomass by functional type, and placed each functional type in individual bags that were brought back to the laboratory. The functional types varied slightly from those used when estimating percent cover; when clipping biomass, the functional types included evergreen shrubs, herbs, moss and lichen. Rather than removing the entire extent of the moss and lichen, we took 5x5 cm$^2$ subsamples when the percent cover was above 30. When subsamples of moss and lichen
were taken, we re-estimated percent cover after the removal of the shrubs. In the event that percent cover values were not recorded, the smallest possible area was estimated for lichen and moss: 5x5 cm² (Appendix 3). To account for the imprecise volume measurements of the subsamples, we excluded the upper 10% of the dry weight m⁻² values for both moss and lichen in the calculations. Unlike the other functional groups, deciduous shrubs (*Alnus* sp., *Betula* sp., and *Salix* ssp.) and *Pinus* sp. were not harvested in the quadrat. Instead, we measured basal area using allometric relationships to derive biomass.

**Woody Debris**

Carbon stocks in downed woody debris were estimated at each site. Fine woody debris (less than 7 cm in diameter) was differentiated into five classes; coarse woody debris (greater than 7 cm in diameter) was recorded by diameter and decay class. We tallied the number of times woody debris intercepted the transect as per the line intercept method. Class I (0.0-0.49 cm in diameter) and II (0.5-0.99 cm) debris were tallied along the first 2 m of each transect, Class III (1.0 – 2.99cm) along the first 10 m of each subsection, and classes IV (3.0-4.99 cm), V (5.0-6.99 cm), and downed coarse woody debris (CWD; > 7 cm diameter) along the entire 20 m length. Snags were considered downed woody debris if they were at angle < 45 degrees to the forest floor. We calculated the mass of fine woody debris using abundance, decay class, and multiplier values. We obtained coarse woody debris mass using abundance, decay class, diameter, and density values (Appendix 1). Woody debris was converted to C pools using 47% C.
Soils

Thaw depth/Organic layer depth

Thaw depth and organic layer depth (OLD) were collected along each transect. Using a permafrost probe, we measured thaw depth every meter along each transect. All thaw depths measurements were taken between July 9th and July 22nd, except one, which was taken on August 3, 2013. OLD was measured at 5 m intervals along each transect by cutting down to frozen ground with a serrated knife and visually identifying and measuring the depth to the organic-mineral boundary. All OLD’s and thaw depths were recorded to the nearest cm.

Soil samples

We collected a total of six soil samples in each site from thawed active layer soils, with one soil sample collected at the end of each transect. The O horizon was collected by using a serrated knife to cut an 8 x 8 cm block. We measured the width, length, and depth of each O horizon sample. Litter was included in the O layer, but aboveground vegetation was discarded. Using a 2 cm diameter metal soil corer, the top 10 cm (or depth to the bottom of the active layer, whichever was less) of mineral soil was collected. In the laboratory, coarse-roots (> 2 mm) were extracted from the O layer, while charcoal was discarded (Appendix 4). Soils were dried for at least one day at room temperature, and then dried in the drying oven at 60°C for at least 24 hours (O layer soils) or 48 hours (mineral soils). We estimated organic matter content on oven-dried subsamples by loss-on-ignition (LOI). Organic matter content (%) was subsequently converted to C (%) using the linear relationship (C content = (0.51 * LOI) - 0.6) which was developed from soils collected from the Kolyma region [Alexander et al., 2012]. We excluded the five soil cores with the shallowest depths (1 – 3 cm depth) from the mineral soils dataset. These soil cores were excluded because they had disproportionate
(high) Loss-On-Ignition values compared to their bulk density. Coarse-root C was assumed to be 50% in roots.

2.3. **Environmental Correlates**

2.3.1. **Leaf Area Index**

In this study, we compared several techniques for estimating canopy cover, including spherical densiometry, hemispherical photography, and the 2000 Plant Canopy Analyzer (LI-COR, Nebraska, NE, USA). Hemispherical photography and the LAI-2000 were used at 16 sites to quantify leaf area index (LAI). LAI is defined as the hemisurface area of green leaves per horizontal ground surface area [Chen and Black, 1992], and thus is a measure of the photosynthetically active tissue in a stand [Majasalmi et al., 2012].

We used the LAI-2000 at the center of each site. All values were obtained using the lens cap at ~1 m above the ground in overcast conditions. As estimates of LAI are often underestimated in coniferous forests when the foliage is clumped [Chen et al., 1997], we divided the LAI estimates by a clumping factor of .68 [Chen et al., 2005]. We also took hemispherical photographs at ~1 m off the ground using a Sigma SD 15 digital reflex camera with Sigma 4.5 mm F2.8 EX DC circular fisheye lens. The camera was mounted on a tripod, and a N-S reflector was used for N orientation. Photographs were taken using automatic settings at the center of each of the three transects (per site). All photographs were taken in overcast conditions, which allowed for differentiation between obscured and visible sky.

The hemispherical photographs were analyzed using the accompanying Hemiview software. Parts of some images were painted to compensate for dark sky regions or exclude
objects in the photographs. This was done using GIMP, GNU Image Manipulation Program. Photograph classification was dependent upon the determination of a threshold intensity value. In order to reduce the subjectivity when deciding threshold values [Rich et al., 1998], we chose a value of 170, although there were two exceptions; one exception was an over-exposed photograph while the other was subject to cloud cover, and thus 205 was a more accurate depiction of canopy separation. Of the 48 photographs taken, the N-S reflector could not be seen in seven photographs. In these cases, N was aligned to the top of the page. One person analyzed all of the photographs (KEH). For more details about leaf area index, refer to Appendix 5.

2.3.2. **Spherical Densiometer**

Canopy density percentage was estimated using a convex spherical densiometer at the center point of each transect. We held the densiometer level at waist height and 12-18 inches in front of the body. Four equispaced dots were assumed in each corner of the grid, and the dots were systematically counted to assess canopy density. At each location, canopy density was measured in four cardinal directions (N, S, E, and W).

2.3.3. **Solar Insolation and Slope**

Solar insolation was calculated using the Solar Radiation analyses toolset in ArcGIS version 10 [ESRI 2011; Appendix 6]. The toolset used variability in the orientation (slope and aspect) to calculate direct and diffuse radiation for each pixel of the elevation model in the Y4 catchment using viewshed algorithms [Rich et al. 1994, Fu and Rich 2002]. We used total
insolation on the summer solstice and equinox for each pixel (in units of kWh m\(^{-2}\)) as environmental covariates in our correlation analyses. PGC (Polar Geospatial Center) provided the stereo-based Digital Elevation Model, from which we obtained values for slope and aspect.

2.4. **Statistical Analysis**

In this analysis, carbon pools (g C m\(^{-2}\)) in the vegetation and soils were calculated. Calculations derived using the three transect means in each site will hereafter before referred to as “within-site” C pool values, whereas among-site C pools were calculated using one mean value per site. Carbon in aboveground biomass was computed by summing the values for woody debris, snags, trees, and understory biomass. Belowground C pools were calculated using two methods which included normalizing to a depth of 10 cm from the surface of the O horizon, as well as assessing the O horizon and mineral soils to a depth of 10 cm independently. O horizon C pools, which included coarse-roots (> 2 mm), were calculated to the depth measured. The normalization of mineral soils relies on the assumption that C density will be overestimated as you extrapolate from shallow to deep depths because greater C concentrations are found near the soil surface. Likewise, C density will be underestimated as you interpolate from deep to shallow depths.

The statistical program R [R Core Team, 2013] was used to conduct all statistical analyses. Within-site variance homogeneity was assessed using Bartlett’s test. Variability among the C pools was compared using the coefficient of variation (CV). For this research, the CV was calculated for aboveground biomass, O horizon, and mineral soil C pools.
Within-site CV values were evaluated using three transect means (per site) whereas among-site CV values were calculated using one value per site. As the among-site CV incorporates both true among-site variation, as well as some within-site variation, additional calculations were performed to separate the two. We looked at the expected mean squares in the ANOVA output, and separated the factors “site + transect” from the factor “site”. Transects were subtracted from the sites, and divided by three, to obtain a squared standard deviation value. The square-root of the standard deviation for each C pool was used to compute the among-site CV.

We used a one-way analysis of variance (ANOVA) to test the hypothesis that C pools do not differ among sites. Normality was not tested due to an insufficient number of data points while variance homogeneity was informally tested using qualitative assessments, and formally tested using Bartlett’s test. When a significant p-value was observed when using an ANOVA (p < 0.05), Tukey’s test was used to determine which sites contributed to the difference in C pools.

Correlations between the C in aboveground biomass, O horizon, mineral soils, and normalized soils (among sites) were determined using Pearson’s correlation analyses. The relationship between soils, vegetation, and the four environmental correlates — slope, solar insolation, canopy density, and leaf area index — were also analyzed using Pearson’s correlation analyses. Holm’s test was used to correct for multiple comparisons. The relationships were deemed significant at a critical value (α) of 0.05. Normality was not assessed as there were an insufficient number of data points, while variance heterogeneity was examined qualitatively. In the event that variance heterogeneity was evident, the
relationship was tested using Kendall’s Tau non-parametric method. Kendall’s Tau was chosen over Spearman’s Rho non-parametric method as there were numerous ties.

3. RESULTS

3.1. Among-Site Carbon Distribution

The site C pools for aboveground biomass ranged from 348 to 2569 g C m\(^{-2}\), with a mean and standard error of 1128 ± 273 g C m\(^{-2}\) (Table 1; Figure 5; Appendix 7). The site C pools for the O horizon, mineral soils, and normalized soils in g C m\(^{-2}\) ranged from 1055 to 3742, 1068 to 4705, and 1156 to 3834 with a mean and standard error of 2414 ± 391, 2231 ± 432, and 2268 ±391, respectively. Mean coarse-roots constituted 9.7% of the O horizon C pool and 5.1% of the total soil C pool (summed normalized mineral soils and O layer). The average thaw depth was 27.3 cm, but site values ranged from 15.7 to 42.3 cm.

There were significant differences among sites in C pools for aboveground biomass (p < 0.001; F= 4.22), the O horizon (p = 0.006; F= 2.698), mineral soils (p = 0.003; F=3.103), and normalized soils (p = 0.005; F= 2.712; Table 1; Table 2). Sites 5 and 6 were influential in contributing to the difference in the O horizon, aboveground biomass, and normalized soils whereas sites 4, 17, and 18 had a large effect on mineral soil C pools (Figure 6). Variance heterogeneity was not evident (not shown).

There was no significant association between coarse-root and aboveground C pools. Snags were positively associated with normalized belowground C pools (Table 3), but the assumption of homogeneity of variance was violated in this relationship. To test the strength of this relationship, Kendall’s Tau non-parametric test was used. When using Kendall’s Tau
non-parametric method, our confidence in the relationship between snags and normalized belowground C pools was lessened, as a significant relationship did not exist.

Table 1. Mean, standard error, range, and coefficient of variation for above- and belowground C pools in g C m$^{-2}$. CV$^w$ is the coefficient of variation within sites. CV$^a$ is the coefficient of variation among sites (n=18).

<table>
<thead>
<tr>
<th>C pool</th>
<th>C (g C m$^{-2}$)</th>
<th>Variability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SE</td>
</tr>
<tr>
<td>Aboveground Biomass</td>
<td>1129</td>
<td>273</td>
</tr>
<tr>
<td>Tree</td>
<td>453</td>
<td>204</td>
</tr>
<tr>
<td>Snag</td>
<td>55</td>
<td>32</td>
</tr>
<tr>
<td>Woody Debris</td>
<td>91</td>
<td>33</td>
</tr>
<tr>
<td>Understory Biomass</td>
<td>530</td>
<td>142</td>
</tr>
<tr>
<td>Shrub Biomass</td>
<td>152</td>
<td>80</td>
</tr>
<tr>
<td>Mineral Soil</td>
<td>2232</td>
<td>432</td>
</tr>
<tr>
<td>O horizon</td>
<td>2415</td>
<td>392</td>
</tr>
<tr>
<td>Coarse Root Biomass</td>
<td>235</td>
<td>96</td>
</tr>
<tr>
<td>Normalized Soil (10 cm)</td>
<td>2269</td>
<td>391</td>
</tr>
</tbody>
</table>

Table 2. Among-site one-way ANOVA results. A significant difference in C pools was evident for aboveground biomass, the O horizon, mineral soils, and normalized soils.

<table>
<thead>
<tr>
<th></th>
<th>F-value</th>
<th>Influential Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aboveground Biomass</td>
<td>4.22***</td>
<td>5**; 6***; 16*</td>
</tr>
<tr>
<td>Mineral Soil</td>
<td>3.103**</td>
<td>4*; 17**; 18*</td>
</tr>
<tr>
<td>O horizon</td>
<td>2.698**</td>
<td>5*; 6*, 18*</td>
</tr>
<tr>
<td>Normalized Soil (10 cm)</td>
<td>2.712**</td>
<td>5*; 6*</td>
</tr>
</tbody>
</table>

p < 0.001***

p < 0.01**

p < 0.05*
Figure 5. Above- and belowground C pools (mean +/- SE, g C m$^{-2}$). Aboveground C pools consisted of woody debris, tree, snag, and understory C values. Belowground C pools consisted of soil and coarse-roots, and were normalized to a depth of 10 cm. Belowground C pool standard errors were calculated using the total number of soil cores per site (6 soil cores per site were extracted in 14 of the 18 sites). In the other 4 sites, soil cores could not be extracted due to shallow active layer depths. Aboveground C pool standard errors were calculated using three transect means per site.
Figure 6. Stacked bar graph displaying C distribution in each site. The five categories of C stocks are belowground, woody debris, tree, snag, and understory biomass. Belowground C pools were calculated by normalizing to a depth of 10 cm.
3.2. **Variation in Carbon Distribution**

A primary objective of this research was to determine if the within-site variance differed among sites for above- and belowground C pools (Appendix 8). Results from Bartlett’s test suggested that the within-site variances were homogeneous across sites for the C pools in aboveground biomass, the O horizon, mineral soils, and normalized soils (p > 0.05). Carbon pool variability was assessed using the CV, with the results indicating that a similar amount of variability existed within- and among sites for each C pool (Figure 7). Comparison of within- and among site C pool variability clarifies how accurate C pool estimates are at different spatial scales. Aboveground C pools exhibited the highest degree of variability, while O horizon and mineral soil C pools were similar both within- and among sites.

Table 3. Pearson’s correlation analyses among sites for above- and belowground C pools (n=18). Understory biomass includes deciduous and evergreen shrubs, herbs, lichens, and mosses. Shrub biomass includes the three genera of deciduous shrubs: *Betula*, *Salix*, and *Alnus*. Coarse-roots are > 2 mm.

<table>
<thead>
<tr>
<th>C pool</th>
<th>Tree</th>
<th>Snag</th>
<th>WD</th>
<th>Understory Biomass</th>
<th>Shrub Biomass</th>
<th>Coarse-Root</th>
<th>Aboveground</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mineral Soil</strong></td>
<td>-0.368</td>
<td>-0.21</td>
<td>-0.06</td>
<td>-0.14</td>
<td>0.476</td>
<td>-0.027</td>
<td>-0.335</td>
</tr>
<tr>
<td><strong>Organic Soil</strong></td>
<td>0.267</td>
<td>0.522</td>
<td>0.136</td>
<td>0.146</td>
<td>-0.044</td>
<td>0.596*</td>
<td>0.333</td>
</tr>
<tr>
<td><strong>Normalized Soil (10 cm)</strong></td>
<td>0.348</td>
<td>0.614*</td>
<td>0.211</td>
<td>0.035</td>
<td>0.005</td>
<td>0.593</td>
<td>0.389</td>
</tr>
</tbody>
</table>

p < 0.05*
Figure 7. Coefficient of variation within and among sites in g C m\(^{-2}\). Within-site values were calculated using three transect means within each site, and then the CV per site was averaged among sites. Among-site CV values were calculated using the site means. As the among-site CV incorporates both true among-site variation, as well as some within-site variation, calculations were performed to separate the within- and among site variation using the expected mean squares in the ANOVA output. Eighteen sites were used to calculate the CV within- and among sites.
3.3. **Abiotic Environmental Correlates**

To determine if there were abiotic correlates, the relationships between soils, vegetation, and the abiotic variables — solar insolation and slope — were analyzed (Table 4). Solar insolation did not correlate with above- or belowground C stocks. Slope was significantly associated with aboveground C pools \( (p = 0.013) \), but not related to belowground C pools. The assumption of homogeneity of variance was violated in the relationship between snags and slope because of the abundance of zero values. When using Kendall’s Tau non-parametric method, our confidence in the relationship between snags and slope \( (p = 0.002) \) was strengthened.
Table 4. Pearson’s correlation analyses for C pools, environmental correlates, and thaw depth.

<table>
<thead>
<tr>
<th></th>
<th>Summer Solstice Solar Insolation</th>
<th>Equinox Solar Insolation</th>
<th>Slope</th>
<th>% Canopy Density</th>
<th>LAI (Hemispherical Photography)</th>
<th>LAI (LAI-2000)</th>
<th>Thaw Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aboveground Biomass</td>
<td>-0.467</td>
<td>-0.359</td>
<td>0.669*</td>
<td>0.812***</td>
<td>0.814***</td>
<td>0.792**</td>
<td>0.464</td>
</tr>
<tr>
<td>Tree</td>
<td>-0.511</td>
<td>-0.417</td>
<td>0.613*</td>
<td>0.824***</td>
<td>0.786**</td>
<td>0.766**</td>
<td>-0.556*</td>
</tr>
<tr>
<td>Snag</td>
<td>-0.426</td>
<td>-0.295</td>
<td>0.689*</td>
<td>0.471</td>
<td>0.535*</td>
<td>0.615</td>
<td>-0.327</td>
</tr>
<tr>
<td>Woody Debris</td>
<td>-0.083</td>
<td>-0.051</td>
<td>0.302</td>
<td>0.402</td>
<td>0.231</td>
<td>0.298</td>
<td>-0.098</td>
</tr>
<tr>
<td>Understory Biomass</td>
<td>-0.119</td>
<td>-0.055</td>
<td>0.345</td>
<td>0.414</td>
<td>0.546</td>
<td>0.434</td>
<td>-0.024</td>
</tr>
<tr>
<td>Shrub Biomass</td>
<td>0.271</td>
<td>0.255</td>
<td>-0.212</td>
<td>-0.109</td>
<td>0.076</td>
<td>-0.029</td>
<td>0.364</td>
</tr>
<tr>
<td>Mineral Soil</td>
<td>0.067</td>
<td>0.049</td>
<td>-0.134</td>
<td>-0.361</td>
<td>-0.234</td>
<td>-0.229</td>
<td>0.138</td>
</tr>
<tr>
<td>O Horizon</td>
<td>-0.203</td>
<td>-0.15</td>
<td>0.182</td>
<td>0.199</td>
<td>0.441</td>
<td>0.543</td>
<td>0.063</td>
</tr>
<tr>
<td>Coarse Root Biomass</td>
<td>-0.288</td>
<td>-0.191</td>
<td>0.588</td>
<td>0.111</td>
<td>0.256</td>
<td>0.52</td>
<td>0.391</td>
</tr>
<tr>
<td>Normalized Belowground (10 cm)</td>
<td>-0.123</td>
<td>-0.029</td>
<td>0.0378</td>
<td>0.061</td>
<td>0.190</td>
<td>0.300</td>
<td>0.257</td>
</tr>
<tr>
<td>Thaw Depth</td>
<td>0.403</td>
<td>0.403</td>
<td>-0.137</td>
<td>-0.592*</td>
<td>-0.378</td>
<td>-0.048</td>
<td>—</td>
</tr>
</tbody>
</table>

p < 0.001***
p < 0.01**
p < 0.05*
3.4. **Biotic Environmental correlates**

All three canopy measures were significantly related when using Pearson’s correlation analyses (p < 0.05; Appendix 9). Leaf area index values derived from hemispherical photography were strongly associated with canopy density values obtained using the densiometer (p < 0.001; r = 0.907) whereas the LAI-2000 values were less so (p = 0.017; r = 0.566). After we removed a conspicuous outlier in the LAI-2000 (site 18), the fit with canopy density was much improved (p < 0.001; r = 0.778), but the correlation coefficient was still higher when canopy density was compared with hemispherical photography. As there is good correspondence between the three canopy measures, hereafter we will refer to only the values obtained using the spherical densiometer (Appendix 10). Canopy density was chosen as the representative canopy environmental correlate because the spherical densiometer is the most cost effective, easiest to transport, and most straightforward to use.

To determine if there were biotic correlates, we assessed the relationships between soil C, vegetation C, and canopy cover (Table 4). Canopy cover was positively correlated with aboveground biomass (Figure 8), but not significantly related to soil C stocks.
Figure 8. Positive correlation between canopy cover (% canopy density) and aboveground biomass (g C m$^{-2}$). Forest overstory density was estimated using a convex spherical densiometer. The summed constituents of aboveground biomass are woody debris, understory vegetation, trees, and snags.
4. DISCUSSION

4.1. Among-Site Carbon Distribution

With the strongest climate warming predicted in the northern high-latitudes [McGuire et al., 2009], understanding the feedback of terrestrial C pools is increasingly important. A paucity of measurements in the Arctic has resulted in imprecise terrestrial C pools that warrant more accurate quantification at both the regional and catchment scale. Our findings demonstrate that carbon in the surface O horizon (2414 ± 391 g C m$^{-2}$, mean +/- SE) and underlying mineral soil layer to a depth of 10 cm or to the bottom of the active layer, whichever was less, (2231 ± 432 g C m$^{-2}$) were, together, approximately four times that of the aboveground C pools (1128 ± 273 g C m$^{-2}$). These results are consistent with previous studies that indicate greater quantities of belowground C storage in arctic terrestrial ecosystems [Houghton et al., 2007; McGuire et al., 2009]. On average, mineral soil C pools were slightly smaller than the C pools in the O horizon, but the depth considered has a major effect on the stores reported [Michaelson et al., 1996]. Carbon stores have been reported to a variety of depths in arctic ecosystems, although a scarcity of data exists at deeper depths [Tarnocai et al., 2009].

In the Arctic, few studies with similar aboveground C pool estimates exist in larch-dominated forests. Estimates from our study were similar to previous estimates near Cherskiy [Alexander et al., 2012], and much lower than estimates of larch forests in northeast China [Gower et al., 2001]. While these Chinese larch estimates are considerably larger than our aboveground biomass values, the variation is unsurprising. Our ANOVA results indicated a significant difference in aboveground C pools among sites, which has been substantiated by
previous studies [Kajimoto et al., 2010; Alexander et al., 2012]. Both random variation and strong differences in abiotic conditions likely drive C pools in our sites.

The difference in aboveground C pools among sites in this study may arise from differences in tree size [Kajimoto et al., 2010], tree density [Alexander et al., 2012], or variable understory vegetation, all of which could be linked to abiotic factors, including disturbance history. For example, previous studies have indicated a positive association between greater larch biomass and the time elapsed since fire [Schulze et al., 2012], although considerable variability can exist in larch pools of similar successional stages [Berner et al., 2012]. In Siberian forests, fires influence stand structure and composition, as well as promote larch regeneration [Schulze et al., 2012]. While fire activity varies considerably across the Siberian landscape [Berner et al., 2011], most larch stands experience several surface fires during their life cycle [Schulze et al., 2012]. Although fire data is lacking for our specific sites, aboveground C pools are likely affected by the high fire activity that has been noted in the Kolyma Mountains relative to other parts of the Arctic [Berner et al., 2011].

Like aboveground C pools, belowground C pools can vary with successional stages in a larch forest. One study near Cherksiy evaluated C pools with differing successional stages and stand densities [Alexander et al., 2012]. We chose to compare our C pools with those previously reported in a medium density, mid-successional larch stand. Stands of this age were chosen for comparison as this is an intermediate age in a heterogeneous landscape, and mid-successional stands are likely to become more common if a climate-induced increase in fire activity occurs [Alexander et al, 2012]. For our research, mean O horizon C pools were similar to previous estimates near our sites, while mean mineral soil C pools were slightly less than those previously reported [Alexander et al., 2012]. Even though our mean C pools
were similar to those formerly reported, our results indicate that both mineral and O horizon C pools are significantly different among sites. Previous research has shown variability in O layer C pools in early to mid-successional low-density larch stands, with an age-related increase in O layer C in a late-successional stage (> 70 years) [Alexander et al., 2012], but local site conditions including temperature [Kirschbaum, 2000; Gersper et al., 1980], and moisture [Gersper et al., 1980] also likely contribute to the differences in O horizon C pools.

The sites contributing to the significant difference in O horizon C pools were not the same as the most influential sites in the mineral soil C pools. Mineral soil C stocks can be similarly influenced by the local factors that affect O horizon C pools, although unrelated site conditions can play a role. Just as O horizon C pools can increase with age in a larch forest, mineral soils can potentially do the same if the organic matter is buried deeper in the soil profile [Harden et al., 2000]. If an age-related increase accounted for the disparity in mineral soil C pools, then this would suggest that the three sites contributing to the difference in mineral soil C pools were late-successional larch stands, as were the two influential sites in the O horizon. Our data indicated that at least one site contributing to the difference in mineral soil C pools was largely lacking larch trees, and was instead dominated by understory biomass. Therefore, other site conditions such as soil mixing due to local freeze/thaw processes (cryoturbation) may affect mineral soil C pool distribution. In the Arctic, the soil mixing from the surface to depth through cryoturbation can strongly influence the distribution and size of C pools [Michaelson et al., 1996] and produce distinctive soils within 1m of each other [Ping et al., 1998].

While knowledge of belowground C pools in larch-dominated ecosystems is still lacking, studies have indicated that roots are an important component of C storage [Kajimoto
et al., 1999]. Because much of the error in vegetation estimates is attributed to the difficulty in estimating coarse and fine roots [Li et al., 2003], our research attempted to discern a relationship between aboveground and coarse-root C pools, but a significant association did not exist. In this work, coarse-roots were only found in the O layer, and constituted 9.7% of this pool. The percentage of coarse-roots found in the total soil C pool (summed mineral and O layer) was 5.1%, which is slightly more than the 3% of coarse material (roots, charcoal, buried wood) calculated in previous work in Cherskiy [Alexander et al., 2012].

Previous work has calculated root pools using allometric relationships for *Larix gmelinii* [Kajimoto et al., 2006]. The aboveground-total to coarse-root biomass ratio (T/R) in the aforementioned study was 2.14, with coarse-roots considered to be ≥ 5 mm in diameter. If our calculations complied with this T/R model, we would estimate that larch root C pools in our 18 sites would average 211.9 g C m\(^{-2}\), which is 8.7% of the O horizon and 4.5% of the total soil C pool. These estimates are slightly less than were calculated in this study. If we combined snag (25.7 g C m\(^{-2}\)) and larch root C pools using this model, roots would comprise 9.8% of the O horizon and 5.1% of the total soil C pool. These percentages are almost identical to the root values obtained when we extracted the soil layers. In our work, aboveground shrub C pools averaged 151.6 g C m\(^{-2}\). If we used the T/R ratio, there would be 70.8 g C m\(^{-2}\) of shrub-root biomass. When larch, snag, and shrub coarse-root C pools are combined using the T/R ratio, the coarse-roots total 308 g C m\(^{-2}\), which exceeds the roots extracted in this study by a large amount (72.7 g C m\(^{-2}\)). These calculations indicate that root C pools are under-represented and not effectively quantified in this study. Additionally, coarse-roots are not solely associated with the vegetation previously discussed; instead,
coarse-roots can also be found in other understory vegetation. Therefore, better methods need to be developed to reduce the disparity in Arctic vegetation estimates.

4.2. **Variation in Carbon Distribution**

For this research, we quantified C pools and variability to provide context for future C-cycling inquiries in the Y4 catchment of Siberia, and boreal forests more generally. Carbon pool variability was assessed both within- and among sites. As topographical similarities were more prevalent within sites than among sites, we speculated that more variability would exist among sites. Our results did not support this hypothesis. The within- and among-site CV exhibited a similar percentage of variability for all C pools. High within-site variability suggests that disparate ecosystem dynamics can prevail among transects that are only 10 m apart. For this research, a high relative measure of variability was evident among sites for aboveground C pools, which has been confirmed by other studies in the Siberian Arctic [Alexander et al., 2012; Berner et al., 2012]. High variability in aboveground C pools is unsurprising as each site was stratified based on tree density. Compared to an Alaskan study of soil organic carbon stocks in the active layer [Mishra and Riley, 2012], our belowground C pools had a lower CV (Table 1). While the relative measure of variability was lower, these data nonetheless indicate that accurate quantification of C pools at various spatial scales will be difficult.

The similar variability evident in O horizon C pools and mineral soil C pools is likely affected by the differences in soil sample sizes. As the O layer was ~64 cm$^2$, more fine-scale variability could be captured than with the smaller ~2 cm$^2$ mineral soil sample [Homann,
2014, in press]. If the size of the soil samples were similar, we would expect the O horizon C pools to be more variable than the mineral soil C pools. As soil organic C accumulates from aboveground plant parts and litter [Kirschbaum, 2000], the corresponding variability would likely follow a trend similar to that in aboveground C pools.

Variability in mineral soils may be further influenced by the method of soil extraction. When calculating mineral soil C, these calculations rely upon the assumption that when the mineral soil cores were taken, the soil was compacted and ended up in the soil corer, rather than being pushed down by the core. If this assumption was violated, more variability would be introduced because of problems associated with soil sampling depth. To better understand where the variability came from, we analyzed our bulk density values for mineral soils. Bulk density values ranged from 0.3 to 1.6 g cm$^{-3}$, which is similar to the range for the 2012 terrestrial survey. For additional comparisons, we looked at the bulk density of thawed mineral soil taken from a permafrost core in the Y4 catchment. The bulk density of the permafrost core was 0.93 ± .13 g cm$^{-3}$, which falls within the range of our 2013 terrestrial survey bulk densities. These comparisons indicate that while variability can be introduced by soil sampling depth, random variability is also a likely culprit.

4.3. **Environmental Correlates**

Equipped with the knowledge that local conditions can affect C pools [Kajimoto et al., 2010], we set out to determine if site-scale abiotic or biotic factors helped predict above- or belowground C pools. Environmental correlates would present alternatives to directly measuring C stocks, and provide information to better predict C-cycling dynamics using
ecosystem models. Of the environmental correlates considered, none were significantly related to belowground C pools. Canopy cover and slope were both correlated with aboveground C pools, with canopy cover having the most robust association. Solar insolation did not have any significant relationships.

The identification of slope as an environmental correlate emphasizes the large influence that the physical template of the landscape has in controlling C pools. In the small larch-dominated Y4 catchment, the slope variation was relatively subtle with a range of 1.5 – 16.0°, but this variation was still influential in affecting C pools. Previous studies have suggested that slope can affect soil C pools [Kang et al., 2006; Michaelson et al., 1996; Riveros-Iregui and McGlynn, 2009], but our results indicated that slope could only control the variation in aboveground C pools. Upon dissection, this positive correlation with aboveground C stocks is largely due to the association between slope, tree, and snag C pools.

In the Arctic, larch trees prevail on steeper slopes because of their adventitious root system [Osawa and Zyryanova, 2010 quoted in Russian by Dylis, 1981] that can exploit the shallow, nutrient-poor permafrost soils [Kajimoto et al., 1999]. The extensive, densely-overlapping root system of *Larix gmelinii* stands [Schulze et al., 1995] strongly indicates a proliferation of larch above- and belowground, which can confer a competitive advantage. Previous research has indicated that in similarly-aged stands, larch density and understory biomass were inversely related [Alexander et al., 2012], but in our research, no such relationship was established (p = 0.104; r = 0.219).

As canopy cover is often used as a primary driver in ecosystem models simulating C-cycling dynamics, the relationships with canopy cover will help to better predict C pools. In this catchment, canopy cover was comprised of one species of tree, which is quite
homogeneous compared to elsewhere in the Arctic. In this research, forest canopy cover was positively associated with aboveground C pools, and negatively associated with active layer depth (Table 4). The negative association between canopy cover and active layer depth can be explained by stand age [Kajimoto, 2010 quoted in Russian by Kharuk et al., 2005], vegetation density [Osawa and Zyryanova, 2010], the thickness of moss, lichen, and forest floor materials [Van Cleve et al., 1983], and infrequent fire activity. In central Siberian larch stands, a gradual decrease in active layer depth accompanied an increase in stand age [Kajimoto, 2010 quoted in Russian by Kharuk et al., 2005]. As larch trees age and gain more biomass, the characteristically thin canopy [Sofronov and Volokitina, 2010] of larch forests increases [Alexander et al., 2012]. Increased canopy cover is associated with a greater thickness of moss, lichen, and forest floor material, which insulates permafrost from thawing [Van Cleve et al., 1983].

The lack of a relationship between environmental correlates and belowground C pools underscores the complex dynamics occurring in Arctic terrestrial ecosystems. Nonetheless, the correlation between canopy cover, tree C pools, and thaw depth can potentially shed light on belowground C-cycling dynamics. As canopy cover and tree C pools are negatively associated with active layer depths (Table 4), reduced soil temperatures can be inferred. The potentially reduced soil temperatures under greater canopy cover may slow microbial activity and decomposition [Chapin et al., 2000]. In turn, this may lessen the efflux of soil C (though many other factors can also influence the rate of decomposition) [Hobbie et al., 2002]. Conversely, if canopy cover is reduced due to an increase in fires as is expected in warmer and drier world [Flannigan et al., 2005], active layer depths will deepen and C will be released.
4.4. Implications for Modeling

The inaccessibility, vast landscape, and complexity of local site conditions in northeastern Siberia make it difficult to precisely estimate biomass and leaf area index. While field-based measurements are the most accurate for determining biomass [Lu et al., 2006], and indirect optical methods estimating leaf area index are known to be robust [Majalsami et al., 2012], it is impossible to map these parameters in a spatially explicit manner solely using field-based measurements [Song, 2012]. An alternative method to the more laborious field measurements [Lu et al., 2006] is remote sensing.

Remote sensing, or satellite-derived data, is used to survey large areas and more accurately assess spatial variability [Fuchs et al., 2009]. When remote-sensing techniques augment field-based measurements, ecosystem models can be developed. If the input parameters of the models include leaf area index and C pool estimates (as were measured in this study), ecosystem processes can be simulated [Song, 2012] and future C-cycling dynamics can be evaluated. The validation of these models can only be tested with local scale studies [Lu et al., 2006], such as those performed at the catchment-level.

The C pool estimates used in the model are often determined using published values for the C content in biomass. In our study, C content was estimated to comprise 46-50% of biomass, depending on the specific component. While the values were not applied in this research due to the late analysis, our use of a C/N analyzer will reduce the error when converting from biomass to C content, and subsequently extrapolating to models (Appendix 11).
5. SUMMARY and CONCLUSIONS

5.1. Summary

For this research, above- and belowground C pools were quantified in a small watershed near Cherskiy, Siberia. Our findings demonstrated that C in the surface O horizon and underlying mineral soil layer to a depth of 10 cm or to the bottom of the active layer, whichever was less, were, together, approximately four times that of the aboveground C pools. These results are consistent with previous studies that indicate greater quantities of belowground C storage in arctic terrestrial ecosystems, but the depth considered has a major effect on the stores reported. In addition to quantifying C pools, this research sought to discern relationships between above- and belowground C pools. No relationships were apparent.

High variability was evident both within- and among sites. Aboveground C pools exhibited the highest degree of variability, while the O horizon and mineral soil C pools were similar both within- and among sites. Variance heterogeneity within-sites was not evident, while significant differences were indicated in all mean C pools among sites. The differences in C pools can likely be attributed to several factors including local site conditions, fire activity, vegetation prevalence, and soil fixing due to cryoturbation. High variability will make it more difficult to accurately quantify above- and belowground C pools at both a catchment and regional scale, unless we can identify easily measured correlates of C pool sizes.

Of the environmental correlates considered, canopy cover was the most robustly related to aboveground C pools. Solar insolation was a poor environmental correlate, while significant correlations did not exist between any of the environmental correlates and
belowground C pools. Overall, these results show that there is not a lot of coupling between environmental correlates and C pools. The relationship between canopy cover and aboveground C pools presents an alternative to directly measuring C stocks, but this relationship needs to be verified elsewhere in the Arctic before using it in lieu of field data collection. Furthermore, caution should be exercised when using environmental correlates as alternatives to directly measuring C pools because error is associated with both the field measurements and modeling.

5.2. **Limitations and Uncertainty**

A few methodological improvements would help with the precision of our estimates. When harvesting moss and lichen biomass at each site, inconsistent subsample collections were made between the collectors, and percent cover was often not re-estimated after removal of the shrubs. While removing the upper 10% of dry weight values mitigated the error, some uncertainty was still perpetuated in the final calculations using percent cover. This uncertainty skews the aboveground estimates. Furthermore, as lichen accounted for 3% of the understory C pools, and moss accounted for 52%, uncertainty in these two functional groups is of large consequence. In the future, it is recommended to collect the entire extent of moss and lichen in the quadrat.

Another source of uncertainty involves the calculations of mineral soil C pools. In this work, five soil cores were excluded from the mineral soils dataset. These soil cores had the five shallowest depths of the mineral cores, and were excluded due to disproportionate (high) LOI values compared to their bulk density. The potential for uncertainty was greater
for these shallow-depth cores, and the exploratory results revealed this probable error in the LOI vs. bulk density plot. Future recommendations for the collection of mineral soils include extracting the soil in a block, and measuring the width, length, and depth of the sample. This adheres to the terrestrial protocol procedure for collecting the O horizon. Additional mineral soil C pool calculations used to explore mineral soil relationships can be found in Appendix 12.

Soil C pool calculations relied on the underlying assumptions that the entire O layer was extracted and that mineral soil cores were taken to a depth of 10 cm. As 18.5% (20 out of 108) of the O layer cores in our research did not have an associated mineral core, the entire O layer may not have been extracted prior to hitting the frozen ground. If this were the case, then potentially imprecise O layer C pools may have contributed to the difference in O horizon C pools among sites. Furthermore, an examination of multiple sites with variable mineral depths suggests that a trend does not exist relating C density to depth, which prohibits the estimation of C density at deeper depths. In our data, an evident trend relating bulk density to depth is lacking, which may be due to the core pushing down on the soils in some sites and not in others.

Thaw depth measurements were another potential source of uncertainty. For this research, thaw depths in 2013 were taken over a three week period starting on July 9th and ending on August 3rd. The two sites visited in 2012 were taken on July 11th and 12th. In addition to these measurements potentially being a few weeks shy of the maximum depth attainable, thaw depths also vary temporally. Future endeavors should try to minimize the time between thaw depth measurements.
5.3. **Future Work**

This research has shown that C in the surface O horizon and underlying mineral soil layer to a depth of 10 cm or to the bottom of the active layer, whichever was less, were, together, approximately four times that of the aboveground C pools. Two environmental correlates, slope and canopy cover, were able to characterize aboveground variation across the watershed. No associations were evident between belowground C pools and environmental correlates. Broadly, future studies can expand on this work by assessing the relationship between C pools and environmental correlates outside of the Y4 catchment. More narrowly, additional research can focus on:

1. One site was excluded from this analysis as it was located in a riparian area with plentiful understory vegetation. Calculations for this site were obtained using allometric relationships for terrestrial upland shrubs, which may over predict shrub biomass in riparian areas. Shrub biomass calculations from the excluded site were 22,693 g C m\(^{-2}\), which is approximately 46 times larger than the largest shrub estimate in any of the other sites (Appendix 13). This indicates that we are severely underestimating shrub biomass in riparian areas. As shrubs are expanding to areas that are nutrient-rich [Tape et al., 2006] and accumulate moisture [Zyryanova et al., 2010b], the disparity between the understory biomass estimates in riparian and upland sites should be addressed. In doing so, above- and belowground biomass in the Y4 catchment will be more accurately quantified. This should be done using a modified version of the terrestrial protocol.
2. Mineral C pools to a depth of 10 cm in the yedoma-dominated soils in northeastern Siberia do not sufficiently represent the C stored in the soil. As belowground C pools are severely underestimated due to shallow mineral soil sampling depths, future endeavors should focus on extracting deeper mineral soil cores. At the minimum, the depth of these cores should extend to the bottom of the active layer, but many comparable soil C estimates extract soil to a depth of 1 m.

5.4. Conclusions

With the strongest climate warming predicted in the high-latitudes, understanding arctic carbon (C) cycling and the feedback of terrestrial C pools is increasingly important. In order to predict arctic C-cycling dynamics, we first need a more precise quantification of the current terrestrial C storage. As the C in biomass, soils, and permafrost in high-latitude ecosystems has considerable error associated with estimates, refining these estimates is important. In this work, above- and belowground C analyses were performed to contribute to a more precise estimate of arctic C pools. Our results for above- and belowground C pools were similar to those previously reported in larch-dominated ecosystems, but a high degree of variability existed in C pools. The high variability among sites will make it more difficult to accurately quantify above- and belowground pools at both a catchment and global scale.

Additionally, in this research, associations between environmental correlates and C pools were assessed as an alternative to directly measuring C stocks. Of the four environmental correlates examined, none were significantly related to belowground C pools.
We found that canopy cover had the most robust association with aboveground C pools. The relationship between aboveground C pools and canopy cover presents an alternative to directly measuring C stocks if validated elsewhere in the Arctic, while the absence of a relationship with belowground C pools emphasizes the complexity of terrestrial C dynamics.
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6. APPENDICES

A.1. 2013 Polaris Terrestrial Protocol

Polaris Project Terrestrial Survey: 2013 Sample Collection Protocol

1. Introduction and Rationale
This document outlines the protocol for collecting vegetation and soil data as part of the Polaris Project Terrestrial Survey. In the interest of producing a consistent long-term data set, this protocol should be followed precisely. New samples or analyses may be added, but the basic sampling and sample processing procedures described here should not be modified unless absolutely necessary.

The objective of the Terrestrial Survey is to measure carbon stocks in vegetation and soils from boreal and tundra ecosystems in the Kolyma watershed. At some point in the future we will measure carbon fluxes, but our knowledge of the mean and especially the variation of terrestrial carbon is insufficient for understanding the transport and transformation of carbon in the Kolyma watershed. Recall that these are the primary objectives of the Polaris Project. Data collected as part of this protocol will eventually be tied into satellite imagery that covers a much wider footprint than we will be able to directly measure. This will allow spatial extrapolation across parts of the watershed. In future work, we also will link the terrestrial stocks of carbon (and nutrients) to the biogeochemical processes we measure in lakes, streams, and rivers through an integrative modeling effort.

2. Safety
Remember that we are working in one of the most remote corners of the largest country on earth and that if you get hurt it is a long way to quality medical assistance. Please be careful and pay attention to your surroundings. Brown bears are uncommon in the region, but have previously been encountered while conducting the terrestrial survey. Be alert for bears and always carry appropriate safety equipment. Please adhere to the Polaris Project’s safety procedures at all time.

3. Classification Scheme
To separate terrestrial carbon into pools we need to establish a simple classification scheme for the various ecosystem components we are measuring. These pools and divisions aim to maximize ecological differences while still being tractable.
A. Overstory
Dahurian Larch (a.k.a. Cajander larch; *Larix cajanderi*) is the only tree species we will encounter. Note that European botanists tend to classify this species as subspecies (*cajanderi*) of *Larix gmellinii* while Russian botanists use *Larix cajanderi* as the standard name. There is a species of pine (Dwarf Siberian pine, *Pinus pumila*) that grows in a shrubby form at some locations (e.g., outside of the station), but we’ll count it as a shrub. We will differentiate three classes of larch trees based on a forestry standard known as the diameter at breast height (DBH). Breast height is defined as 1.4 m above the ground on the up-hill side of the tree (1.37 m was an old standard in forestry. Now it is 1.4 m). Trees are stems having >5 cm DBH. Saplings are taller than breast height but less than 5 cm DBH. Seedlings are trees shorter than breast height. Note that this means saplings might be 50 years old or more in this cold environment but that these definitions work well from a carbon accounting perspective.

B. Understory
Understory species will be grouped into these three classes:
1) Shrubs: Multi-stemmed woody plants. These could range in height from a few centimeters to several meters. Shrubs can be either deciduous or evergreen.
   a. The three dominant genera of deciduous shrubs are willow (*Salix*), alder (*Alnus*), and birch (*Betula*).
   b. Dominant evergreen shrubs include Labrador tea (*Ledum*) and bog cranberry (*Vaccinium vitis-idaea*).

Note: When we estimate percent cover in a plot (Section 6A) we lump deciduous or evergreen together. When we measure the mass of the understory (6B), we separate deciduous and evergreen shrubs.

2) Herbs: Non-woody plants. These include graminoids (sedges/grasses) and forbs (e.g., cloudberry, wildflowers).

3) Moss: Mosses are non-vascular plants.

4) Lichens: Lichens are a symbiotic association between fungi and algae. Along with mosses, these often make up a mat covering the forest floor.

5) Other: This includes bare ground and woody debris (Section 5A).

There are many more levels we could differentiate but these classes serve our purpose of getting a good measure of the different carbon pools without going into species identification. Make note of anything that deviates meaningfully from the categories above (e.g., a patch of mushrooms).
C. Belowground
The active layer is the soil region above the permafrost that thaws and freezes annually. We measure the depth of the thawed portion of the active layer (thaw depth) and its carbon content. Note that actual depth of the active layer can only be known when it is at its maximum thaw in late summer.

4. Plot Set-Up
We will establish three 20-m-long plots at each site. Having multiple plots within a site will allow us to account for intra-site variability and make statistically robust comparisons among sites. The number of stands we are able to sample during the field season will vary depending upon logistical constraints. The size of the terrestrial survey team should range from 3-5 people.

A. Information to Include in Field Books
- Date (mm/dd/yy) and start time (four numbers in 24-hr format)
- Long name of sampling site
- Short name of sampling site (a three letter code - see below)
- GPS coordinates (Lat/Long in decimal degrees using the WGS 84 datum) at both ends of the 20 m plots (i.e., 0 and 20 meters)
- Names of people on sampling crew
- Weather conditions – approximate air temperature, wind, clouds
- A site description including an overview of the flora and other conditions that may affect the data
- Finally, take a photo at the center of plot two looking north. The photo should be of one team member holding the whiteboard with the site name and date clearly visible

Make note of any deviations from the protocol, unusual features, etc. It is essential that the appropriate information be clearly recorded. Data will be entered into a computer spreadsheet daily and/or digital photos of each datasheet will be collected. Once entered into the computer, data should be backed up.

B. Sample Labeling Scheme
All Terrestrial Survey samples will be labeled according to the following scheme: T-Site-Plot-Location-Date. ‘T’ designates the samples as part of the terrestrial survey. Plot will be designated as 1, 2, or 3 (see next section). Location refers to the location along the plot (e.g., 5m). Date will be designated by a six-letter code (mmddyy). For example, a soil sample collected behind the Northeast Science Station at the start (0 meters from edge) of plot 1 on July 23, 2013 might be labeled: ‘T-NSS-1-0m-072313’. Different types of samples may have additional labels.
C. Plot Establishment
We will set up three plots at each site (Figure 1). Plots will be 20-m long and 1 to 4 m wide, depending on stand density. Each plot will be centered around a 20-m transect line run down the center of the length of the plot. Plots will run parallel to slope contours and to one another and will be separated by a distance of at least 10 m. Plot 1 for each site will be the plot furthest to the left (and uphill if on a slope) when standing at the 0-m end of the plot (Figure 1). If there is no obvious slope, then run plots along a N-S transect, and name the plot to the W as Plot 1.

5. Forest Measurements
We will measure biomass in trees and the understory, and organic matter content of the active layer. The steps below move from aboveground to belowground measurements. Ask for instruction if you are unfamiliar with any of the tools (e.g., densiometer). The tools we use are simple in the sense that they have few if any moving parts, but data cannot be rescued later if you measure incorrectly in the field. Remember that there are no stupid questions (except “Who is Townes van Zandt?” Get that one right immediately).

A. Tree Diameter Measurements
Within each 20 m long plot, we will measure DBH (diameter at breast height) of all trees tall enough to have a DBH, and basal diameter (BD) of any tree shorter than DBH height. DBH is defined as 1.4 m above the ground on the uphill side of the tree. Measurements will be taken with a DBH tape or caliper to the nearest 0.1 cm. These measurements will form the basis of our above and belowground carbon budgets for these forests using published allometric relationships (Appendix 1). For diameter measurements, sample all trees to the left and right of the transect line within a distance of 0.5 m (1 m total width) if the stand is high density (> 2 trees m⁻²), 1 m (2 m total width) if the stand is moderate density (1-2 trees m⁻²), and 2 m if the stand is low density (< 1 tree m⁻²).
B. Snags
Measure the DBH/BD and estimate the decay stage (See Appendix 2) of all standing dead trees within the 20 m long plots. Note whether the top of the snag is broken off or mostly intact. You can collect snag data while sampling live tree diameters.

C. Forest Canopy Cover
Use a densiometer to record canopy cover (%) at the 10-m point on each transect. At each point, measure and record four densiometer readings facing North, South, East, and West and average.

D. Leaf Area Index
We will use hemispherical canopy photographs as an indirect way of calculating leaf area index (LAI). LAI is a commonly used vegetation structural measurement in biogeosciences and used in carbon balance modeling among other things. LAI is closely associated with the canopy cover estimates you collect with densitometry but a much richer dataset. Use the Hemiview-DC camera to take a photograph at the 10-meter point of each transect at 1-m height on the tripod and another ground level (3x2=6 photographs per site). All photographs should be taken as close to sunrise/sunset as possible under clear sky conditions. This helps to create images that are homogeneous and have shadow-free illumination of the canopy. The goal is to have high contrast between the canopy and the sky in the blue band of the electromagnetic spectrum.

E. Woody Debris
Carbon pools in downed woody debris will be estimated using the line intercept method (Brown 1974). To make these estimates, we will record the number of times woody debris intercepts the transect line in each plot. Woody debris less than 7 cm diameter is classified as fine woody debris (FWD); larger diameter debris is classified as coarse woody debris (CWD). We will record the number of times Class I (0-0.5 cm, diameter) and II (0.5-0.99 cm) FWD intersect the first 2 m of the 20-m transect lines. Class III (1.0 – 2.99 cm) FWD will be tallied along the first 10 m of each subsection, and classes IV (3.0-4.99 cm), V (5.0-6.99 cm), and all CWD will be tallied along the entire 20-m length. Diameter and decay class of CWD will be recorded according to Manies et al. (2005) (Appendix 2). The decay class of FWD will be recorded according to Nalder et al., 1997. Trees will be considered CWD and not snags if they are at an angle < 45° to the forest floor.

6. Understory Vegetation Measurements
We will quantify understory percent cover and biomass at each end of the three 20-m transect lines within each site (Figure 1). Percent cover will be estimated in a 1 m² plot located 1 m
distance away from the 0-m and 20-m ends of the transect. If the plot location lands on a tree taller than breast height, move the plot further away from the transect. Biomass will be estimated in a 0.25 m$^2$ quadrat located within the percent cover plot (Figure 1). All of the samples that should be brought back from a terrestrial survey are listed in Appendix 3.

A. Understory Percent Cover Estimates
Separate each 1 m$^2$ plot into four quadrats. If you are facing the transect, the quadrat to your lower right is quadrat ‘a’, and move counterclockwise to label quadrats ‘b’, ‘c’, and ‘d’. In each quadrat estimate percent cover by functional type to the nearest 5% (in a 1 m$^2$ quadrat the area of your clenched fist is about 1%). For each quadrat, your percentages must add up to 100%. Record thaw depth for each quadrat.

B. Understory Biomass
We have developed allometric equations for Pinus, Alnus, Betula and Salix (Appendix 1). For these three shrubs, use calipers to measure BD of all individuals that occur within the quadrat. In cover quadrat ‘d’, use clippers to remove and sort all the aboveground biomass by functional type. You can clip and remove the Pinus, Alnus, Betula and Salix shrubs from quadrat ‘d’ if necessary. (You do not need to save these shrubs for biomass estimation because we can determine biomass from their BD.) For all other vegetation, clip, sort by functional group and place the vegetation into paper bags (if weather is dry) or ziploc bags (if weather is wet).

Note: If the moss coverage in the plot is higher than about 30%, you can subsample a 5 x 5 cm$^2$ area rather than taking all of the moss. This is to save time in the field and space in the drying ovens in the lab. If you do this, make sure to note the exact size of the area from which you are subsampling. Also re-estimate the % moss after you cut away the larger shrubs. Cut the moss sub-sample from the ground, clip off and save all green moss.

When you are done you should have five bags of biomass: deciduous shrubs, evergreen shrubs, herbs, moss, and lichens. Label each bag with the site ID and the type of material. E.g., ‘T-NSS-1-0m-072313 Herbs.’

7. Soil Sampling
A. Thaw Depth
Using the permafrost probe, measure thaw depth every meter along the center transect of each plot. Take a depth measurement by pressing the probe into the ground until it strikes the frozen surface (rarely deeper than 100 cm in July for most areas around Cherskii). Be careful not to bend or stress the permafrost probe, and do not attach the extensions.
unless you need them. Record thaw depth to the nearest cm. If you land on a tree, move the measurement adjacent to the transect line.

B. Organic Layer Depth
Organic layer depth will be measured at 5-m intervals along each transect by cutting down to frozen ground with a serrated knife and visually identifying and measuring the depth to the organic-mineral boundary. If the soil is frozen above the organic-mineral boundary (i.e., the entire thawed area is organic) note this in your field notes with the letter “F”, along with the depth to frozen ground.

C. Soil Samples
Collect one sample from each end of the transect, for a total of six samples per site. Cut a ‘brownie’ (8 x 8 cm) using a serrated knife. Measure the depth of the organic layer, cut off above-ground vegetation (‘If it’s green it goes’) and place the organic matter brownie in foil and a gallon ziplock bag. Label. Use a soil auger (2-cm diameter) to collect the top 10 cm of mineral soil. Place each core in a plastic whirlpak bag and label. Each sample should be labeled using the site name and plot number and location (0 m or 20 m). E.g., the organic layer might be labeled ‘T-NSS-1-0m-072313 O’. Accurate volume measurements are essential for good bulk density and carbon pool determination.

8. List of Field Gear

Safety:
- Satellite/cell phone
- First-aid kit
- Whistle

Sampling:
- White board and Dry Erase marker
- Sharpies, pencils, field books
- Permafrost probe
- GPS with extra batteries
- Three 30 m transect tapes
- Flags and flagging tape
- Write-On Whirl-Pak bags (7-oz)
- Two DBH tapes
- Calipers
- Compass
- Soil Auger
- Serrated soil knife (2) and folding saw
• Aluminum foil
• Ruler
• 1m² understory quadrat frame
• Paper bags
• Trowel
• Clippers
• Ziplock and garbage bags
• Densiometer
• LAI equipment
• Go-NoGo
• N-S reflector
• Camera
• Tripod
• Ground tripod

9. Appendices

**Larix:** Allometric equations from Alexander et al. (2012) for calculating Larix biomass in the Kolyma River watershed. The equations are in the form of \( y = ax^b \), where \( y \) is the total plant aboveground dry weight (g), \( a \) and \( b \) are fitted coefficients, and \( x \) is the diameter at breast height (cm) for trees taller than breast height (Table 1) and basal diameter (cm) for trees shorter than breast height (Table 2).

<table>
<thead>
<tr>
<th>Table 1. Trees taller than breast height (1.4m)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td></td>
</tr>
<tr>
<td>Stem</td>
<td>81.42</td>
<td>2.10</td>
</tr>
<tr>
<td>Branch</td>
<td>69.66</td>
<td>1.99</td>
</tr>
<tr>
<td>Foliage</td>
<td>40.50</td>
<td>1.41</td>
</tr>
<tr>
<td>Root*</td>
<td>97.00</td>
<td>2.07</td>
</tr>
<tr>
<td>Total</td>
<td>179.20</td>
<td>2.01</td>
</tr>
</tbody>
</table>

* Root data are from Kajimoto et al. (2006) with n=7 while Alexander et al. (2012) include the Kajimoto data and 30 other Larix of more DBH classes.
### Table 2. Trees shorter than breast height (1.4m)

<table>
<thead>
<tr>
<th></th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stem</td>
<td>8.00</td>
<td>2.56</td>
</tr>
<tr>
<td>Branch</td>
<td>22.91</td>
<td>2.13</td>
</tr>
<tr>
<td>Foliage</td>
<td>22.55</td>
<td>1.45</td>
</tr>
<tr>
<td>Total</td>
<td>39.46</td>
<td>2.26</td>
</tr>
</tbody>
</table>

**Shrubs:** Allometric equations for calculating total aboveground biomass for four genera of large shrubs that occur in the Kolyma River watershed (Berner, unpublished). The equations are in the form of $y = ax^b$, where $y$ is the total plant aboveground dry weight (g), $a$ and $b$ are fitted coefficients, and $x$ is the basal diameter (cm).

<table>
<thead>
<tr>
<th>Genus</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alnus</td>
<td>24.02</td>
<td>2.67</td>
</tr>
<tr>
<td>Betula</td>
<td>23.51</td>
<td>3.21</td>
</tr>
<tr>
<td>Pine</td>
<td>70.85</td>
<td>1.90</td>
</tr>
<tr>
<td>Salix</td>
<td>5.26</td>
<td>3.87</td>
</tr>
</tbody>
</table>
### Appendix 2: Decay classes for Snags and Coarse Woody Debris

**Snags:** Physical characteristics by deterioration stage (adapted from Table 2.3 in Maser et al. 1988)

<table>
<thead>
<tr>
<th>Decay Class</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Limb &amp; branches</strong></td>
<td>All present</td>
<td>Few limbs, no fine branches</td>
<td>Only limb stubs</td>
<td>Few or no stubs</td>
<td>None</td>
</tr>
<tr>
<td><strong>Top</strong></td>
<td>Pointed</td>
<td>Broken</td>
<td>Broken</td>
<td>Broken</td>
<td>Broken</td>
</tr>
<tr>
<td><strong>Bark remaining (%)</strong></td>
<td>100</td>
<td>Varies</td>
<td>Varies</td>
<td>Varies</td>
<td>&lt;20</td>
</tr>
<tr>
<td><strong>Sapwood presence</strong></td>
<td>Intact</td>
<td>Sloughs</td>
<td>Sloughs</td>
<td>Sloughs</td>
<td>Gone</td>
</tr>
<tr>
<td><strong>Sapwood condition</strong></td>
<td>Sound, incipient decay, hard, original color</td>
<td>Advanced decay, fibrous, firm to soft, light brown</td>
<td>Fibrous, soft, light to reddish brown</td>
<td>Cubical, soft, reddish to dark brown</td>
<td></td>
</tr>
<tr>
<td><strong>Heartwood condition</strong></td>
<td>Sound, hard, original color</td>
<td>Sound at base, incipient decay in outer edge of upper stem, hard, light to reddish brown</td>
<td>Incipient decay at base, advance decay throughout upper stem, fibrous, hard to firm, reddish brown</td>
<td>Advanced decay at base, sloughing from upper stem, fibrous, or cubical soft, dark reddish brown</td>
<td>Sloughing, cubical, soft, dark brown or fibrous, very soft, dark reddish brown, encased in hardened shell</td>
</tr>
</tbody>
</table>

**Coarse Woody Debris:** Physical characteristics by deterioration stage (Manies et al. 2005).

<table>
<thead>
<tr>
<th>CWD Decay Classes</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bark and wood intact, knife able to penetrate samples</td>
</tr>
<tr>
<td>2</td>
<td>Wood beginning to get mealy, still hard for knife to penetrate sample</td>
</tr>
</tbody>
</table>
Appendix 3: Handling and storing samples

Bringing data back to the lab that are vaguely labeled wastes a lot of time. At the end of every survey the following samples should be labeled and stored properly.

These samples should be brought back from every terrestrial survey:

12 Soil Samples Upon returning from the field, the soils should be refrigerated. Example label: ‘T-NSS-1-0m-072313 O’

<table>
<thead>
<tr>
<th>Plot 1</th>
<th>0m Organic</th>
<th>20m Organic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plot 1</td>
<td>0m Mineral</td>
<td>20m Mineral</td>
</tr>
<tr>
<td>Plot 2</td>
<td>0m Organic</td>
<td>20m Organic</td>
</tr>
<tr>
<td>Plot 2</td>
<td>0m Mineral</td>
<td>20m Mineral</td>
</tr>
<tr>
<td>Plot 3</td>
<td>0m Organic</td>
<td>20m Organic</td>
</tr>
<tr>
<td>Plot 3</td>
<td>0m Mineral</td>
<td>20m Mineral</td>
</tr>
</tbody>
</table>

15 Biomass Samples Upon returning from the field the samples should be dried at 60°C. Example label: ‘T-NSS-1-0m-072313 Herbs’

<table>
<thead>
<tr>
<th>Plot 1</th>
<th>Deciduous Shrubs</th>
<th>Evergreen Shrubs</th>
<th>Moss</th>
<th>Lichens</th>
<th>Herbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plot 2</td>
<td>Deciduous Shrubs</td>
<td>Evergreen Shrubs</td>
<td>Moss</td>
<td>Lichens</td>
<td>Herbs</td>
</tr>
<tr>
<td>Plot 3</td>
<td>Deciduous Shrubs</td>
<td>Evergreen Shrubs</td>
<td>Moss</td>
<td>Lichens</td>
<td>Herbs</td>
</tr>
</tbody>
</table>
A.2. Coordinates of 18 sites in the Y4 catchment

Table A-2. Coordinates of 18 sites in the Y4 catchment of the Kolyma watershed near the Northeast Science Station in Cherskiy, Sakha Republic, Russia.

<table>
<thead>
<tr>
<th>Site</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>68.74747</td>
<td>161.38988</td>
</tr>
<tr>
<td>2</td>
<td>68.74529</td>
<td>161.38908</td>
</tr>
<tr>
<td>3</td>
<td>68.74472</td>
<td>161.41486</td>
</tr>
<tr>
<td>4</td>
<td>68.74164</td>
<td>161.41562</td>
</tr>
<tr>
<td>5</td>
<td>68.74834</td>
<td>161.41350</td>
</tr>
<tr>
<td>6</td>
<td>68.74939</td>
<td>161.41759</td>
</tr>
<tr>
<td>7</td>
<td>68.74915</td>
<td>161.39000</td>
</tr>
<tr>
<td>8</td>
<td>68.74932</td>
<td>161.38820</td>
</tr>
<tr>
<td>9</td>
<td>68.75267</td>
<td>161.38544</td>
</tr>
<tr>
<td>10</td>
<td>68.75352</td>
<td>161.39455</td>
</tr>
<tr>
<td>11</td>
<td>68.74869</td>
<td>161.40834</td>
</tr>
<tr>
<td>12</td>
<td>68.74837</td>
<td>161.40237</td>
</tr>
<tr>
<td>13</td>
<td>68.74660</td>
<td>161.40433</td>
</tr>
<tr>
<td>14</td>
<td>68.74513</td>
<td>161.40063</td>
</tr>
<tr>
<td>15</td>
<td>68.75188</td>
<td>161.39095</td>
</tr>
<tr>
<td>16</td>
<td>68.75519</td>
<td>161.40013</td>
</tr>
<tr>
<td>17</td>
<td>68.74632</td>
<td>161.38776</td>
</tr>
<tr>
<td>18</td>
<td>68.74479</td>
<td>161.38410</td>
</tr>
</tbody>
</table>
A.3. 2013 Understory Biomass Laboratory Protocol and Calculations

Understory Biomass Laboratory Protocol

I. Summary
This document outlines the laboratory protocol for understory biomass collected as part of the terrestrial survey.

II. Protocol
1. Dry samples for 24 - 48 hours in the sauna. The use of the sauna lessens the demand for the drying oven.
2. After samples have been in the sauna, dry samples for 48 hours at 60°C in the drying oven.
3. Weigh dried samples. Be sure to note the weight of the bag. The weight of the paper bag can be calculated by individually weighing 20 bags, and then averaging.
4. Small moss and lichen subsamples often need to be weighed using a weigh boat. Again, be sure to record the weight of the weigh boat.
5. Put all weights in a well organized lab notebook.
6. Record the re-estimated percent cover for moss and lichen.

Understory Biomass Calculations

I. Summary
The moss and lichen values (g dry weight m\(^{-2}\)) have a high magnitude of uncertainty. This uncertainty is derived from imprecise volume measurements for both moss and lichen, and is perpetuated in the calculations using percent cover.

II. Protocol
Due to the high magnitude of uncertainty in the moss and lichen biomass values, the upper 10% of the dry weight m\(^{-2}\) values for both moss and lichen shall be excluded. After the removal of the upper 10% of the values, the median of the lower 90% of the moss and lichen values will be calculated (g dry weight m\(^{-2}\)). The median values will be used to avoid the influence of outliers, and are calculated prior to an adjustment using % cover. The calculated medians will be multiplied by percent cover to obtain the corrected g dry weight m\(^{-2}\) value, and multiplied by .48 to obtain the mass in g C m\(^{-2}\).
A.4. 2013 Polaris Soil Lab Protocol

Polaris Project Terrestrial Survey: Soil Moisture and Loss on Ignition Protocol

I. Summary
This document outlines the protocol for measuring soil moisture and organic matter content for soils collected as part of the terrestrial survey. We want to know the soil moisture content so as to relate soil characteristics (e.g., acidity, cation exchange capacity, etc.) to the soil dry weight. Likewise, we wish to know the organic matter content which we will determine by measuring the weight before and after burning the sample. This “loss-on-ignition” (LOI) occurs when organic carbon oxidizes to CO₂.

The overarching principle is that the soil sample is dried in an oven at 60°C and the moisture content estimated as the weight loss. Thereafter, the samples are burnt at 450°C and the organic matter estimated as the weight loss as LOI. This protocol is modified from Reeuwijk (2002).

II. Protocol
Organic layer:
1. All containers (white weigh boat, large crucibles, plastic container) should be weighed and labeled before placing any soil in them.
2. Place the organic layer in a plastic container.
3. Confirm that the top of the organic layer has been trimmed for excess aboveground vegetation. If not trimmed, trim it.
5. Take out coarse-roots and rinse to remove any dirt.
6. Place coarse-roots in white weigh boat and record the weight of the roots.
7. Place 10g of organic layer in large crucible.
8. Weigh crucible + organic layer.
9. Put organic layer in white weigh boat. The organic layer should fill the dish.
10. Weigh organic layer + dish.
11. Place remaining organic layer in clear bag and label.
13. Dry samples for 48 hours at 60°C.

Mineral layer:
1. All containers (blue weigh boat and small crucibles) should be weighed and labeled before placing any soil in them.
2. Plastic bag weight will be determined by the average of 20 bag weights.
3. Weigh bag + mineral sample.
4. Place 10 g of mineral sample in small crucible.
5. Put remaining mineral layer in blue weigh boat and weigh.
6. Place crucible and blue weigh boat into drying oven.

**Muffle furnace:**
1. Weigh each sample.
2. Set the muffle furnace temperature to 450°C. Leave four porcelain crucibles in it for 8 hours. The furnace is extremely hot. **Use tongs to handle anything heated to this temperature.**
3. Use tongs and remove crucibles from furnace and allow them to cool in the glass desiccator.
4. Weigh each crucible using the balance. (\(A\) gram)
5. Transfer 5 to 10 g fine soil (sieve at 2 mm) into the crucibles and re-weigh the crucible. The difference yields the water content. (\(B\) gram)
6. Place crucible with sample in the oven at 105°C until dry (overnight).
7. Remove crucibles from oven, cool in the desiccator, and weigh. (\(C\) gram)
8. Place the crucibles in a muffle furnace at 450°C and leave the crucibles in for six hours (1 hour to warm up, 4 hours at 450°C, 1 hour to cool down with door closed).
9. Remove crucibles from furnace and allow to cool in the desiccator and re-weigh. (\(D\) gram) The difference from the dry state yields the organic content.

**II. Calculations**

- Soil moisture percent [SM%] = \(\frac{(B-C)}{(C-A)} \times 100\) [wt%]
- Moisture correction factor [mcf] = \(\frac{(100 + SM\%)}{100}\) [unitless]
- Loss on ignition percent [LOI%] = \(\frac{(C-D)}{(C-A)} \times 100\) [% of DW]

Where:
A = weight of porcelain crucible
B = weight of porcelain crucible + fresh soil sample
C = weight of porcelain crucible + sample after drying at 105°C
D = weight of porcelain crucible + sample after burning at 450°C

The moisture correction factor (mcf) is used as a multiplication factor to convert parameters measured on fresh or air-dried samples to a dry weight basis.
A.5. Additional Canopy Cover Details

Three methods were used to assess canopy cover: spherical densiometry, hemispherical photography, and the LAI-2000. The spherical densiometer measures wide sky angles and is often preferred as it is an inexpensive, simple instrument that works reasonably well for evaluating canopy change over time [Englund et al., 1999]. More versatile alternatives to the densiometer are hemispherical photography and the LAI-2000. While both methods measure radiation transmittance using inversion models [Chen et al., 1997], the technique differs. The LAI-2000 measures transmitted blue sky light and calculates the gap fraction for five zenith angle ranges [Chen et al., 1997] whereas hemispherical photography utilizes wide-angle upward-looking photographs of plant canopies [Rich et al., 1998]. The LAI-2000 is described as a convenient version of hemispherical photography as image-processing is not required [Chen et al., 1997]; however, unlike the LAI-2000, hemispherical photographs provide permanent digital images of canopy elements and allows for manipulation of the threshold values [Chen et al., 1997]. Forest canopy cover is assessed using all aforesaid methods, and in turn, information about terrestrial C pools is obtained.
A.6. **Slope, Aspect, and Solar Insolation in the Y4 Catchment**

Table A-6. Slope, aspect, and solar insolation (summer solstice and equinox) in the Y4 catchment. Solar insolation was calculated using the Solar Radiation analyses toolset in ArcGIS version 10. The toolset used variability in the orientation (slope and aspect) to calculate direct and diffuse radiation for each pixel of the elevation model in the Y4 catchment using viewshed algorithms.

<table>
<thead>
<tr>
<th>Site</th>
<th>Slope</th>
<th>Aspect</th>
<th>Summer Solstice Solar Insolation</th>
<th>Equinox Solar Insolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.5</td>
<td>144.1</td>
<td>4483.6</td>
<td>677.2</td>
</tr>
<tr>
<td>2</td>
<td>9.2</td>
<td>79.8</td>
<td>3970.6</td>
<td>456.8</td>
</tr>
<tr>
<td>3</td>
<td>10.6</td>
<td>237.3</td>
<td>4447.6</td>
<td>683.3</td>
</tr>
<tr>
<td>4</td>
<td>9.9</td>
<td>248.3</td>
<td>4365.5</td>
<td>645.0</td>
</tr>
<tr>
<td>5</td>
<td>13.6</td>
<td>82.4</td>
<td>3795.6</td>
<td>398.2</td>
</tr>
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<td>16.0</td>
<td>268.3</td>
<td>4188.3</td>
<td>595.5</td>
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<td>4183.5</td>
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<td>8</td>
<td>6.4</td>
<td>40.7</td>
<td>4148.4</td>
<td>530.2</td>
</tr>
<tr>
<td>9</td>
<td>4.3</td>
<td>231.1</td>
<td>4198.5</td>
<td>546.7</td>
</tr>
<tr>
<td>10</td>
<td>14.6</td>
<td>74.5</td>
<td>4094.6</td>
<td>540.4</td>
</tr>
<tr>
<td>11</td>
<td>13.5</td>
<td>226.4</td>
<td>4542.6</td>
<td>737.4</td>
</tr>
<tr>
<td>12</td>
<td>11.1</td>
<td>59.0</td>
<td>4055.0</td>
<td>505.2</td>
</tr>
<tr>
<td>13</td>
<td>12.4</td>
<td>53.4</td>
<td>3960.7</td>
<td>459.3</td>
</tr>
<tr>
<td>14</td>
<td>1.5</td>
<td>134.3</td>
<td>4380.9</td>
<td>624.4</td>
</tr>
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<td>15</td>
<td>3.8</td>
<td>158.9</td>
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<td>647.1</td>
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<td>6.2</td>
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<td>540.6</td>
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<tr>
<td>18</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
A.7. **Carbon Pool Values and their Associated Standard Errors**

Table A-7. C pool values in g C m\(^{-2}\) for aboveground biomass, the O horizon, mineral soil, and normalized soils (10 cm). Among-site standard error values are associated with each C pool. Standard error values for soil C pools were calculated using the total number of soil cores per site while aboveground C pools were calculated using three transect means per site.

<table>
<thead>
<tr>
<th>Site</th>
<th>O horizon</th>
<th>SE</th>
<th>Mineral Soil</th>
<th>SE</th>
<th>Aboveground Biomass</th>
<th>SE</th>
<th>Normalized Soil (10cm)</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1924.5</td>
<td>96.3</td>
<td>1957.5</td>
<td>324.8</td>
<td>895.3</td>
<td>352.7</td>
<td>2408.9</td>
<td>275.7</td>
</tr>
<tr>
<td>2</td>
<td>1559.9</td>
<td>185.8</td>
<td>1396.2</td>
<td>253.0</td>
<td>1049.8</td>
<td>113.1</td>
<td>1376.2</td>
<td>247.5</td>
</tr>
<tr>
<td>3</td>
<td>1964.8</td>
<td>302.2</td>
<td>1368.2</td>
<td>189.2</td>
<td>1452.8</td>
<td>319.5</td>
<td>1884.7</td>
<td>313.4</td>
</tr>
<tr>
<td>4</td>
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<td>164.7</td>
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<td>5</td>
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<td>467.4</td>
<td>1487.6</td>
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<td>2151.9</td>
<td>506.7</td>
<td>3764.9</td>
<td>432.4</td>
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<td>6</td>
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<td>875.9</td>
<td>2131.9</td>
<td>404.5</td>
<td>2569.0</td>
<td>375.8</td>
<td>3834.9</td>
<td>875.7</td>
</tr>
<tr>
<td>7</td>
<td>1228.0</td>
<td>154.8</td>
<td>2216.2</td>
<td>341.3</td>
<td>936.3</td>
<td>73.7</td>
<td>1156.0</td>
<td>192.9</td>
</tr>
<tr>
<td>8</td>
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<td>2148.8</td>
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<td>518.0</td>
<td>1786.2</td>
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<td>4705.9</td>
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<td>391.7</td>
<td>2231.7</td>
<td>432.2</td>
<td>1128.6</td>
<td>273.3</td>
<td>2268.5</td>
<td>391.1</td>
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</table>
A.8. **Histogram of Above- and Belowground C Pools**

Figure A-8. Aboveground C pools consisted of woody debris, tree, snag, and understory C values. N=3 (per site). Belowground C pools consisted of soil and coarse-roots. Belowground C pools were calculated by normalizing to a depth of 10 cm from the surface of the O horizon, as well as assessing the O horizon and mineral soils to a depth of 10 cm independently. Belowground C pools were calculated using the total number of soil cores per site (6 soil cores per site were extracted in 14 of the 18 sites).
A.9. **Leaf Area Index and Percent Cover**

Table A-9. Leaf area index values derived using hemispherical photography and the LAI-2000. A clumping factor of .68 was used to compensate for the nonrandom distribution of foliage. Canopy density was estimated using the spherical densiometer.

<table>
<thead>
<tr>
<th>Site</th>
<th>Densiometry</th>
<th>Hemispherical Photography</th>
<th>LAI-2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16.38</td>
<td>0.03</td>
<td>0.13</td>
</tr>
<tr>
<td>2</td>
<td>21.58</td>
<td>0.26</td>
<td>0.13</td>
</tr>
<tr>
<td>3</td>
<td>28.60</td>
<td>0.47</td>
<td>0.68</td>
</tr>
<tr>
<td>4</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>5</td>
<td>29.12</td>
<td>0.39</td>
<td>1.35</td>
</tr>
<tr>
<td>6</td>
<td>21.06</td>
<td>0.35</td>
<td>0.47</td>
</tr>
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<td>7</td>
<td>19.24</td>
<td>0.14</td>
<td>0.00</td>
</tr>
<tr>
<td>8</td>
<td>10.14</td>
<td>0.02</td>
<td>0.29</td>
</tr>
<tr>
<td>9</td>
<td>9.62</td>
<td>0.07</td>
<td>0.00</td>
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<tr>
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<td>26.78</td>
<td>0.42</td>
<td>1.41</td>
</tr>
<tr>
<td>11</td>
<td>7.28</td>
<td>0.11</td>
<td>0.22</td>
</tr>
<tr>
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<td>0.00</td>
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<tr>
<td>15</td>
<td>1.82</td>
<td>0.03</td>
<td>0.00</td>
</tr>
<tr>
<td>16</td>
<td>27.56</td>
<td>0.40</td>
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<td>5.20</td>
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<td>NA</td>
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<tr>
<td>18</td>
<td>13.10</td>
<td>0.24</td>
<td>2.03</td>
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</table>
A.10. Relationship between LAI and Canopy Density

Figure A-10. Comparison of canopy density with leaf area index derived from hemispherical photography (A) and LAI-2000 (B). When using the LAI-2000, the outlier in site 18 was excluded.
A.11. C:N Content Ratio Of The Dominant Vegetation

I. Summary
Carbon and Nitrogen ratios (C:N) were measured in the dominant vegetation of the Y4 catchment. The functional types included: herbs, evergreen shrubs, deciduous shrubs, moss, and lichen. The evergreen and deciduous shrubs were differentiated into the leaves and stem. Coarse-roots (> 2mm) were also analyzed.

II. Protocol
1. Vegetation and coarse-roots were collected in three 1 m² quadrats in each site.
2. In the laboratory, the vegetation and coarse-roots were dried.
3. The coarse roots from 12 sites were pooled.
4. The vegetation (per functional type) from 3 sites was pooled.
5. A well-mixed 2 (+) g sample was selected from each of the pools.
6. All samples were ground in preparation for analysis.
7. Three subsamples for each functional type were used in the analysis.

Nitrogen and carbon content were analyzed using a FlashEA 1112 nitrogen and carbon analyzer (Thermo Electron Corp.). Quality control was tested at the beginning of the analysis using soil, fine woody debris, and apple leaf standards. Variable sample amounts for the standards were used to fall within an appropriate range for the carbon and nitrogen calibration curve. After every 8 samples, the quality control apple leaf standard was tested. Approximately 20 mg of each dried sample was placed in a tin capsule prior to analysis.

III. Results
Mean carbon and nitrogen values (%) for each functional type are provided below. The affiliated standard deviation values are shown. The soil standard was tested against the nitrogen and carbon values of 0.351 and 8.15, respectively. The apple leaf standard was tested against the nitrogen value of 2.25.

<table>
<thead>
<tr>
<th>Type</th>
<th>Nitrogen</th>
<th>Standard Dev.</th>
<th>Carbon</th>
<th>Standard Dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple Leaf Standard</td>
<td>2.41</td>
<td>0.11</td>
<td>50.76</td>
<td>3.43</td>
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<tr>
<td>LTEP Sisk Soil Standard</td>
<td>0.38</td>
<td>0.05</td>
<td>7.83</td>
<td>0.54</td>
</tr>
<tr>
<td>LTEP Sisk FWD Standard</td>
<td>0.24</td>
<td>0.04</td>
<td>50.20</td>
<td>0.18</td>
</tr>
<tr>
<td>Coarse-roots</td>
<td>0.66</td>
<td>0.03</td>
<td>52.96</td>
<td>0.35</td>
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<tr>
<td>Deciduous Leaves</td>
<td>1.81</td>
<td>0.07</td>
<td>50.44</td>
<td>0.34</td>
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<td>Deciduous Stem</td>
<td>0.60</td>
<td>0.02</td>
<td>51.32</td>
<td>0.33</td>
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<tr>
<td>Evergreen Leaves</td>
<td>0.98</td>
<td>0.02</td>
<td>52.35</td>
<td>0.35</td>
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<tr>
<td>Evergreen Stem</td>
<td>0.55</td>
<td>0.01</td>
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<td>Herb</td>
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<td>0.05</td>
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<td>Lichen</td>
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<td>0.14</td>
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<td>Moss</td>
<td>0.96</td>
<td>0.07</td>
<td>48.31</td>
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</table>
A.12. Alternative Mineral Soil Calculations

I. Summary
In addition to normalizing mineral soil C pools to a depth of 10 cm, two other methods were used to explore mineral soil relationships.

II. Protocol
The first alternative method was to calculate mineral soils to the depth measured.

Secondly, mineral soils were calculated to a depth of 10 cm or a sampling depth less than 10 cm. If the soil depth measured was greater than 10 cm, soil C pools were normalized to a depth of 10 cm, whereas if the core was shallower, the calculations were performed on the depth measured. When using this method, specific assumptions were adhered to. This method assumes that the carbon density is uniform throughout the entire sample; however, C density is generally higher in the surface soils and decreases as you continue down [Homann, 2012, in press]. Furthermore, these calculations rely on the assumption that when the cores were taken, the soil was compacted and ended up in the soil corer, rather than being pushed down by the core.

III. Conclusions
As neither of the alternative mineral soil calculations provided unique insight into mineral soil relationships between depth, bulk density, and C content, mineral soils were normalized to 10 cm for this research.
A.13. **Understory Biomass in the Riparian Site**

![Stacked bar graph displaying C allocation in each site. The five categories of C stocks are belowground, woody debris, tree, snag, and understory biomass. Belowground C was calculated by normalizing to a depth of 10 cm. Site 19 was located in a riparian area.](image)

Figure A-13. Stacked bar graph displaying C allocation in each site. The five categories of C stocks are belowground, woody debris, tree, snag, and understory biomass. Belowground C was calculated by normalizing to a depth of 10 cm. Site 19 was located in a riparian area.