Modeling the effect of active layer deepening on stocks of soil organic carbon in the Pechora River Basin

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Förord

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Abstract

This study investigates how the estimated thickening of the active layer will affect the soil organic carbon in permafrost soils. The focus lies on estimating how much of the upper permafrost soil organic carbon will be affected by the active layer deepening due to global warming, on what timescale the deepening will take place and if the estimated changes differ depending on the extent of permafrost in the region. A model made in a Geographic Information System (GIS) combines datasets from The Northern Circumpolar Soil Carbon Database, field data of soil organic carbon content (SOCC) in different permafrost soil horizons in the Usa basin and data of recent and future active layer depth from a spatially distributed permafrost dynamics model in the Pechora River Basin. The model shows that in 1980, 75% of the available 0–100 cm Gelisol soil organic carbon mass (SOCM) has affected by seasonal thawing. In 2050 the proportion is increased to 86% and by 2090 almost the whole study area has an active layer deeper than 1 meter (98%). This indicates an increase from approximately 0.64% to 0.84% of the total 1–100 cm SOCM in the northern permafrost region. The change is more gradual in the isolated and the sporadic permafrost zones and more abrupt in the continuous and discontinuous regions.
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1 Introduction

The northern circumpolar permafrost region (Figure 1) makes up approximately 16% of the globe’s terrestrial area but may hold more than half of earth’s soil organic carbon (SOC) (Tarnocai et al., 2009). This amount of carbon corresponds to twice the quantity of what the atmosphere holds today (Schuur et al., 2011). Therefore the high latitude terrestrial ecosystems are considered key components in the global carbon cycle (McGuire et al., 2009).

As the active layer (the layer of the permafrost soil that thaws in summer and freezes again coming fall) deepens, more of the organic matter that has accumulated in permafrost soils becomes available for biological decomposition resulting in an increased fluxes of greenhouse gases such as carbon dioxide (CO2) and methane (CH4) to the atmosphere. This could result in a positive feedback...
where emissions accelerate global warming which thaws more permafrost exposing more ancient carbon which decompose and release even more greenhouse gases to the atmosphere (Schuur et al., 2008).

There are several possible feedback mechanism linked to active layer deepening and increasing summer air temperature, such as albedo change caused by fires or changes in vegetation cover, hydrology, photosynthetic rates and a longer growing season. These mechanisms can either have a positive or a negative feedback on global and regional warming which makes climate predictions extremely complex and uncertain (Schuur et al., 2008).

Because thawing permafrost is subject to a time lag, global climate models are unsuitable to model soil thawing and freezing processes. The Geophysical Institute Permafrost Laboratory 2.0 model (GIPL-2) is a spatially distributed permafrost dynamics model (Marchenko et al., 2008), which was used to investigate how the observed and projected changes in air temperature, vegetation, snow accumulation, and soil moistures influence permafrost dynamics in Alaska. The model was driven by a high resolution (4 km) HIRAM5 regional climate model (Stendel et al., 2011) using the output for the 21st century from the global circulation model ECHAM5/MPI-OM where the carbon dioxide concentration is near 700 ppm (average 317 ppm in Mauna Loa, 1960 and 391 ppm in 2011 (NOAA Earth System Research Laboratory 2012)) and the global average warming is 3.5°C. The GIPL-2 simulates the dynamics in the permafrost soil, in the sense of snow depth and density, soil and air temperature and permafrost table / seasonal freezing depth for the time slices: 1980–1999, 2046–2065 and 2080–2099 in the Pechora River Basin in Northeast European Russia (Figure 2).
The Northern Circumpolar Soil Carbon Database (NCSCD) was compiled to address the lack of knowledge on the role of permafrost-affected soils in the global carbon cycle (Hugelius et al., 2012a). The spatial base for the datasets are digitized regional or national soil maps and the SOC was calculated from representative pedons for each type of soil. This has resulted in thousands of polygon shape files, covering the northern circumpolar region, all connected to an attribute table with information about the coverage of different soil types, non-soil areas, calculated soil organic carbon mass (SOCM) and soil organic carbon content (SOCC) for the top soil (0–30 cm and 0–100 cm).

Hugelius et al., (2011) did a study describing detailed partitioning of phytomass carbon and soil organic carbon for four study areas in discontinuous permafrost terrain in the Usa Basin, Northeast European Russia.

Since the intensity of the global warming have been highest towards the poles (Randall et al., 2007) the carbon-climate feedbacks at high latitudes may consequently be the most significant (Schuur et al., 2008), therefore it is important to study how the estimated thickening of the active layer will effect the soil organic carbon in permafrost soils. The aim of this study is to get an indication of how the estimated thickening of the active layer will affect the soil organic carbon in permafrost soils. The focus lies on estimating (1) how much of the upper permafrost soil organic carbon will be affected by active layer deepening due to global warming, (2) on what timescale the deepening will take place and (3) if the estimated changes differ depending on the extent of permafrost in the region. Combining the datasets from NCSCD with the data of the modeled active layer depth and the field data in a Geographic Information System (ArcGIS 10) should give an idea of the amount of carbon, in the Pechora River Basin, that is in the active layer today and give an estimation of how that could change during the 21st century.

2 Background

The extent of permafrost in the northern hemisphere is roughly north to south bound and it is divided into four zones based on the percentage of the landscape that is underlain by permafrost, Continuous and Discontinuous being the most extensive and Sporadic and Isolated the least (Figure 1) (Hugelius et al., 2012a).

In the areas with most extensive permafrost the ground can be frozen down to 650 meters with an active layer stretching from a few centimeters to a couple of
meters. Reaching the Discontinuous Permafrost Zone the frozen ground reaches down to 50 meters and may have an active layer of several meters (Yershov 1998).

The permafrost in the north hemisphere differs in age. In Siberia and Alaska areas unglaciated during the Pleistocene are covered by Yedoma (permafrost affected loess deposits from the Pleistocene) that dates back at least 50 000 years (Schuur et al., 2008). The areas in the southernmost permafrost region that has been most affected by recent warming is thought to have developed during the Little Ice Age (1650–1850 BC) (Jorgenson et al., 2001).

In the permafrost region low temperature is the leading soil-forming factor but the soil parent material, topography and hydrology is essential on a local scale. All these factors that affect the thickness of the active layer vary with different types of soil. In the United States Department of Agriculture’s (USDA) soil taxonomy (Soil Survey Staff, 1999) all permafrost affected soils are classified as Gelisols and are divided into three suborder: Histels, Turbels and Orthels. Histels are organic soils (> 40 cm of peat in the upper 50 cm of soil) affected by permafrost. Turbels are mineral permafrost soils affected by cryoturbation, whereas Orthels are mineral permafrost soils that are not cryoturbated (Soil Survey Staff, 1999).

2.1 ACTIVE LAYER DEEPENING

Active layer deepening can be the result of higher summer air temperature or an increase of infiltration of precipitation, both, with the consequence of a more extensive thaw in summer. Winter temperature and winter precipitation is also a factor that can increase or decrease the active layer. Low winter temperature maintains permafrost but snow depth, density and time of snowfall is significant since it decides the efficiency of the snow cover’s insulation. Moss and organic soil

![Map showing the extent of permafrost in the study area: Continuous, 90–100%; Discontinuous, 50–90%; Sporadic, 10–90%; Isolated Patches, 0–10%. Through the area stretches the treeline. (extent data from Hugelius et al., 2012a and tree line from National Snow & Ice Data Center, 2012)](image)
also insulate underlying permafrost so changes in vegetation cover may therefore have a considerable effect on ground heat fluxes (Zhang et al., 1999).

Active layer deepening and talik formation (a body of unfrozen ground, between the lower and upper part of the frozen soil, a consequence of an active layer so thick the entire ground is not able to freeze again in winter) are relatively slow mechanisms and due to the talik’s high moisture content and, consequently, high heat capacity it can withstand negative changes in the climate that otherwise could have refrozen the layer (Schuur et al., 2008).

Peat formation and sedimentation can bury organic material in the soil and freeze-thaw cycles can redistribute surface material down toward the base of the active layer. In the transition zone between the seasonally frozen and perennially frozen ground the organic material can freeze into the permafrost carbon pool. Here the soil organic carbon lies relatively undisturbed until the active layer thickens (Schuur et al., 2008).

2.2 DECOMPOSITION OF SOIL ORGANIC MATTER

The active layer deepening affects the carbon in the uppermost part of the permafrost. The dominant continuous process that transfers terrestrial organic carbon to inorganic carbon, released to the atmosphere or to be solved in water, is the decomposition of organic material by soil microbes and fungi (Price et al., 2004). Low temperatures decrease the speed of the biological decomposition but even in subzero films of liquid water microbial decomposition of organic carbon occurs but to a much lesser extent (Price et al., 2004). The decomposition and the respiration are limited by water saturation and the temperature sensitivity of the decomposition increases with increasing molecular complexity of the substrate (Grosse et al., 2011). The quality of the substrate and disturbance history can dictate whether the substrate is most vulnerable to combustion, leaching or microbial decomposition if subjected to thawing and sub aerial exposure (Grosse et al., 2011). However some landscapes will be more vulnerable to fires and some to changes in air temperature since the local soil processes and physical and biological systems differ greatly (Grosse et al., 2011).

3 Study area

The study area is located in Northeast European Russia (Figure 1) west of the Ural Mountains (Figure 2) in the Pechora Lowland with the Barents Sea to the north. The lowland rests on quaternary sediments and several glaciations have overlain
the area during Pleistocene, the Barents-Kara ice sheet being the latest (160–140 ka in the southern parts followed by Eemian interglacial and the return of the ice sheet in the northern parts around 90–80 ka and lake Komi in the south) (Svendsen et al., 2004).

The southern part of the area only has isolated permafrost patches but further north the extent of permafrost increases (Figure 3). The tree line, dominated by Siberian Spruce (Picea obovata) and Downy Birch (Betula pubescens) (Hugelius et al., 2011), stretches through the area roughly following the outer border of the sporadic permafrost zone (Figure 3). The vegetation is dominated by shrub tundra, tundra heath, vast peatland complexes and, on permafrost free soils, Spruce forest. (Hugelius et al., 2011)

![Figure 4. Map showing the spatial distribution of Histels, Turbels and Orthels in the study area. The soil type coverage is illustrated with red where the deeper red is the highest percentage. The blue lines are the borders of the permafrost extent zones.]

The different Gelisols are unevenly distributed in the study area (Figure 4). Turbels are the most common type of soils in the region especially in the northern parts with continuous and discontinuous permafrost were almost all the soil is affected by cryoturbation. The Histels (Figure 4) can be found in the lower elevations of the Pechora Lowland (Figure 2). The Orthels are by far the least widespread (Figure 4) but dominate areas around major fluvial deposits (Figure 2).

4 Method

The geographic analyzes were made in the geographic information system ArcGIS 10. The projection used was Lambert Azimuthal Equal Area (LAEA), an equal area projection. To make the datasets more manageable and the analyzes less complex.
the study area was extracted and vector features was converted to raster images with a 100 m resolution and then resampled using bilinear interpolation to 1000 m. An overview of the ArcGIS procedure can be found in the flow chart (Appendix). Some calculations and all diagrams were made in Microsoft Excel 2010

4.1 VERTICAL DISTRIBUTION OF ORGANIC CARBON IN PERMAFROST SOILS

Field data of the organic carbon content in different soil horizons was acquired from Hugelius et al., (2011). In that study, soil sampling transects were chosen to represent the main vegetation types and geomorphology in the area. Soil samples were taken with a vertical resolution of 5–10 cm and dry bulk density and organic carbon content was measured to enable calculation of SOCC. Based on a high-resolution satellite imagery a land cover classification (LCC) was made allowing ecosystem carbon upscaling for a larger area. In this study, the data was used to calculate the average vertical distribution of the soil organic carbon content in the three suborders of Gelisols: 18 Histel sites, 12 Turbel sites and 8 Orthel sites were chosen from the study area.

The soil organic carbon content (SOCC) was calculated in Microsoft Excel 2010 for every site using the formula: \( \text{SOCC} = C \times BD \times T \times (1 - CF) \) where \( C \) is the proportion of organic carbon mass, \( BD \) is the bulk density in g/cm\(^3\), \( T \) is the soil layer thickness and \( CF \) is the proportion of mass that consists of coarse fragments > 2 mm in diameter. To get the vertical distribution of the SOCC in the different soils, the average SOCC in every soil layer were calculated for the Histels, Turbels and Orthels. Traditionally soil organic carbon is presented at the depths 0–30 or 0–100 with the highest proportion of the organic carbon closer to the surface (Hugelius et al. 2011). Therefore, for every site the soil data was vertically subdivided into 2 cm layers from the surface down to 30 cm and from 30 cm down to 100 cm the soil horizons were divided into 5 cm layers.

4.2 PERMAFROST EXTENT, SOIL COVER AND CARBON CONTENT

Spatially distributed vector datasets of permafrost soil coverage and soil organic carbon storage was acquired from The Northern Circumpolar Soil Carbon Database (Hugelius et al., 2012a). The data used was: the total soil organic carbon content (SOCC) for the top meter (kg/m\(^2\)); the coverage of Histels, Turbels and Orthels (%); the extent of permafrost in four categories: continuous, discontinuous, sporadic and isolated.

Following conversion into raster images the raster of the total soil organic carbon content (SOCC) for the top meter, the three images showing the coverage of
Histels, Turbels and Orthels and the field data with SOCC percentage for the 29 depth intervals in Histels, Turbels and Orthels were multiplied resulting in 87 raster images, each showing the amount of SOCC on a specific depth in a specific type of soil. First the corresponding depth intervals in the soil suborders were summarized and then all the upper layers of every depth were summarized resulting in 29 raster showing the amount of Gelisol SOCC from the surface down to: 2; 4; 6; 8; 10; 12; 14; 16; 18; 20; 22; 24; 26; 28; 30; 35; 40; 45; 50; 55; 60; 65; 70; 75; 80; 85; 90; 95; 100 cm.

4.3 RECENT AND FUTURE ACTIVE LAYER AND SEASONAL FREEZING DEPTH

Data of the permafrost table and seasonal freezing depth was acquired from a simulation model from Marchenko et al..

In every time slice (1980–1999, 2046–2065 and 2080–2099) four individual years were chosen: 1980, 1985, 1990, 1995, 2050, 2055, 2060, 2055, 2080, 2085, 2090, 2095 and made into vector points. To get a full coverage of the study area the vector points were converted to Thiessen polygons, which were further transformed into raster data. These 12 raster images were divided into the same depth intervals as the analyzes above resulting in 348 rasters, each showing a specific depth of the active layer at a specific year.

4.4 RECENT AND FUTURE THAWING OF SOIL ORGANIC CARBON

The 29 raster images showing the amount of Gelisol SOCC down to a certain depth were multiplied with the raster were the active layer reached that same depth for the 12 individual years. The SOCC values for each year were then summarized resulting in 12 raster images showing the amount of Gelisol SOCC in 1980, 1985, 1990, 1995, 2050, 2055, 2060, 2055, 2080, 2085, 2090 and 2095.

To calculate the soil organic carbon mass (SOCM) the SOCC was multiplied with the Gelisol area, which in this case is the cell value, multiplied with the cell size (1000 x1000 m).

To find out how much of the soil organic carbon is in the active layer, the Gelisol SOCC raster of each year was divided with the raster of the total Gelisol SOCC. The data was subdivided according to the permafrost zonation and the tables were brought into Microsoft Excel 2010 to calculate the average percentage for each year.
5 Results

5.1 CURRENT VERTICAL DISTRIBUTION OF ORGANIC CARBON IN GELISOLS
All the Gelisols have a rather small proportion of the soil organic carbon content (SOCC) in the upper few centimeters. The Histels has the most even distribution of SOCC (Figure 5). The Turbels has relatively uneven SOCC values down to 80 cm where it levels out, whereas the Orthels has the largest proportion of the carbon content in the upper 30 cm.

![Diagram showing the vertical distribution of carbon in Gelisols. The Histels and Turbels have rather even distribution whereas the Orthels has most carbon near the surface.](image)

5.2 RECENT AND FUTURE THAWING OF SOIL ORGANIC CARBON
The Gelisols in the study area holds 4.23 Pg soil organic carbon mass (SOCM) in the 0–100 cm layer (Table 1). In 1980 a total 3.17 Pg of that carbon was predicted by the model to be in the active layer. In 2050 it was 3.63 Pg and in 2090 it was 4.16 Pg. By then, as good as the whole area is expected to have an active layer deeper than 1 meter (Figure 7). The 1–100 cm Gelisol SOCC is distributed relatively even in the study area, stretching from parts by the eastern border where the SOCC in less than 10 Kg/m2 to the center of the area where the Gelisol SOCC is more than 40 Kg/m2 (Figure 7). The continuous and discontinuous permafrost zones to the northeast are the most stable areas and almost the only
region with shallow (< 1 m) active layer in 2090 (Figure 7). In the southern parts of the area, where the extent of permafrost is not great, the active layer thickness is beyond a meter even in 1980. The region that seems to undergo the greatest change is situated by the sea to the far north (Figure 7).

Table 1. Table showing the study areas total amount of soil organic carbon mass in the 0–100 cm layer that is also in the active layer.

<table>
<thead>
<tr>
<th>YEAR</th>
<th>TOTAL SOCM IN THE ACTIVE LAYER (Pg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>3.17</td>
</tr>
<tr>
<td>1985</td>
<td>2.82</td>
</tr>
<tr>
<td>1990</td>
<td>3.06</td>
</tr>
<tr>
<td>1995</td>
<td>2.80</td>
</tr>
<tr>
<td>2050</td>
<td>3.63</td>
</tr>
<tr>
<td>2055</td>
<td>4.03</td>
</tr>
<tr>
<td>2060</td>
<td>3.78</td>
</tr>
<tr>
<td>2065</td>
<td>3.52</td>
</tr>
<tr>
<td>2080</td>
<td>4.19</td>
</tr>
<tr>
<td>2085</td>
<td>4.22</td>
</tr>
<tr>
<td>2090</td>
<td>4.21</td>
</tr>
<tr>
<td>2095</td>
<td>4.16</td>
</tr>
<tr>
<td>0–100 cm Gelisol SOCM</td>
<td>4.23</td>
</tr>
</tbody>
</table>

The change in proportion of the 0–100 cm layer that is seasonally thawing was different in the four permafrost extent zones (Figure 8). In 1980 the continuous permafrost zone had 70% of the 0–100 cm SOCC in the active layer. With decreasing permafrost extent the amount of carbon that thaws in summer increases. The highest proportion of SOCC in the active layer, with just below 100%, is the isolated permafrost zone that in 1980 already has an active layer that is close to a meter thick or more. The southernmost zones have the deepest active layers but do not thaw as quickly as the continuous and discontinuous permafrost zones. By 2080 almost all the soils in the study area has reached one meter (Figure 8) and since the datasets in NCSCD contains data of SOCC down to one meter this makes up is the limit of this study.

6 Discussion

In this study combining the datasets from NCSCD (Tarnocai et al., in prep.), the field data from Hugelius et al., 2011 and model output from Stendel et al., 2011’s in a geographic information system allowed estimation of (1) how much of the upper permafrost soil organic carbon will be affected by active layer deepening due to global warming, (2) how, and on what timescale, the thickening of the active layer will take place and (3) if the estimated changes differ depending on the extent of permafrost in the region.

In 1980, 3.17 Pg which is 75% of the available Gelisol SOCM (4.23 Pg) in the upper meter was affected by seasonal thawing (Table 1) and, consequently, exposed to biological decomposing. In 2090 it will increase to 4.16 Pg, 98% of the available
Gelisol SOCM (4.23 Pg) in the upper meter will be affected by seasonal thawing (Table 1). This amount is an increase from approximately 0.64% to 0.84% of the estimated total 1–100 cm SOCM in the northern permafrost region (496 Pg (Tarnocai et al., 2009)). The projected changes are more gradual in the isolated and the sporadic permafrost zones and more abrupt in the continuous and discontinuous regions (Figure 8).

Figure 6. Map showing the amount of Gelisol SOCC in the upper meter in the study area and the percentage of seasonally thawed soil organic carbon in recent and future years. The blue lines are the borders of the permafrost extent zones.
6.1 CURRENT VERTICAL DISTRIBUTION OF ORGANIC CARBON IN GELISOLS

The Histels vertical distribution of SOCC is even compared to the Orthels that has the largest proportion of the carbon content in the upper 30 cm. The Turbels SOCC distribution is less even than the Histels and levels out after 80 cm. The Gelisols all have a small proportion of SOCC in the first few centimeters because the surface material in not compressed and therefore have a low bulk density. Most of the Histel’s peat is accumulated in permafrost free fen vegetation (Hugelius et al., 2012b) but following permafrost aggradation Sphagnum is the dominated vegetation that continues to build the peat. After the yearly growth and decomposition of Sphagnum the peat grows approximately 0.5 mm per year (Schuur et al., 2008) and since it is not affected by cryoturbation the Histels were expected to have a relatively even vertical carbon distribution (Figure 5). Because of the cryoturbation, the organic carbon in the Turbels is more unevenly distributed. The effect on the cryoturbation is not shown as distinctly as expected due to the different cryoturbation patterns in different the sampled sites. The organic matter in the Orthels was mainly in the topsoil since it is not cryoturbated and also because the thickness of the active layer sets the plant rooting depth (Schuur et al., 2008). The Orthels have no mechanisms other than deep roots, leaching, or burial to move carbon into the deeper soil layers (Tarnocai et al., 2009).

Well-drained sandy deposits are less affected by peat formation and cryoturbation and are therefore usually found in sandy fluvial deposits. Sediment deposited by rivers contains organic matter. Since the deposition is recurring, these freshly deposited materials are buried by the new deposits and, in most cases, become perennially frozen (Tarnocai et al., 2009). This mechanism could explain the occurrence of carbon deeper in the Orthels.

6.2 RECENT AND FUTURE THAWING OF SOIL ORGANIC CARBON

The region by the sea in the far north undergoes the greatest change (Figure 7) possibly due to the disappearing sea ice and consequently greater influence from the ocean (Matthes et al., 2009). The region to the northeast is the one furthest from the ocean and therefore has the most continental climate. As expected this part of the study area is the most stable and the only region that still has relatively shallow (< 1 m) active layer in 2090.

In the sporadic and isolated permafrost zones (Figure 3) permafrost only covers 10–50% or less than 10% and these are the areas with the deepest active layer in 1980 (Figure 7). These areas could be expected to respond to climate change quickest, however, vegetation and organic matter feedbacks can reduce deep soil
temperatures and help permafrost (ecosystem protected permafrost) to persist even at mean annual air temperatures above zero (Shur et al., 2007) and therefore thaw relatively slowly.

![Diagram showing active layer development](image)

**Figure 7.** Active layer development over time in different permafrost extent zones. The diagram shows the proportion of the Gelsol soil organic carbon content in the 0-100 cm layer that is thawing in summer.

### 6.3 POSSIBLE FEEDBACK SYSTEMS DUE TO ACTIVE LAYER DEEPENING

The results above show that almost all the soil organic carbon content in the top meter will thaw and consequently be available for biological decomposition and perhaps result in an increase of emission of greenhouse gases. However, in a warming climate permafrost ecosystems might also cause a loss of carbon from the atmosphere. With increasing temperature there are likely to be higher photosynthetic rates and a longer growing season. New plant functional groups with larger biomass might take over and consequently result in increased ecosystem carbon storage (Schuur et al., 2008). Other, direct or indirect, positive or negative feedbacks caused by climate forcing and active layer deepening include that the tree line is likely to move further north and fires are predicted to be more frequent with increasing temperature (Schuur et al., 2008). Above the tree line the fires will remove the insulated moss cover and consequently speed up the warming, but south of the tree line fires in coniferous forest will have an early succession of broadleaf deciduous trees whose leafs has higher albedo than the needle leafs in summer and expose more high albedo snow in winter resulting in a reversal of the local warming.
6.4 SOURCE OF ERROR

When using data from huge databases there might be limitation such as The Modifiable Areal Unit Problem (MAUP) (the result in a geographical analyze might be affected by the spatial choices the maker of the map did) and Ecological fallacy (results built on grouped data - one point’s value might be translated to the whole polygon and lead to misleading results) (Hugelius et al., 2012a). The NCSCD, the permafrost dynamics model and the field data comes in varying resolution and are done by people that might have different terminology, definitions and methods. These factors are bound to affect the results. However on a smaller scale the generalizations and upscaling are a lesser fact (Hugelius et al., 2012a) and should not affect the results on significantly.

7 Conclusion

Because of the different dominant pedogenic processes within the Gelisol suborder’s, such as peat formation, cryoturbation and repeated deposition, the vertical distribution of SOCC differs in the Histels, Turbels and Orthels. In 1980, 75% (3.17 Pg) of the available 0–100 cm Gelisol soil organic carbon mass (4.23 Pg) is affected by seasonal thawing. In 2050 the proportion is increased to 86% (3.63 Pg) and by 2090 almost the whole study area has an active layer deeper than 1 meter (98%, (4.16 Pg). The change is more gradual in the isolated and the sporadic permafrost zones and more abrupt in the Continuous and discontinuous regions.

Over the studied time period the region by the sea in the far north undergoes the greatest change due to the disappearing sea ice and consequently greater influence from the ocean. By 2090 almost the whole study area will have an active layer deeper than 1 meter. Only the most stable region farthest from the ocean to the northeast is still has an active layer shallower than 1 meter. This means that, only in the area studied an increase from 0.64% to 0.84% of the northern permafrost region’s total 1–100 cm SOCC will be exposed to decomposition.
Acknowledgements

Thanks to my amazingly positive and patient supervisor Gustaf Hugelius. Thanks to the few remaining class mates, in BioGeo 09, that held out to the end, and finally, thanks to all our teachers who helped us raise a solid foundation of knowledge for us to build on.

References


Modeling the Effect of Active Layer Deepening on Stocks of Soil Organic Carbon

Appendix

[2] Vector data from the Northern Circumpolar Soil Carbon Database

PROJECT: Lambert Azimuthal Equal Area

CLIP: EXTRACT THE STUDY AREA

POLYGON TO RASTER: SOCC 0–100 CM ATTRIBUT TO RASTER

RESAMPLE: FROM 100 M TO 1000 M RESOLUTION

(3) Raster of SOCC at 0–100 CM

POLYGON TO RASTER: Histel, turbel, orthel cover attribute to raster

RESAMPLE: FROM 100 M TO 1000 M RESOLUTION

(4) Raster of the Histel, Turbel, and Orthel Cover in the Study Area

(1) Field data with the vertical distribution of SOCC in Histel, Turbel, and Orthel at twenty-nine depth intervals:

0–2: 2–4; 4–6; 6–8; 8–10; 10–12; 12–14; 14–16; 16–18; 18–20; 20–22; 22–24; 24–26; 26–28; 28–30; 30–35; 35–40; 40–45; 45–50; 50–55; 55–60; 60–65; 65–70; 70–75; 75–80; 80–85; 85–90; 90–95; 95–100 CM

Raster Calculator:

(5) Raster of SOCC in 2 or 5 CM Layers in Histels, Turbels, and Orthels in the Study Area

Raster Calculator:
OVERLAY ANALYSIS: [5, 6, 7] OR [5, 6, 7, 8] FOR EVERY DEPTH INTERVAL

(6) Raster of SOCC in 2 or 5 CM Layers in the Study Area

Raster Calculator:
OVERLAY ANALYSIS: [OVERVIEW] SUMMARIZE EVERY DEPTH INTERVAL FROM THE SURFACE DOWN

(7) Raster of SOCC in the Study Area at: 0–2; 0–4; 0–6; 0–8; 0–10; 0–12; 0–14; 0–16; 0–18; 0–20; 0–22; 0–24; 0–26; 0–28; 0–30; 0–35; 0–40; 0–45; 0–50; 0–55; 0–60; 0–65; 0–70; 0–75; 0–80; 0–85; 0–90; 0–95; 0–100

(8) Table showing the Active Layer and Seasonal Freezing Depth [PT, SFD] in: 1980; 1985; 1990; 1995; 2010; 2015; 2060; 2065; 2080; 2085; 2090; 2095

PROJECT: Lambert Azimuthal Equal Area

Create Feature Class: FROM XY TABLE TO POINTS

CLIP: EXTRACT THE STUDY AREA

Polygon To Raster: PT, SFD attribute to raster

Resample: FROM 100 M TO 1000 M RESOLUTION

(9) Raster of PT, SFD for Every Year

Reclassify: The Active Layer Depth 1980 WITHOUT THE SEASONAL FREEZING DEPTH

Raster Calculator:

(10) Raster of the Area with Permafrost 1980

Raster Calculator:

(11) Raster of the Twelve Year’s PT, SFD for the Area with Permafrost in 1980

Reclassify: PT, SFD at 2 CM Layers at the Depth of 0–30 CM AND 5 CM at 30–100 CM

(12) Raster of OF the Twelve Year’s PT, SFD AT: 0–2: 2–4; 4–6; 6–8; 8–10; 10–12; 12–14; 14–16; 16–18; 18–20; 20–22; 22–24; 24–26; 26–28; 28–30; 30–35; 35–40; 40–45; 45–50; 50–55; 55–60; 60–65; 65–70; 70–75; 75–80; 80–85; 85–90; 90–95; 95–100

Raster Calculator:
Overlay Analysis: [OVERVIEW] (AND)

(13) Raster of SOCC in Active Layer or Seasonal Frozen Ground at the Depth Intervals in: 1980; 1985; 1990; 1995; 2010; 2015; 2060; 2065; 2080; 2085; 2090; 2095