Solid Earth, 5, 595–609, 2014
www.solid-earth.net/5/595/2014/
doi:10.5194/se-5-595-2014

Solid Earth
Open Access

Permafrost-affected soils and their carbon pools with a focus on the Russian Arctic

S. Zubrzycki, L. Kutzbach, and E.-M. Pfeiffer

Institute of Soil Science, Center for Earth System Research and Sustainability, Universität Hamburg, Hamburg, Germany

Correspondence to: S. Zubrzycki (sebastian.zubrzycki@uni-hamburg.de)

Received: 30 January 2014 – Published in Solid Earth Discuss.: 25 February 2014
Revised: 19 May 2014 – Accepted: 26 May 2014 – Published: 1 July 2014

Abstract. Permafrost-affected soils have accumulated enormous pools of organic matter during the Quaternary period. The area occupied by these soils amounts to more than 8.6 million km^2, which is about 27 % of all land areas north of 50° N. Therefore, permafrost-affected soils are considered to be one of the important cryosphere elements within the climate system. Due to the cryopedogenic processes that form these particular soils and the overlying vegetation that is adapted to the arctic climate, organic matter has accumulated to the present extent of up to 1024 Pg (1 Pg = 10^{15} g = 1 Gt) of soil organic carbon stored within the uppermost 3 m of ground. Considering the observed progressive climate change and the projected polar amplification, permafrost-affected soils will undergo fundamental property changes. Higher turnover and mineralisation rates of the organic matter are consequences of these changes, which are expected to result in an increased release of climate-relevant trace gases into the atmosphere. The controversy of whether permafrost regions continue accumulating carbon or already function as a carbon source remains open until today. An increased focus on this subject matter, especially in underrepresented Siberian regions, could contribute to a more robust estimation of the soil organic carbon pool of permafrost regions and at the same time improve the understanding of the carbon sink and source functions of permafrost-affected soils.

1 Introduction

In wide areas of the high latitudes of northern Europe, Greenland, Canada, Alaska, China and Russia, a particular group of soils has developed during the Quaternary whose diversity is based primarily on cryopedogenic processes within the pedosphere of the Earth system. Among the most important cryopedogenic processes are the cryogenic weathering (frost wedging), ice segregation and accumulation (by increased freezing on of water on existing ice lenses), cryoturbation (mixing of soils by repeated freezing and thaw and, consequently, expansion and contraction processes), cryometamorphosis (transformation of soil structures due to ice), gelifluction (slow, wide-area downflow of soil material of the seasonally thawed layer on slopes with an inclination of $> 2°$), frost heave, frost sorting (material dislocation caused by the increase in volume during the freezing of water) and frost crack formation (due to the contraction of the frozen soil at very low temperatures) (Fig. 1).

The areas of the Northern Hemisphere covered by permafrost extend over almost 23 million km^2, approximately one-quarter of its total land surface (Baranov, 1959; Shi, 1988; Zhang, 1999, 2003; French, 2007). About 60 % of the Russian land surface is underlain by permafrost (Kudryavtsev et al., 1978; Brown et al., 1998; Kotlyakov and Khromova, 2002) (compare Fig. 5). These areas are called permafrost areas if their subsurface soils and sediments maintain temperatures of 0 °C or below during at least two consecutive years (van Everdingen, 2005) (see Fig. 2a). Under this definition, the ground water – if it contains many dissolved substances or is hold in fine pores – can also exist in liquid form in permafrost. In order to unambiguously demarcate permafrost from the "supra-permafrost" above it, the term *cryotic* (temperature < 0 °C) was introduced (French, 2007). In addition to this point of view, which focuses on the ground temperature regime and designates the boundary of the ground that is permanently below 0 °C as the so-called permafrost table, there is another point of view that focuses

Published by Copernicus Publications on behalf of the European Geosciences Union.

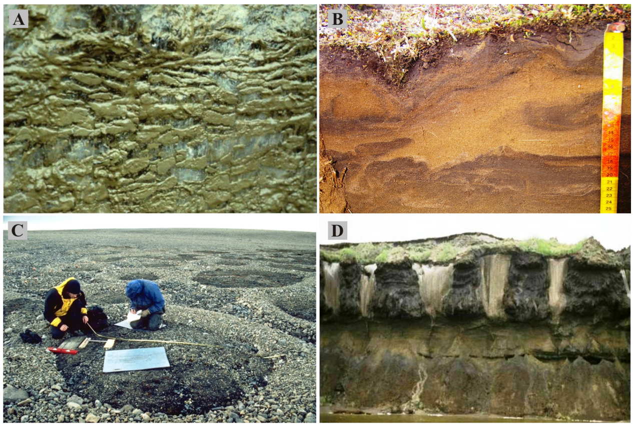


Figure 1. Results of cryopedogenic processes in permafrost. **(A)** Segregated ice, Lena River Delta, Siberia 2007. **(B)** Cryoturbation in the top soil of a Gelisol (Typic Psammoturbel), Arga Complex, northwestern Lena River Delta, Siberia 2009. **(C)** Sorted circles (frost patterns) formed by frost sorting, Brøgger Peninsula, Spitsbergen 1999. **(D)** Ice wedges, cliff exposure at the Olenyokskaya Channel, Lena River Delta, Siberia 2007. Photo C by Julia Boike.

on the thaw–freeze cycle. In the upper ground zone, this distinguishes the seasonal thaw layer from the underlying permanently frozen ground (Fig. 2b). Frozen ground is defined as ground material in which part or all of the pore water has turned into ice (van Everdingen, 2005).

A spatial differentiation of the permafrost areas is based on the portion of the areas with permafrost in relation to the total area and classifies continuous, discontinuous, and sporadic and isolated permafrost. In addition to the high latitudes of the Northern Hemisphere, permafrost and permafrost-affected soils are also found in the mountains of the Earth and the ice-free areas of Antarctica – there, however, only in small portions of the surface (0.35 % of Antarctica) (Bockheim, 1995; Vieira et al., 2010). The Antarctic permafrost-affected soils represent special, extremely cold and salt-rich habitats (Bockheim, 1979, 2002; Bockheim and McLeod, 2008).

The extension of the terrestrial permafrost areas does not entirely correspond to the extension of the permafrost-affected soils. These soils form their own class or reference group of the highest category in the various international soil systematics.

In current use are primarily the American classification system "Keys to Soil Taxonomy" (Soil Survey Staff, 2010) with the so-called Gelisols (*gelus*, ice) as permafrost-affected soil class (Figs. 3 and 4), and the international reference system of the "WRB: World Reference Base for Soil Resources" of the international Food and Agriculture Organization (FAO, 2007) with the Cryosol group (*cryos*, cold). The diagnostic horizons, or characteristics, of these soils are the existence of permafrost in the uppermost metre of the soil, or clear cryoturbation characteristics and/or segregation ice (*gelic* material according to US Soil Taxonomy; Soil Survey Staff, 2010) in the active layer of the soil above the permafrost present within a depth of 2 m (Figs. 2 and 4). An advantage of using both of these systems is the easy comparability of the various national and international studies on permafrost-affected soils.

In the morphogenetic Russian soil classification systems, permafrost is considered as being only a parameter of a soil thermal regime and not a diagnostic horizon or diagnostic property. Therefore, only permafrost-affected soils with cryoturbated soil profiles, widespread only in the far north of the Russian Federation, are treated as Cryozems in a separate soil class (Fig. 5). This soil class covers about 1 % of the Russian land surface (Stolbovoi et al., 2002), whereas around 60 % of the land surface is underlain by permafrost (Kudryavtsev et al., 1978; Brown et al., 1998; Kotlyakov and Khromova, 2002). All other soils of these areas without cryoturbation are allocated to other soil classes with the additional mentioning of the subjacent permafrost (such as Gleyzem with underlying permafrost; Shishov et al., 2004). Within the permafrost-underlain areas, several soil classes can be detected in the different vegetation zones of the Russian Federation. The polar desert is characterised by Cryozems and "shallow weakly developed" soils (Leptosols). In the tundra zone, Gleyzems (Gleysols) dominate, followed by Al-Fe-humic soils (Podzols). In the transition area to the taiga zone the two soil types of the tundra zone and organic-rich peat soils (Histosols) dominate. The taiga zone is dominated by Al-Fe-humic soils, metamorphic soils (Cambisols) and "texture-differentiated" soils (Albeluvisols) (Fig. 5).

In Germany, permafrost-affected soils only exist as relictic or fossil remnants of periglacial soil formations. In the current German soil classification (AG Boden, 2005), they are not independently described, but can be considered as palaeosoils (such as Podzol on top of buried Turbic Cryosol). Remnants of these soils are occasionally described in connection with the periglacial layers (AG Boden, 2005; Altermann et al., 2008).

The spatial extension of the Gelisols or Cryosols north of 50° latitude covers 27 % of the land mass (Jones et al., 2010) and corresponds to approximately 8.6 million km^2. The permafrost-affected soils (here Cryosols according to the WRB, FAO, 2007) are combined with other important soil types of these latitudes such as Podzols (acidified soils, 15 %), Leptosols (hard rock soils, 8 %) and Cambisols (brunified soils, 8 %) (Jones et al., 2010).

The properties and the spatial distribution of the permafrost-affected soils within the various countries were collected by Tarnocai (2004) and Smith and Veldhuis (2004) for Canada; by Ping et al. (2004a) for Alaska; by Goryachkin and Ignatenko (2004), Naumov (2004), Karavaeva (2004), Sokolov et al. (2004) and Gracheva (2004) for the diverse and extensive areas of Russia; by Maximovich (2004) for Mongolia; and by Ping et al. (2004b) for China and published as a book titled "Cryosols: Permafrost-Affected Soils" by

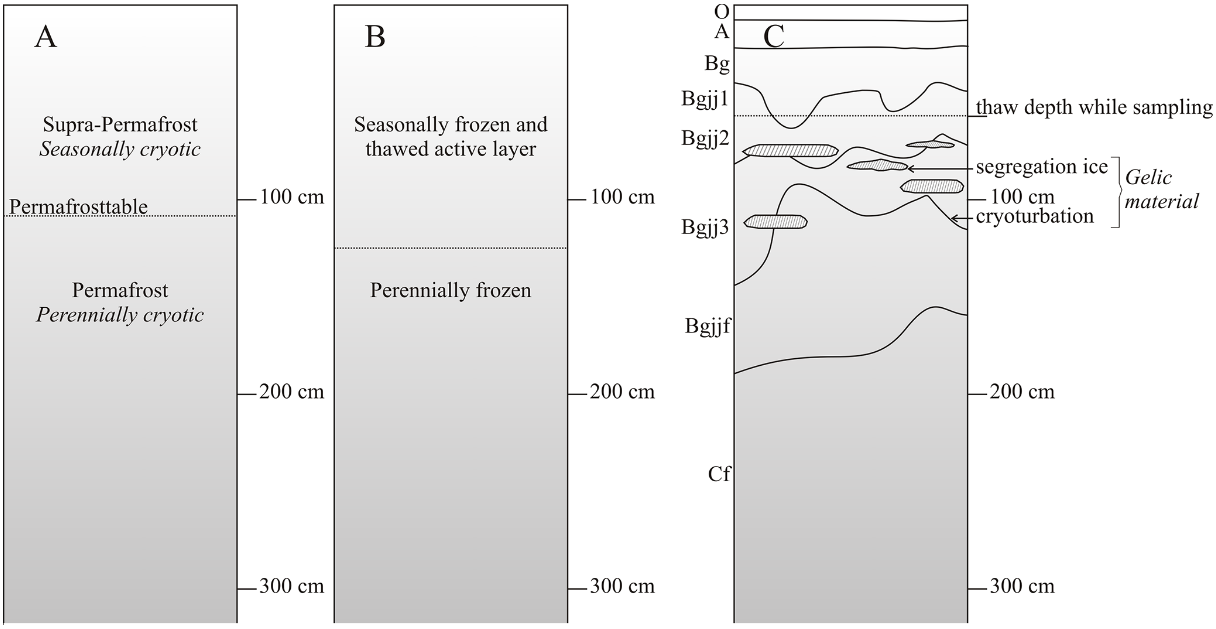


Figure 2. Schematic view of properties of permafrost-affected soils. **(A)** The soil thermal properties. The permafrost table divides the supra-permafrost (temperature can temporarily be higher than 0 °C within two consecutive years) and the permafrost (temperature is at least two consecutive years lower than 0 °C). **(B)** The freeze–thaw regime of the soils with the seasonally frozen and thawed active layer and the subjacent perennially frozen soil. **(C)** Example of a permafrost-affected soil profile. Cryoturbation and segregated ice (*gelic* material according to US Soil Taxonomy; Soil Survey Staff, 2010) are indicated.

Kimble (2004). The book contains a comprehensive description of the research into permafrost-affected soils and their history, as well as the spatial distribution of these soils along with their properties. It not only addresses the discussion of the various national and international classification systems, but also the potential uses as settlement areas, agricultural land, and as supplier of natural resources. “Permafrost Soils” by Margesin (2009) is a comprehensive book focusing on the biology of permafrost-affected soils. Aspects such as biodiversity and bioactivity (e.g. Ozerskaya et al., 2009; Panikov, 2009), the effect of global warming (e.g. Wagner and Liebner, 2009) and the problems of pollutant accumulation in permafrost area (e.g. Barnes and Chuvilin, 2009) are covered in this book.

2 Permafrost-affected soils as a carbon store

The low average temperatures and the extreme annual temperature differences in the permafrost areas have led to a considerable accumulation of organic matter in the Quaternary. The biomass, newly formed during the short summer phase, is initially accumulated after die-off in the uppermost active layer of the soil. The annually recurring accumulation of organic matter – and often also fluvial or aeolian sedimentation of mineral matter – can lead to an upward shift of the soil surface as well as of the surface of the permanently frozen ground, so that gradually more and more organic matter is incorporated. Cryoturbation also leads to the inclusion of organic matter into deeper soil horizons. Another process is the relocation of organic matter in dissolved state and its precipitation and deposition above the permafrost table, where it can accumulate in some soils due to the very low temperatures and low decay rates. The permafrost-affected soils, therefore, are relevant carbon sinks, which are effective over long periods of time (Post et al., 1982; Corradi et al., 2005; Kutzbach et al., 2007; van der Molen et al., 2007; McGuire et al., 2009). The sink function occurred primarily via the soils near the surface, which incorporate the biomass of the typical arctic climate-adapted tundra vegetation after its die-off as litter in their carbon sink. According to current estimates, 1024 Pg of organic carbon is stored in permafrost-affected soils down to a depth of 3 m (Tarnocai et al., 2009). Adding the deep-reaching sediments rich in organic carbon of the Yedoma landscapes and arctic deltas, the total estimates of the organic carbon stored in permafrost areas amount to about 1670 Pg (Tarnocai et al., 2009). These estimates were based on the Northern Circumpolar Soil Carbon Database (NCSCD, Tarnocai et al., 2007), the most comprehensive currently available database on organic carbon in permafrost-affected soils, which has recently been updated (Hugelius et al., 2013a, b). However, even the information in this database is still fraught with great uncertainties at the present time. When looking closely at the distribution of the sites considered so far, it becomes apparent that when evaluating the reliability of the soil data stored in

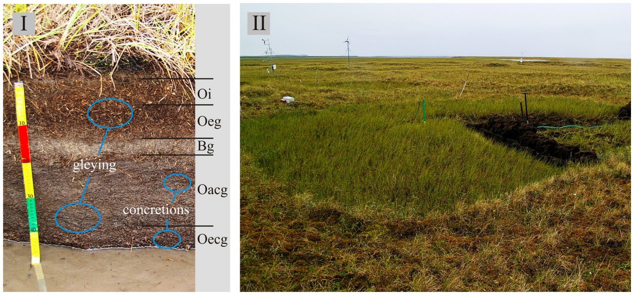


Figure 3. A "non-cryoturbated organic-dominated" permafrost-affected soil, Typic Historthel **(I)** and the study area it is from **(II)** – Samoylov Island, central Lena River Delta, Siberia 2007. **Historthel**, great group: **Hist** from *histos*, meaning tissue (plant); suborder: **orth**, from Orthels, which are soils with little or no cryoturbation, and except for polygons, patterned ground is absent; order: **el**, formative element of Gelisols, from Latin *gelu*, meaning frost, coldness. "O" and "B" indicate soil horizons. "O" indicates an organic matter-dominated horizon that has formed at the soil surface. It consists of undecomposed or partially decomposed litter (i.e. needles, twigs, moss, and lichens). "B" indicates a subsurface horizon that has formed below an "O" or "A" horizon. It shows the obliteration of all or much of the parent soil material structure. It can be characterised by many qualifiers. Examples are gleying properties (suffix "g") described as formation of grey, greenish and bluish spots caused by reduced iron. Iron reduction occurs when soils are water-saturated for long periods. In this case, the soil parent material consists of fluvial sands that were deposited during a flood in the study area. Suffixes "i", "e" and "a" classify the O horizon's organic matter in "slightly", intermediately" and "highly" decomposed. The existence of iron and/or manganese concretions is indicated by suffix "c".

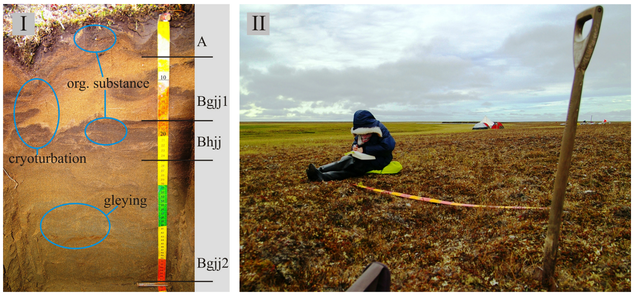


Figure 4. A "sand-dominated and cryoturbated" permafrost-affected soil, Typic Psammoturbel **(I)** and the study area it is from **(II)** the Arga Complex, northwestern Lena River Delta, Siberia 2009. **Psammoturbel**, great group: **Psamm(o)** from *psamm*, meaning sand; suborder: **turb**, from Latin *turbatio*, meaning disturbance; order: **el**, formative element of Gelisols, from Latin *gelu*, meaning frost, coldness. "A" and "B" indicate soil horizons. "A" indicates a mineral horizon that has formed at the surface or below an organic horizon. It has accumulated humified organic matter that is mixed with the mineral fraction. "B" indicates subsurface horizons (see Fig. 3). Within this profile there are several B horizons with different properties. The suffix "h" indicates an illuvial accumulation of organic matter or sesquioxides and "jj" stands for cryoturbated horizons. Suffix "g" is explained in the caption of Fig. 3.

the database (100 % being "reliable" and 0 % "unreliable", according to Kuhry et al., 2010), the arctic delta areas and the Yedoma landscapes with ice-rich permafrost sediments in Siberia (Fig. 6), based on the very sketchy and difficult-to-access data situation regarding permafrost-affected soils of this region until now, can only be assessed with a reliability of less than 33 %. The areas of the North American region, on the other hand, are very well represented, with up to 80 % reliability (Kuhry et al., 2010). This can be attributed to the above-average number of published soil studies in these regions. In publications of recent years, some ambiguities were apparent in the estimates of the carbon quantities stored in the permafrost-affected soils. These stemmed, on the one hand, from the unbalanced distribution of existing soil study data and, on the other hand, the widely varying definitions of the respective research objects. The number of publications on carbon contents in permafrost-affected soils is manageable (Table 1). Using the two most-cited publications, Post et al. (1982) and Tarnocai et al. (2009), as examples, these different points of view are easily illustrated: while Post et al. (1982), in the course of a global determination of the carbon pools of all life zones, only consider 48 soil profiles in arctic tundra areas to a depth of 100 cm, Tarnocai et al. (2009) combined and updated the pedological results of existing studies from permafrost regions (e.g. Zimov et al., 2006; Schuur et al., 2008) and supplemented them with their own data. More than 400 soil profiles were evaluated, and the pool of organic carbon for various studies objects such as the permafrost-affected soils to a depth of 3 m, the arctic delta areas (up to 50 m depth) or the Yedoma landscapes (up to 25 m depth) were calculated.

Looking at the results compiled in Table 1, one will notice that the study results can be divided into two main groups: the results to a depth of 30 cm and those to 100 cm. Another group comprises carbon studies that limit their sampling to the active layer that is further defined (depths of 20 cm up to 50 cm) or only to certain soil horizons. All study results show that the permafrost-affected soils store a large quantity of carbon per soil surface. The carbon pool fluctuates between 4 and 25 $\mathrm{kg\,m^{-2}}$ for the upper 30 cm of the soils. When the authors (listed in Table 1) inspected the soils to the maximum thaw depth on the day of sampling, the carbon pools lay between 13 and 29 $\mathrm{kg\,m^{-2}}$. The results of the studies that examined the carbon pool up to a depth of 100 cm vary between 4 and 71 $\mathrm{kg\,m^{-2}}$ (Table 1). These carbon pools derived from small scale field work seem to be lower than the estimated carbon pools stored in the NCSCD (compare Fig. 7). Furthermore, the field data reveal the very high fluctuation range of the results from different permafrost regions.

Observing the data of the current literature on the total mass of organic carbon in the permafrost areas (Table 1), the problematic aspect of comparability becomes obvious. The results of the studies refer to very different surfaces in

Table 1. Overview of carbon studies from different permafrost regions. Only results related to the permafrost-affected soils are presented. This list shows only some examples and is not intended to be exhaustive. SOC stands for soil organic carbon.

Sampling depth/ authors	SOC pool kg m^{-2} (min)	SOC pool kg m^{-2} (max)	Mass SOC Pg	Study sites as described in publication
Depth 0–30 cm				
Stolbovoi (2002a)	11.6	13.3	62	Russia
Tarnocai et al. (2009)			191	Northern permafrost regions
Hugelius et al. (2010)		16.3		Tulemalu Lake, central Canadian Arctic
Zubrzycki et al. (2012a)	4.0	24.0		Latitudinal transect (73.5–69.5° N) along the Lena River, Siberia
Pastukhov and Kaverin (2013)	9.6	24.6		NE European Russia, Rogovaya River and Seida River basins
Active layer depth				
Oechel and Billings (1992)	13.0	29.0	55	Tundra
Tarnocai and Ballard (1994)	21.7	26.2		Canadian Arctic/subarctic
Orlov et al. (1996)		14.5	59	Russia
Nadelhoffer et al. (1997)		20.3		Alaska
Gundelwein et al. (2007)		14.5		Taymyr Peninsula, Lake Labaz
Depth 0–100 cm				
Post et al. (1982)		21.8	192	Tundra
Tarnocai and Smith (1992)	4.0	63.0		Canada
Desyatkin et al. (1994)		16.0		Yakutian tundra
Matsuura and Yefremov (1995)	11.0	20.0		Russia
Kolchugina et al. (1995)		21.4		Russian tundra soils
Rozhkov et al. (1996)			116	Tundra and northern taiga in Russia
Ping et al. (1997)	31.4	69.2		Tundra in Alaska
Chestnyck et al. (1999)		17.8		Eastern European Russian tundra
Stolbovoi (2002a)	16.6	26.9	107	Russia
Tarnocai et al. (2003)	25.6	59.2	268	Northern permafrost regions
Post (2006)		14.2		Tundra
Gundelwein et al. (2007)		30.7		Taymyr Peninsula, Lake Labaz
Ping et al. (2008)		34.8	98	North American Arctic region
Tarnocai et al. (2009)	22.6	66.6	496	Northern permafrost regions
Hugelius et al. (2010)		33.8		Central Canadian Arctic, Tulemalu Lake
Bliss and Maursetter (2010)		54.5	38	Alaska, Gelisols of Alaska
Ping et al. (2010)	12.6	50.9		Alaska, discontinuous, warm permafrost, boreal forests
Palmtag (2011)	21.7	29.0		NE Siberia, Shalaurovo and Chersky
Ping et al. (2011)		41.0		Alaska, Beaufort Sea coastline, river deltas
Ramage (2012)	27.6	31.3		Taymyr Peninsula, Ari-Mas and Logata
Pastukhov and Kaverin (2013)	16.9	71.3		NE European Russia, Rogovaya River and Seida River basins
Zubrzycki et al. (2013)	6.6	48.0	0.241	Siberia, Lena River Delta, Holocene units
Depth 0–300 cm				
Tarnocai et al. (2009)	159.2	358.2	1024	Northern permafrost regions
Pastukhov and Kaverin (2013)	16.9	147.0		NE European Russia, Rogovaya River and Seida River basins
Depth > 300 cm				
Tarnocai et al. (2009)		65.0	241	Arctic deltas
Authors	OC (min) % wt	OC (max) % wt	Mass SOC Pg	Study sites as described in publication
Zimov et al. (2006)		2.56	450	Yedoma landscapes in northern Siberia
Tarnocai et al. (2009)		2.6	407	Yedoma landscapes in northern Siberia
Schirrmeister et al. (2011)	1	17	250–375	20 coastal exposures in northern Siberia
Strauss et al. (2013)	0.8	4.6	58–371	Yedoma landscapes

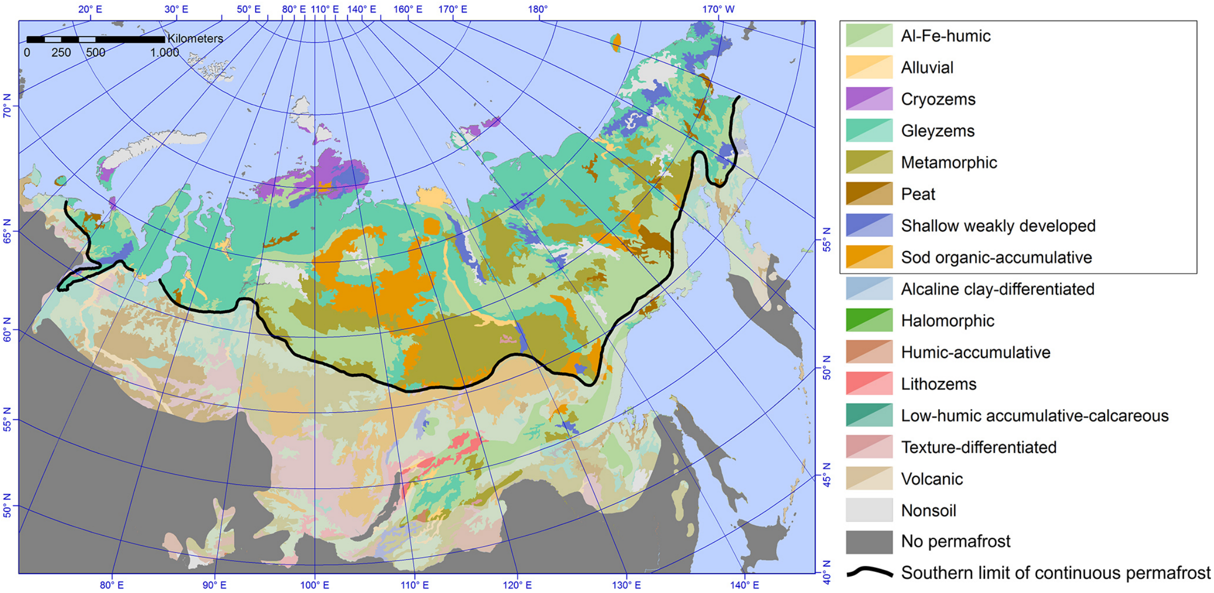


Figure 5. Distribution of soil types across permafrost-affected parts of the Russian Federation. Soils developing within the area of continuous permafrost can certainly be assumed as permafrost-affected soils (dominating soil types in the grey box). Soils in the area of discontinuous, sporadic and isolated permafrost plotted in pastel colours (south of the black limit line of continuous permafrost) are likely to be assumed as permafrost-affected soils. Based on Stolbovoi et al. (2002) and Brown et al. (1998).

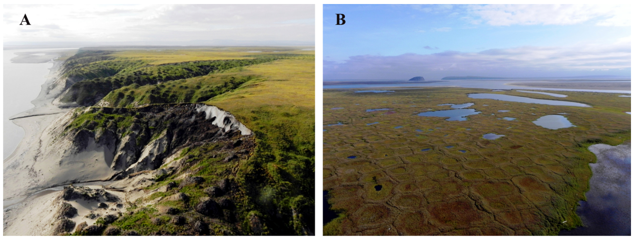


Figure 6. Examples of underrepresented landscapes in the Northern Circumpolar Soil Carbon Database (NCSCD). **(A)** Yedoma landscape of Kurungnakh Island. An erosional river cliff with exposed ice-rich sediments. **(B)** Polygonal tundra of Samoylov Island. Both islands are located in the Lena River Delta in northeastern Siberia. Photos 2010.

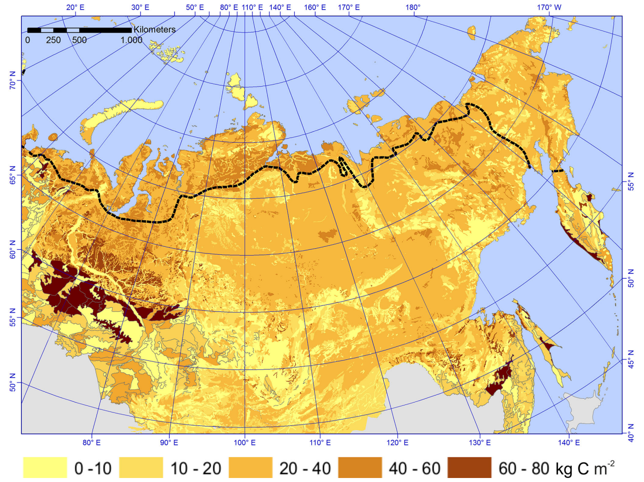


Figure 7. Spatial distribution of the soil organic carbon contents in Russian Federation. The dashed line illustrates the tree limit. Based on Hugelius et al. (2013a), Stolbovoi (2002b) and Brown et al. (1998).

terms of size. The studied surfaces may be countries, regions or even vegetation units. Despite the difficult comparability, the results of these studies illustrate that the total pool of the permafrost-affected soils' organic carbon is very high at 1024 Pg (Tarnocai et al., 2009) and exceeds the mass of carbon of the entire global vegetation biomass (650 Pg) as well as the atmosphere (750 Pg) (IPCC, 2007). The carbon quantities stored in permafrost-affected soils are therefore to be considered one important factor for the understanding and function of the cryosphere within the climate system. Permafrost-affected soils with their special carbon dynamics are very sensitive to environmental and climatic changes due to their temperature dependence. It can be assumed – for the past as well as for the present – that global and regional environmental and climatic changes, as well as the dynamics of soil carbon in permafrost areas, interact and will continue to interact with one another via physical and biogeochemical feedback mechanisms (McGuire et al., 2009; Grosse et al., 2011). With the currently predicted climate warming and its particularly strong effects in the arctic regions (Lembke et al., 2007) and the concurrent local and regional decline and degradation of permafrost (Anisimov and Nelson, 1997), the

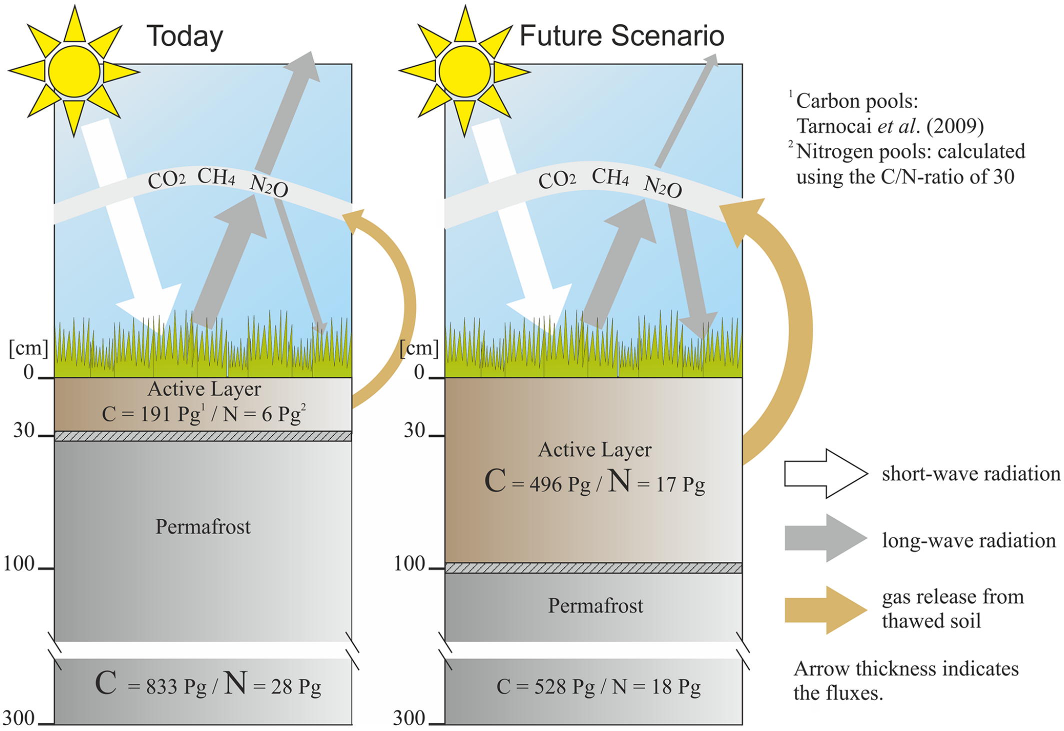


Figure 8. Schematic illustration of the carbon and nitrogen dynamic feedbacks and the climate-driven changes within the permafrost-affected soils. C pools (Tarnocai et al., 2009) and N pools calculated using the C/N ratio of 30. Figure according to Beer (2009).

properties of permafrost-affected soils will undergo a fundamental change.

Warming within the permafrost areas can lead to an augmentation of the thickness of the seasonally thawed layer in the upper soil (Fig. 2) and to a change in its hydrological site conditions (Koven et al., 2011). This leads to an increased microbial decay of the organic matter and a more intensive release of the climate-relevant trace gases carbon dioxide, methane and nitrogen oxide (Dutta et al., 2006; Wagner et al., 2007; Khvorostyanov et al., 2008; Schuur et al., 2009; Lee et al., 2012; Knoblauch et al., 2013).

In other words, if the current warming of the arctic climate is the cause of an increased decline in the extent of the permafrost areas, which in turn leads to an increased release of greenhouse gases in the Earth's atmosphere, a further rise in temperatures on a global scale and also in the permafrost areas themselves might be expected (Fig. 8).

These processes show the potential positive feedback effects in permafrost landscapes or in the cryosphere of the Earth system that are not yet sufficiently considered in the climate models relating to temperature projection. Because of these complex effects, the permafrost areas are likely to represent a tipping element of the global climate system, relevant even for politics and society (Lenton and Schellnhuber, 2010). A tipping element is considered to consist of those components of the Earth system that can essentially and irrevocably be altered under loads beyond critical limits (Lenton and Schellnhuber, 2010). Whether the soils of the permafrost areas already act as carbon sources (Oechel et al., 1993, 2000; Zimov et al., 1997) or still accumulate carbon (Corradi et al., 2005; Kutzbach et al., 2007; van der Molen et al., 2007; Hayes et al., 2011) is not yet clear and has to be assessed on a regional scale.

The complexity of these carbon source–sink functions of the permafrost-affected soils is not yet sufficiently understood. There is a lack of measurements as well as robust, adequately validated modelled projections and predictions to make reliable prognoses for the development of the carbon dynamics of permafrost-affected soils in the warming climate system (McGuire et al., 2009).

3 Current level of knowledge of the carbon pool in permafrost-affected soils in Russian Arctic

Because of the particular relevance of the cryosphere and especially the terrestrial permafrost for climate system research, the number of published scientific articles focusing on carbon in the permafrost regions has dramatically increased over the past 5 years compared to the last 20 years (Fig. 9).

The largest part of these published articles deals with the North American region. In recent years, however, areas of the Eurasian permafrost – especially in the Russian region – have also been increasingly studied in detail. The data of

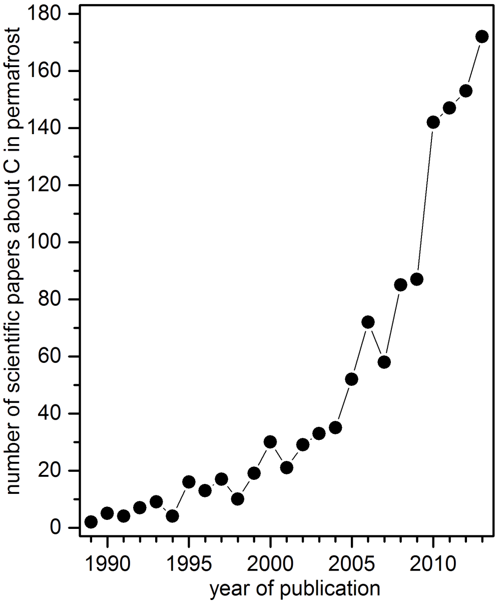


Figure 9. Number of scientific papers published between 1989 and 2013 as a result of a search for the keywords "permafrost + carbon" in Web of Science (www.webofknowledge.com) on 14 January 2014.

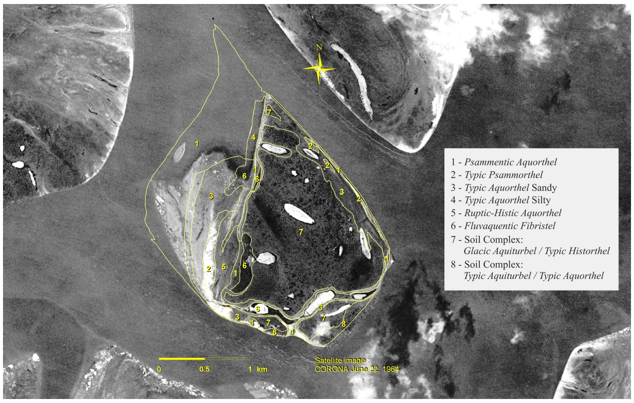


Figure 10. A soil map of Samoylov Island as a result of long-term soil research within this area of the Lena River Delta. Generated from data by Pfeiffer et al. (2000, 2002) (see Sanders et al., 2010). Soil classification according to the US Soil Taxonomy (Soil Survey Staff, 2010). The plotted coast line from July 1964 points out the high coastal dynamics within the beach and floodplain in the western part of island.

these small research areas can only be used reliably so far for local upscaling of the carbon quantities. Special permafrost phenomena such as "ice-" and organic-rich sediments of the Yedoma landscapes, which have until now been largely neglected, were increasingly being studied (Zimov et al., 2006; Schirrmeister et al., 2011; Strauss et al., 2013).

The near-surface soils of the permafrost areas of northern Siberia have long played a large role in the study of carbon pools and greenhouse gas emissions by Russian scientists and, since the 1990s, by large German–Russian cooperation projects. In addition to the classic soil survey with its genesis and distribution in permafrost areas (Krasuk, 1927; Ivanova, 1965, 1971; Karavaeva, 1969; Targulyan, 1971; Elovskaya et al., 1979; Desyatkin and Teterina, 1991; Pfeiffer, 1998; Pfeiffer et al., 2000, 2002) (for examples see Figs. 3, 4, 10 and 11), numerous physicochemical properties and processes of permafrost-affected soils were also studied (e.g. Pfeiffer and Jansen, 1992; Okoneshnikova, 1994; Pfeiffer et al., 1997; Fiedler et al., 2004; Kutzbach et al., 2004; Desyatkin and Desyatkin, 2006; Zubrzycki et al., 2008; Sanders et al., 2010) (for examples see Figs. 11–13 and Table 2).

The turnover of organic matter in the soil and the associated formation of greenhouse gases in moist tundra areas of Eurasia were also researched on a small scale as part of field campaigns (e.g. Wüthrich et al., 1999; Rivkina et al., 2007; Knoblauch et al., 2008, 2013; Wagner et al., 2009; Liebner et al., 2011; Shcherbakova et al., 2011). The emissions of greenhouse gases were initially captured in the northern Siberian Lena River Delta starting in 2000 via small-scale closed-chamber measurements (Kutzbach et al., 2004; Sachs et al., 2010) and later expanded by eddy covariance measurements (Kutzbach et al., 2007; Sachs et al., 2008; Wille et al., 2008; Runkle et al., 2013). The seasonally averaged methane emissions determined via closed-chamber measurements for polygon rims and centres lay between 4.3 and 28 mg CH_4 m^{-2} d^{-1} (Kutzbach et al., 2004), and between 4.9 and 100 mg CH_4 m^{-2} d^{-1}, respectively (Sachs et al., 2010). The eddy covariance measurements estimated landscape-scale emissions on the order of magnitude of 0.01 to 0.55 g CO_2 h^{-1} m^{-2} for releasing carbon dioxide by respiration processes (Kutzbach et al., 2007). The methane fluxes amounted to 18.7 to 30 mg CH_4 m^{-2} d^{-1} for averaged daily emissions within the measuring period (Sachs et al., 2008; Wille et al., 2008).

First English-language works on the survey of the carbon quantities in the permafrost-affected soils of the Siberian Arctic also exist (Gundelwein et al., 2007; Zubrzycki et al., 2012a, 2013). Their results determined for small areas of Siberia are comparable to those of other areas (see Table 1). It also becomes apparent, however, that inaccuracies can occur in global extrapolations if the data situation from the individual regions is insufficient (Zubrzycki et al., 2012a). The carbon pools are recorded not only in the Siberian Arctic but also in the European–Russian Arctic by means of field work and are extrapolated onto larger areas via remote sensing methods (Mazhitova et al., 2003; Hugelius and Kuhry, 2009; Hugelius et al., 2011).

In addition to the above studies limited to 1 through 3 m of the carbon pools in the permafrost-affected soils, the study of permafrost phenomena such as the sediments of the Yedoma landscapes is important. The studies of Siberian regions show that these sediments have high gravimetric carbon contents,

Table 2. Chemical properties of two exemplary soil profiles (see Fig. 11 and Fig. 13) with their horizons according to the US Soil Taxonomy (Soil Survey Staff, 2010), horizon depth, texture, hydromorphology, pH value, organic carbon content in weight percent, C/N ratio and rooting.

Glacic Aquiturbel – polygonal rim of a “low-centred” ice wedge polygon

Horizon	Depth (cm)	Texture	Red. conditions	pH	OC	C/N	Roots
Ajj	0–12	Loamy sand	No	5.9	1.8	21	Many
Bjjg1	12–15	Sandy loam	No	6.2	2.2	21	Frequent
Bjjg2	15–47	Loam	Yes	5.5	2.9	24	Frequent
Bjjgf	47–70	Loam	Yes	6.0	3.0	20	None

Typic Historthel – polygonal centre of a “low-centred” ice wedge polygon

Horizon	Depth (cm)	Texture	Red. conditions	pH	OC	C/N	Roots
Oi	0–11	Peat	No	5.0	22.1	43	Few
OeBg	11–26	Peat + sand	Yes	4.8	12.6	35	Many
Bg	26–31	Sand	Yes	4.8	2.1	17.5	Frequent
Bgf	31–64	Sandy loam	Yes	5.0	4.2	30	None

Table 3. Current projects and programmes with the focus on permafrost-affected regions with their carbon pools and carbon dynamics.

Acronym	Project/programme title	Website
CAPP	Carbon Pools in Permafrost Regions	http://www.geowiss.uni-hamburg.de/i-boden/capp
CarboPerm	Carbon in Permafrost. Formation, Turnover and Release	http://www.carboperm.net
CRAICC	Cryosphere-atmosphere interactions in a changing Arctic climate	http://www.atm.helsinki.fi/craicc
CryoCARB	Advancing organic carbon estimates for cryoturbated soils	http://www.univie.ac.at/cryocarb
DEFROST	Impact of a changing cryosphere – Depicting ecosystem-climate feedbacks from permafrost, snow and ice	http://www.ncoe-defrost.org
GRENE-TEA	Change in the terrestrial ecosystems of the pan-Arctic and effects on climate	
NACP	North American Carbon Program	http://www.nacarbon.org/nacp
NGEE Arctic	Next-Generation Ecosystem Experiments	http://www.ngee-arctic.ornl.gov
PAGE21	Changing permafrost in the Arctic and its Global Effects in the 21st Century	http://www.page21.eu
POLYGON	Polygons in tundra wetlands: state and dynamics under climate variability in Polar Regions	http://www.gepris.dfg.de/gepris/projekt/164232461
RCN	Vulnerability of Permafrost Carbon Research Coordination Network	http://www.biology.ufl.edu/permafrostcarbon
TOMCAR	Terrestrial organic matter characterization in Arctic Rivers	http://www.2020-horizon.com

which, however, are subject to strong fluctuations depending on the studied site. They are usually between 1 and 4 %, but can also reach values of up to 17 % in the case of peaty layers (Zimov et al., 1997, 2006; Schirrmeister et al., 2011; Strauss et al., 2013).

4 Research requirements

A significant number of new data records on soils and the quantities of carbon stored in them from the under-represented areas of the circumpolar regions – especially the Siberian Arctic – is necessary to update the Northern Circumpolar Soil Carbon Database (Tarnocai et al., 2009; Kuhry et al., 2010; Hugelius et al., 2013a, b). This can only be achieved by combining measuring fieldwork with modelling work for the permafrost areas, primarily for the Eurasian and especially for the Siberian region. Because of the sketchy data situation, special focus should be directed not only to the delta deposits, the ice-rich sediments of the Yedoma landscapes (see Tarnocai et al., 2009), but also to the permafrost-affected soils of the hilly and mountainous regions. A more comprehensive data basis is necessary for a better understanding of the interactions between the particular climate,

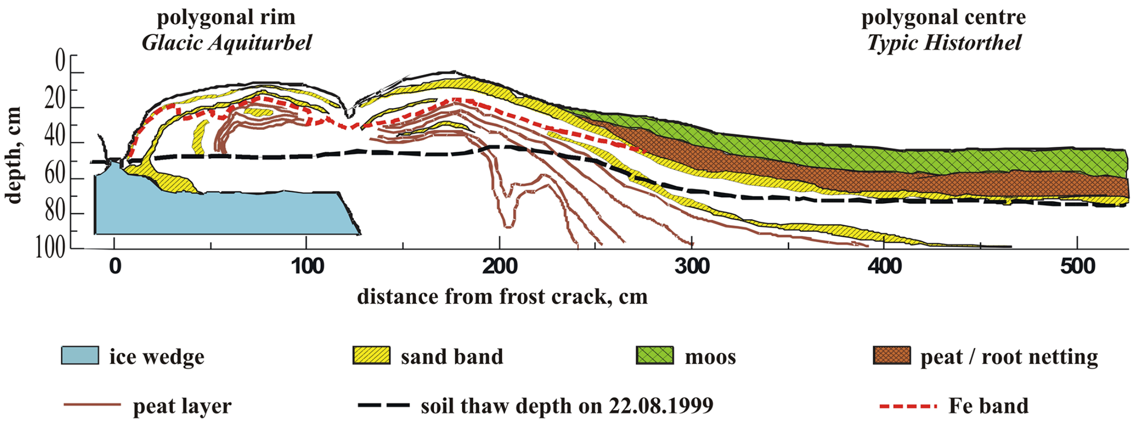


Figure 11. Cross section of a low-centred polygon with a surface depression above the ice wedge and another one at the ice wedge's end. Soils that have developed in this polygon are a Glacic Aquiturbel at the polygon rim above the ice wedge and a Typic Historthel in the polygon centre. Scheme compiled from field observations of 22 August 1999.

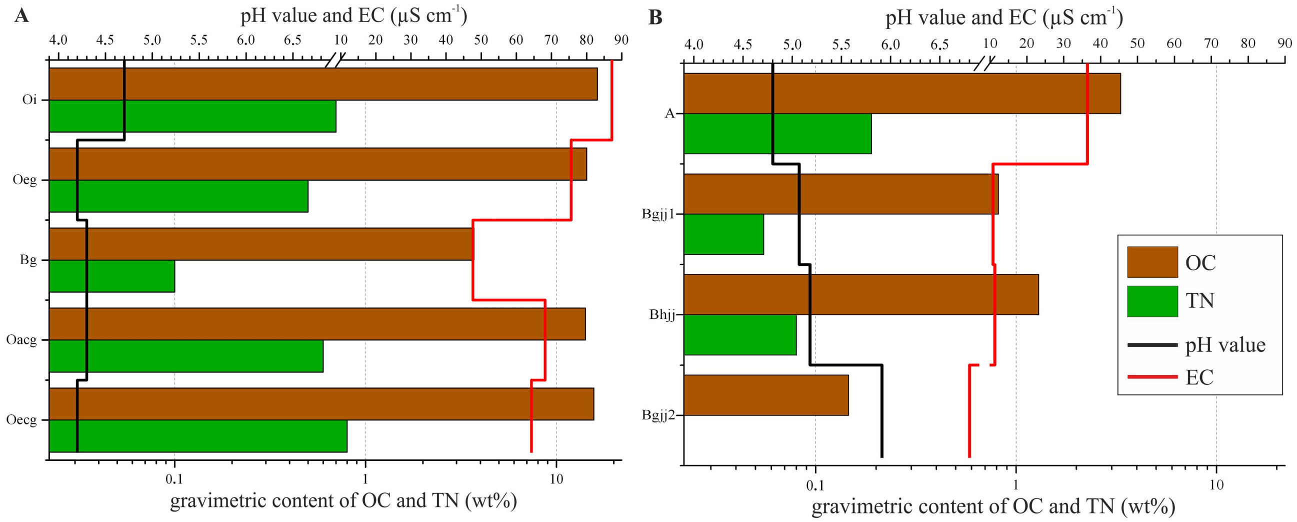
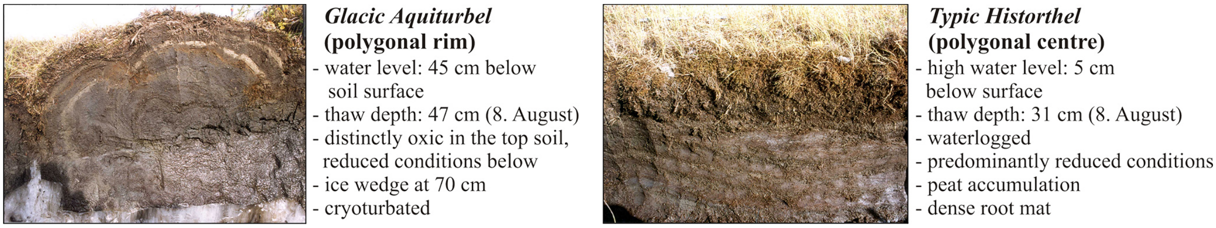


Figure 12. Chemical analyses of in Figs. 3 and 4 presented permafrost-affected soils. **(A)** Chart for Typic Historthel. **(B)** Chart for Typic Psammoturbel. For better comparison, both charts use the same scaling. The upper scale is for the pH value and electrical conductivity ($\mu\,\mathrm{S\,cm}^{-1}$). Both properties were measured in a soil suspension of the soil sample and water. The scale at the bottom represents the contents of organic carbon (OC) and total nitrogen (TN) in %wt.



Glacic Aquiturbel
(polygonal rim)
- water level: 45 cm below soil surface
- thaw depth: 47 cm (8. August)
- distinctly oxic in the top soil, reduced conditions below
- ice wedge at 70 cm
- cryoturbated

Typic Historthel
(polygonal centre)
- high water level: 5 cm below surface
- thaw depth: 31 cm (8. August)
- waterlogged
- predominantly reduced conditions
- peat accumulation
- dense root mat

Figure 13. Two examples of permafrost-affected soils from Samoylov Island with a brief description of soil properties. The presented soil complex consisting of Glacic Aquiturbels and Typic Historthels dominates the soils of this island in the Lena River Delta (see Fig. 11).

soil and vegetation conditions in the permafrost areas. From this information, a drawing of conclusions will be enabled regarding the factors of the processes occurring today or the future remobilisation of the labile organic carbon of the permafrost-affected soils. The importance of investigations of carbon-related issues in permafrost regions was recognised. Today, there are several research projects and programmes collecting and synthesising such data from different permafrost-affected regions (Table 3). For future research projects, it is important to reach high interdisciplinarity among the researchers in one area because only the synthesis of the various research approaches and their results can lead to an improved understanding of the permafrost-affected soils and their carbon dynamics.

Since not only the size of the carbon pool in permafrost-affected soils varies regionally (McGuire et al., 2009), its recent carbon source and sink function is also different from region to region. In addition, since field research cannot be carried out everywhere with sufficient intensity, large-scale thematic soil-type maps should initially be drawn up on a regional basis. These results, gathered from fieldwork and shown in maps, may serve as the basis for future extrapolations of various element fluxes. With the help of high-resolution vegetation and soil-type maps of underrepresented areas containing soil texture and hydrology, more accurate estimates of the carbon pool of the circumpolar permafrost region can be performed using GIS analyses (compare to Hugelius, 2012; Pastukhov and Kaverin, 2013; Zubrzycki et al., 2013). To this end, many already existing soil and sediment samples could be reanalysed. Afterwards, new work areas can be targeted to fill the research gaps.

Data on the carbon pools and processes in the permafrost areas, obtained via targeted field and lab work, can be integrated into new and more reliable models. Through the synergistic and interdisciplinary collaboration of measurement and modelling permafrost researchers, it will be possible to model the development of these vast areas with their enormous quantities of potentially labile organic carbon and facilitate prognoses regarding possible greenhouse gas emissions from permafrost-affected soils. These, in turn, will lead to new, more realistic future projections of global temperature development and reduce the current uncertainty surrounding the significance of the cryosphere, including the carbon pools in permafrost-affected soils, for the climate system.

Acknowledgements. The authors thank the chief-executive editor of the journal *Polarforschung*, Dieter K. Fütterer, for the assent to publish an updated and English-written version of our previously printed manuscript (Zubrzycki, S., Kutzbach, L., and Pfeiffer, E.-M.: Böden in Permafrostgebieten der Arktis als Kohlenstoffsenke und Kohlenstoffquelle, Polarforschung, 81, 33–46, 2012b). We thank Darren R. Gröcke, the chief-executive editor of *Solid Earth*, for giving an opportunity to broader the audience by accepting the submission of the new English-written version of our manuscript.

Edited by: A. Navas

References

AG Boden: Bodenkundliche Kartieranleitung, E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, 2005.

Altermann, M., Jäger, K.-D., Kopp, D., Kowalkowski, A., Kühn, D., and Schwanecke, W.: Zur Kennzeichnung und Gliederung von periglaziär bedingten Differenzierungen in der Pedosphäre, Waldökologie, Landschaftsforschung und Naturschutz, 6, 5–42, 2008.

Anisimov, O. A. and Nelson, F. E.: Permafrost zonation and climate change in the Northern Hemisphere: results from transient general circulation models, Clim. Change, 35, 241–258, 1997.

Baranov, I. Y.: Geographical distribution of seasonally-frozen ground and permafrost, General Geocryology, Obruchev Institute of Permafrost Studies. Academy of Science Moscow, Part 1, Chapter 7, National Council of Canada, Technical translation, 193–219, 1959.

Barnes, D. L. and Chuvilin, E.: Migration of petroleum in permafrost-affected regions, in: Permafrost Soils, edited by: Margesin, R., Springer, Berlin, 263–278, 2009.

Beer, C.: Soil science: the Arctic carbon count, Nat. Geosci., 9, 569–570, 2008.

Bliss, N. B. and Maursetter, J.: Soil organic carbon stocks in Alaska estimated with spatial and pedon data, Soil Sci. Soc. Am. J., 74, 565–579, 2010.

Bockheim, J. G.: Relative age and origin of soils in eastern Wright Valley, Antarctica, Soil Sci., 128, 142–152, 1979.

Bockheim, J. G.: Permafrost distribution in the Southern Circumpolar region and its relation to the environment – a review and recommendations for further research, Permafrost Periglac., 6, 27–45, 1995.

Bockheim, J. G.: Landform and soil development in the McMurdo Dry Valleys, Antarctica: a regional synthesis, Arct. Antarct. Alp Res., 34, 308–317, 2002.

Bockheim, J. G. and McLeod, M.: Soil distribution in the McMurdo Dry Valleys, Antarctica, Geoderma, 144, 43–49, 2008.

Brown, J., Ferrians Jr., O. J., Heginbottom, J. A., and Melnikov, E. S.: Circum-arctic map of permafrost and ground ice conditions, Boulder, CO, National Snow and Ice Data Center, Digital media, 1998, revised February 2001, 1998.

Chestnyck, O. V., Zamolodchikov, D. G., and Karelin, D. V.: Organic matter reserves in the soils of tundra and forest-tundra ecosystems of Russia, Ecologia, 6, 426–432, 1999 (in Russian).

Corradi, C., Kolle, O., Walter, K., Zimov, S. A., and Schulze, E. D.: Carbon dioxide and methane exchange of a north-east Siberian tussock tundra, Global Change Biol, 11, 1–16, doi:10.1111/j.1365-2486.2005.01023.x, 2005.

Desyatkin, R. and Teterina, L.: The soils of Lena River Delta. Genesis and melioration of Yakutian soils, 55–66, 1991 (in Russian).

Desyatkin, R. V. and Desyatkin, A. R.: Thermokarst transformation of soil cover on cryolithozone flat territories, Hokkaido University Press, 213–223, 2006.

Desyatkin, R. V., Maximov, T. S., and Ivanov, B. I.: Carbon storage of plant ecosystems in Yakutia, in: Proc. of the Second Symp. on the Joint Siberian Permafrost Studies between Japan and Russian in 1993 (NIES, Tsukuba, Japan, 1994), 187–195, 1994.

Dutta, K., Schuur, E. A. G., Neff, J. C., and Zimov, S. A.: Potential carbon release from permafrost soils of Northeastern Siberia, Glob. Change Biol., 12, 2336–2351, 2006.

Elovskaya, L. G., Petrova, E. I., and Teterina, L. V.: Soils of Northen Yakutia, Novosibirsk, 303 pp., 1979.

FAO – Food and Agriculture Organization: WRB – World reference base for soil resources 2006, first update 2007, FAO, Rom: 128 pp., 2007.

Fiedler, S., Wagner, D., Kutzbach, L., and Pfeiffer, E.-M.: Element redistribution along hydraulic and redox gradients of low-centered polygons, Lena-Delta, northern Siberia, Soil Sci. Soc. Am. J., 68, 1002–1011, 2004.

French, H. M.: The Periglacial Environment, John Wiley & Sons Ltd, West Sussex, 458 pp., 2007.

Goryachkin, S. V. and Ignatenko, I. V.: Cryosols of the Russian European North, Cryosols, Permafrost-Affected Soils, edited by: Kimble, J. M., Springer, Berlin, 185–208, 2004.

Gracheva, R. G.: Cryosols of the mountains of Southern Siberia and far Eastern Russia, Cryosols, Permafrost-Affected Soils, edited by: Kimble, J. M., Springer, Berlin, 231–252, 2004.

Grosse, G., Harden, J., Turetsky, M., McGuire, A. D., Camill, P., Tarnocai, C., Frolking, S., Schuur, E. A. G., Jorgenson, T., Marchenko, S., Romanovsky, V., Wickland, K. P., French, N., Waldrop, M., Bourgeau-Chavez, L., and Striegl, R. G.: Vulnerability of high-latitude soil organic carbon in North America to disturbance, J. Geophys. Res.-Biogeo., 116, G00K06, doi:10.1029/2010JG001507, 2011.

Gundelwein, A., Müller-Lupp, T., Sommerkorn, M., Haupt, E. T., Pfeiffer, E.-M., and Wiechmann, H.: Carbon in tundra soils in the Lake Labaz region of arctic Siberia, Eur. J. Soil Sci., 58, 1164–1174, doi:10.1111/j.1365-2389.2007.00908.x, 2007.

Hayes, D. J., McGuire, A. D., Kicklighter, D. W., Gurney, K. R., Burnside, T. J., and Melillo, J. M.: Is the northern high-latitude land-based CO_2 sink weakening?, Global Biogeochem. Cy., 25, GB3018, doi:10.1029/2010GB003813, 2011.

Hugelius, G.: Spatial upscaling using thematic maps: An analysis of uncertainties in permafrost soil carbon estimates, Global Biogeochem. Cy., 26, GB2026, doi:10.1029/2011GB004154, 2012.

Hugelius, G. and Kuhry, P.: Landscape partitioning and environmental gradient analyses of soil organic carbon in a permafrost environment, Global Biogeochem. Cy., 23, GB3006, doi:10.1029/2008GB003419, 2009.

Hugelius, G., Kuhry, P., Tarnocai, C., and Virtanen, T.: Soil organic carbon pools in a periglacial landscape: a case study from the central Canadian Arctic, Permafrost Periglac., 21, 16–29, 2010.

Hugelius, G., Virtanen, T., Kaverin, D., Pastukhov, A., Rivkin, F., Marchenko, S., Romanovsky, V., and Kuhry, P.: High-resolution mapping of ecosystem carbon storage and potential effects of permafrost thaw in periglacial terrain, European Russian Arctic, J. Geophys. Res.-Biogeo., 116, G03024, doi:10.1029/2010JG001606, 2011.

Hugelius, G., Tarnocai, C., Broll, G., Canadell, J. G., Kuhry, P., and Swanson, D. K.: The Northern Circumpolar Soil Carbon Database: spatially distributed datasets of soil coverage and soil carbon storage in the northern permafrost regions, Earth Syst. Sci. Data, 5, 3–13, doi:10.5194/essd-5-3-2013, 2013a.

Hugelius, G., Bockheim, J. G., Camill, P., Elberling, B., Grosse, G., Harden, J. W., Johnson, K., Jorgenson, T., Koven, C. D., Kuhry, P., Michaelson, G., Mishra, U., Palmtag, J., Ping, C.-L., O'Donnell, J., Schirrmeister, L., Schuur, E. A. G., Sheng, Y., Smith, L. C., Strauss, J., and Yu, Z.: A new data set for estimating organic carbon storage to 3 m depth in soils of the northern circumpolar permafrost region, Earth Syst. Sci. Data, 5, 393–402, doi:10.5194/essd-5-393-2013, 2013b.

IPCC – Intergovernmental Panel on Climate Change: Climate Change 2007 – IPCC Fourth Assessment Report. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

Ivanova, E. N.: Taiga cryogenic soils of Northern Yakutia, Pochvovedenie (Soil Sci.) No. 7, 1965.

Ivanova, E. N.: Soils of Central Yakutia, Pochvovedenie (Soil Sci.) No. 9, 3–18, 1971.

Jones, A., Stolbovoy, V., Tarnocai, C., Broll, G., Spaargaren, O., and Montanarella, L. (Ed.): Soil Atlas of the Northern Circumpolar Region, European Commission, Publications Office of the European Union, Luxembourg, 144 pp., 2010.

Karavaeva, N. A.: Tundra soils of Northern Yakutia, Moscow, Nauka (Science), 206 pp., 1969.

Karavaeva, N.: Cryosols of Western Siberia, Cryosols, Permafrost-Affected Soils, edited by: Kimble, J. M., Springer, Berlin, 209–230, 2004.

Khvorostyanov, D. V., Krinner, G., and Ciais, P.: Vulnerability of permafrost carbon to global warming, Part I. Model description and role of heat generated by organic matter decomposition, Tellus B, 60, 343–358, 2008.

Kimble, J. M. (Ed.): Cryosols, Permafrost-Affected Soils, Springer, Berlin, 726 pp., 2004.

Knoblauch, C., Zimmermann, U., Blumenberg, M., Michaelis, W., and Pfeiffer, E.-M.: Methane turnover and temperature response of methane-oxidising bacteria in permafrost-affected soils of northeast Siberia, Soil Biol. Biochem., 40, 3004–3013, 2008.

Knoblauch, C., Beer, C., Sosnin, A., Wagner, D., Pfeiffer E- M.: Predicting long-term carbon mineralization and trace gas production from thawing permafrost of Northeast Siberia, Glob. Change Biol., 19, 1160–1172, doi:10.1111/gcb.12116, 2013.

Kolchugina, T. P., Vinston, T. S., Gaston, G. G. Rozhkov, V. A., and Shwidenko, A. Z.: Carbon pools, fluxes and sequestration potential in soils of the former Soviet Union, in: Soil Management and Greenhouse Effect, edited by: Lal, R., Kimble, J., Levine, E., and Stewart, B. A., Lewis, Boca Raton, FL, 25–40, 1995.

Koven, C. D., Ringeval, B., Friedlingstein, P., Ciais, P., Cadule, P., Khvorostyanov, D., Krinner, G., and Tarnocai, C.: Permafrost carbon-climate feedbacks accelerate global warming, P. Natl. Acad. Sci. USA, 108, 14769–14774, 2011.

Kotlyakov, V. and Khromova, T.: in: Land Resources of Russia, Stolbovoi, V. and McCallum, I., Laxenburg, Austria, International Institute for Applied Systems Analysis and the Russian Academy of Science, CD-ROM, Distributed by the National Snow and Ice Data Center, Boulder, 2002.

Krasuk, A. A.: Soils of Lensk-Amginsk drainage-basin (Yakutsk district), Materials of the committee of Yakutsk ASSR, Issue of Academy of Science SSR, Moscow, 176 pp., 1927.

Kudryavtsev, V. A., Dostovalov, B. N., Romanovsky, N. N., Kondrat'yeva, K. A., and Melamed, V. G.. Geocryology (in Russian), Moscow University Press, 464 pp., 1978.

Kuhry, P., Dorrepaal, E., Hugelius, G., Schuur, E. A. G., and Tarnocai, C.: Potential Remobilization of Belowground Permafrost Carbon under Future Global Warming, Permafrost Periglac., 21, 208–214, 2010.

Kutzbach, L., Wagner, D., and Pfeiffer, E.-M.: Effect of microrelief and vegetation on methane emission from wet polygonal tundra, Lena-Delta, Northern Siberia, Biogeochem., 69, 341–362, 2004.

Kutzbach, L., Wille, C., and Pfeiffer, E.-M.: The exchange of carbon dioxide between wet arctic tundra and the atmosphere at the Lena River Delta, Northern Siberia, Biogeosciences, 4, 869–890, doi:10.5194/bg-4-869-2007, 2007.

Lee, H., Schuur, E. A. G., Inglett, K. S., Lavoie, M., and Chanton, J. P.: The rate of permafrost carbon release under aerobic and anaerobic conditions and its potential effects on climate, Glob. Change Biol., 18, 515–527, doi:10.1111/j.1365-2486.2011.02519.x, 2012.

Lembke, P., Ren, J., Alley, R. B., Allison, I., Carrasco, J., Flato, G., Fujii, Y., Kaser, G., Mote, P., Thomas, R. H., and Zhang, T.: Observations: Changes in Snow, Ice and Frozen Ground, in: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, Cambridge, UK and New York, NY, USA, 2007.

Lenton, T. M. and Schellnhuber, H. J.: Tipping elements: Jokers in the pack, Climate Change: Global Risks, Challenges, and Decisions, edited by: Richardson, K., Steffen, W., and Liverman, D., Cambridge University Press, Cambridge, UK, 2010.

Liebner, S., Zeyer, J., Wagner, D., Schubert, C., Pfeiffer, E.-M., and Knoblauch, C.: Methane oxidation associated with submerged brown mosses reduces methane emissions from Siberian polygonal tundra, J. Ecol., 99, 914–922, 2011.

Margesin, R. (Ed.): Permafrost Soils, Springer, Berlin, 348 pp., 2009.

Matsuura, Y. and Yefremov, D. P.: Carbon and nitrogen storage of soils in a forest-tundra area of northern Sakha, Russia, in: Proceedings of the Third Symposium on the Joint Siberian Permafrost Studies between Japan and Russia in 1994, Forest & Forest Products Research Unit, University of Sapporo, Sapporo, Japan, 97–101, 1995.

Maximovich, S. V.: Geography and Ecology of Cryogenic Soils of Mongolia, Cryosols, Permafrost-Affected Soils, edited by: Kimble, J. M., Springer, Berlin, 253–274, 2004.

Mazhitova, G. G., Kazakov, V. G., Lopatin, E. V., and Virtanen, T.: Geographic information system and soil carbon estimates for the Usa River basin, Komi Republic, Eurasian Soil Sci., 36, 123–135, 2003.

McGuire, A. D., Anderson, L. G., Christensen, T. R., Dallimore, S., Guo, L., Hayes, D. J., Heimann, M., Lorenson, T. D., Macdonald, R. W., and Roulet, N.: Sensitivity of the carbon cycle in the Arctic to climate change, Ecol. Monogr., 79, 523–555, 2009.

Nadelhoffer, K. J., Shaver, G. R., Giblin, A., and Rastetter, E. B.: Potential impacts of climate change on nutrient cycling, decomposition and productivity in Arctic ecosystems, Global Change and Arctic Terrestrial Ecosystems (Ecological Studies 124), Springer, Berlin, 349–364, 1997.

Naumov, Ye. M.: Soils and soil cover of northeastern Eurasia, Cryosols, Permafrost-Affected Soils, edited by: Kimble, J. M., Springer, Berlin, 161–184, 2004.

Oechel, W. C. and Billings, W. D.: Effects of Global Change on the Carbon Balance of Arctic Plants and Ecosystems, Arctic Ecosystems in a Changing Climate, Academic Press, San Diego, CA, 139–168, 1992.

Oechel, W. C., Hastings, S. J., Vourlrtis, G., Jenkins, M., Riechers, G., and Grulke, N.: Recent change of Arctic tundra ecosystems from a net carbon dioxide sink to a source, Nature, 361, 520–523, 1993.

Oechel, W. C., Vourlitis, G. L., Hastings, S. J., Zulueta, R. C., Hinzman, L., and Kane, D.: Acclimation of ecosystem CO_2 exchange in the Alaskan Arctic in response to decadal climate warming, Nature, 406, 978–981, 2000.

Okoneshnikova, M. V.: Humus of alas soils of Lena-Amginsk interfluves, Dissertation, Novosibirsk, 147 pp., 1994.

Orlov, D. S., Biryukova and, O. N., and Sakhanova, N. I.: Soil organic matter of Russia, Nauka, ISBN 5-02-003643-9, 256 pp., 1996 (in Russian).

Ozerskaya, S., Kochkina, G., Ivanushkina, N., and Gilichinsky, D.: Fungi in Permafrost, Permafrost Soils, edited by: Margesin, R., Springer, Berlin, 85–96, 2009.

Palmtag, J.: Soil organic carbon storage in continuous permafrost terrain with an emphasis on cryoturbation, Two case studies from NE Greenland and NE Siberia, Master thesis at the Department for Physical Geography and Quaternary Geology, Stockholm University, 2011.

Panikov, N. S.: Microbial Activity in Frozen Soils, Permafrost Soils, edited by: Margesin, R., Springer, Berlin, 119–148, 2009.

Pastukhov, A. V. and Kaverin, D. A.: Soil Carbon Pools in Tundra and Taiga Ecosystems of Northeastern Europe, Eurasian Soil Sci., 46, 958–967, 2013.

Pfeiffer, E.-M.: Methanfreisetzung aus hydromorphen Böden verschiedener naturnaher und genutzter Feuchtgebiete (Marsch, Moor, Tundra, Reisanbau) bodenkundliche Arbeiten, Hamburg, 37, 208 pp., 1998.

Pfeiffer, E.-M. and Janssen, H.: C-isotope analysis of permafrost soil samples of NE-Siberia, in: Joint Russian-American Seminar on Cryopedology and Global Change, edited by: Gilichinsky, D. A., Pushchino Research Center, Russian Academy of Science, Pushchino, 1992.

Pfeiffer, E.-M., Gundelwein, A., Becker, H., and Mueller-Lupp, T.: Soil organic matter (SOM) studies at Taimyr Peninsula, Polar Res., 237, 113–126, 1997.

Pfeiffer, E.-M., Wagner, D., Becker, H., Vlasenko, A., Kutzbach, L., Boike, J., Quass, W., Kloss, W., Schulz, B., Kurchatova, A., Pozdnyakov, V., and Akhmadeeva, I.: Modern processes in permafrost affected soils, Reports on Polar and Marine Research, 354, 22–54, 2000.

Pfeiffer, E.-M., Wagner, D., Kobabe, S., Kutzbach, L., Kurchatova, A., Stoof, G., and Wille, C.: Modern processes in permafrost affected soils, Reports on Polar and Marine Research, 426, 21–41, 2002.

Ping, C. L., Michaelson, G. J., and Kimble, J. M.: Carbon storage along a latitudinal transect in Alaska, Nutr. Cycl. Agroecosys., 49, 235–242, 1997.

Ping, C.-L., Clark, M. H., and Swanson, D. K.: Cryosols in Alaska, Cryosols, Permafrost-Affected Soils, edited by: Kimble, J. M., Springer, Berlin, 71–94, 2004a.

Ping, C.-L., Qiu, G., and Zhao, L.: The periglacial environment and distribution of cryosols in China, Cryosols, Permafrost-Affected Soils, edited by: Kimble, J. M., Springer, Berlin, 275–290, 2004b.

Ping, C. L., Michaelson, G. J., Jorgenson, M. T., Kimble, J. M., Epstein, H., Romanovsky, V. E., and Walker, D. A.: High stocks of soil organic carbon in the North American Arctic region, Nat. Geosci., 1, 615–619, 2008.

Ping, C. L., Michaelson, G. J., Kane, E. S., Packee, E. C., Stiles, C. A., Swanson, D. K., and Zaman, N. D.: Carbon stores and biogeochemical properties of soils under black spruce forest, Alaska, Soil Sci. Soc. Am. J., 74, 969–978, 2010.

Ping, C. L., Michaelson, G. J., Guo, L., Jorgenson, T., Kanevskiy, M., Shur, Y., Dou, F., and Liang, J.: Soil carbon and material fluxes across the eroding Alaska Beaufort Sea coastline, J. Geophys. Res., 116, G02004, doi:10.1029/2010JG001588, 2011.

Post, W. M.: Organic matter, global distribution in world ecosystems, in: Encyclopedia of Soil Sci., 2nd edn., edited by: Lal, R., Taylor & Francis, New York, 1216–1221, 2006.

Post, W. M., Emanuel, W. R., Zinke, P. J., and Stangenberger, A. G.: Soil carbon pools and world life zones, Nature, 298, 156–159, 1982.

Ramage, J.: Phytomass and soil organic carbon inventories related to land cover classification and periglacial features at Ari-Mas and Logata, Taimyr Peninsula, Master thesis at the Department for Physical Geography and Quaternary Geology, Stockholm University, unpublished, 2012.

Rivkina, E., Shcherbakova, V., Laurinavichius, K., Petrovskaya, L., Krivushin, K., Kraev, G., Pecheritsina, S., and Gilichinsky, D.: Biogeochemistry of methane and methanogenic archaea in permafrost, FEMS Microbiol. Ecol., 61, 1–15, 2007.

Rozhkov, V. A., Wagner, V. B., Kogut, B. M., Konyushkov, D. E., Nilsson, S., Sheremet, V. B., and Shvidenko, A. Z.: Soil Carbon Estimates and Soil Carbon Map for Russia, Working Paper WP-96-60, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1996.

Runkle, B. R. K., Sachs, T., Wille, C., Pfeiffer, E.-M., and Kutzbach, L.: Bulk partitioning the growing season net ecosystem exchange of CO_2 in Siberian tundra reveals the seasonality of its carbon sequestration strength, Biogeosciences, 10, 1337–1349, doi:10.5194/bg-10-1337-2013, 2013.

Sachs, T., Wille, C., Boike, J., and Kutzbach, L.: Environmental controls on ecosystem-scale CH_4 emission from polygonal tundra in the Lena River, J. Geophys. Res.-Biogeo., 113, G00A03, doi:10.1029/2007JG000505, 2008.

Sachs, T., Giebels, M., Boike, J., and Kutzbach, L.: Environmental controls on CH_4 emission from polygonal tundra on the microsite scale in the Lena River Delta, Siberia, Global Change Biol., 16, 3096–3110, doi:10.1111/j.1365-2486.2010.02232.x, 2010.

Sanders, T., Fiencke, C., and Pfeiffer, E.-M.: Small-scale variability of Dissolved Inorganic Nitrogen (DIN), C/N ratios and ammonia oxidizing capacities in various permafrost affected soils of Samoylov Island, Lena River Delta, Northeast Siberia, Polarforschung, 80, 23–35, 2010.

Schirrmeister, L., Grosse, G., Wetterich, S., Overduin, P. P., Strauss, J., Schuur, E. A. G., and Hubberten, H.-W.: Fossil organic matter characteristics in permafrost deposits of the northeast Siberian Arctic, J. Geophys. Res., 116, G00M02, doi:10.1029/2011JG001647, 2011.

Schuur, E., Bockheim, J., Canadell, J., Euskirchen, E., Field, C., and Goryachkin, S.: Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle, Biogeoscience, 58, 701–714, 2008.

Schuur, E., Vogel, J., Crummer, K., Lee, H., Sickman, J., and Osterkamp, T.: The effect of permafrost thaw on old carbon release and net carbon exchange from tundra, Nature, 459, 556–559, 2009.

Shi, Y. (Ed.): Map of Snow, Ice and Frozen Ground in China (1 : 4 000 000), with Explanatory Notes, China Cartographic Publishing House, Peking, 1988.

Shishov, L., Tonkonogov, V., Lebedeva, I., Gerasimova, M., and Krasilnikov, P.: Russian Soil Classification System: Second Approximation, Moscow, 342 pp., 2004.

Shcherbakova, V., Rivkina, E., Pecheritsyna, S., Laurinavichius, K., Suzina, N., and Gilichinsky, D.: Methanobacterium arcticum sp. nov., a methanogenic archaeon from Holocene Arctic permafros, Int. J. Syst. Evol. Micr., 61, 144–147, 2011.

Smith, C. A. S. and Veldhuis, H.: Cryosols of the Boreal, Subarctic, and Western Cordillera Regions of Canada, Cryosols, Permafrost-Affected Soils, edited by: Kimble, J. M., Springer, Berlin, 119–138, 2004.

Soil Survey Staff: Keys to Soil Taxonomy, United States Department of Agriculture & Natural Resources Conservation Service, Washington DC, 329 pp., 2010.

Sokolov, I. A., Ananko, T. V., and Konyushkov, D.Ye.: The soil cover of Central Siberia, Cryosols, Permafrost-Affected Soils, edited by: Kimble, J. M., Springer, Berlin, 303–338, 2004.

Stolbovoi, V.: Carbon in Russian soils, Clim. Change, 55, 131–156, 2002a.

Stolbovoi V.: Soil Carbon Pools, CO_2 and CH_4 Emissions, in: Land Resources of Russia, edited by: Stolbovoi V. and McCallum, I., Laxenburg, Austria: International Institute for Applied Systems Analysis and the Russian Academy of Science, CD-ROM, Distributed by the National Snow and Ice Data Center, Boulder, 2002b.

Stolbovoi, V. V., Savin, I., and Sheremet, B.: Soils and Soil Reference Profiles, in: Land Resources of Russia, edited by: Stolbovoi V., and McCallum, I., Laxenburg, Austria, International Institute for Applied Systems Analysis and the Russian Academy of Science. CD-ROM, Distributed by the National Snow and Ice Data Center, Boulder, 2002.

Strauss, J., Schirrmeister, L., Grosse, G., Wetterich, S., Ulrich, M., Herzschuh, U., and Hubberten, H.-W.: The deep permafrost carbon pool of the Yedoma Region in Siberia and Alaska, Geophys. Res. Lett., 40, 6165–6170, doi:10.1002/2013gl058088, 2013.

Targulyan, V. O.: Soil Formation and Weathering in Cold Humid Zones, Moscow, 267 pp., 1971.

Tarnocai, C.: Cryosols of Arctic Canada, Cryosols, Permafrost-Affected Soils, edited by: Kimble, J. M., Springer, Berlin, 95–118, 2004.

Tarnocai, C. and Ballard, M.: Organic carbon in Canadian soils, in: Soil Processes and Greenhouse Effect, edited by: Lal, R., Kimble, J. M., and Levine, E., USDA Soil Conservation Service, Lincoln, NE, 31–45, 1994.

Tarnocai, C. and Smith, C. A. S.: The formation and properties of soils in the permafrost regions of Canada, in: Cryosols: the Effect of Cryogenesis on the Processes and Peculiarities of Soil Formation, Proceedings of the 1st International Conference on Cryopedology, 10–16 November, Pushchino, Russia, edited by: Gilichinsky, D. A., 21–42, Russian Academy of Sciences, Pushchino, Russia, 1992.

Tarnocai, C., Kimble, J., and Broll, G.: Determining Carbon Stocks in Cryosols using the Northern and Mid Latitudes Soil Database, in: Permafrost, vol. 2, edited by: Philips, M., Springman, S., and Arenson, L. U., 1129–1134, 2003.

Tarnocai, C., Swanson, D., Kimble, J., and Broll, G.: Northern Circumpolar Soil Carbon Database, Digital Database, Research Branch, Agriculture and Agri-Food Canada, Ottawa, Canada, 2007.

Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P. Mazhitova, G., and Zimov, S.: Soil organic carbon pools in the northern circumpolar permafrost region, Global Biogeochem. Cy., 23, GB2023, doi:10.1029/2008GB003327, 2009.

van der Molen, M. K., van Huissteden, J., Parmentier, F. J. W., Petrescu, A. M. R., Dolman, A. J., Maximov, T. C., Kononov, A. V., Karsanaev, S. V., and Suzdalov, D. A.: The growing season greenhouse gas balance of a continental tundra site in the Indigirka lowlands, NE Siberia, Biogeosciences, 4, 985–1003, doi:10.5194/bg-4-985-2007, 2007.

van Everdingen, R. O. (Ed.): Multi-Language Glossary of Permafrost and Related Ground-Ice Terms, National Snow and Ice Data Center/World Data Center for Glaciology, 1998, revised 2005.

Vieira, G., Bockheim, J., Guglielmin, M., Balks, M., Abramov, A., and Boelhouwers, J.: Thermal state of permafrost and active-layer monitoring in the Antarctic: advances during the international Polar Year 2007–2009, Permafrost Periglac., 21, 182–197, 2010.

Wagner, D. and Liebner, S.: Global Warming and Carbon Dynamics in Permafrost Soils: Methane Production and Oxidation, Permafrost Soils, edited by: Margesin, R., Springer, Berlin, 219–236, 2009.

Wagner, D., Gattinger, A., Embacher, A., Pfeiffer, E.-M., Schloter, M., and Lipski, A.: Methanogenic activity and biomass in Holocene permafrost deposits of the Lena Delta, Siberian Arctic and its implication for the global methane budget, Glob. Change Biol., 13, 1089–1099, 2007.

Wagner, D., Kobabe, S., and Liebner, S.: Bacterial community structure and carbon turnover in permafrost-affected soils of the Lena Delta, northeastern Siberia, Can. J. Microbiol., 55, 73–83, 2009.

Wille, C., Kutzbach, L., Sachs, T., Wagner, D., and Pfeiffer, E.-M.: Methane emission from Siberian arctic polygonal tundra: eddy covariance measurements and modeling, Glob. Change Biol., 14, 1395–1408, 2008.

Wüthrich, C., Möller, I., and Thannheiser, D.: CO_2-fluxes in different plant communities of a high-Arctic tundra watershed (Western Spitsbergen), J. Veg. Sci., 10, 413–420, 1999.

Zhang, T., Barry, R. G., Knowles, K., Heginbottom, J. A., and Brown, J.: Statistics and characteristics of permafrost and ground ice distribution in the Northern Hemisphere, Polar Geogr., 23, 147–169, 1999.

Zhang, T., Barry, R. G., Knowles, K., Ling, F., and Armstrong, R. L.: Distribution of seasonally and perennially frozen ground in the Northern Hemisphere, Permafrost, edited by: Phillips, M., Springman, S., and Arenson, L., Swets & Zeitlinger Publishers, 2003.

Zimov, S. A., Voropaev, Y. V., Semiletov, I. P., Davidov, S. P., Prosiannikov, S. F., Chapin, F. S., Chapin, M. C., Trumbore, S., and Tyler, S.: North Siberian lakes: a methane source fuelled by Pleistocene carbon, Science, 277, 800–802, 1997.

Zimov, S. A., Davydov, S. P., Zimova, G. M., Davydova, A. I., Schuur, E. A. G., Dutta, K., and Chapin III, F. S.: Permafrost carbon: Stock and decomposability of a globally significant carbon pool, Geophys. Res. Lett., 33, L20502, doi:10.1029/2006GL027484, 2006.

Zubrzycki, S., Wetterich, S., Schirrmeister, L., Germogenova, A., and Pfeiffer, E.-M.: Iron-oxides and pedogenesis of modern gelisols and paleosols of the Southern Lena Delta, Siberia, Russia, in: Proceedings of the 9th International Conference on Permafrost, edited by: Kane, D. L. and Hinkel, K. M., University of Alaska Fairbanks, Institute of Northern Engineering, 2095–2100, 2008.

Zubrzycki, S., Kutzbach, L., Vakhrameeva, P., and Pfeiffer, E.-M.: Variability of Soil Organic Carbon Stocks of Different Permafrost Soils: Initial Results from a North-South Transect in Siberia, in: Proceedings of the 10th International Conference on Permafrost, edited by: Hinkel, K. M., Salekhard, 485–490, 2012a.

Zubrzycki, S., Kutzbach, L., and Pfeiffer, E.-M.: Böden in Permafrostgebieten der Arktis als Kohlenstoffsenke und Kohlenstoffquelle, Polarforschung, 81, 33–46, 2012b.

Zubrzycki, S., Kutzbach, L., Grosse, G., Desyatkin, A., and Pfeiffer, E.-M.: Organic carbon and total nitrogen stocks in soils of the Lena River Delta, Biogeosciences, 10, 3507–3524, doi:10.5194/bg-10-3507-2013, 2013.