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Permafrost-Affected Soils of the Russian Arctic and their Carbon Pools

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

Institute of Soil Science, KlimaCampus, University of Hamburg, Hamburg, Germany

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

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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 most 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 three meters of ground. Considering the observed progressive climate change and the projected polar amplification, permafrost-affected soils will undergo fundamental property changes. Higher turnover and mineralization 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. As a result, permafrost regions with their distinctive soils are likely to trigger an important tipping point within the global climate system, with additional political and social implications. 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 and Russia, a particular group of soils has developed during the Quaternary whose diversity is based primarily on special cryopedogenetic processes within the pedosphere of our Earth system. Among the most important cryopedogenetic processes are the

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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 $> 2^{\circ}$), 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 their total land surface (Baranov, 1959; Shi, 1988; Zhang, 1999, 2003; French, 2007). They are called permafrost areas if their subsurface soils and sediments maintain temperatures of 0 °C or below during 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 on the thaw-freeze cycle. This distinguishes, in the upper ground area, the seasonal thaw layer from the underlying permanently frozen ground (Fig. 2b).

A spatial differentiation of the permafrost areas is based on the portion of the areas on top of the permafrost in relation to the total surface of an area in 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 (from Latin *gelus* = ice) as permafrost-affected soil class (Fig. 3 and Fig. 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 meter 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 (Fig. 2 and Fig. 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 Russian classification systems, permafrost-affected soils with cryoturbation and cryometamorphosis, widespread in Russian Federation, are treated as Cryozems in a separate soil class. All other soils of these areas without these two characteristics are allocated to other soil classes with the additional mention of the subjacent permafrost (such as *alluvisol* with underlying permafrost (Shishov et al., 2004)). Alternatively, permafrost is included as a state of soils and their specifications (Elovskaya, 1987). 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 described independently, but can be counted as paleo soils (such as recent *podzol* on top of cryoturbated nonsorted circles). 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 the fiftieth degree latitude covers 27 % of the land mass (Jones et al., 2010) and corresponds to approx. 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), (see Fig. 5).

The properties and the spatial distribution of the permafrost-affected soils within the various countries were collected by Tarnocai (2004) und 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 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 carbon stores

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

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incorporated. Cryoturbation also leads to the inclusion of organic matter in 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 was able to accumulate over millennia 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 are 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 currently is being 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 the database (100 % = "reliable," 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 % (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 lifezones, 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 $kg\,m^{-2}$ and 25 $kg\,m^{-2}$ for the upper 30 cm of the soils. When the authors inspected variously defined depths of the thaw soils on the day of sampling, the carbon pool lay between 13 $kg\,m^{-2}$ and 29 $kg\,m^{-2}$. The results of the studies that examined the carbon pool up to a depth of 100 cm vary between 4 $kg\,m^{-2}$ and 71 $kg\,m^{-2}$ (Table 1). Furthermore, these data reveal the very high fluctuation range of the results from different permafrost regions.

Observing the data of current literature on 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 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

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mass of carbon of the entire global vegetation biomass or the atmosphere of 650 Pg and 750 Pg (IPCC, 2007), respectively. The carbon quantities stored in permafrost-affected soils are therefore to be considered one of the most important factors 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 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, but also in the permafrost areas themselves must be expected (Fig. 7).

These processes show the positive feedback effects in permafrost landscapes or in the cryosphere of our Earth system that are not yet sufficiently considered in the climate models relating to temperature projection. Because of these complex effects, the

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permafrost areas in particular represent an important possible 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 differently 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 during the past five years compared to the last 20 years (Fig. 8).

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 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).

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The near-surface soils of the permafrost areas of North 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, 9 and 10), 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. 10–12 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 North 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 centers, respectively, lay between 4.3 and 28 $mg\,CH_4\,m^{-2}\,d^{-1}$ (Kutzbach et al., 2004), and between 4.9 and 100 $mg\,CH_4\,m^{-2}\,d^{-1}$ (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;

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Zubrzycki et al., 2012a; Zubrzycki et al., 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 not only recorded in the Siberian Arctic, but also in the European–Russian Arctic by means of field work, and 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 m through 3 m of the carbon pools in the permafrost-affected soils, the study of special 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 content, which however, is subject to strong fluctuations depending on the studied site. It is usually between 1 %wt and 4 %wt, but can also reach values of up to 17 %wt 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. The more comprehensive data basis is necessary for a better understanding of the interactions between the particular climate, soil and vegetation conditions in the permafrost areas. From this information, a drawing of conclusions will be enabled re-

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garding the factors of the processes occurring today or the future remobilization of the labile organic carbon of the permafrost-affected soils. 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 reanalyzed. 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.

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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 = 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 (2002)	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, Labaz Lake
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		East European Russian tundra
Stolbovoi (2002)	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, Labaz Lake
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 North Siberia
Tarnocai et al. (2009)		2.6	407	Yedoma-landscapes in North Siberia
Schirrmeister et al. (2011)	1	17	250–375	20 coastal exposures in North Siberia
Strauss et al. (2013)	0.8	4.6	58–371	Yedoma-landscapes

Table 2. Chemical properties of two exemplary soil profiles (see Fig. 10 and Fig. 12) 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	> 100	Frequent
Bgf	31–64	Sandy loam	Yes	5.0	4.2	30	None

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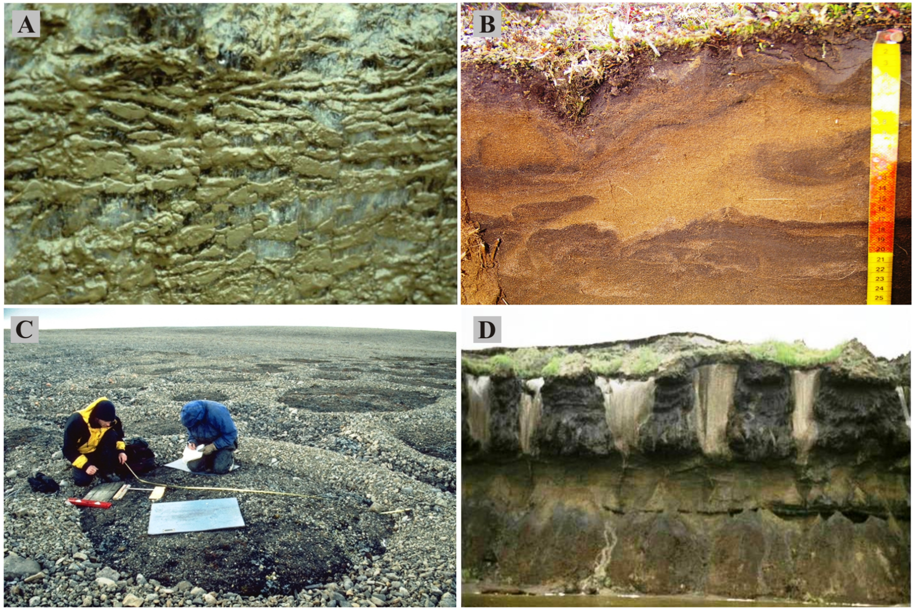

Fig. 1. Results of cryopedogenic processes in permafrost. **(A)** segregated ice, Lena River Delta, Siberia 2007. **(B)** cryoturbation in the top soil of a Gelisol (*Typic Psammoturbel*), Arga Complex, northwestern Lena River Delta, Siberia 2009. **(C)** Sorted circles (frost patterns) formed by frost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

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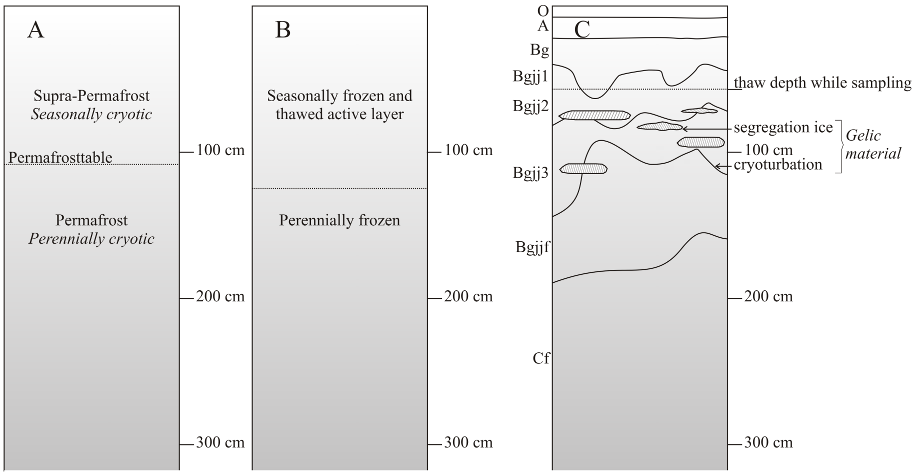

Fig. 2. Schematic view of properties of permafrost-affected soils. **(A)** the soil-thermal properties. The permafrost table divides the supra-permafrost (temperature can temporarily be higher than 0 °C within two consecutive years) and the permafrost (temperature is at least two consecutive years lower 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.

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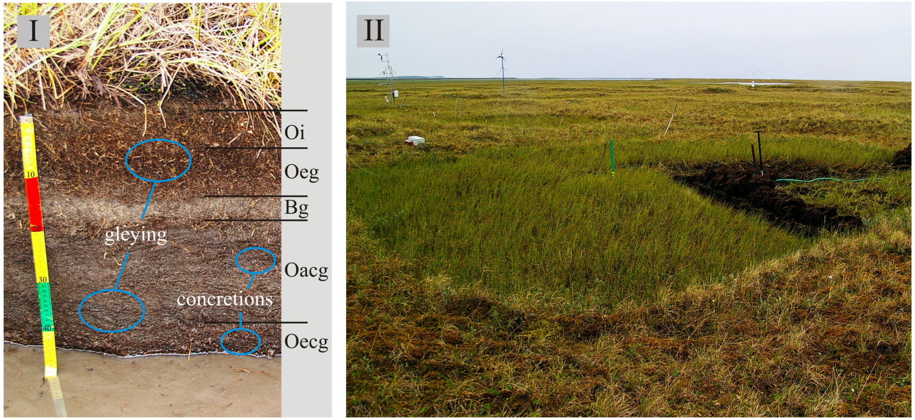
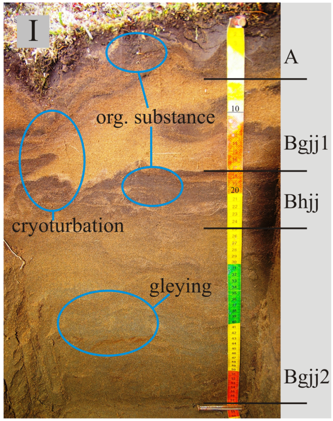


Fig. 3. A non cryoturbated organic dominated permafrost-affected soil, *Typic Historthel* **(I)** and the study area it is from **(II)** – Samoylov Island, central Lena River Delta, Siberia 2007. **Historthel** = Great Group: **Hist** = (histos) = tissue (plant); Suborder: **orth** = Orthels are soils with little or no cryoturbation and except polygons, patterned ground is leaking; Order: **el** = formative element of Gelisols = lat. Gelu = 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 characterized 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".



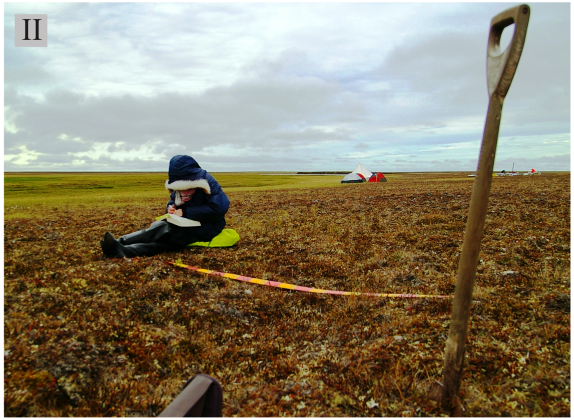


Fig. 4. A sand-dominated and cryoturbated permafrost-affected soil, *Typic Psammoturbel* **(I)** and the study area it is from **(II)** the Arga Complex, northwestern Lena River Delta, Siberia 2009. **Psammoturbel** = Great Group: **Psamm(o)** = (psamm) = sand; Suborder: **turb** = lat. Turbatio = disturbance; Order: **el** = formative element of Gelisols= lat. Gelu = 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.

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Fig. 5. Soil map of territories above 50° N. The legend represents soils dominating this area and Andosols that developed from volcanic ash and are prevalent in Iceland, Kamchatka and Alaska. Soil classification according to the World Reference Base for Soil Resources (FAO, 2007). Figure slightly modified from Jones et al., 2010.

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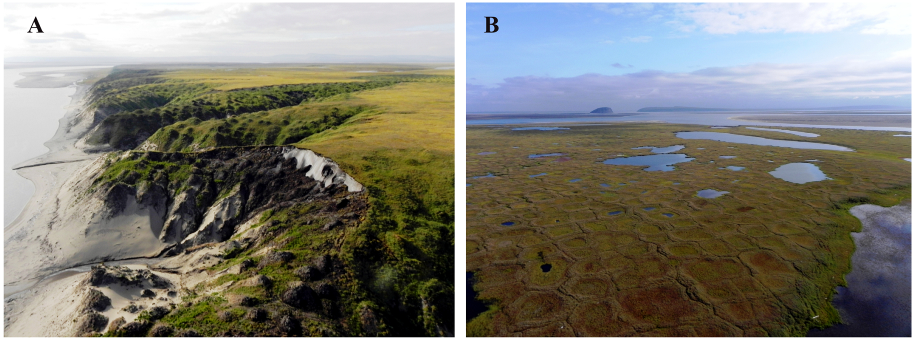

Fig. 6. Examples of underrepresented landscapes in the Northern Circumpolar Soil Carbon Database (NCSCD). **(A)** Yedoma landscape of Kurungnakh Island. An erosional river cliff with exposed ice-rich sediments. **(B)** polygonal tundra of Samoylov Island. Both islands are located in the Lena River Delta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

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Permafrost-Affected Soils of the Russian Arctic and their Carbon Pools

S. Zubrzycki et al.

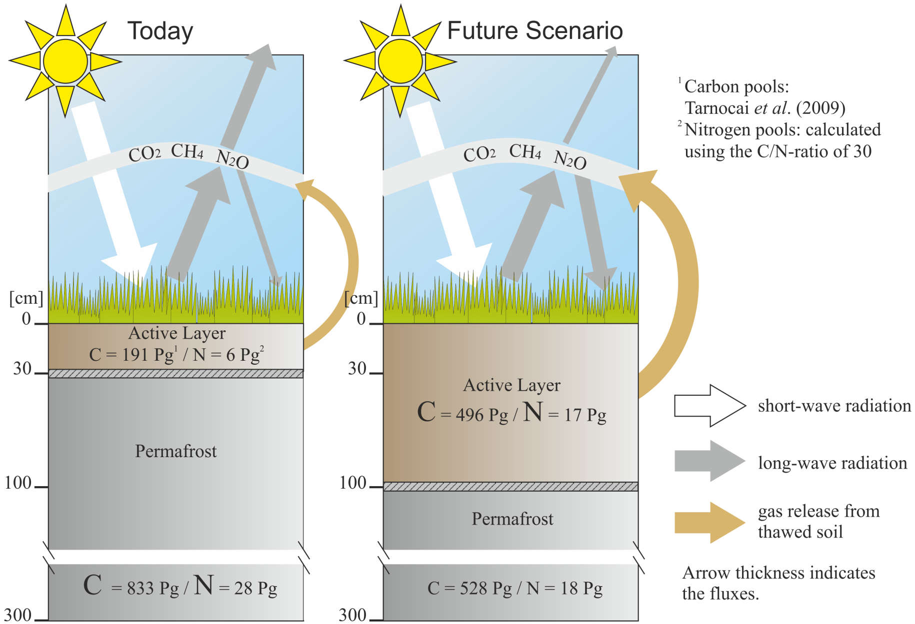

Fig. 7. Schematic illustration of the carbon and nitrogen dynamic feedbacks and the climate-driven changes within the permafrost-affected soils. C pools (Tarnocai et al., 2009), N pools calculated using the C/N ratio of 30. Figure according to Beer (2009).

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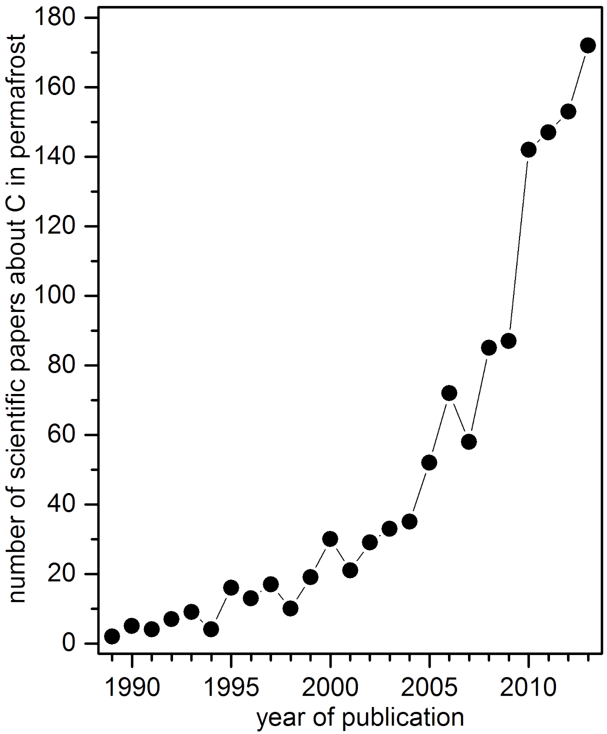

Fig. 8. Number of scientific papers published between 1989 and 2013 as a result of a search for the keywords "permafrost + carbon" in Web of Science (www.webofknowledge.com) on 14.01.2014.

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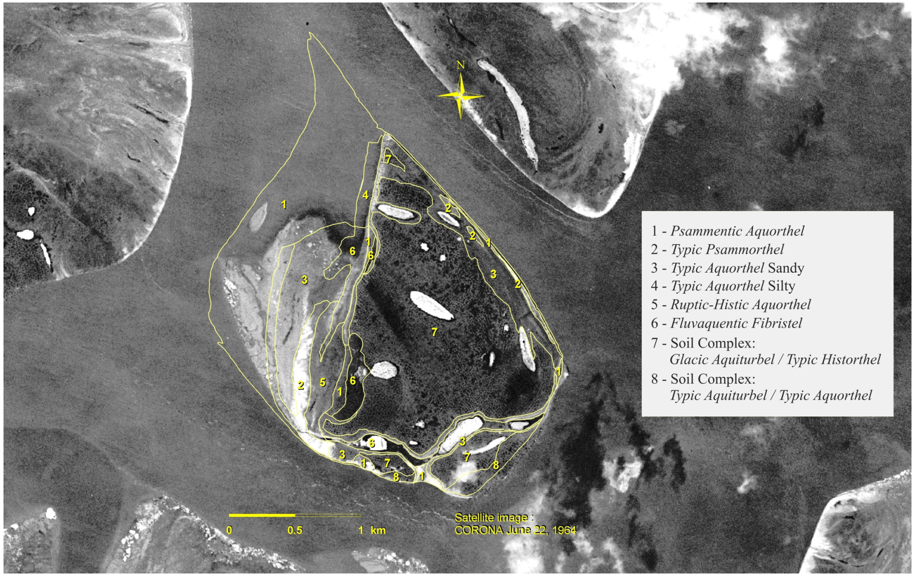

Fig. 9. A soil map of Samoylov Island as a result of long-term soil research within this area of the Lena River Delta. Generated from data by Pfeiffer et al. (2000, 2002) (see Sanders et al., 2010). Soil classification according to the US Soil Taxonomy (Soil Survey Staff, 2010). The plotted coast line from July 1964 points out the high coastal dynamics within the beach and floodplain in the western part of island.

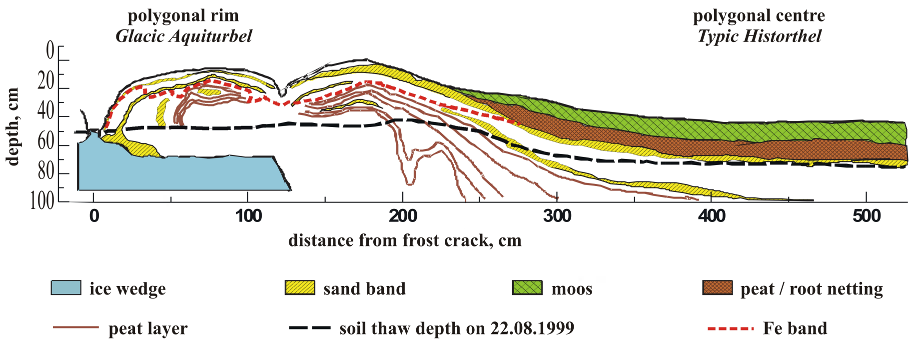

Fig. 10. Cross section of a low centred polygon with a surface depression above the ice wedge and another one at the ice wedge's end. Soils that have developed in this polygon are a *Glacic Aquiturbel* at the polygon rim above the ice wedge and a *Typic Historthel* in the polygon centre. Scheme compiled from field observations of 22.08.1999.

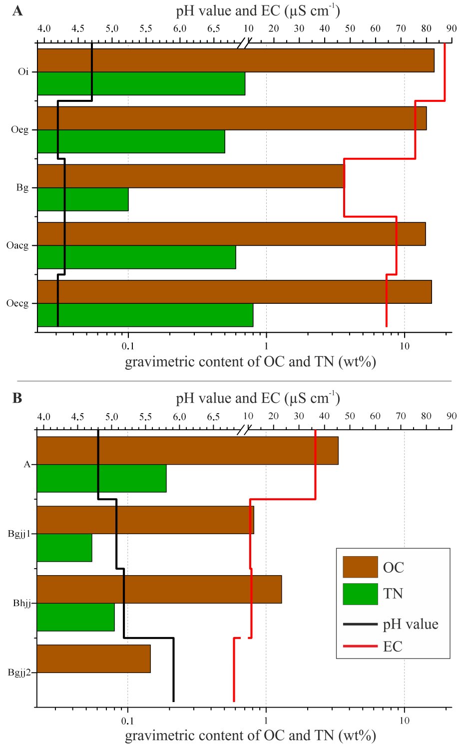

Fig. 11. Chemical analyses of in Figs. 3 and 4 presented permafrost-affected soils. **(A)** Chart for *Typic Historthel*. **(B)** Chart for *Typic Psammoturbel*. For better comparison, both charts use the same scaling. The upper scale is for the pH value and electrical conductivity (µS cm^{-1}). Both 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.

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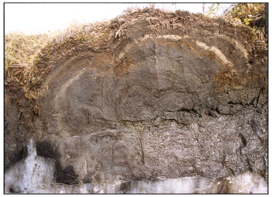

Glacic Aquiturbel
(polygonal rim)
- water level: 45 cm below soil surface
- thaw depth: 47 cm (8. August)
- distinctly oxic in the top soil, reduced conditions below
- ice wedge at 70 cm
- cryoturbated

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

Fig. 12. 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. 10).

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