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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

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Abstract: During the Russian-German expedition to the island Samoylov in the Northeast Siberian Lena River Delta in summer 2008, permafrost-affected soils were characterized and samples were collected over the vegetation period (04 July-07 September). These samples were analyzed for composition of the dissolved inorganic nitrogen (DIN) and the nitrification capacities for evidence of the mechanisms of the N-Cycle in this investigation site. Ammonium, nitrite and nitrate as DIN compounds have small amounts and their concentrations depend on the content of organic matter, the air and soil temperature and the vegetation cover of the soils. Ammonium was detectable only in organic-rich soils at the beginning of the vegetation period (up to 10 $\mu g\ g^{-1}$ dw). Nitrite was only enriched on relative cold days with soil temperatures below 5 °C (up to 2.3 $\mu g\ g^{-1}$ dw). At the end of the vegetation period, nitrate enrichment was limited to soils without vegetation (up to 90 $\mu g\ g^{-1}$ dw). The C/N ratios indicating the degree of decomposition of the soils were dependent on organic contents. Relatively high nitrification capacities were found in the dry and sandy soils of the floodplain and in the dry river terrace. In the polygonal tundra nitrification capacity was only detectable in the mineral horizon of the polygon rim. The small-scale variability of DIN availability as well as changes in the nitrifying capacities argue for nitrogen as the decisive - limiting - factor in the ecosystem soil of Samoylov Island.

Zusammenfassung: Während der russisch-deutschen Expedition auf die, im nordsibirischen Lena-Delta gelegene, Insel Samoylow wurden im Sommer 2008 verschiedene Permafrostböden charakterisiert und über die Vegetationsperiode beprobt. Diese Proben wurden auf ihre Zusammensetzung an gelösten anorganischen Stickstoffverbindungen (DIN) und die potentiellen Nitrifikationsraten untersucht, um Hinweise auf die Mechanismen des N-Kreislaufs im Untersuchungsgebiet zu bekommen. Gelöste anorganische Stickstoffverbindungen (DIN), wie Ammonium, Nitrit und Nitrat, wurden in geringen Mengen nachgewiesen, variieren kleinräumig und sind abhängig vom Gehalt der Böden an organischer Substanz, der Luft- und Bodentemperatur und der Bedeckung der Böden mit Vegetation. Ammonium war vor allem in den Böden mit einem hohen Gehalt an organischer Substanz zu Beginn der Vegetationsperiode nachweisbar (bis etwa 10 $\mu g\ g^{-1}$ TG). Nitrit wurde nur an relativ kalten Tagen mit Lufttemperaturen <10 °C und Bodentemperaturen <5 °C angereichert (bis zu 2,3 $\mu g\ g^{-1}$ TG). Am Ende der Vegetationsperiode reicherte sich Nitrat nur in den Böden ohne Vegetationsbedeckung an (bis zu 90 $\mu g\ g^{-1}$ TG). Die C/N-Verhältnisse, als ein Hinweise für den Zersetzungsgrad der Böden, variieren mit dem Gehalt an organischer Substanz. In den trockenen und sandigen Böden der Überflutungsebene und der trockenen Flussterrasse sind hohe potentielle Nitrifikationsraten zu finden. In der polygonalen Tundra können potentielle Nitrifikationsraten nur in Mineralhorizonten des Polygonwalls nachgewiesen werden. Die kleinräumige Variabilität der Verfügbarkeit an DIN und die variierenden potentiellen Nitrifikationsraten machen deutlich, dass Stickstoff ein bestimmender – limitierender – Faktor für das Ökosystem Boden auf der Insel Samoylow ist.

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INTRODUCTION

One quarter of the terrestrial surface of the northern hemisphere is covered by permafrost-affected soils (ZHANG et al. 1999), which stores about 15 to 30 % of the global organic soil carbon (POST et al. 1982, PING et al., 2008, TARNOCAI et al. 2009a, ZIMOV et al. 2010). In recent years, permafrost soils have received much attention because of global climate changes. Soils that are strongly affected by the underlying permafrost are termed Gelisols (SURVEY STAFF 2006) or Cryosols (FAO, 2006) and are mainly covered by tundra, i.e. treeless ecosystems. Freeze-thaw cycles and cryopedogenesis lead to the formation of patterned grounds with prominent microrelief like ice-wedge polygons or sand wedges. The prominent micro-relief causes pronounced small-scale variability of soil types, vegetation and soil hydrology (KESSLER & WERNER 2003) and the short summer period leads to formation of a thawed active layer near to the surface. Within this layer most of the chemical, physical and microbial processes take place.

For the global carbon and nitrogen cycle the tundra soils play an important role; besides representing a large global carbon pool, they retain more than twice as much N as temperate soils (POST et al. 1985, HOBBIE et al. 2000). Although tundra soils – mostly also permafrost affected soils – store high amount of nitrogen in the organic matter, the ecosystem remains nitrogen limited since only a small amount of the total nitrogen is available as inorganic N (DIN) such as ammonium (NH_4^+) or nitrate (NO_3^-) or dissolved organic nitrogen (DON) (SCHIMEL & BENNETT 2004, KAISER et al. 2005). In the Arctic, N-limitation is caused by very low N-deposition (HOLLAND et al. 1999) and very small N-fixation rates in contrast to temperate ecosystems (CLEVELAND et al. 1999, HOBARA et al. 2006). Furthermore, microbial decomposition of organic matter and therefore N-mineralization is restricted by low temperatures, high water saturation conditions, a short vegetation period, lower litter quality, high C/N ratios and hence low nutrient availabilities (MACK et al. 2004, KAISER et al. 2005, MEYER et al. 2006, RODIONOV et al. 2007). Some authors report that the mineralization of organic matter is spatially decoupled for C and N since most N-mineralization takes place in the mineral horizons whereas C-mineralization mainly takes place in the organic horizons (NADELHOFFER et al.1991, KAISER et al. 2005, MEYER et al. 2006). In the anaerobic water-saturated organic soils the nitrification as a part of the N-mineralization could not takes place and ammonium enriched, but the C-mineralization also takes place in anaerobic condition and methane is emitted. A further important characteristic of these nitrogen-limited ecosystems is that plants and micro-organisms may take up organic nitrogen, but will not release ammonium to the surrounding soil (Jones & Kieland 2002, Schimel & Bennett 2004, Hobbie & Hobbie 2006).

Aber (1992) described an ecosystem as N-limited i.e., if 100 % of the available nitrogen is ammonium, the soils have a high C/N ratio and there is a high CH_4 production and a zero N_2O production. In contrast an N-saturated ecosystem is characterized by high N_2O and low CH_4 production, respectively, low C/N ratios and the DIN composed of ammonium (50 to 75 %) and 25 to 50 % nitrate. Generally, arctic ecosystems have been presumed to be N-limited and only low concentrations of dissolved and total nitrogen were detectable (Schimel et al. 1996). However Weintraub & Schimel (2003) suggest that beside nitrogen other factors such as soil temperature and moisture limit the growth of micro-organisms. In addition the net primary production (NPP) is generally nutrient- limited in arctic tundra ecosystems (Jonasson et al. 1999, Shaver & Chapin 1980, Shaver et al. 1998). Therefore in N-limited ecosystems plants and micro-organisms are in competition for rare nitrogen compounds like DIN, amino acids and other organic N forms (Schimel & Bennett 2004). The turnover of soil micro-organisms has been demonstrated to be the largest source of dissolved organic and inorganic nitrogen available to plants over a growing season (Schmidt et al. 2007).

Very little is known about the nitrogen dynamics and their control by soil properties in cold environments with a very short vegetation period. The data on nitrogen dynamics are predominantly available from the arctic tundra of Alaska and Svalbard (Norway) but are rare from the Russian tundra (Weintraub & Schimel 2005, Bardgett et al. 2007). In Russia there have been some studies in West Siberia (Gundelwein 1998, Kaiser et al. 2005, Meyer et al. 2006) and on the Taimyr Peninsula (Wolfe et al. 1999). In recent years there have been many studies about the carbon cycle and therefore the CO_2 and CH_4 emissions with this relevance for the climate change (IPPC 2001, Wagner et al. 2005, Knoblauch et al. 2008, Zimov et al. 2010).

Carbon and nitrogen dynamics were examined in relation to the small-scale variability of the soils of Samoylov Island to test the hypothesis that soil nitrogen availability can be used to indicate nitrogen limitation of tundra ecosystems.

INVESTIGATION AREA

The Lena River Delta is located in northeastern Siberia, where the Lena River cuts through the Verkhoyansk Mountains Ridge and discharges into the Laptev Sea, which is part of the Arctic Ocean. The study site is located on Samoylov Island (72°22' N, 126°28' E) (Hubberten et al. 2006), situated at one of the main Lena River channels, the Olenyokskaya Channel in the southern part of Lena Delta (Fig. 1).

Samoylov Island can be divided into two major geomorphological units (Akhmadeeva et al. 1999), which vary in their moisture regime and contents of organic matter in the soils. The western part of Samoylov represents a relative young floodplain up to 4 m above river level (a.r.l.), which is flooded annually in spring. The eastern part of Samoylov is formed by a higher-elevated (10-16 m a.r.l.) river terrace of late Holocene age (Pavlova & Dorozhkina 1999; Fig. 2). The river terrace is flooded only during extreme flooding events (Kutzbach 2005).

The climate in the Lena River Delta is arctic with continental influence and characterized by low temperatures and low precipitation. The mean annual air temperature, measured at the meteorological station in Tiksi, which is located about 110 km to the south-east of the investigation site directly on the

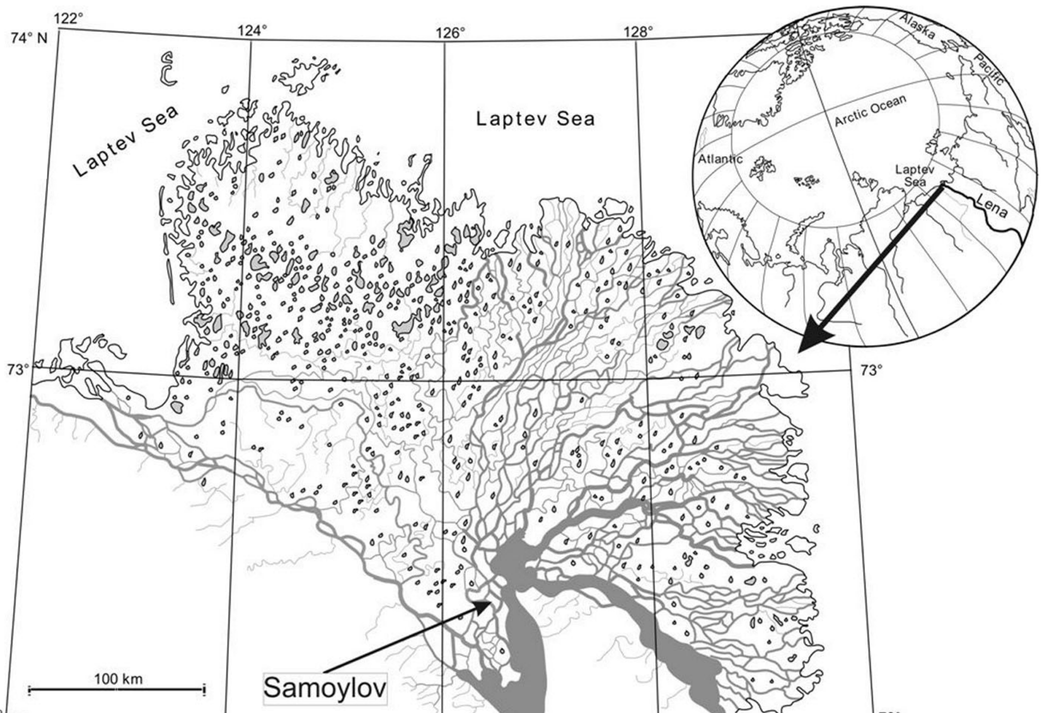

Fig. 1: Map of the Lena River Delta with location of the study site on the Samoylov island.

Abb. 1: Karte des Lena-Deltas mit Lage des Untersuchungsgebietes auf der Insel Samoylow.

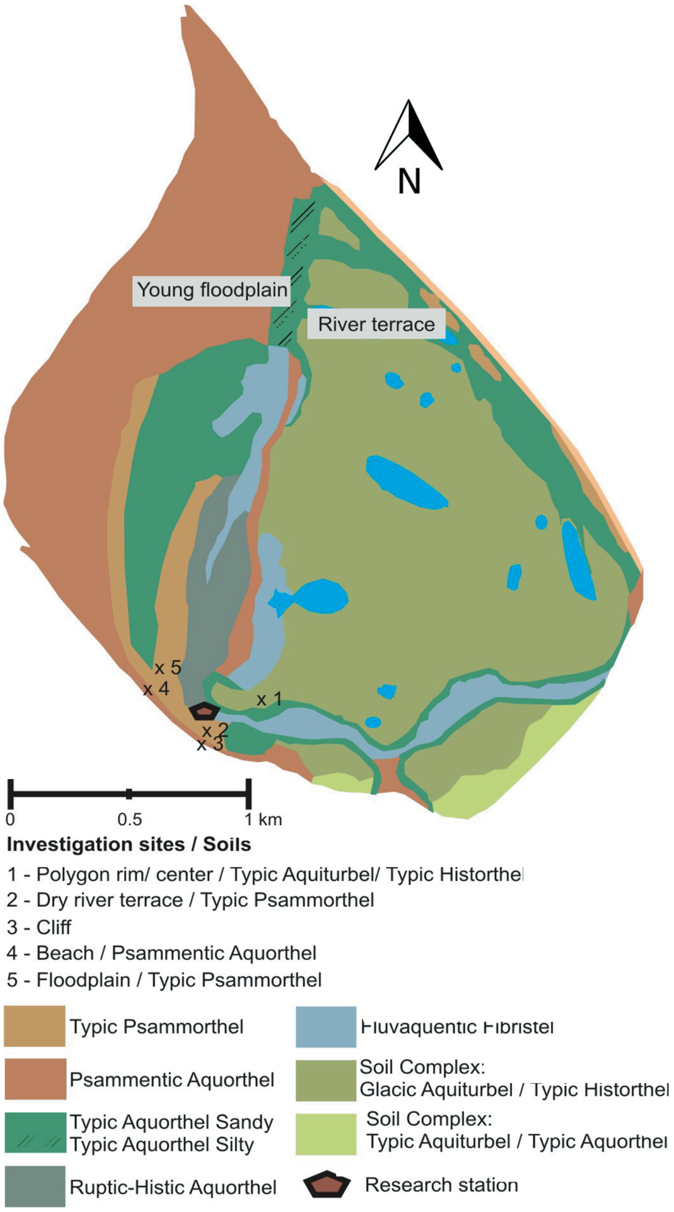

Fig. 2: Soil map of the Samoylov Island based on data of PFEIFFER et al. (1999; 2000; 2002) with location of investigated sites.

Abb. 2: Bodenkarte der Insel Samoylow nach Daten von PFEIFFER et al. (1999, 2000, 2002) mit Lage der Untersuchungsstandorte.

coast of the Laptev Sea, was -13.5 °C during the 30-year period 1961-1990; the mean annual precipitation in the same period was 323 mm. The extreme climatic contrasts between polar day and night typical for continental polar regions are clearly visible in average temperatures of the warmest month August and the coldest month January with 11.5 °C and -28.0 °C, respectively (ROSHYDROMET 2008).

MATERIAL AND METHODS

Since 1998, soil studies were carried out on Samoylov Island during several expeditions to the Lena River Delta (PFEIFFER et al. 1999, PFEIFFER et al. 2000, PFEIFFER et al. 2002). During the summer expedition in 2008 (04 July to 07 September) soil samples were collected down to the permafrost at five different locations (Fig. 2). Soils were sampled at each site at two to three different depths with three replicates each (for sampling depths see Tab. 1). Sample size was between 500 and 1000 g each. Two sites were situated at the young floodplain and three sites at the river terrace. At the young floodplain, samples were taken from the beach (site 4) without vegetation and the floodplain (site 5) covered by willow shrub (Fig. 2). These alluvial soils are characterized by sandy and silty fluvial deposition by the Lena River with high ground water table at the beach and low soil moisture conditions above the permafrost at sites at the floodplain. At the higher situated river terrace samples were taken from the polygonal tundra (site 1), dominated by low-centred ice-wedge polygons, a dry plain area with sand wedges (site 2) and the cliff near the shore of the Lena River (site 3; Fig. 2).

Pedological descriptions of permafrost soils including Munsell soil colour (MUNSELL 1975), fresh weight, soil texture and structure, organic matter, bulk density, root density and extent of hydromorphic features were done and the permafrost soils were classified by soil taxonomy (SOIL SURVEY STAFF 2006), World Reference Base for Soil Resources (WRB; FAO 2006) and the Russian classification system (RSS; ELOVSKAYA 1987).

For measurement of the potential nitrification we used the modified ISO/DIN 15685:2001 standard tests. 12.5 g fresh soil was taken on the 15 July 2008 weighs in 50 ml 0.75 mM ammonium sulfate solution. The bottle was shacked at 125 rpm at in situ temperature. The activities were measured by nitrite formation up to a period of six weeks in the field. Samples were taken twice a week.

In addition soil samples were taken every two weeks during the summer expedition for measuring dry weight, C/N ratio, dissolved inorganic nitrogen (DIN: ammonium, nitrite and nitrate) and pH. For sampling, a 30 cm-deep small pit alternative to the frozen permafrost table was opened with a spade. One pit was digged per investigation site and two mixed replicated of bulk soil were collected in different depths (see Tab. 1). Dry weight, nitrite and pH were directly measured in our field laboratory in two replicates after homogenizing the samples by sieving (<2 mm). A sub-sample was used for nitrogen extraction and pH determination and another sub-sample was dried at 105 °C for dry weight measurement and further analyses. Inorganic nitrogen compounds were extracted from 10 g moist soil with 20 ml of 0.0125 mM KCl_2 solution. The nitrite concentration was immediately measured by photometric methods with sulfanilacid and NEDA (lowest detectable value 14 $\mu g\ l^{-1}$) (GARRETT & NASON 1969). For determination of nitrate and ammonium concentrations, frozen KCl_2 extracts were transported to Hamburg, where nitrate concentrations were measured by HPLC (MEINKE et al. 1992) and ammonium concentrations by photometer (lowest detectable value 0.1 mg l^{-1}) (DIN 38406–E5-1). Dried soil samples were milled, the C/N ratio was measured by a C-N-S elemental analyzer (Vario MAX) (DIN ISO 10694).

For the statistical analyses we used the program SPSS16.

Investigation site	vegetation (dominated)	depth (cm)	horizon	texture[a]	Munsell colour[b]	bulk density[2] (g cm $^{-3}$)	pore volume[2] (vol %)	org. matter[c] (%)	particle size distribution[2]			phosphor[2] (mg kg^{-1} dw^{-1})	potassium[2] (mg kg^{-1}dw^{-1}	pH[1] (H_2O)	water[1] content (%)
									clay (%)	silt (%)	sand (%)				
River terrace															
Polygon rim	*Carex aquatilis, Salix polaris, Arctostaphphylos octopetala Dryas alpina*	0-5	O,Ajj	peat	10YR4/1	0.96±0.05	67.5±2.8	17.1±5.9	n.d.	n.d.	n.d.	22.9±14.0	296.5±210.0	6.2±0.2	37-65
		5-15	Bjjgl	sandy loam	10YR4/2 10YR5/3	1.12±0.06	55.4±1.2	5.3±0.9	4.51±2.01	28.71±9.28	66.78±11.29	4.7±0.1	55.0±15.6	6.5±0.2	31-38
Typic Aquiburbel		15-25	Bjjg2	sandy loam	10YR4/1 10YR5/3	1.14±0.27	63.5±9.9	4.9±0.1	7.84±0.95	37.87±7.81	54.28±8.81	2.6±0.8	29.5±5.0	6.2±0.1	33-38
Polygon centre	*Carex aquatilis, Salix glauca, Arctos, Dryas octopetala, Pedicularis sudetica,Caltha palustris*	0-5	Oi	peat	10YR4/1	n.d.	n.d.	37.1±5.0	n.d.	n.d.	n.d.	24.0±9.3	804.5±224.2	5.8±0.1	80-87
		5-15	Oe1	peat	10YR4/1 10YR3/1	0.46±0.07	86.9±2.9	36.1±4.4	n.d.	n.d.	n.d.	5.9±3.4	197.5±102.5	5.6±0.1	75-81
Typic Histhortel		15-25	Oe2	peat sand band	10YR3/2 10YR3/2	0.14±0.01	97.3±1.5	13.0±1.6	n.d.	n.d.	n.d.	1.4±0.7	50.5±37.5	5.8±0.0	59-74
Dry river terrace		0-5	A	sand	10YR4/1	1.33±0.08	54.1±2.0	1.3±0.2	1.89±0.43	4.48±1.55	93.58±1.88	8.6±2.7	78.0±4.0	6.3±0.1	3-10
		5-15	A,Bw	sand	10YR4/1 10YR3/1	1.34±0.08	52.7±3.4	1.1±0.2	2.27±0.50	5.39±2.89	92.37±3.41	4.5±1.3	41.7±6.0	6.4±0.1	4-10
Typic Psammorthel		15-25	Bw	sand	10YR3/1 10YR3/2	1.50±0.03	48.5±2.4	n.d.	2.48±0.80	4.92±0.38	92.64±1.12	2.5±1.5	23.0±2.7	n.d.	n.d.
Cliff[3]		150	n.d.	sand	n.d.	1.43±0.07	53.7±0.8	1.0±0.6	2.40	4.73	92.83	4.4	19.0	6.7±0.075	6-25
		250	n.d.	sand	n.d.	1.03±0.13	66.3±5.0	4.9±2.6	1.57	6.02	92.43	5.1	12.0	6.7±0.1	23-55
Young floodplain															
Beach		0-5	Cg1	sandy loam	10YR3/1	1.48±0.02	60.0±0.02	3.9±1.0	8.02±3.21	32.23±18.49	50.06±12.50	13.0±1.7	38.2±9.0	6.9±0.1	28-40
Psammentric Aquorthel		10-20	Cg2	Sand	10YR6/4	1.37±0.04	52.7±3.5	0.3±0.2	1.63±0.69	2.25±0.13	96.09±0.73	5.4±0.4	11.7±1.5	7.0±0.11	2-20
Floodplain		0-5	A	sand	10YR4/2	1.38±0.06	57.4±3.5	1.6±0.2	3.11±1.15	7.40±1.68	89.50±0.92	7.5±0.7	42.0±23.3	7.3±0.0	10-15
Typic Psammorthel		5-15	A,Ab /C	loamy sand	10YR4/2 10YR3/1	1.31±0.06	55.6±5.8	1.8±0.7	4.14±1.28	12.25±4.29	83.62±5.52	7.9±0.8	26.0±10.4	7.2±0.1	11-19
		15-25	C/Ab	Sand	10YR4/2 10YR3/1	1.24±0.04	62.0±4.8	–	3.14±1.75	8.99±8.55	87.87±10.08	5.6±1.8	28.7±12.3	n.d.	n.d.

Tab. 1: Selected properties of the soils of the investigation sites. a = after Soil Survey Staff (2006); b = soil colours determined with Munsell Soil Color Chart (1975); c = calculated per total organic carbon (TOC); 1 = measured in field in two replicates; 2 = measured after transport in our laboratory in Hamburg in three parallels with two replicates; 3 = on the cliff only two samples were taken; n.d. = not determined.

Tab. 1: Ausgewählte Eigenschaften der Böden der Untersuchungsgebiete.

CHARACTERIZATION OF SOILS OF THE ISLAND SAMOYLOV AT THE FIVE INVESTIGATION SITES

At the soil map of Samoylov Island (Fig. 2), which is based on field mapping of PFEIFFER et al. (1999, 2000, 2002) the five investigation sites are marked. During the vegetation period the water level of the river Lena varied extremely and consequently also the shoreline of the beach. At the beginning of the vegetation period there was a higher water level. Later the water level steadily decreased and the beach area extended.

Soils of the river terrace

The polygonal tundra

The polygonal tundra is characterized by polygonal-patterned ground with ice-wedge growth dominated by low-centred ice-wedge polygons (Fig. 3).

At the polygonal tundra samples were taken from the rim and centre of one polygon (Figs. 3, 4) (72°22'11.3" N, 126°29' 00.1" E). The diameter of the polygon was about 12-18 m. Due to high permafrost table of about 24 cm below surface at the rim and 22 cm below surface at the centre at the first sampling day (15 July 2008), soils were characterized by high moisture and accumulation of peat. The water level was found at the surface of the centre and at the permafrost table of the rim. At the rim 2 cm below surface, mineral soil compounds dominated. In contrast the soil of the centre consisted exclusively of soil organic material (Fig. 3, Tab. 1). Soils of the polygon rim showed cryoturbation, and are thus classified as Typic Aquiturbel (ST), Cryosol (Reductaquic) (WRB) and Permafrost Peatish Gley (RSS) (Fig 4a), and soils in the polygon centre were classified as Typic Historthel (ST), Cryic Histosol (WRB) and Permafrost Alluvial Muddy-Peat Gley (RSs) (Fig 4b). The dominant plant was *Carex aquatilis* in the polygon centre and supplemented by Salix sp. on the polygon rim.

Fig. 3: Aerial picture of the polygonal tundra of Samoylov Island. Photo: T. Sanders, Uni Hamburg.

Abb. 3: Luftaufnahme der polygonalen Tundra auf der Insel Samoylow. Foto: T. Sanders, Uni Hamburg.

Characteristics of the soils of the five investigation sites are given in Table 1. The soils of the polygon centre are more acidic than the only slightly acid soils of the polygon rim and the content of organic matter decreased with soil depths. Due to water saturation during the year, high content of organic material (up to 30 %) was found at the polygon centre. In the polygon centre, mineral components increased with dept due to sandy deposition of former Lena flooding events. At the polygon rim high organic matter content was found in the first centimetre below surface and clearly decreased with depths due to lower water content. The available phosphor and potas-

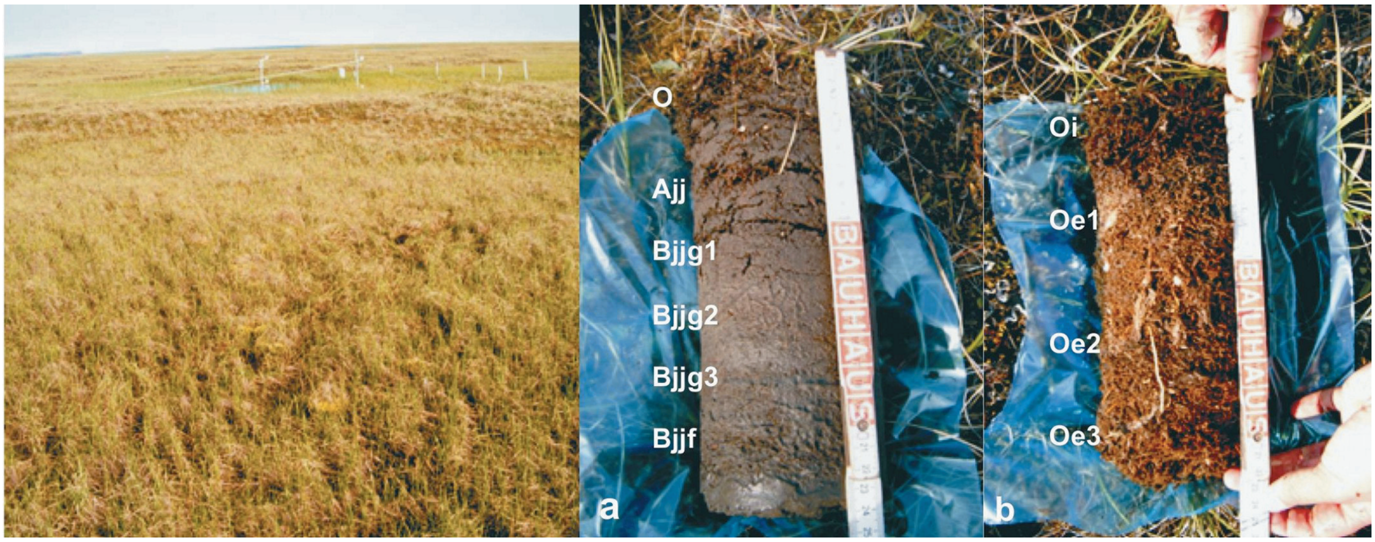

Fig. 4: Site and soil profile of the soils of the polygonal tundra. a = Typic Aquiturbel (ST) of the polygon rim; b = Typic Historthel (ST) of the polygon centre; e = organic material of intermediate decomposition; f = frozen soil; g = strong gleying; i = slightly decomposed organic material; jj = evidence of cryoturbation.

Abb. 4: Standort und Bodenprofile der polygonalen Tundra. a = Typic Aquiturbel (ST) des Polygonrandes. b = Typic Historthel (ST) des Polygonzentrums. e = organisches Material mittlerer Zersetzungsstufe. f = gefrorener Boden. g = starke Vergleyungserscheinungen. i = schwach zersetztes organisches Material. jj = Kryoturbationserscheinungen.

sium were very high in the upper layers of the polygon centre and rim and decreased with soil depths.

The dry river terrace

The dry river terrace sampling point was located about 3 m from the cliff (72°22'06.5" N, 126°28'29.5" E). Due to previous periodically flooding, soils were characterized by sand layers with different content of dark organic soil material (Fig. 5), which were termed as buried A horizons (Ab) (SOIL SURVEY STAFF 2006). There was only some water above the permafrost table at 55 cm. Soils were classified as Typic Psammorthel (ST), Haplic Cryosol (WRB) and Permafrost Alluvial Layered Primitive Sandy (RSS).

The soil horizons of the Typic Psammorthel located at the dry river terrace were relatively homogeneous. The soils were slightly acidic. The water content of the soils was relatively low because of the high content of sand (≈93 %), low content of organic matter (≈1.4 %) and possibility of drainage because of the depth of permafrost table. The availability of phosphor and potassium was clearly lower than in the polygonal tundra.

The cliff

The cliff sampling point was located in the south west of the island (72°22'06.5" N, 126°28'29.5" E) and at a depth of 1.5 and 2.5 m below the soil surface (Fig. 6). Samples at a depth of 1.5 m and 2.5 m varied in moisture, content of organic matter and were obviously differed in colour. Samples taken from 2.5 m depth had a five times higher content of organic matter and were darker than the sample from 1.5 m depth. Both samples were characterized by high content of sand and nearly neutral pH (6.7). The phosphor and potassium availabilities were comparatively low at both depths.

Soils of the young floodplain

The beach

At the beach samples were taken about 5 m (status at the 15 July 2008) from the Lena river shore (72°22'12.5" N, 126° 28'56.8" E).

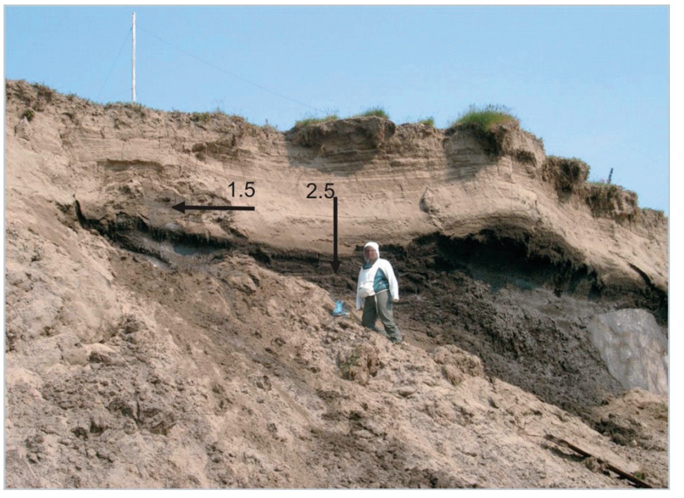

Fig. 6: Sampling location at the cliff located near the station of Samoylov Island. Samples were taken at depth of 1.5 and 2.5 m below surface.

Abb. 6: Probenahmeort am Kliff in der Nähe der Forschungsstation Samoylow gelegen. Proben wurden in einer Tiefe von 1,5 und 2,5 m unter der Geländeoberfläche genommen.

Fig. 5: Site and soil profile of the Typic Psammorthel (ST) located near the station of Samoylov Island. Ab = buried genetic A horizon; Bw = development of colour or structure of a B horizon.

Abb. 5: Standort und Bodenprofil des Typic Psammorthel (ST), der in der Nähe der Forschungsstation liegt. Ab = sedimentierter genetischer A-Horizont. Bw = in Farbe oder Struktur veränderter B-Horizont.

Fig. 7: Site and soil profile of the Psammentic Aquorthel (ST) located at the beach of Samoylov Island. Cg = alluvial deposits with gleying properties.

Abb. 7: Standort und Bodenprofil des Psammentic Aquorthel (ST) am Strand der Insel Samoylow. Cg = Flussablagerungen mit Hydromorphimerkmalen.

Due to annual flooding, soils were characterized by an alteration of layers of bright sand and dark, organic rich sandy loam layers which is allochthonous C material (Fig. 7). The water and permafrost table was at 30 cm and 70 cm below surface, respectively. Soils were classified as Psammentic Aquorthel (ST), Haplic Cryosol Reductaquic (WRB) and Permafrost Alluvial Layered Primitive Sandy (RS). These soils were not covered by vegetation. The soil horizons of the beach differed in their texture, organic matter and water content (Tab. 1). The dark sediments of the upper layer had a higher content of silt (≈30 %) and organic matter and thus a higher water content compared to the sandy horizon. The soil horizons were neutral and the bulk density and pore volume decreased with depth.

The floodplain

The sampling site at the floodplain was about 150 m from the Lena River shore (15 July 2008) (72°22'14.1" N, 126°28' 06.7" E). Due to periodic flooding, soils were characterized by

Fig. 8: Site and soil profile of the Typic Psammorthel (ST) located at the floodplain of Samoylov Island and dominated by willows (*Salix* spec.). Ab = buried genetic A horizon.

Abb. 8: Standort und Bodenprofil des Typic Psammorthel (ST), in der Überflutungsebene der Insel Samoylow, bewachsen mit Weiden (*Salix* spec.). Ab = überschütteter genetischer A-Horizont.

layers with different content of dark organic soil material (Fig. 8), which were termed as buried A horizons (Ab) (Soil Survey Staff 2006). In contrast to soils of the beach, the soils were covered mainly by *Salix glauca* vegetation. There was no water above the permafrost table at 74 cm. Soils were classified as Typic Psammorthel (ST), Haplic Cryosol Oxyaquic (WRB) and Permafrost Alluvial Layered Primitive Sandy (RS).

The horizons of the neutral soil of the floodplain were different. Layers dominated by sand alternated with layers with higher silt content due to fluvial deposits of the river Lena. Differences in texture resulted in different bulk density and pore volumes. The soils of the floodplain had a relatively high bulk density and thus a small pore volume.

Air and soil temperature during expedition time

The air temperatures measured 2 m above surface of the polygonal tundra varied between one and 20 °C during the expedition time from 30 June 2008 to 29 August 2008 (Fig. 9). There was a warm period in the middle of July and during all of August. The soil temperatures were only measured in the soils of the polygonal tundra. They showed the same fluctuations but temporally delayed compared to the air temperature and with less amplitude. The soil temperatures were in the range between 0-10.5 °C with a mean value of 5.2 °C in the polygon centre and 6.2 °C at the polygon rim. On the first and third sampling dates (17 July and 13 August) the air temperature was below 10 °C and the soil temperatures below 5 °C in all depths. On the second and forth sampling dates (31 July and 27 August) the air temperatures were clearly higher than 10 °C and the soil temperatures were above 5 °C.

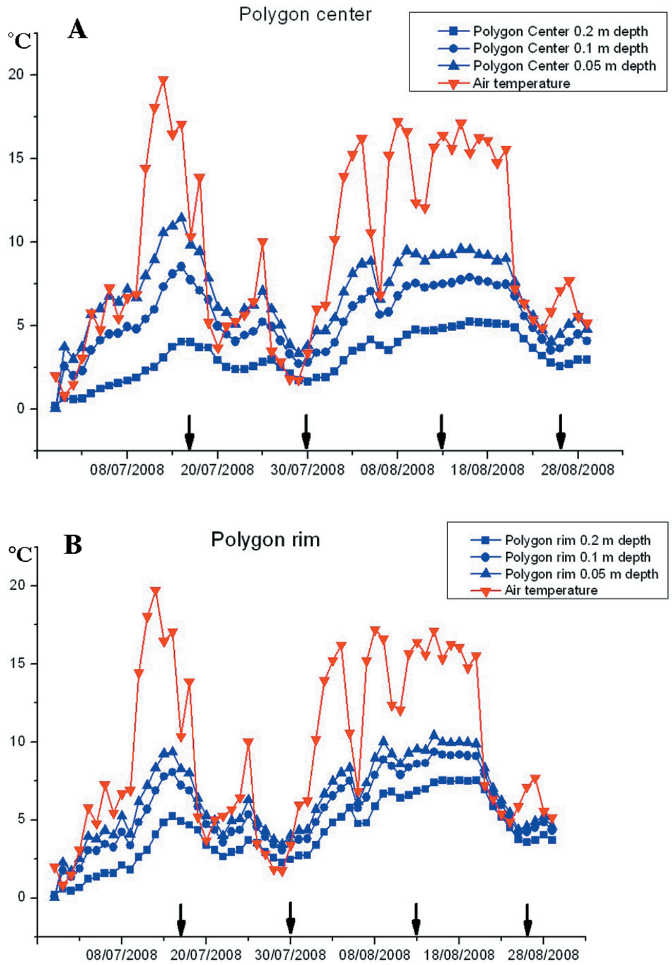

Fig. 9: Air and soil temperatures in the polygonal tundra. A = polygon centre; B = polygon rim. Data provided by J. Boike et al., AWI Potsdam. Arrows mark the sampling days. Air temperatures were measured at 2 m above surface.

Abb. 9: Luft- und Bodentemperaturen der Polygonebene. A = Polygonzentrum. B = Polygonrand. Daten von J. Boike et al., AWI Potsdam. Die Pfeile markieren die Tage der Probenahme. Die Lufttemperatur wurde 2 m über Geländeoberfläche gemessen.

Dissolved nitrogen compounds and C/N ratios of soils

Table 2 presents the available dissolved inorganic nitrogen compounds (DIN) like ammonium, nitrite and nitrate in the vegetation or sampling period (17 July to 27 August 2008). Figure 10 showed for a better visualization in A the DIN over time in the investigation sites and in B the ammonium and nitrate concentrations. Highest ammonium concentrations were found in the water saturated soils of the polygon centre over the whole vegetation period and in soils without vegetation cover like on the cliff and the beach at the beginning of the vegetation period (up to 10 $\mu g\ g^{-1}$ dw). Generally, ammonium decreased with soil depth. The cliff constitutes an exception because the deeper sample has a higher content. In the wet polygonal tundra, the soils of polygon rim and centre accumulate ammonium during the vegetation period. In contrast to the dry soils of the cliff and beach without vegetation ammonium decreased over time. The ammonium concentration correlates with the organic content of the soils, high ammonium concentrations were found in soils with high organic content like soils of the polygon centre, cliff (2.5 m depth) or beach (upper layer). Low concentrations were found in soils with low organic content and covered by vegetation like soils of the young floodplain, the dry river terrace and the mineral horizon of the polygon rims. The correlation is significant on the last two sampling dates ($p < 0.01$).

The concentration of nitrite varied over vegetation period and with soil depths. The highest nitrite concentrations were found in the water-saturated organic-rich layer of the polygons and the organic-rich soils without vegetation cover of the beach and cliff. Relatively high concentrations were found in the end of the vegetation period at the polygons, the beach and the floodplain of up to 2.3 $\mu g\ g^{-1}$ dw. The nitrite concentrations seem to correlate with the air and soil temperature (Fig. 9). At low air temperatures <10 °C measured on the 30 July and 27 August nitrite accumulated in the soil. In contrast at high air temperature >10 °C measured on the 17 July and 13 August, less nitrite was detected. But there is no correlation.

Nitrate was detectable only in samples of the young floodplain (beach and floodplain), and the cliff. In the soils without vegetation cover, like soils of the cliff and beach, the highest nitrate concentrations were found. At vegetation covered soils of the floodplain and at 1.5 m depth of the cliff nitrate was only detectable at the beginning of the vegetation period. In contrast, at 2.5 m depth of the cliff and soils of the beach without vegetation nitrate accumulated to high amounts at the

Investigation sites	depth (cm)	Ammonium-N (µg g^{-1} dw)				Nitrite-N (µg g^{-1} dw)				Nitrate-N (µg g^{-1} dw)				sum of dissolved inorganic nitrogen (DIN)			
		17/07 2008	30/07 2008	13/08 2008	27/08 2008	17/07 2008	30/07 2008	13/08 2008	27/08 2008	17 07 2008	30 07 2008	13 08 2008	27 08 2008	17/07 2008	30/07 2008	13/08 2008	27/08 2008
River terrace																	
Polygon rim	0-5	0.3±0.1	0.6±0.1	0.6±0.6	2.3±2.7	0.02±0.02	bdl	0.02±0.03	0.66±0.13	bdl	bdl	bdl	bdl	0.4±0.1	0.6±0.1	0.7±0.6	3.0±2.9
Typic Aquiburbel	5-15	0.3±0.1	2.2±0.1	0.6±0.0	0.6±0.1	bdl	0.01±0.01	0.01±0.01	0.44±0.16	bdl	bdl	bdl	bdl	0.3±0.1	2.3±0.1	0.6±0.1	1.1±0.3
	15-25	0.1±0.0	0.4±0.0	0.4±0.5	0.7±0.4	bdl	0.01±0.00	0.01±0.02	0.41±0.01	bdl	bdl	bdl	bdl	0.1±0.0	0.4±0.0	0.4±0.5	1.1±0.5
Polygon centre	0-5	0.5±0.0	1.5±0.4	11.6±0.6	4.9±0.0	0.01±0.01	bdl	bdl	0.25±0.35	bdl	bdl	bdl	bdl	0.5±0.0	1.5±0.4	11.6±0.6	5.2±0.4
	5-15	0.2±0.0	3.6±0.5	5.4±0.6	5.2±0.4	0.01±0.01	0.02±0.03	0.01±0.01	0.19±0.19	bdl	bdl	bdl	bdl	0.2±0.0	4.7±0.5	5.4±0.6	5.4±0.6
Typic Historthel	15-25	0.6±0.1	1.7±0.0	1.9±0.1	1.8±0.2	bdl	0.03±0.01	0.00±0.01	0.48±0.17	bdl	bdl	bdl	bdl	0.6±0.1	1.7±0.0	1.9±0.2	2.3±0.4
Dry river terrace	0-5	0.3±0.0	0.2±0.0	0.3±0.1	0.3±0.1	0.01±0.00	0.02±0.01	0.00±0.01	0.36±0.03	bdl	bdl	bdl	bdl	0.3±0.0	0.3±0.1	0.3±0.2	0.6±0.1
Typic Psammorthel	5-15	0.0±0.0	0.1±0.0	0.2±0.1	0.2±0.0	0.01±0.01	0.01±0.00	bdl	0.18±0.09	bdl	bdl	bdl	bdl	0.1±0.0	0.1±0.2	0.2±0.1	0.4±0.1
Cliff [3]	150	5.5±0.0	3.0±0.1	0.1±0.1	bdl	0.03±0.04	0.04±0.01	bdl	bdl	0.1±0.1	0.1±0.0	bdl	bdl	5.6±0.2	3.2±0.1	0.1±0.1	bdl
	250	10.0±0.4	5.4±0.2	2.1±0.0	1.7±0.0	0.02±0.02	0.06±0.00	0.00±0.00	0.43±0.15	bdl	bdl	bdl	1.7±0.0	10.1±0.4	5.5±0.2	2.0±0.0	3.9±0.2
Young floodplain																	
Beach	0-5	9.4±3.6	7.2±0.1	4.9±0.1	0.1±0.1	0.04±0.03	0.08±0.04	0.02±0.00	2.28±0.50	bdl	bdl	0.7±0.1	89.0 ±56.7	9.5±3.6	7.3±0.1	5.5±0.2	91.4 ±57.3
Psammentric Aquorthel	10-20	0.3±0.0	0.2±0.0	0.1±0.0	0.1±0.0	0.02±0.00	0.03±0.00	0.01±0.02	0.60±0.23	0.2±0.1	0.1±0.0	bdl	2.3±0.0	0.5±0.1	0.3±0.0	0.1±0.1	3.0±0.3
Floodplain	0-5	0.1±0.1	0.1±0.0	0.1±0.0	0.1±0.0	bdl	0.03±0.00	bdl	0.18±0.25	0.1±0.1	bdl	bdl	bdl	0.2±0.2	0.2±0.0	0.1±0.0	0.3±0.3
Typic Psammorthel	5-15	0.2±0.0	0.2±0.0	0.1±0.1	0.2±0.0	bdl	0.03±0.01	bdl	0.24±0.33	0.1±0.1	bdl	bdl	bdl	0.3±0.2	0.2±0.1	0.1±0.1	0.4±0.3

Tab. 2: Concentrations of dissolved inorganic nitrogen compounds (DIN = ammonium, nitrite and nitrate) in extracts of soil samples from different investigation sites, different depths and over the vegetation period. The values are means of two samples with two replicates. bgs = below ground surface; dw = dry weight; bdl = below detection limit.

Tab. 2: Konzentrationen gelöster anorganischer Stickstoffverbindungen (DIN = Ammonium, Nitrit und Nitrat) in Bodenextrakten aus Bodenproben von unterschiedlichen Probenahmeorten aus verschiedenen Tiefen und über die Vegetationsperiode. Es sind Mittelwerte aus zwei Parallelen mit Doppelbestimmung angegeben.

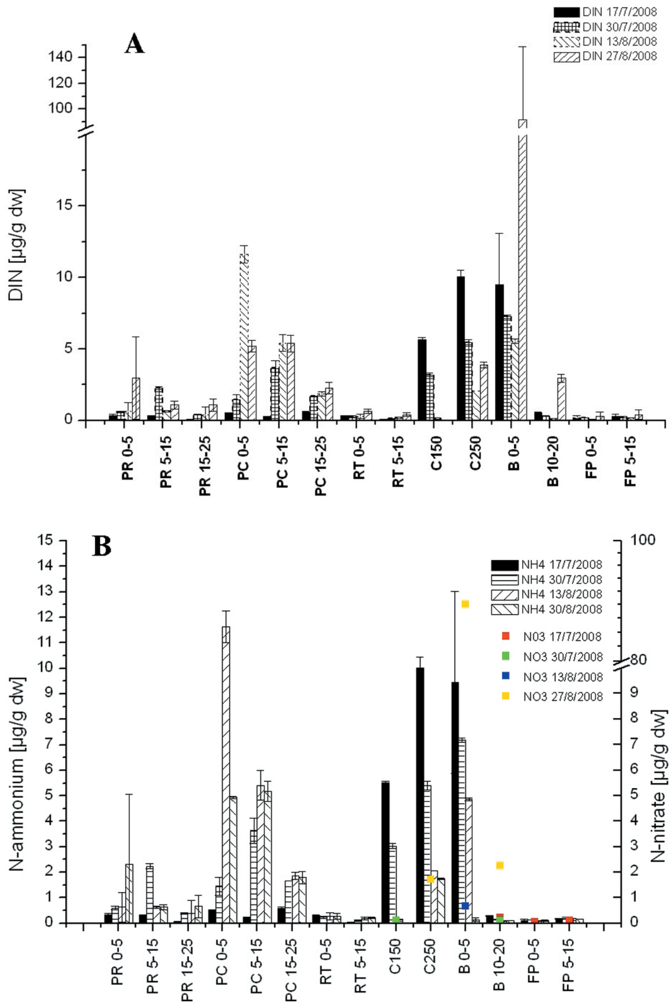

Fig. 10: A = Dissolved inorganic nitrate (DIN) over vegetation period at investigation sites. B = Ammonium and nitrate over vegetation period and investigation sites; PR = polygon rim; PC = polygon center; RT = river terrace; C = cliff; B = beach; FP = floodplain. Numbers at sampling sites indicate sample depth.

Abb. 10: A = Gelöster anorganischer Stickstoff (DIN) während der Vegetationsperiode an den Untersuchungsstandorten. B = Ammonium und Nitrat während der Vegetationsperiode an den Untersuchungsstandorten. PR = Polygonwall, PC = Polygonzentrum, RT = Flussterrasse, C = Kliff, B = Strand, FP = Überflutungsebene. Zahlen an den Untersuchungsorten stehen für die Probentiefe.

end of the vegetation period. A maximal amount of 89 μg g^{-1} dw (≈130 mg l^{-1}) was found at the end of August in the upper soil sample of the beach.

The average of total carbon (C), total nitrogen, and C/N ratios determined at all investigation sites over the vegetation period are presented in Figure 11. High N values were found in soils with high organic matter content like the polygons, the upper layer of the beach and in 2.5 m soil depths of the cliff. All other soils contain less N. In all soil depths of the polygon centre and the upper part of the polygon rim with total carbon content higher than 6 % the highest C/N average ratios of >33 were found. In contrast in all other soil horizons narrow C/N average ratios <18 were detected.

The measured potential nitrification rates of the investigated soil samples are shown in Figure 12. In the water-saturated soils of the polygon centre only in the upper layer very low rates were detectable. In the relatively dry polygon rim potential nitrification rates were measured only in the mineral horizon at 5-15 cm. Similar rates of about 100 ng N g^{-1} dw h^{-1} were measured in the dry river terrace. The highest potential nitrification rates were measured in the organic rich layer of the beach and the cliff of up to 500 ng N g^{-1} dw h^{-1}.

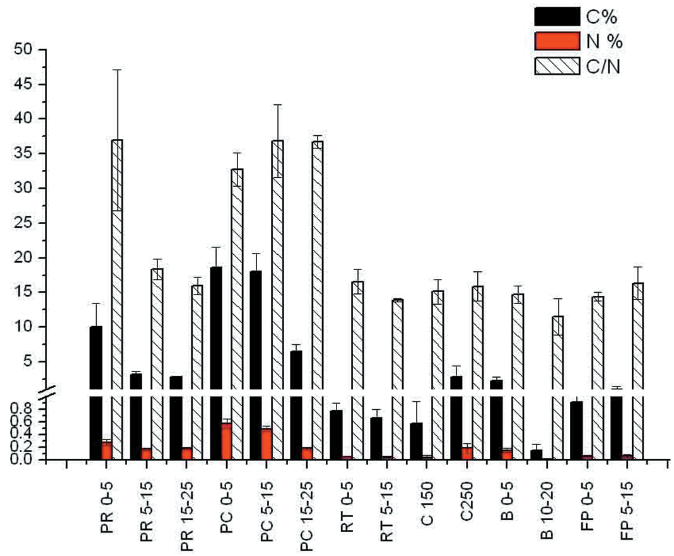

Fig. 11: Average of total carbon (C), total nitrogen (N) and C/N ratios over the investigation period. C % equals C_{org}; PR = polygon rim; PC = polygon centre; RT = river terrace; C = cliff; B = beach; FP = floodplain. Numbers indicate sample depth.

Abb. 11: Durchschnittswerte von Gesamtkohlenstoff (C), Gesamtstickstoff (N) und C/N Verhältnisse über die Vegetationsperiode. C % entspricht C_{org}. PR = Polygonwall, PC = Polygonzentrum, RT = Flussterrasse, C = Kliff, B = Strand, FP = Überflutungsebene. Die Zahlen an den Untersuchungsorten stehen für Probentiefe.

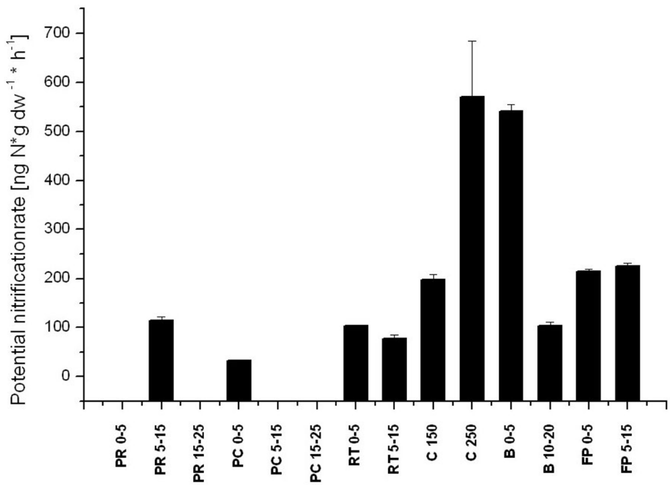

Fig. 12: Potential nitrification rates at different investigation sites. Samples were taken at the 15 July 2008. PR= polygon rim; PC = polygon centre; RT = river terrace; C = cliff; B = beach; FP = floodplain. Numbers indicate sample depth.

Abb. 12: Potentielle Nitrifikationsraten an verschiedenen Untersuchungsgebieten. Die Proben wurden am 15. Juli 2008 genommen. PR = Polygonwall, PC = Polygonzentrum, RT = Flussterrasse, C = Kliff, B = Strand, FP = Überflutungsebene. Die Zahlen an den Untersuchungsorten stehen für die Probentiefe.

DISCUSSION

Distinct small-scaled variability of the soils of Samoylov Island and the consequences for the nitrogen cycle

The investigation of the different permafrost-affected soils on Samoylov Island in the Lena River Delta (northeast Siberia) showed a wide-spread small-scaled variability of soil types and their properties, which is a typical pattern for the Arctic tundra environment (TARNOCAI 2009b). Although the Samoylov Island is small (5 km^2) it represents a typical example for the eastern part of the delta. Owing to the various geomorphologic units multiple types of soil can be found. The two different landscape units, the upper river terrace with the polygonal tundra and the lower floodplain show different properties concerning soil texture, bulk density, pore volume, organic matter and water content.

Soils of the river terrace, especially at the polygon centre and the soils of the younger floodplain, both showed high organic matter content, but the quality of the organic matter may differ. The soil organic matter (SOM) has different origins and decomposition status. As the SOM of the polygon centre was formed by the in situ vegetation and accumulated as peat due to the inhibition of its mineralization, the SOM of the floodplain was formed allochthonously by river depositions. Because soil nitrogen mainly originates from soil organic matter there might be differences in the nitrogen qualities of the soils and this might cause differences in the nitrogen cycle.

Dissolved inorganic nitrogen (DIN)

Ammonium originates from the N-mineralization and N-fixation and can either be absorbed by plants or micro-organisms for building up biomass. It can be oxidized aerobically via nitrite to nitrate by nitrifying micro-organisms or it can be anaerobic oxidized to N_2 during the anamox process (STROUS et al. 1997). The investigated soils differed mainly in water content and therefore oxygen supply, organic content and vegetation cover. Ammonium accumulated during the vegetation period only in soils with anaerobic conditions like in the polygon centre where no potential nitrification was gaugeable and high methane concentrations found in the polygonal tundra (WILLE et al. 2008).

In contrast, in the oxygen-rich sandy and sandy loamy soils of the beach and cliff ammonium decreased during the vegetation period where high potential nitrification rates were measured and where no vegetation cover exist: It was obvious that the availability of ammonium also depends on the content of organic matter. In the soils and horizons with higher organic matter content, high amounts of ammonium were found as a result of nitrogen mineralization. Therefore the ammonium concentrations generally decreased with soil depths.

Since nitrite is an intermediate of nitrification and denitrification, it is usually found only in trace amounts in aerobic habitats (KNOWLES 2000). Probably because of the low concentrations found, nitrite has rarely been quantified. Nitrite only accumulates if the second step of nitrification, the nitrite oxidation, is inhibited or is slower e.g., at low oxygen partial pressure in soils with high water potential or in alkaline environments (PHILIPS et al. 2002) and the denitrification does not take place (SMITH et al. 1997). It has been reported that at high pH and ammonium concentrations nitrite-oxidizers are selectively inhibited resulting in the accumulation of nitrite (SMITH et al. 1997). In our study nitrite was detected at all investigation sites and soil depths at up to 2.3 $\mu g\ g^{-1}dw$ soil concentrations, but varied over time of sampling. Most cases the nitrite concentration was hardly detectable. Generally, lower nitrite concentrations were detected during the first and third sampling date than on the second and forth sampling date. Since the air and therefore soil temperature varied with the time of sampling, these changes may provide one possible explanation for the variation of nitrite in the soils. Low air and soil temperatures of <10 °C and <5 °C respectively found on the second and forth sampling time might inhibit the nitrite oxidation, but we did not find significant correlation.

We suggest that nitrate might only be detected as the product of nitrification, because there was no deposition of nitrate to the soils by fertilization or by the Lena River. We indeed spatially investigated the DIN concentrations in the Lena River and we did not detect high concentrations of nitrate (data not shown). Therefore, nitrite could only accumulate where ammonium was available for nitrification by mineralization of organic substances, nitrification took place and nitrate uptake by denitrification and N-assimilation was inhibited. In the soils of Samoylov Island the highest nitrate concentrations were only found in alluvial soils of the young floodplain and cliff where we also found the highest potential nitrification rates of up to 500 $ng\ g^{-1}dw\ h^{-1}$. The reason that nitrate was only detected at the beginning of the vegetation period in soils with vegetation cover might be that the available nitrate was immediately taken up by plants during the growing period. In contrast to aerated soils without vegetation cover like the beach, nitrate accumulation may be due to the activity of N-mineralization of the organic rich soils and nitrification and missing N-uptake and denitrification. Interestingly, in the upper layer of the beach the accumulation of nitrate was so high (≈130 $mg\ l^{-1}$ or rather ≈90 $\mu g\ g^{-1}dw$) that the limiting value for drinking water of 50 $mg\ l^{-1}$ was exceeded nearly threefold at one sampling date. The results showed that dissolved nitrogen (DIN) is available and detectable in all different permafrost affected soils of Samoylov Island. Mainly the DIN was measured as ammonium. The nitrite concentrations were very low and depended on temperature and nitrate accumulated only in soils without vegetation cover. This is good evidence that it is otherwise taken up by vegetation.

Total carbon and nitrogen and their ratio

The measured total nitrogen was composed of organic and inorganic, bonded and dissolved nitrogen. The ratio of total carbon and nitrogen of the organic matter can be used to describe the extent of transformation. The higher the C/N ratio, the stronger the material was altered. SCHIMEL et al. (1996a) dissuade using the C/N ratio as estimation for the short-term availability of organic matter. The changes in the C/N ratio in the course of turnover of the organic matter and the applicability as a parameter for the ongoing turnover also in polar regions were unquestioned (VAN CLEVE 1974). In this context many authors use the C/N ratios (e.g., ARP et al. 1997).

The soils in the polygonal tundra have high C/N ratios between approximately 32 and more than 36, such as the polygon centre and the organic horizon of the rim. These values are comparable to the C/N ratios reported in other studies of soils of the polar regions (Bardgett et al. 2007, Knoblauch et al. 2008). This high C/N ratio indicated that the organic matter was only little degraded although methane emissions were measured (Wagner et al. 2003, Wille et al. 2008). Due to the low temperature and water saturation and the resulting oxygen deficiency, the decomposition of the organic matter was very slow.

On the other hand the relatively dry and sandy soils of the floodplain and the beach had relatively low C/N ratios, which might be due to the origin of organic material, i.e. they are younger and more decomposed with presumably higher mineralization rates. For example, although the upper layer of the beach and the A-horizon of the polygon rim showed nearly similar organic matter content they obviously differed in C/N ratio. The higher C/N ratio in the soils of the beach might be due to the quality and origin of the organic material.

The organic matter in the polygon rim was formed autochthonously by mineralization of persistent vegetation; in contrast the readily degradable organic matter of the floodplain, which was allochthonously decomposed by the river. More studies are necessary to investigate the differences in the quality of the organic matter. The origin of the organic matter of the river has not been investigated. We speculate upon two possible origins: first one part came with the river from the moderate climate regions and a second part may have originated from the soils of the delta as a result of erosion.

CONCLUSION AND OUTLOOK

Our data give a first overview of nitrogen cycle in permafrost soils in the Lena River Delta. We have shown that the soils of Samoylov Island were very diverse across small spatial scales also concerning the nitrogen availability and therefore the nitrogen turnover. Our data suggest, that in one part of Samoylov Island, the polygonal tundra, there is no high N-turnover, which can implicate that the processes can be N-limited; while in the other soils of the young floodplain and the drier river terrace nitrogen were available and other factors like temperature or water logging were more important for control the processes in the soils.

These studies depend on the important question of how the Arctic ecosystem will respond to climate changes, and what implications these changes have for the nitrogen cycle. The climate warming can cause the depressing of the permafrost table with a strong influence on the water balance. This can cause a shift in oxygen availability, what again cause the rates of mineralization or nitrification. Probably there will be changes in the N-availability, resulting in an enrichment of nitrate and causing high N_2O emissions. This study provides a nice baseline for comparison in the future. For the further understanding and accounting of the N-cycle in permafrost affected soils there should be more measurements of other nitrogen compounds, like dissolved organic nitrogen (DON), ^{15}N and turn-over rates of different processes like gross and net mineralization or respiration. Furthermore also the investigation of the diversity of the key organisms could be very interesting.

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