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Permafrost thaw and release of inorganic nitrogen from polygonal tundra soils in eastern Siberia

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Abstract. The currently observed climate warming will lead to substantial permafrost degradation and mobilization of formerly freeze-locked matter. Based on recent findings, we assume that there are substantial stocks of inorganic nitrogen (N) within the perennially frozen ground of arctic ecosystems. We studied eleven soil profiles down to one meter depth below surface at three different sites in arctic eastern Siberia, covering polygonal tundra and river floodplains, to assess the amount of inorganic N stores in arctic permafrost-affected soils. Furthermore, we modeled the potential thickening of the seasonally unfrozen uppermost soil (active) layer for these sites, using the CryoGrid2 permafrost model and representation concentration pathway (RCP) 4.5 and 8.5 scenarios. The first scenario, RCP4.5, is a stabilization pathway that reaches plateau atmospheric carbon concentrations early in the 21st century; the second, RCP8.5, is a *business as usual* emission scenario with increasing carbon emissions. The modeled increases in active layer thickness (ALT) were used to estimate potential annual N mobilization from permafrost-affected soils in the course of climate-induced active-layer deepening. We observed significant stores of inorganic ammonium in the perennially frozen ground of all investigated soils, up to 40-fold higher than in the active layer. The modeled ALT increase until 2100 under the RCP8.5 scenario was between 19 ± 3 cm and 35 ± 6 cm, depending on the location. Under the RCP4.5 scenario, the ALT remained stable in all investigated soils. Our estimated mean annual N release under the RCP8.5 scenario is between 8 ± 3 mg m^{-2} and 81 ± 14 mg m^{-2} for the different locations, which reaches values up to the order of magnitude of annual fixation of atmospheric N in arctic soils. However, the thawing induced release of N represents only a small flux in comparison with the overall ecosystem N cycling.

1 Introduction

In the last decades, numerous studies have been conducted to quantify the belowground organic carbon (C) pool of permafrost-affected soils (Hugelius et al., 2013; Post et al., 1982; Strauss et al., 2013; Tarnocai et al., 2009; Zubrzycki et al., 2014). Currently, the soils of these high-latitude ecosystems are estimated to contain approximately 1300 Pg C

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(1 Pg =10^{15} g = 1 Gt; Hugelius et al. 2014). The projected increases in air and ground temperatures will have major impacts on arctic ecosystems: Substantial portions of the permafrost will thaw in the coming decades, which will lead to a mobilization of previously frozen organic matter and nutrients (Lawrence and Slater 2005, Kuhry et al. 2010, Grosse et al. 2011a, Schuur et al. 2015). The formerly freeze-locked organic matter will become vulnerable to microbial decomposition, resulting in increased greenhouse gas emissions from arctic soils (Dutta et al., 2006; Johnson et al., 1996; Nadelhoffer et al., 1991; Schmidt et al., 2011; Schuur et al., 2009). Especially, large amounts of labile organic C in permafrost-affected soils will be prone to rapid microbial decomposition when the permafrost thaws (Mueller et al., 2015; Strauss et al., 2015). The additional warming through the release of C from newly thawed permafrost is expected as 0.03 °C to 0.23 °C by the end of the 21st century (Schneider Von Deimling et al., 2012, 2015).

Increased decomposition rates in response to higher soil temperatures will not also lead to increased C emissions but also to increased nutrient availability (Keuper et al., 2012; MacDonald et al., 1995; Rustad et al., 2001; Schaeffer et al., 2013). Increased nutrient availability and long-term warming in high latitudes can compensate increased greenhouse gas emissions by increased primary production (Natali et al., 2012; Sistla et al., 2013). Furthermore, as nitrogen (N) is known to be a main limiting nutrient for plant growth in the arctic tundra (Beermann et al., 2015; Mack et al., 2004; Reich et al., 2006), increased N availability will influence the plant community composition of arctic ecosystems (Aerts, 2006; Eriksson et al., 2010; Sistla et al., 2013). Changes in the plant species composition of arctic ecosystems will control different positive climate feedback mechanisms like reduction of the surface albedo and amplification of the regional greenhouse warming by increased evapotranspiration (Foley, 2005; Loranty et al., 2011; Swann et al., 2010). On the other hand, shrub expansion may also reduce permafrost thaw by insulating the soils in winter due to their higher snow-holding capacity and by increased shading in summer due to their high leaf area (Blok et al., 2010; Myers-Smith et al., 2011). Thus, nutrient availability indirectly controls both positive and negative feedback mechanisms to climate warming and is an important factor for the further progression of arctic ecosystems.

Similar to the quantification of the belowground organic C pool in arctic soils, there are also recent approaches to quantify the total N stock of arctic permafrost-affected soils (Zubrzycki et al., 2013). Northern peatland soils alone store 8 to 15 Pg N, which is approximately 10 % of the global soil organic matter N pool (Limpens et al., 2006; Loisel et al., 2014). However, only small proportions of this N are available for plant nutrition as dissolved inorganic nitrogen (DIN) and furthermore, plants can also take up organic N forms like amino acids and oligo-peptides (Harms and Jones, 2012; Schimel and Bennett, 2004; Wild et al., 2013). Thus, total N is not an appropriate measure to describe the current N availability in arctic permafrost-affected soils.

In spite of frequent studies investigating the availability of inorganic N in the active layer of permafrost-affected soils (e.g. Nadelhoffer et al. 1992, Chapin 1996, Weintraub and Schimel 2005a, Rodionov et al. 2007, Chu and Grogan 2009), there are

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only few studies which quantify inorganic N compounds in the perennially frozen ground. Recently, Keuper et al. (2012) found significant amounts of ammonium in the perennially frozen ground of Swedish peatlands. Furthermore, the release of large amounts of inorganic N from thawing permafrost of arctic and alpine permafrost environments was reported (Barnes et al., 2014; Harms et al., 2014), and increased uptake of N by plants following permafrost thaw was observed (Schuur et al., 2007). Although there is growing evidence of plant-available N stores in arctic and alpine permafrost-affected soils, uncertainties are high and data from Siberia - the largest tundra region of the world - are sparse.

The present study aims to quantify the potential release of inorganic N (Including NH_4^+ and NO_3^-) from thawing permafrost. Eleven soil profiles reaching up to 1 m depth below surface (b.s.) have been studied in the Lena River Delta as well as in the Lowlands of the Indigirka River and in the Kolyma River Delta (Republic of Sakha, Russian Federation; Fig. 1). By modeling the potential active layer increase of the studied soils in the course of climate change, we are able to give a rough estimate of the potential annual N mobilization in these ecosystems in the coming decades. The thickness of the active layer is influenced by many factors, including surface temperature (Hinkel, 2003), thermal properties of the surface cover (Beringer et al., 2001), grain size distribution and organic matter content of the soil (Hinzman et al., 1991; Inaba, 1983; Koven et al., 2009; Lawrence and Slater, 2008), soil moisture and ice content (Langer et al., 2013; Romanovsky and Osterkamp, 2000), and also thickness of the snow cover (Zhang, 2005). Detailed cryolithological analyses of the studied soil profiles were conducted, including determination of ice contents and grain size distribution, in order to provide reliable input data for modelling the active layer thickness (ALT) evolution in the coming decades.

2 Material and methods

2.1 Site descriptions

The three study areas of this work are dominated by polygonal tundra. Polygonal tundra distribution is assumed to reach about 250,000 km^2 in circumarctic coastal lowlands (Minke et al., 2007). The polygonal pattern results from thermal contraction cracks, which fill with re-freezing snow melt water in spring (Lachenbruch 1962). Repetition of this process leads to the formation of ice-wedges and the development of a distinct polygonal pattern. A common feature of polygonal tundra ecosystems is their pronounced spatial heterogeneity with regard to microtopography, hydrology, soils and vegetation. While the elevated polygon ridges are characterized by a moderately wet soil moisture regime, the soils in the depressed polygon centers are typically waterlogged, which leads to active peat accumulation.

The first study area is located on Samoylov Island in the Lena River Delta (72.3676° N, 126.4838° E). The Lena River Delta consists of three main geomorphic terraces of different ages as well as the modern floodplain level (Schwamborn et al., 2002). Our investigation at this study site focuses on the youngest river terrace of Holocene age. The nearest weather station

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is located in the village Tiksi (WMO 21824, ~110 km southeast to the study location) and reports for the period from 2002 to 2012 a mean annual air temperature of -12.8 °C. Monthly mean air temperature of the warmest month (July) is +8.7 °C; mean air temperature of the coldest month (February) is -31.6 °C. The annual mean precipitation (period from 2000-2002) does not exceed 260 mm (Russia's Weather Server, 2013). The vegetation on Samoylov island is described by the Circumpolar Arctic Vegetation Map (CAVM) as unit W2 (sedge, moss, dwarf-shrub, wetland, Walker et al. 2005). Following the US Soil Taxonomy (Soil Survey Staff, 2014), typical soil profiles are *Typic Historthels* in the polygon centers and *Typic Aquiturbels* on the polygon ridges (Boike et al., 2013). *Historthels* are permafrost-affected soils containing mainly mineral material but also substantial amounts of peats. *Aquiturbels* contain mainly mineral material, are influenced by cryoturbation and furthermore characterized by redoximorphic conditions.

The second study area is located in the Indigirka Lowlands, 30 km northwest of the village Chokurdakh near the World Wildlife Fund station Kytalyk at the Berelekh River, a tributary to the Indigirka River (70.8296° N, 147.4895° E). The nearest weather station is located in Chokurdakh (WMO~21946, 30 km distant to the study location) and reports for the period from 2001 to 2011 a mean annual air temperature of -12.4 °C. Monthly mean air temperature of the warmest month (July) is +11.8 °C; mean air temperature of the coldest month (February) is -34.6 °C. The monthly mean air temperature is above 0 °C between June and September. The annual mean precipitation (period from 2001-2003) does not exceed 250 mm (Russia's Weather Server, 2013). The vegetation at this site is described by the CAVM as unit W3 (sedge, moss, low-shrub, wetland, Walker et al. 2005). Most of the soils at this site belong to the groups of *Histels* or *Orthels* (Beermann et al., 2015; Soil Survey Staff, 2014). *Histels* are permafrost-affected soils (*Gelisols*) that comprise 80%, by volume, of organic material to a depth of 50 cm. The second group *Orthels* ("normal Gelisols") contains less organic material and shows no features of cryoturbation

The third study area is located in the Kolyma River Delta near the village Pokhodsk, 40 km northwest of the city Chersky (69.0790° N, 160.9634° E). Climatic parameters measured at the nearest weather station in Chersky (WMO 25123) show a mean annual air temperature of -9.7 °C, an average temperature of the warmest month (July) of 13 °C and that of the coldest month (January) of -33.5 °C. Annual precipitation is about 150 mm (Russia's Weather Server, 2013). The vegetation cover of this site is described in the CAVM as unit S2 (Low shrub tundra, Walker et al. 2005). The soils in this area were characterized as *Histels*, *Turbels* and *Orthels*.

2.2 Soil sampling

On Samoylov Island in the Lena River Delta, two soil profiles each approximately one meter deep of a polygon ridge (LEN-1-R) and a polygon center (LEN-1-C) were sampled in August 2012. At the site in in the Indigirka Lowlands, one soil profile of a polygon ridge (IND-1-R) was sampled in August 2011 for analyses of the soil chemistry as well as for palaeoecological

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analyses (Schirrmeister et al., 2012). This profile was excavated from a pit, 1.1 m deep. A detailed description of the profile IND-1-R is given by Teltewskoi et al. (2016). Eight pairs of soil cores were drilled (0.5 m to each other) in the Kolyma River Delta near Pokhodsk (Schirrmeister et al., 2016). The soil cores labelled as KOL-X-X were used for analyses of the soil chemistry, and the soil cores labelled as 12P were used for cryolithological studies. Due to the duplicate sampling we summarized description and analytical data from both replicate cores. In three ice-wedge polygons, a soil core was drilled on the polygon ridge (KOL-1-R, KOL-3-R, KOL-4-R) and in the polygon center (KOL-1-C, KOL-3-C, KOL-4-C). Additionally, two soil cores were drilled on the floodplains of the Kolyma River (KOL-5, KOL-7), which was not characterized by ice wedge polygons. For drilling of the soil cores, a portable permafrost auger set (SIPRE, Snow-Ice-Permafrost-Research-Establishment coring auger, Jon´s Machine Shop, Fairbanks, Alaska) equipped with a small engine (STIHL BT 121) was used (Zubrzycki, 2011). All soil cores were divided into subunits of 5 cm which were analyzed for their contents of extractable plant-available ammonium and nitrate, for total C and N and for water content and bulk density. A comprehensive overview on the different soil profiles is given in Fig. S1.

2.3 Soil chemistry

The samples from the Indigirka Lowlands and the Kolyma River Delta were analyzed for water content, bulk density and contents of ammonium and nitrate in the field laboratory directly after drilling. Contents of total C and total N were analyzed after transport in frozen state to the laboratories at the University of Hamburg. The samples from the Lena River Delta were analyzed after transport under frozen conditions to the laboratories at the University of Hamburg. The water content of the samples was calculated by the mass loss of the samples after drying at 105 °C. Bulk density of the samples was calculated using the dry mass of the samples and the volume of a cylindrical subsample. Extractable ammonium (NH_4^+) and nitrate (NO_3^-) were measured photometrically after extraction with 0.0125 M $CaCl_2$ (VDLUFA, 1991). In the field laboratory, these extracts were measured by using photometrical test-kits for Ammonium and Nitrate analyses (LCK304 and LCK339, HACH-Lange GmbH, Germany). These test-kits use colorimetrical reactions, namely the Indophenolblue-reaction for Ammonium (Selmer-Olsen, 1971) and the Dimethylphenol-reaction for Nitrate (Elton-Bott, 1977). Total C (TC) and total N (TN) contents in the soil samples were measured using a C/N analyzer (Variomax CNMS, Elementar Analysensysteme GmbH, Germany). All values were multiplied with the bulk density of the sample and expressed as element contents (in g N m^{-3}or g C m^{-3}). Potential annual release of N was calculated as element release rate (in mg N m^{-2} yr^{-1}) by multiplying the mean annual active layer increase (as modeled by CryoGrid2) by the mean N content in the permanently frozen soil zone.

2.4 Cryolithology

Sediment and ice structures were described, sketched and photographed in the field to document the stratigraphy of the soil profiles. These data were used as input data for the CryoGrid2 model. The different sediment layers of the soils were

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characterized using the grain size distribution, color, content and kind of plant remains as well as the amount and structures of segregation ice (French and Shur, 2010). Grain-size distribution was analyzed using a LS 200 laser particle analyzer (Beckman-Coulter) and computed with GRADISTAT 4.0 (Blott and Pye, 2001). Volumetric contents of ice, mineral soil and organic matter were calculated following Strauss et al. (2012, 2013), using absolute ice contents, total carbon contents and bulk density estimation.

2.5 Monitoring of active layer thermal dynamics

In order to assess current on-site soil-climatic conditions, annual monitoring of soil moisture and temperatures was conducted at all three study areas in a soil profile on a polygon ridge. At the study site in the Kolyma River Delta, this monitoring included the active layer and the perennially frozen ground, whereas the monitoring at the two other sites was conducted only in the active layer. The longest available record of ground temperatures and active layer depth for Samoylov Island in the Lena River Delta between 1998 and 2011 is given in Boike et al. (2013). Comparable data for the Kytalyk study site in the Indigirka Lowlands between 2008 and 2009 is summarized in Parmentier et al. (2011) and between 2009 and 2011 in Iwahana et al. (2014).

The hourly climate data record (air temperature, net radiation, humidity, wind speed and direction, rainfall, snow depth) on Samoylov Island in the Lena River Delta is derived from a weather station installed in 1998 (Boike et al., 2008). Continuous monitoring of soil temperatures and soil moisture was initiated in 1998. Soil temperatures were recorded using calibrated thermistors (±0.1 °C, Campbell Scientific Ltd., UK), and liquid water content was calculated from time domain reflectometry measurements (Tektronix 1502 and TDR100, Campbell Scientific Ltd., UK) using the semi empirical mixing model of Roth et al. (1990). Ice was included as the fourth phase (air, water, soil, ice) to account for the composition of permafrost-affected soils. The precision of the instrument is ± 0.01 $m^3\ m^{-3}$, the absolute accuracy ± 0.05 $m^3\ m^{-3}$.

The monitoring at the Indigirka Lowlands took place between July 2011 and July 2012 for temperatures and in July-August 2011 for soil moisture, and in the Kolyma River Delta between July 2012 and July 2013 for soil temperature and soil moisture. The data sets were obtained by HOBO 12-Bit Temperature and Soil Moisture Smart Sensors (S-TMB-M002 and S-SMD-M005, Onset Computer Corporation, USA) at different depth below surface. All data loggers measured their specific value with a temporal resolution of 30 minutes. The overall accuracy of the temperature measurements by the sensors S-TMB-M002 is ± 0.5 °C, and the overall accuracy of the soil moisture sensors (S-SMD-M005) is ±0.05 $m^3\ m^{-3}$. Soil moisture values obtained below the operating temperature of 0 °C ± 0.5 °C, after freezing of the active layer are not considered.

2.6 Modeling active layer thickness

The evolution of the active layer thickness (ALT) was simulated at each site under different climate warming scenarios using the CryoGrid2 permafrost model (Langer et al., 2013; Westermann et al., 2012). CryoGrid2 is a 1D transient permafrost model, which calculates ground temperatures according to conductive heat transfer with phase change in the soil and in the snow pack. The model is forced by time series of surface temperature and snow depth at the upper boundary of the model domain and with a geothermal heat flux at the lower boundary. The modeled ground domain extends to a depth of 600 m. The thermal properties of the ground domain were set according to the specific ground composition at each site, consisting of the volumetric contents of organic matter and mineral soil and of ice and water. For the uppermost two meters, this information was directly inferred from cryolithological analyses of the soils, whereas the composition of the deeper ground was estimated according to field observations and geological maps (see Tab. S1). Note that the model assumes a static soil water content so that moisture changes either due to changes in precipitation, snow melt, or the general ground water level are neglected. However, estimations of future changes in landscape wetness would be speculative anyhow. The thermal properties of the snow cover were calculated according to snow density, which was estimated using a scheme similar to the snow cover reanalysis product by the Canadian Meteorological Centre (CMC, Brasnett 1999).

The model was forced by air temperature, which is a good approximation of the surface temperature on timescales longer than the diurnal cycle. For the purpose of model spin-up and validation, the model was run from 1979 until 2013. A forcing dataset was generated for each site using ERA-INTERIM reanalysis data for air temperature (Dee et al., 2011) and the CMC snow reanalysis product for snow depth. The forcing dataset was found to be realistic in comparison with site meteorological data (cf. Langer et al., 2013). The model was initialized assuming thermal equilibrium based on the average air temperature from 1979 to 1989. After initialization, the model was brought into a dynamic equilibrium by running the model for 50 years using the same period. The following period from 1989 to 2012 was used for controlling the annual active layer dynamics. A reasonable agreement with differences of less than 5 cm between modeled and observed maximum active layer thickness was found at each site. For the simulation of active layer thicknesses from 2012 to 2100, we generated a fully synthetic forcing dataset for each site. Air temperature warming trends for each site were extracted from climate projections based on the CCSM4 coupled climate model (Meehl et al., 2012). Specifically, we made use of the Permafrost Carbon RCN forcing dataset obtained from Earth System Grid (Earth System Grid, 2015). The same product was used by Koven et al. (2015) for investigating permafrost C feedback processes. We selected a moderate and a strong climate warming scenario following the Representative Concentration Pathways (RCP) 4.5 and 8.5. At the investigated sites, RCP4.5 corresponds to a warming trend of approximately 0.01°C y^{-1} and RCP8.5 to a warming trend of about 0.06°C y^{-1}, respectively. The temperature trends of the RCP scenarios were added to a synthetic air temperature time series, made up of randomly selected annual periods of the period from 1979 to 2012. The corresponding snow depth forcing was modified in order to avoid snow above 0 °C. In addition, the model was forced with a synthetic air temperature time series without trend as control run.

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2.7 Statistics and data presentation

Volumetric mean contents of C, N, ammonium and nitrate in the active layer and the perennially frozen ground were calculated for each of the eleven records. The eight soil profiles from the study site in the Kolyma River Delta were allocated to three groups (*Polygon Ridges*, *Polygon Centers*, *Floodplain*), and mean elemental contents were calculated for the three groups. Significance of the differences between the active layer and the perennially frozen ground were investigated by Student's two sample *t*-test by treating the different depths in the active layer and the perennially frozen ground as replicates for each soil profile. For each soil profile, Pearson´s correlation coefficient was calculated between the contents of TC and TN on the one side and the contents of ammonium on the other side. Mean annual N release was estimated by multiplying the mean densities of ammonium-N with the modeled annual ALT increase for the three groups from the Kolyma River Delta and also for the three soil profiles from the study sites in the Lena River Delta and the Indigirka Lowlands.

3. Results

3.1 Cryolithology

The soil profiles at Samoylov Island in the Lena River Delta were characterized by relatively high volumetric contents of mineral components of 0.2-0.6 m^3 m^{-3} and low volumetric ice contents of 0.3-0.6 m^3 m^{-3} if compared to the other study sites. The profile of the polygon ridge (LEN-1-R) consisted of alternations between mineral components and organic material, while the profile of the polygon center (LEN-1-C) was mainly composed of organic material. Thaw depth in the end of August 2012 was 30 cm on the polygon ridge and 40 cm in the polygon center. The dominant texture in both soil profiles was *Sandy Silt*.

The profile IND-1-R consisted of peat with many inclusions of silt between 15 cm and 30 cm depth. Volumetric contents of organic material were between 0.1 and 0.5 m^3 m^{-3} and volumetric ice contents were between 0.2 and 0.9 m^3 m^{-3}. Thaw depth in August 2011 was 42 cm. There was no visible cryostructure in the frozen part of this profile. The dominant texture of the mineral components in this profile was *Sandy Silt.*

The cores from the Kolyma River Delta were dominated by high volumetric contents of water and ice (cf. Fig. S1,Tab. S1). Thaw depth (end of August 2012) was highest on the floodplains (60 ± 1 cm) and in the polygon centers (56 ± 4 cm), and lowest on the polygon ridges (43 ± 5 cm). In the frozen parts, the cryostructure was horizontal reticulate with several horizontal ice belts and lenses (5-10 mm thick) and thin (≤ 1 mm) vertical ice veins. The cores from the ridges contained several horizons with volumetric contents of mineral components of about 0.5 m^3 m^{-3}. The floodplain cores contained

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approximately 0.3 m^3 m^{-3} mineral components. The volumetric content of organic matter in the floodplain cores was lower than on the polygon ridges and in the polygon centers with contents between 0.03 and 0.06 m^3 m^{-3}, besides of near-surface samples of compacted unfrozen peat (0.8-1.0 m^3 m^{-3}). The mineral soil material was composed of clay, silt and fine-grained sand. The dominant texture on the polygon ridges and in the polygon centers was *Sandy Silt*, whereas the dominant texture of the floodplain cores was *Silty Clay*.

3.2 Soil chemistry

Overall, the total carbon (TC) contents showed a large variability from less than 20 kg m^{-3} up to almost 100 kg m^{-3} within and also between the different soil profiles (Fig.2). The contents of TC and also total nitrogen (TN) were highly variable, dependent on the stratigraphy of the soil profiles (cf. Fig.S1, Fig.S3). The stratigraphies of the soil profiles from the polygon centers in Pokhodsk were rather homogeneous, similar to the contents of TC in these soils (Fig. 2a). The contents of TN were less diverse than the contents of TC. All soil profiles from the study area in the Kolyma River Delta showed volumetric TN contents between 2 and 4 kg m^{-3}. The soils from the Lena River Delta showed overall the lowest contents of TN with values around 0.5 kg m^{-3}. Highest TN contents were found in the soil profile at the Indigirka Lowlands (IND-1-R), showing values up to 6 kg m^{-3} (Fig. 2b). A significant increase in the contents of TC and TN in the perennially frozen ground was only found in the soil profile LEN-1-R. On the other hand, across all investigated soil cores, ammonium contents (in mg N m^{-3}) were significantly higher in the frozen ground than in the active layer; irrespective of the study area, the study site and the stratigraphy of the respective soil core (Fig. 2c). Highest amounts of ammonium in the perennially frozen ground were found in the soil cores from the floodplains in the Kolyma River Delta, and the smallest amounts of ammonium in the perennially frozen ground were observed in the soil cores from the Lena River Delta. Highest amounts of ammonium in the active layer were found in the three soil cores of the polygonal centers in the Kolyma River Delta. In contrast, the volumetric contents of nitrate were about ten times lower than the contents of ammonium and showed no overall increases towards the perennially frozen ground (Fig. 2d). A comprehensive overview of the soil chemistry of all soil profiles from the three study areas is given in figure S3. Furthermore, there was no overall correlation between the contents of ammonium and the contents of TC as well as TN in all soil profiles (R_{TC}=0.01; R_{TN}=0.01). Only in the soil profile LEN-1-C, there was a strong positive relationship between the contents of ammonium and the contents of TC (R = 0.86), whereas in the soil profile KOL-7, there was also a moderate negative relationship between the contents of ammonium and the contents of TC (R = -0.55). There were no significant differences in the contents of TN and nitrate between the active layer and the perennially frozen ground in the polygon tundra and the floodplain of the Kolyma River Delta. The contents of TC were significantly increased only in the perennially frozen ground of the polygon centers in the Kolyma River Delta. On the other hand, significant differences between the ammonium contents in the active layer and the perennially frozen ground were observed in all investigated soil units: The ammonium contents in the perennially frozen ground were between two-fold (polygonal tundra,

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Lena River Delta) and 40-fold (floodplains, Kolyma River Delta) higher than the ammonium contents in the active layer (Tab. 1).

3.3 Soil thermal dynamics

The soil temperatures and volumetric water content profiles at the three sites show the typical active layer processes in permafrost-affected soils, characterized by: i) large seasonal temperature amplitudes of approximately -25 °C to +10 °C in the uppermost layers, ii) seasonal freeze-thaw as indicated by the decrease/increase of liquid water content, iii) pronounced temperature stabilization during phase change at 0 °C during fall freeze back ("zero curtain") and during spring, iv) liquid water contents in frozen soils up to ~ 0.1 m^3 m^{-3}.

The volumetric water contents of the polygon ridges ranged between 0.1-0.6 m^3 m^{-3}, whereas the center of the polygon was always saturated with water contents up to 1 m^3 m^{-3}. Differences in the water content indicate differences in the texture/porosity (peat with up to nearly 100% of porosity) of the soil, as well as depth of the sensor (the surface sensors showing drying and wetting due to response to rain events). At all sites, snow melt water infiltrates and warms the (frozen) soil during spring.

The soil temperatures at the study site in the Lena River Delta were recorded in the active layer between 6 cm below surface (b.s.) and 38 cm b.s. Water contents in the same soil profile were recorded between 5 cm b.s. and 34 cm b.s. The soil was continuously frozen approximately between October 2011 and May 2012. Thawing and re-freezing of the soil occurred between May and June 2012. Minimum soil temperatures were ranging between approximately -27 °C at 6 cm b.s. and -24 °C at 38 cm b.s. Volumetric contents of liquid water of approximately 0.1 m^3 m^{-3} were measured during the winter period in all soil layers. Water contents increased quickly after thawing of the soil. Highest volumetric water contents in the summer period of more than 0.6 m^3 m^{-3} were measured at 22 cm b.s., whereas the uppermost soil layer at 5 cm b.s. showed values between 0.3 and 0.4 m^3 m^{-3} (Fig. S2a).

Monitoring of soil temperatures at the study site in the Indigirka Lowlands were conducted in depths between 6 cm b.s. and 20 cm b.s. and monitoring of water contents in the same soil profile was conducted between 12 cm b.s. and 30 cm b.s.. Minimum soil temperatures in the winter period were ranging between -24 °C at 6 cm b.s. and -26 °C at 20 cm b.s. Volumetric water contents at the study site in Kytalyk were only measured in a short period between mid of July 2011 and mid of August 2011. Highest volumetric water contents between 0.4 and 0.5 m^3 m^{-3} were measured at 27 cm b.s., and lowest volumetric water contents of approximately 0.1 m^3 m^{-3} were measured at 12 cm b.s. (Fig. S2b).

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The soil temperature data at the Pokhodsk study site include continuous records from the active layer as well from the underlying perennially frozen ground down to 95 cm below surface. Highest variation is observed in the uppermost soil layers down to 13 cm b.s. where minimum temperatures were below -20 °C. The soil temperatures in the deeper soil layers showed less variation and minimum soil temperatures were between approximately -18 °C at 25 cm b.s. and -14 °C at 95 cm b.s. Below a depth of about 50 cm, soil temperatures remain perennially below 0 °C which is also reflected by the maximum observed ALT of 43 ± 5 cm for polygon ridges at this site. Soil moisture of the active layer is mainly affected by summer precipitation and soil thaw as well as by dry-out during rain-free periods. The highest volumetric moisture content of 0.5 m^3 m^{-3} was recorded 14 cm below surface. The general pattern shows moister conditions in the middle part of the active layer at depths of 14 and 23 cm while the lowermost sensor, located directly above the perennially frozen ground at 28 cm, measured slightly lower volumetric water contents (Fig. S2c).

3.4 Active layer thickness evolution

The ALT evolution under RCP4.5 and RCP8.5 climate warming trends is simulated for all soil profiles at the three different field sites. The model was found to produce reasonable thaw depths under current climate conditions at all sites (Fig. 3). For displaying the ALT evolution we used a 5-year moving average filter in order to smooth out high frequency ALT changes due to individual hot and cold years. The range of high frequency ALT changes is displayed as shaded area. These ranges can be considered an estimate of the ALT uncertainty resulting from the random composition of the forcing dataset. At all sites, the simulations reveal an almost stable ALT under the RCP4.5 scenario with only minor deviations to the control runs until 2100 (Fig. 3). In contrast, pronounced increases in ALT ranging between 14 ± 3 and 35 ± 6 cm were observed for the RCP8.5 scenario. Overall, highest ALT increases were observed for the polygon ridge on Samoylov (35 ± 6 cm) and the floodplain soils in Pokhodsk (29 ± 5 cm). On the other hand, with average ALT increases between 19 cm and 22 cm, the polygon ridge in Kytalyk, the polygon center on Samoylov Island and the polygonal tundra soils in Pokhodsk showed only minor differences (Tab. 2). A clearly increased ALT outside of the assumed uncertainties was simulated to occur as early as 2040 for most of the investigated soil profiles. The results of the ALT modeling show that local differences in ALT evolution can be expected despite a same climate forcing (Fig. 3).

Based on the performed ALT simulations and the measured N concentrations, we estimated the mean annual N release until the year 2100 for the RCP8.5 scenario (Tab. 2). Highest N release rates were estimated for the soils on the floodplains of the Kolyma River (81 ± 14 mg N y^{-1} m^{-2}). The soils on the polygon ridges and in the polygon centers at the study site in Pokhodsk showed mean annual N release rates between 58 mg N y^{-1} m^{-2} and 48 mg N y^{-1} m^{-2}. The annual N release rates for the soils on Samoylov Island and in Kytalyk were substantially lower with values between 8 and 22 mg N y^{-1} m^{-2}.

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4. Discussion

4.1 Nitrogen contents

The present study shows for the first time significant stores of plant-available ammonium within the perennially frozen ground of Siberian permafrost soils. We observed increased amounts of ammonium in eleven soil profiles from three different study sites in the Siberian Arctic. By containing different lacustrine and fluvial sediments as well as peat and pure ice, the different sites represent typical features of arctic periglacial landscapes. Similar accumulations of ammonium were reported previously for permafrost-affected soils in Swedish peatlands (Keuper et al., 2012). As the diversity of soils and study sites represent a large geographical and geomorphological part of the Siberian lowland tundra, we suggest that the accumulation of ammonium in the perennially frozen ground is a general feature of permafrost-affected soils in arctic tundra lowlands.

There is a large seasonal variability in the availability of inorganic nitrogen in arctic soils, with highest nitrogen availability directly after snowmelt (Hobbie and Chapin, 1996) and lowest nitrogen availability at the peak of the growing season in mid-July, when plant growth and competition are highest (Weintraub and Schimel, 2005b). However, due to mineralization throughout the growing season, the pool of inorganic nitrogen re-fills towards the end of the growing season (Chapin, 1996; Weintraub and Schimel, 2005b). As the soil profiles in all study areas were sampled at the end of the growing season, seasonal dynamics in nitrogen availability cannot explain the different contents of ammonium in the active layer and the perennially frozen ground.

Microbial organisms in arctic soils are known to be adapted to cold temperatures and are active down to temperatures of -15 °C (Jansson and Tas, 2014; Mykytczuk et al., 2013; Panikov, 2009). Despite the frozen state of the soil there is still unfrozen pore water in permafrost soils, which is essential for microbial activity (Ershov, 1998; Jessen et al., 2014). Though microbial organisms can be active at temperatures below 0 °C, their temperature optima in arctic soils are above 0 °C (Mikan et al., 2002; Thamdrup and Fleischer, 1998). However, on a timescale of 10^3 to 10^4 years, even low microbial activity under subzero conditions can have a substantial impact on the geochemical composition of arctic permafrost-affected soils (Panikov, 2009). In soil cores from the Lena Delta, high amounts of methane were found in depths down to 400 cm b.s. as a result of Holocene methanogenesis within the frozen soil (Wagner et al., 2007). During the decomposition of soil organic material, organic N is first mineralized to ammonium and afterwards oxidized to nitrite and finally to nitrate. However, under anoxic conditions – typical for water-logged permafrost-affected soils in polygonal landscapes –further oxidation of the ammonium is impeded (Delwiche, 1970; Gebauer et al., 1996). Thus, we assume that the observed accumulation of ammonium in the perennially frozen ground is a result of microbial activity under low temperatures and anoxic conditions, similar to the accumulation of methane in permafrost soils that was observed by Wagner et al. (2007).

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Measuring of thaw depths was conducted in all study areas between mid and end of August. Though re-freezing of the soils in all study areas started in September (as indicated by decreasing soil temperatures), the late summer thaw depths are a good approximation of the maximum annual thaw depths as the thaw rates in the second half of August and September are usually low (Boike et al., 2013; Kutzbach et al., 2004). The increase in the ammonium contents in the perennially frozen ground was highest in the soils from the Kolyma River Delta and smallest in the soils from the Lena River Delta. The soil temperatures and volumetric water content profiles at the three sites show the typical processes of permafrost-affected soils, including a large seasonal temperature amplitude from up to -25 °C to approximately +10 °C in the surface layer and liquid water contents in the frozen soil up to ~ 0.1 m^3 m^{-3}. However, there were strong differences in the minimum soil temperatures between the study site in the Kolyma River Delta and the two other study sites. The soil profile in the Kolyma River Delta showed minimum temperatures that were almost 10 °C higher than in the two other study sites. Furthermore, in 25 cm b.s., the temperatures were even higher and showed less variation, indicating reduced influence of the air temperature on the soil temperature. On the other hand, the soil temperatures in the Lena River Delta were nearly identical between 6 and 38 cm b.s., indicating less pronounced winter insulation of the soil. Probably, continuously warmer soil temperatures provided better conditions for the accumulation of ammonium. Furthermore, reduced insulation of the soil allows for deeper thawing during warmer periods, mobilizing previously accumulated stores of ammonium. Thus, the site-specific differences in the ammonium contents in the perennially frozen ground could be a result of different soil temperatures during winter and differences in the inter-annual variability of active layer depths.

4.2 Active layer thickness evolution

In general, the model was able to realistically reproduce the ALT for all soil profiles under current climate conditions with the used climate forcing datasets. This gave confidence that for the future projections realistic magnitudes of ALT increases are calculated. Nevertheless, it must be pointed out that the model and the used forcing data are highly simplified. In particular, possible changes in soil moisture and the thermal snow properties are not taken into account. Therefore, all model results must be considered first order estimates of possible ALT changes due to the assumed warming rates. Furthermore, permafrost modeling studies (including this study) usually do not take into account the full set of possible permafrost degradation processes like thermokarst and thermo-erosion (van Huissteden and Dolman, 2012). As these processes are assumed to be highly sensitive to small warming rates (e.g. Grosse et al. 2011b), the presented permafrost degradation rates should be considered conservative estimates.

For all soil profiles a significant increase in ALT was only observed under the RCP8.5 scenario. This corresponds to findings of other permafrost sensitivity studies using different model approaches (Chadburn et al., 2015; Koven et al., 2015).

Our results demonstrate that the future evolution of ALT strongly depends on the local soil composition (cf. Langer et al. 2013). In particular, the floodplain sites showed a high sensitivity to climate warming, which is most likely related to the lower contents of ice and higher mineral contents of the soils in comparison with the soils from the polygonal tundra.

4.3 Nitrogen fluxes and release

The results from our ALT model indicate significant permafrost thaw under the RCP8.5 scenario. Under this scenario, we expect a mean increase in active layer thickness between 0.35 and 0.44 cm yr^{-1}. Thawing of permafrost will lead to a mobilization of formerly frozen N stores. The calculated annual release of NH_4^+-N across all soil cores until the year 2100 is between 8 and 81 mg N m^{-2}. A slightly higher amount of N release was projected from thawing permafrost soils in Swedish peatlands (30 to 130 mg N m^{-2}; Keuper et al. 2012). Furthermore, our estimated annual N release from thawing permafrost reaches values up to the amount of annual N fixation rates in arctic surface soils (80 to 130 mg N m^{-2}; Hobara et al. 2006). However, the thawing induced release of N represents only a small flux in comparison with the overall ecosystem N cycling. Though annual net N mineralization in arctic tundra ecosystems accounts for 50 to 500 mg N m^{-2} yr^{-1} (Nadelhoffer et al., 1992; Schimel et al., 2004; Schmidt et al., 1999), gross N mineralization is much higher, with reported daily rates between 130 and 1,500 mg N m^{-2} (Buckeridge et al., 2010; Kaiser et al., 2005). Furthermore, plants can also take up organic N forms such as amino acids (Nasholm et al., 2009; Schimel and Bennett, 2004) and the gross release of amino acids from proteins by far exceeds gross N mineralization rates in arctic tundra soils (Wild et al., 2013). Thus, although there is a substantial accumulation of ammonium within the perennially frozen ground of arctic permafrost soils that will be released upon thaw, it is unlikely that the amount of released N will have a major impact on the overall ecosystem N availability.

5 Conclusions

Our study shows that permafrost thaw can lead to significant releases of inorganic N which reaches values up to the order of magnitude of the annual fixation of atmospheric N. However, while only a small flux compared to the overall ecosystem N budget, the impacts of releasing additional N cannot be foreseen since thawing will affect large areas of the northern permafrost ecosystem. On the other hand, we also demonstrate that the permafrost in arctic riverine landscapes probably is less sensitive to climate change than currently expected; as temperature increases under the RCP4.5 scenario may not lead to significant changes in the active layer depth by the year 2100.

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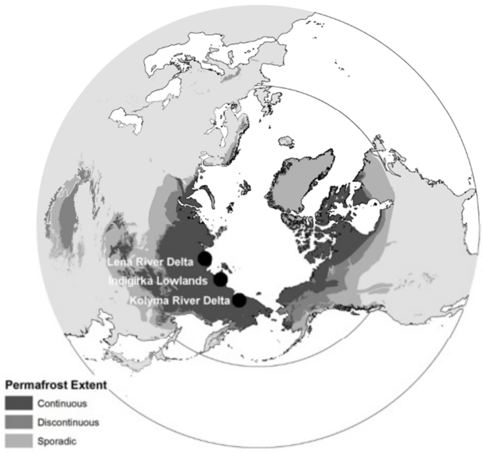

Fig.1 Map of the circumpolar permafrost regions. The locations of the three study areas are marked by black dots. The three permafrost zones (continuous, discontinuous and sporadic permafrost) are shown in grey colors. Modified after Brown et al. (1998).

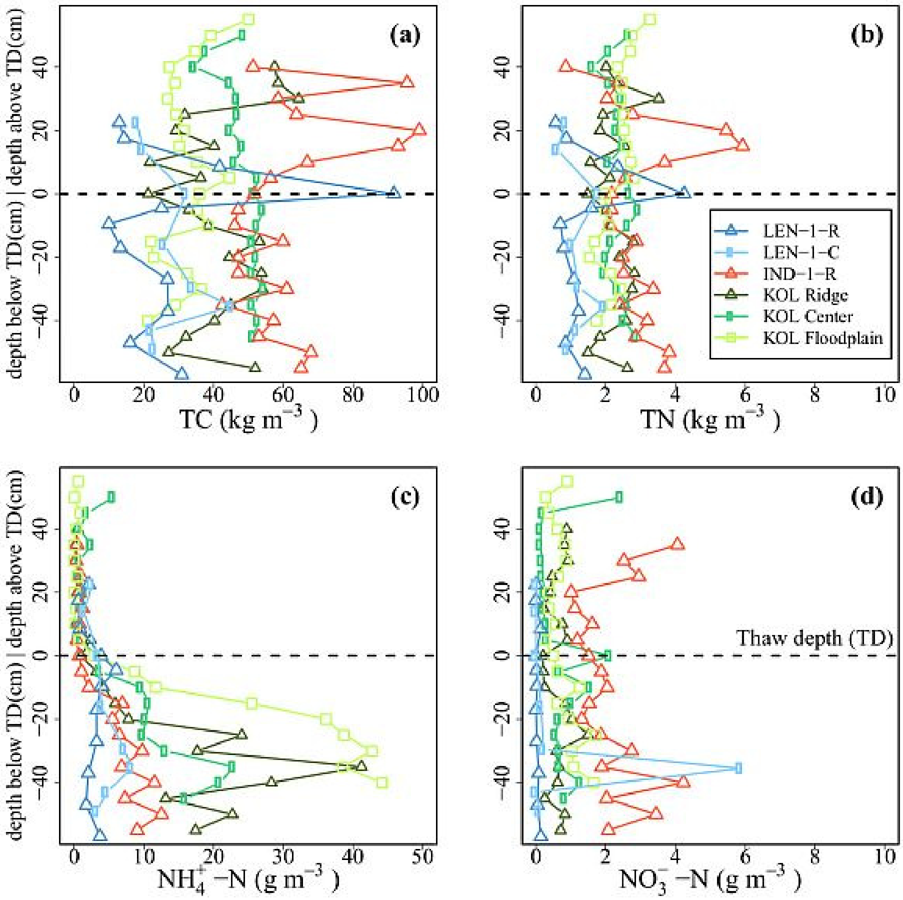

Fig. 2 Contents of total carbon (a) and total nitrogen (b), ammonium (c) and nitrate (d) in soil cores from eastern Siberia. Elemental contents of two soil cores from the Lena River Delta (LEN-1-R, LEN-1-C), one soil core from the Indigirka Lowlands (IND-1-R) and means of three soil cores each from the polygonal tundra in the Kolyma River Delta (KOL Ridge, KOL Center) as well as means of two soil cores from the floodplain of the Kolyma River (KOL Floodplain) are shown. Depth distribution of the elemental contents is adjusted to the respective thawing depth (TD) of each soil profile.

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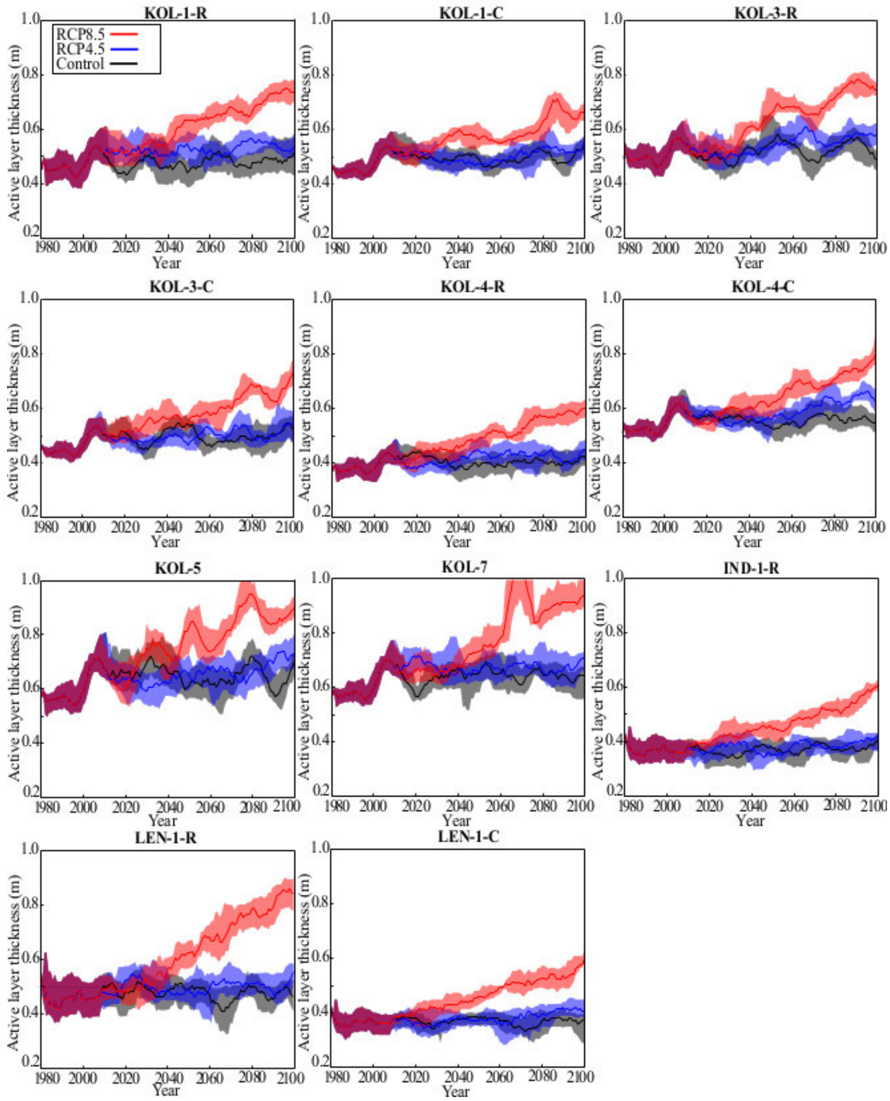

Fig.3 Modeled active layer thickness (ALT) for all soil profiles in the Kolyma River Delta (KOL), the Indigirka Lowlands (IND), and the Lena River Delta (LEN). The ALT simulations were performed for two climate warming scenarios following the Representative Concentration Pathways RCP4.5 and RCP8.5. A control run without warming trend is shown for comparison. The shaded areas indicate the range of high frequency ALT variations within a five year averaging window.

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Tab.1 Average contents of inorganic N compounds, total C and total N in the active layer (AL) and the perennially frozen ground (FG). Mean values of single soil profiles are presented for the study areas in the Lena River Delta (LEN) and the Indigirka Lowlands (IND). Mean values and standard deviations of three and two soil profiles, respectively, are presented for the study area in the Kolyma River Delta (KOL). Due to the lack of replicates in the other study areas, statistical analyses have only been conducted for the study area in the Kolyma Delta. Significant differences between the active layer and the perennially frozen ground are indicated by superscripted asterisks. Significance levels are at * = *p <0.05* and ** = *p <0.01*

			n	TC (kg m^{-3})	TN (kg m^{-3})	NH_4^+ (g m^{-3})	NO_3^- (g m^{-3})
LEN	Polygon ridge	AL	1	23.34	1.1	2.5	<0.01
		FG	1	30	1.3	5.49	1.27
	Polygon center	AL	1	40.2	2	1.87	0.04
		FG	1	22.1	1.1	3.58	0.04
IND	Polygon ridge	AL	1	68.3	3	0.75	1.98
		FG	1	54.7	2.9	7.81	2.32
KOL	Polygon ridge	AL	3	47.2 ± 13.2	3.2 ± 1.5	0.6 ± 0.5	0.6 ± 0.1
		FG	3	41.3 ± 9.3	2.3 ± 0.2	16.0 ± 8.2*	0.7 ± 0.2
	Polygon center	AL	3	45.7 ± 0.7	2.4 ± 0.2	2.3 ± 1.5	0.8 ± 0.5
		FG	3	52.6 ± 0.2**	2.4 ± 0.6	13.2 ± 4.4*	0.9 ± 0.2
	Floodplain	AL	2	36.6 ± 9.8	2.4 ± 0.9	0.6 ± 0.4	0.5 ± 0.2
		FG	2	36.4 ± 12.9	1.9 ± 0.5	24.2 ± 12.6*	1.4 ± 0.8

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Tab. 2 Increase of active layer thickness (ALT) in the three study areas until 2100 (RCP8.5) and annual N release in this period. The results from the Kolyma River Delta (KOL) are based on three and two soil profiles, respectively. The results from the study areas in the Lena River Delta (LEN) and the Indigirka Lowlands (IND) are based on one soil profile each.

		n	ALT increase (cm)	N release (mg y^{-1} m^{-2})
LEN	Polygon ridge	1	35 ± 6	22 ± 4
	Polygon center	1	19 ± 6	8 ± 3
IND	Polygon ridge	1	19 ± 3	17 ± 3
KOL	Polygon ridge	3	22 ± 3	41 ± 6
	Polygon center	3	22 ± 5	34 ± 8
	Floodplain	2	29 ± 5	81 ± 14