Permafrost Thaw and Liberation of Inorganic Nitrogen in Eastern Siberia

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ABSTRACT

The currently observed climate warming will lead to widespread degradation of near-surface permafrost, which may release substantial amounts of inorganic nitrogen (N) into arctic ecosystems. We studied 11 soil profiles at three different sites in arctic eastern Siberia to assess the amount of inorganic N stored in arctic permafrost soils. We modelled the potential thickening of the active layer for these sites using the CryoGrid2 permafrost model and representative concentration pathways (RCPs) 4.5 (a stabilisation scenario) and 8.5 (a business as usual emission scenario, with increasing carbon emissions). The modelled increases in active-layer thickness (ALT) were used to estimate potential annual liberation of inorganic N from permafrost soils during the course of climate change. We observed significant stores of inorganic ammonium in permafrost, up to 40-fold higher than in the active layer. The modelled increase in ALT under the RCP8.5 scenario can result in substantial liberation of N, reaching values up to the order of magnitude of annual fixation of atmospheric N in arctic soils. However, the thaw-induced liberation of N represents only a small flux in comparison with the overall ecosystem N cycling. Copyright © 2017 John Wiley & Sons, Ltd.

KEY WORDS: climate change; permafrost thaw; nitrogen; polygonal tundra

INTRODUCTION

The projected increases in air and ground temperatures in high latitudes will have major impacts on arctic ecosystems. Increased rates of microbial decomposition in response to higher soil temperatures can only lead to increased nutrient availability (MacDonald *et al*., 1995; Rustad *et al*., 2001; Keuper *et al*., 2012; Schaeffer *et al*., 2013). Increased nutrient availability and long-term warming at high latitudes can compensate for 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 (Shaver *et al*., 1992; Beermann *et al*., 2015), increased N availability will influence primary production (Natali *et al*., 2012) and 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 such as a reduction of the surface albedo and amplification of the regional greenhouse warming by increased evapotranspiration (Foley, 2005; Swann *et al*., 2010; Loranty *et al*., 2011). On the other hand, shrub expansion may also reduce permafrost thaw by increased shading in summer due to the high leaf area (Blok *et al*., 2010). Thus, nutrient availability indirectly controls both positive and negative feedback mechanisms to climate warming and is an important factor for the development of arctic ecosystems. Furthermore, there is evidence that increased temperatures and permafrost degradation can also lead to increased denitrification (Repo *et al*., 2009; Elberling *et al*., 2010) and increased hydrological export (McClelland *et al*., 2007; Abbott *et al*., 2015), both removing N from these soils.

There have been recent attempts to quantify the total N stock of arctic permafrost-affected soils (Harden *et al*., 2012; Zubrzycki *et al*., 2013). Northern peatland soils alone store 8–15 Pg N, which is approximately 10 per cent of the global soil organic matter N pool (Limpens *et al*., 2006;

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Loisel *et al.*, 2014). However, only small proportions of this N are available for plant nutrition as dissolved inorganic nitrogen (DIN) and, moreover, plants can also take up organic N forms such as amino acids and oligopeptides (Chapin *et al.*, 1993; Schimel and Bennett, 2004). Thus, total N alone is not an appropriate measure to describe the current N availability in arctic permafrost-affected soils and additional information about dissolved N compounds is needed.

Despite 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), few studies have quantified inorganic N compounds in permafrost. Recently, Keuper *et al.* (2012) found significant amounts of ammonium in permafrost of Swedish peatlands. Furthermore, the release of large amounts of inorganic N from thawing permafrost of arctic and alpine permafrost environments has been 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 liberation of inorganic N (including NH_4^+ and NO_3^-) from thawing permafrost. Eleven soil profiles up to 1 m depth below the surface (b.s.) were 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; Figure 1). By modelling the potential active-layer thickness (ALT) increase of the studied soils in the course of climate change, we roughly estimate the potential annual liberation of inorganic N in these ecosystems in the coming decades. Detailed cryolithological analyses of the studied soil profiles provide reliable input data for the ALT modelling.

MATERIALS AND METHODS

Site Descriptions

The three study areas are located in the zone of continuous permafrost and are dominated by polygonal tundra (Figure 1).

The first is located on Samoylov Island in the Lena River Delta (LEN; 72.3676°N, 126.4838°E). The nearest weather station is located in the village of Tiksi (WMO 21824, ~110 km southeast of the study location) and reports for the period from 2001 to 2011 give a mean annual air temperature (MAAT) of −12.8°C. The vegetation on Samoylov Island is described in the Circumpolar Arctic Vegetation Map (CAVM) as unit W2 (sedge, moss, dwarf-shrub, wetland; Walker *et al.*, 2005).

The second study area is located in the Indigirka Lowlands, 30 km northwest of the village of Chokurdakh near the World Wildlife Fund station Kytalyk at the Berelekh River, a tributary of the Indigirka River (IND; 70.8296°N, 147.4895°E). This is the coldest of the three sites, with an MAAT of −13.1°C at the nearest weather station in Chokurdakh (WMO 21946Tab.1). The vegetation at this site is described in the CAVM as unit W3 (sedge, moss, low-shrub, wetland; Walker *et al.*, 2005).

The third study area is located in the Kolyma River Delta near the village of Pokhodsk, 40 km northwest of the city of Chersky (KOL; 69.0790°N, 160.9634°E). This site is the southernmost and warmest of all three sites, with an MAAT
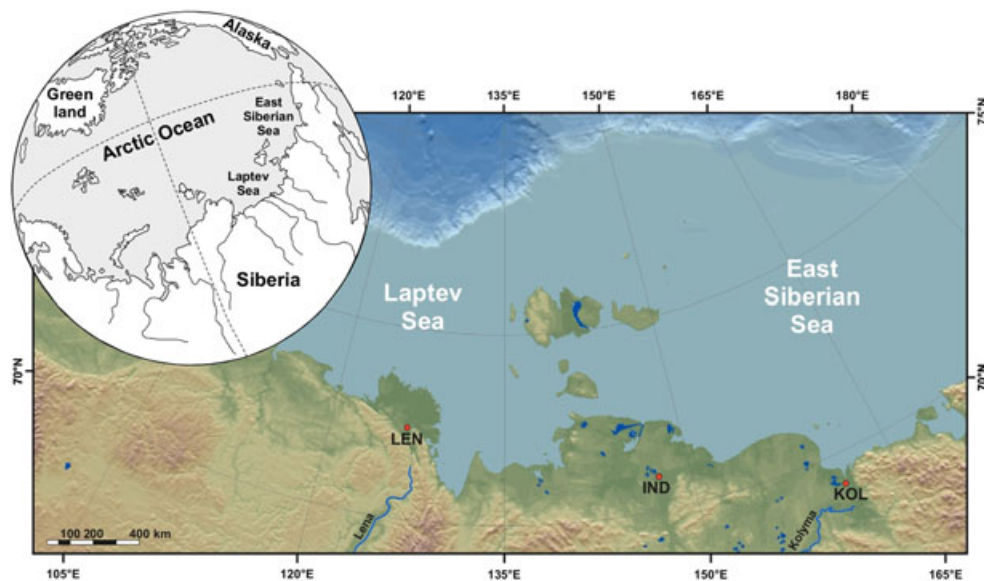

Figure 1   Position of the study sites LEN (Lena Delta), IND (Indigirka lowland), KOL (Kolyma Delta) marked by red circles. Digital elevation model compiled by G. Grosse (AWI Potsdam). [Colour figure can be viewed at wileyonlinelibrary.com]

of $-9.7°C$ at the nearest weather station in Chersky (WMO 25123). The vegetation cover of this site is described in the CAVM as unit S2 (low shrub tundra; Walker *et al.*, 2005). Meteorological parameters of all three sites are summarised in Table 1 and characteristic soil types and vegetation cover in Table 2. Thaw depths were determined in all study areas between mid and end of August by pushing a rod into the thawed ground down to resistance and measuring the distance between the ground surface and the frost table. Although 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 (Kutzbach *et al.*, 2004; Boike *et al.*, 2013).

Soil Sampling

All soil cores were labelled by their specific study site (LEN, IND, KOL), a consecutive number and, in the polygonal tundra, either by their location on a polygon ridge ($-R$) or a polygon centre ($-C$). On Samoylov Island, two soil profiles each approximately 1 m deep from a polygon ridge (LEN-1-R) and a polygon centre (LEN-1-C) were sampled in August 2012. At the Indigirka site, one soil profile from a polygon ridge (IND-1-R) was sampled in August 2011 and described in detail by Teltewskoi *et al.* (2016). Eight pairs of soil cores were drilled (0.5 m apart) in the Kolyma

River Delta near Pokhodsk (Schirrmeister *et al.*, 2016). 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 centre (KOL-1-C, KOL-3-C, KOL-4-C). Additionally, two soil cores were drilled on the floodplain of the Kolyma River (KOL-5, KOL-7). Drilling followed the method described by Zubrzycki (2011). A comprehensive overview on the different soil profiles is given in Supporting Information Figure S1.

Soil Chemistry

The samples from the Indigirka Lowlands and the Kolyma River Delta were analysed for water content, bulk density and ammonium and nitrate contents in the field laboratory, directly after drilling. Total carbon (TC) and total N (TN) contents were analysed after transport in frozen state to the laboratories at the University of Hamburg, as were all the soil chemistry measurements on samples from the Lena River Delta. The water content of the samples was calculated by the mass loss of the samples after drying at $105°C$. Bulk density 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 in the Kolyma River Delta and the Indigirka Lowlands, these extracts were measured by using photometrical test-kits for ammonium and nitrate analyses (LCK304, 0.015–2.0 mg L^{-1} and LCK339, 0.23–13.5 mg L^{-1}; HACH-Lange GmbH, Germany). TC and TN contents in the soil samples were measured using a C/N analyser (Variomax CNMS, Elementar Analysensysteme GmbH, Germany). All values were multiplied by the bulk density of the sample and expressed as element contents (in g N m^{-3} or g C m^{-3}). Potential annual liberation of N was calculated (in mg N m^{-2} $year^{-1}$) by multiplying the mean annual increase in ALT (as modelled by CryoGrid2) by the mean N content in the permafrost.

Table 1 Climatological parameters of the three study sites. Mean annual air temperature (MAAT) and mean temperatures in January and July from a period between 2001 and 2011 as well as mean annual precipitation (MAP, from the period between 2001 and 2003; Russia's Weather Server, 2013).

Site	Maat (°C)	Temp. January (°C)	Temp. July (°C)	MAP (mm)
LEN	-12.8	-29.8	9.1	315
IND	-13.1	-33.8	11.8	221
KOL	-9.8	-32.4	14	202

Table 2 Overview of the different soil cores, soil types, dominant species at the drilling site and thaw depths.

Core number	Site	Soil type	Vegetation	Thaw depth (cm)
IND-1-R	Polygon ridge	Typic Historthel	*Betula nana/Ledum palustre*	42[a]
KOL-1-R	Polygon ridge	Typic Aquiturbel	*B. nana/Alnus glutinosa*	47[b]
KOL-1-C	Polygon centre	Typic Fibristel	Pond	61[b]
KOL-3-R	Polygon ridge	Glacic Histoturbel	*Carex aquatilis/Eriophorus angustifolium*	46[b]
KOL-3-C	Polygon centre	Fluvaquentic Sapristel	*C. aquatilis/E. angustifolium*	53[b]
KOL-4-R	Polygon ridge	Fluvaquentic Historthel	*B. nana/A. glutinosa*	35[b]
KOL-4-C	Polygon centre	Fluvaquentic Sapristel	*C. aquatilis/E. angustifolium*	53[b]
KOL-5	Floodplain	Fluvaquentic Aquorthel	*C. aquatilis/E. angustifolium*	59[b]
KOL-7	Floodplain	Fluvaquentic Aquorthel	*Equisetum fluviatile*	61[b]
LEN-1-R	Polygon ridge	Typic Aquiturbel	*B. nana/L. palustre*	30[b]
LEN-1-C	Polygon centre	Typic Historthel	*C.aquatilis/E. angustifolium*	41[b]

Thaw depths were measured at [a]the end of August 2011 and [b]the end of August 2012. Specification of the soil types were conducted following US Soil Taxonomy (Soil Survey Staff, 2010).

Cryolithology

Sediment and ice structures were described, sketched and photographed in the field to document the stratigraphy of the soil profiles. The different sediment layers of the soils were characterised using the grain-size distribution, colour, content and type of plant remains as well as the amount and structures of segregation ice (French and Shur, 2010). Grain-size distribution was analysed using an LS 200 laser particle analyser (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.

Monitoring of Active-Layer Thermal Dynamics

To assess current on-site soil–climatic conditions, annual monitoring of soil moisture and temperature was conducted at all three study areas in a soil profile on a polygon ridge. At the Kolyma site, this monitoring included the active layer and the permafrost, whereas the monitoring at the two other sites was conducted only in the active layer. The longest available record of ground temperatures and ALT for Samoylov Island between 1998 and 2011 is given by Boike *et al.* (2013). Comparable data for the Kytalyk study site between 2008 and 2009 are summarised by Parmentier *et al.* (2011) and between 2009 and 2011 by Iwahana *et al.* (2014).

The hourly climate data record (air temperature, net radiation, humidity, wind speed and direction, rainfall, snow depth) on Samoylov Island were derived from a weather station installed in 1998 (Boike *et al.*, 2008). Continuous monitoring of soil temperature and soil moisture was initiated in 1998. Soil temperature was 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) 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}, and the absolute accuracy ± 0.05 m^3 m^{-3}.

Monitoring at the Indigirka site took place between July 2011 and July 2012 for temperature and in July–August 2011 for soil moisture, and at the Kolyma site 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 the surface. All data loggers measured their specific value with a temporal resolution of 30 min. The overall accuracy of the temperature measurements by the S-TMB-M002 sensors 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 ± 0.5°C, after freezing of the active layer, are not considered.

Modelling ALT

The evolution of the ALT was simulated at each site under different climate warming scenarios using the CryoGrid2 permafrost model (Westermann *et al.*, 2012; Langer *et al.*, 2013). CryoGrid2 is a one-dimensional transient permafrost model, which calculates ground temperature 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 modelled 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, mineral soil, ice and water. For the uppermost 2 m, 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 (Table S1). The model assumes a static soil water content, so that moisture changes due to precipitation, snow melt or the general ground water level are neglected. However, estimates of future changes in landscape wetness would be speculative. 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). Complex thermomechanical permafrost degradation processes such as surface subsidence, thermokarst and erosion were explicitly excluded from the modelling as reliable parameterisations do not yet exist.

The model was forced by air temperature, which is a good approximation of the surface temperature on timescales longer than the diurnal cycle. For model spin-up and validation, the model was run from 1979 to 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 initialised assuming thermal equilibrium based on the average air temperature from 1979 to 1989. After initialisation, 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 to assess the accuracy of the modelled annual active-layer dynamics. A reasonable agreement with differences of <5 cm between modelled and observed maximum ALT was found at each site. For simulating ALT from 2012 to 2100, we generated a fully synthetic forcing dataset for each site. Increasing air temperature 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 (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 year^{-1} and RCP8.5 to one of about 0.06°C year^{-1}. The temperature trends of the RCP scenarios were added to a synthetic air temperature time series, made up of randomly selected years during the period from 1979 to 2012. The corresponding snow depth forcing was modified to avoid snow above 0°C. In addition, the model was forced with a synthetic air temperature time series without trend as a control run.

Statistics and Data Presentation

Volumetric mean contents of C, N, ammonium, nitrate and water and mean values for the bulk density in the active layer and permafrost were calculated for each of the 11 records. The eight soil profiles from the Kolyma site were allocated to three groups (*polygon ridges*, *polygon centres*, *floodplain*), and mean elemental contents were calculated for the three groups. Differences between the active layer and permafrost were investigated using a Student's two-sample *t*-test by aggregating the data and using the replicate cores for a single test per site. One-way ANOVA was applied for each of the investigated soil parameters and separately for the active layer and permafrost with the different sites (*polygon ridges*, *polygon centres*, *floodplain*) as independent variables to identify differences between the three sites. For each soil profile, Pearson's correlation coefficient was calculated between the TC and TN contents on the one side and the contents of ammonium on the other side. Mean annual liberation of N was estimated by multiplying the mean densities of ammonium-N with the modelled annual ALT increase for the three groups from the Kolyma site and also for the three soil profiles from Samoylov Island and the Indigirka site.

RESULTS

Cryolithology

The soil profiles at Samoylov Island were characterised by relatively high volumetric contents of mineral components (0.2–0.6 m^3 m^{-3}) and low volumetric ice contents (0.3–0.6 m^3 m^{-3}) compared to the other sites. The profile of the polygon ridge (LEN-1-R) consisted of alternations between mineral and organic material, while the profile of the polygon centre (LEN-1-C) was mainly composed of organic material. Thaw depth at the end of August 2012 was 30 cm on the polygon ridge and 40 cm in the polygon centre. 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 and 30 cm depth. Volumetric

contents of organic material were between 0.1 and 0.5 m^3 m^{-3} and volumetric ice contents 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. Figure S1; Table S1). Thaw depth at the end of August 2012 was highest on the floodplain (60 ± 1 cm) and in the polygon centres (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 approximately 0.3 m^3 m^{-3} mineral components. The volumetric content of organic matter in the floodplain cores was lower than that on the polygon ridges and in the polygon centres, with contents between 0.03 and 0.06 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 polygon centres was *sandy silt*, whereas that on the floodplain was *silty clay*.

Soil Chemistry

Overall, the TC contents varied from less than 20 to almost 100 kg m^{-3} within and between the different soil profiles (Figure 2). The TC and TN contents were highly variable, dependent on the soil stratigraphy (cf. Figures S1 and S3). The stratigraphy from the polygon centres in Pokhodsk was rather homogeneous, similar to the TC contents in these soils (Table 3). The TN contents were less diverse than the TC contents. All soil profiles from the Kolyma study area showed volumetric TN contents between 2 and 4 kg m^{-3}. The Lena soils appeared to contain the lowest TN contents, with mean values around 1 kg m^{-3}. The highest TN contents were found in the Indigirka soil profile (IND-1-R), showing values up to 6 kg m^{-3} (cf. Figure S3). A significant increase in the TC and TN contents in permafrost was found only in the soil profile LEN-1-R.

Ammonium contents (in mg N m^{-3}) were significantly higher in the permafrost than in the active layer, irrespective of the study area, study site and soil stratigraphy (Figure 2). The highest ammonium contents in the permafrost were found in the soil cores from the Kolyma floodplain, significantly higher than those in the permafrost of the polygon ridges and polygon centres there. The smallest amounts of ammonium in permafrost were observed in the soil cores from the Lena Delta (Table 3), whereas the highest amounts in the active layer were found in the three soil cores of the polygon centres in the Kolyma 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 permafrost (Table 3). A comprehensive
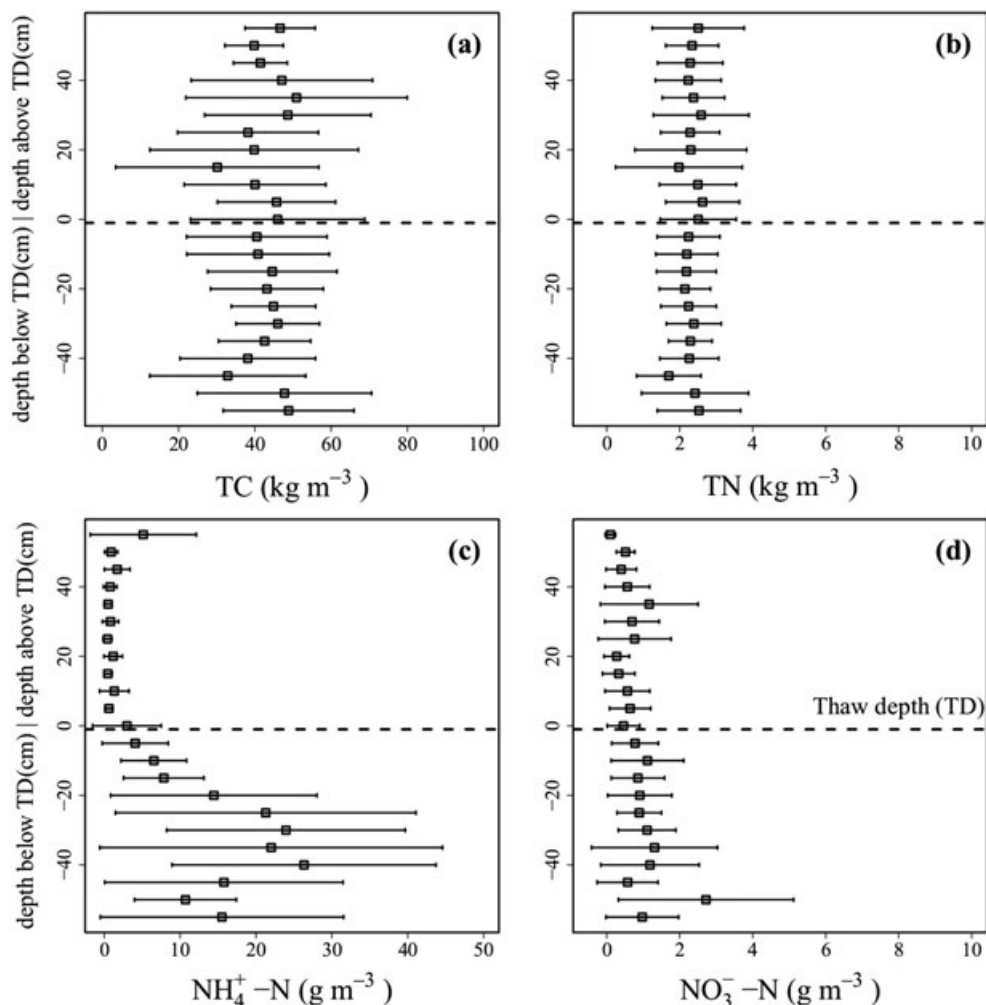
Figure 2 Contents of total carbon (a) and total nitrogen (b), ammonium (c) and nitrate (d) in soil cores from eastern Siberia. Mean elemental contents (grey boxes) and standard deviations (black lines) of all investigated soil cores are shown. Depth distribution of the elemental contents is adjusted to the respective thawing depth (TD) as a measure of the current ALT of each soil profile.

overview of the soil chemistry of all soil profiles from the three study areas is given in Figure S3.

Overall, there was no correlation between the ammonium and TC or TN contents in all soil profiles (R_{TC} = 0.01; R_{TN} = 0.01). Only in soil profile LEN-1-C was there a strong positive relationship between ammonium and TC (R = 0.86), whereas soil profile KOL-7 showed a moderate negative relationship between them (R = −0.55). No significant differences in the TN and nitrate contents were found between the active layer and the permafrost in the polygon tundra and the floodplain of the Kolyma Delta. The TC contents significantly increased only in the permafrost of the polygon centres in the Kolyma Delta. By contrast, significant differences between the ammonium contents in the active layer and the permafrost were observed in all investigated soil units: the ammonium contents in the permafrost were between two-fold (polygonal tundra, Lena Delta) and 40-fold

(floodplain, Kolyma Delta) higher than the those in the active layer (Table 1).

Soil Thermal Dynamics

The soil temperature and volumetric water content profiles at the three sites show the typical active-layer processes in permafrost-affected soils. The soil profiles are characterised by: (i) large seasonal temperature amplitudes (approximately −25 to +10°C) in the uppermost layers; (ii) seasonal freeze–thaw, as indicated by the decrease/increase of liquid water content; (iii) pronounced temperature stabilisation during phase change at 0°C during freezeback ('zero curtain') and spring; and (iv) liquid water contents up to ~0.1 m³ m⁻³ in frozen soils. The volumetric water contents of the polygon ridges ranged between 0.1 and 0.6 m³ m⁻³, whereas the centre of the polygon was always saturated (water contents up to 1 m³ m⁻³). Differences in the water

Table 3 Average contents of inorganic N compounds, total C and total N in the active layer (AL) and the permafrost (PF). Mean values of single soil profiles are presented for the study areas in the Lena 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 Delta (KOL). Due to the lack of replicates in the other study areas, statistical analyses were conducted only for the Kolyma study area. Differences between the polygon ridges the polygon centres and the floodplains were investigated by one-way ANOVA. Significant differences between the active layer at different sites are indicated by superscripted upper case letters, significant differences between the frozen ground of the polygon ridges, the polygon centres and the floodplains are indicated by superscripted lower case letters. Significant differences between the active layer and the permafrost are indicated by asterisks: $*p < 0.05$, $**p < 0.01$.

—	Site	—	n	TC (kg m^{-3})	TN (kg m^{-3})	NH$_4^+$ (g m^{-3})	NO$_3^-$ (g m^{-3})	Water content (vol.%)	Bulk density (g cm^{-3})
LEN	Polygon ridge	AL	1	23.34	1.1	2.5	<0.01	43.3	0.56
		PF	1	30	1.3	5.49	1.27	57.8	0.3
	Polygon centre	AL	1	40.2	2	1.87	0.04	59.5	0.38
		PF	1	22.1	1.1	3.58	0.04	60.4	0.49
IND	Polygon ridge	AL	1	68.3	3	0.75	1.98	75.3	0.22
		PF	1	54.7	2.9	7.81	2.32	84.8	0.14
KOL	Polygon ridge	AL	3	47.2 ± 13.2	3.2 ± 1.5	0.6 ± 0.5	0.6 ± 0.1	50.4 ± 13.2[B]	0.47 ± 0.15[AB]
		PF	3	41.3 ± 9.3[ab]	2.3 ± 0.2	16.0 ± 8.2*[b]	0.7 ± 0.2	66.5 ± 7.6[b]	0.43 ± 0.03[ab]
	Polygon centre	AL	3	45.7 ± 0.7	2.4 ± 0.2	2.3 ± 1.5	0.8 ± 0.5	73.3 ± 7.5[B]	0.24 ± 0.15[B]
		PF	3	52.6 ± 0.2**[a]	2.4 ± 0.6	13.2 ± 4.4*[b]	0.9 ± 0.2	80.4 ± 5.1[a]	0.30 ± 0.02[b]
	Floodplain	AL	2	36.6 ± 9.8	2.4 ± 0.9	0.6 ± 0.4	0.5 ± 0.2	50.8 ± 7.0[B]	0.58 ± 0.11[A]
		PF	2	36.4 ± 12.9[b]	1.9 ± 0.5	24.2 ± 12.6*[a]	1.4 ± 0.8	53.0 ± 1.8[b]	0.62 ± 0.10[a]

content indicate differences in the texture/porosity of the soil (*Sphagnum* peat with high volume, very low dry weight and up to nearly 100% porosity), as well as depth of the sensor (the surface sensors showing drying and wetting in response to rain events). At all sites, snow meltwater infiltrated and warmed the (frozen) soil during spring. The main difference between the three study sites was that soil temperature in winter was substantially higher in the Kolyma Delta site than in the two other sites.

At the Lena Delta site, soil temperature was recorded in the active layer between 6 and 38 cm b.s. Water contents in the same soil profile were recorded between 5 and 34 cm b.s. The soil was continuously frozen approximately between October 2011 and May 2012. Thawing and refreezing of the soil occurred between May and June 2012. Minimum soil temperatures ranged between approximately $-27°C$ at 6 cm b.s. and $-24°C$ at 38 cm b.s. Volumetric liquid water contents of approximately 0.1 m^3 m^{-3} were measured during the winter period in all soil layers. Water contents increased quickly after soil thaw. The highest volumetric water contents in the summer (>0.6 m^3 m^{-3}) were measured at 22 cm b.s., whereas the uppermost soil layer (5 cm b.s.) showed values between 0.3 and 0.4 m^3 m^{-3} (Figure S2a).

At the Indigirka site, soil temperature was monitored at depths between 6 and 20 cm b.s., and water content was monitored between 12 and 30 cm b.S. minimum soil temperature in the winter period ranged between $-24°C$ at 6 cm b.s. and $-26°C$ at 20 cm b.s. Volumetric water content was measured briefly between mid-July 2011 and mid-August 2011. The highest volumetric water contents between 0.4 and 0.5 m^3 m^{-3} were measured at 27 cm b.s., and the lowest (approximately 0.1m^3 m^{-3}) at 12 cm b.s. (Figure S2b).

The soil temperature data at the Kolyma Delta site include continuous records from the active layer and permafrost to 95 cm b.s. The highest variation was observed in the uppermost soil layers (to 13 cm b.s.), where minimum temperature was below $-20°C$. The temperature in the deeper soil layers varied less, with a minimum between approximately $-18°C$ at 25 cm b.s. and $-14°C$ at 95 cm b.s. Below 50 cm depth, soil temperature remained perennially below $0°C$, consistent with the maximum observed ALT of $43 ± 5$ cm for polygon ridges at this site. Soil moisture in the active layer is affected mainly by summer precipitation and soil thaw as well as by drying out during rain-free periods. The highest volumetric moisture content of 0.5 m^3 m^{-3} was recorded at 14 cm b.s. The general pattern shows moister conditions in the middle of the active layer (14 and 23 cm depth), while the deepest sensor (at 28 cm, directly above the permafrost) measured slightly lower volumetric water contents (Figure S2c).

ALT Evolution

The evolution of ALT under RCP4.5 and RCP8.5 climate warming trends was simulated for all soil profiles at the three field sites. The model predicted reasonable thaw depths under current climate conditions at all sites (Figure 3). To display ALT evolution we used a 5-year moving average filter that smoothed out high-frequency ALT changes due to individual hot and cold years. The range of high-frequency ALT changes is displayed as shaded areas, and the 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 from the control runs until 2100 (Figure 3).
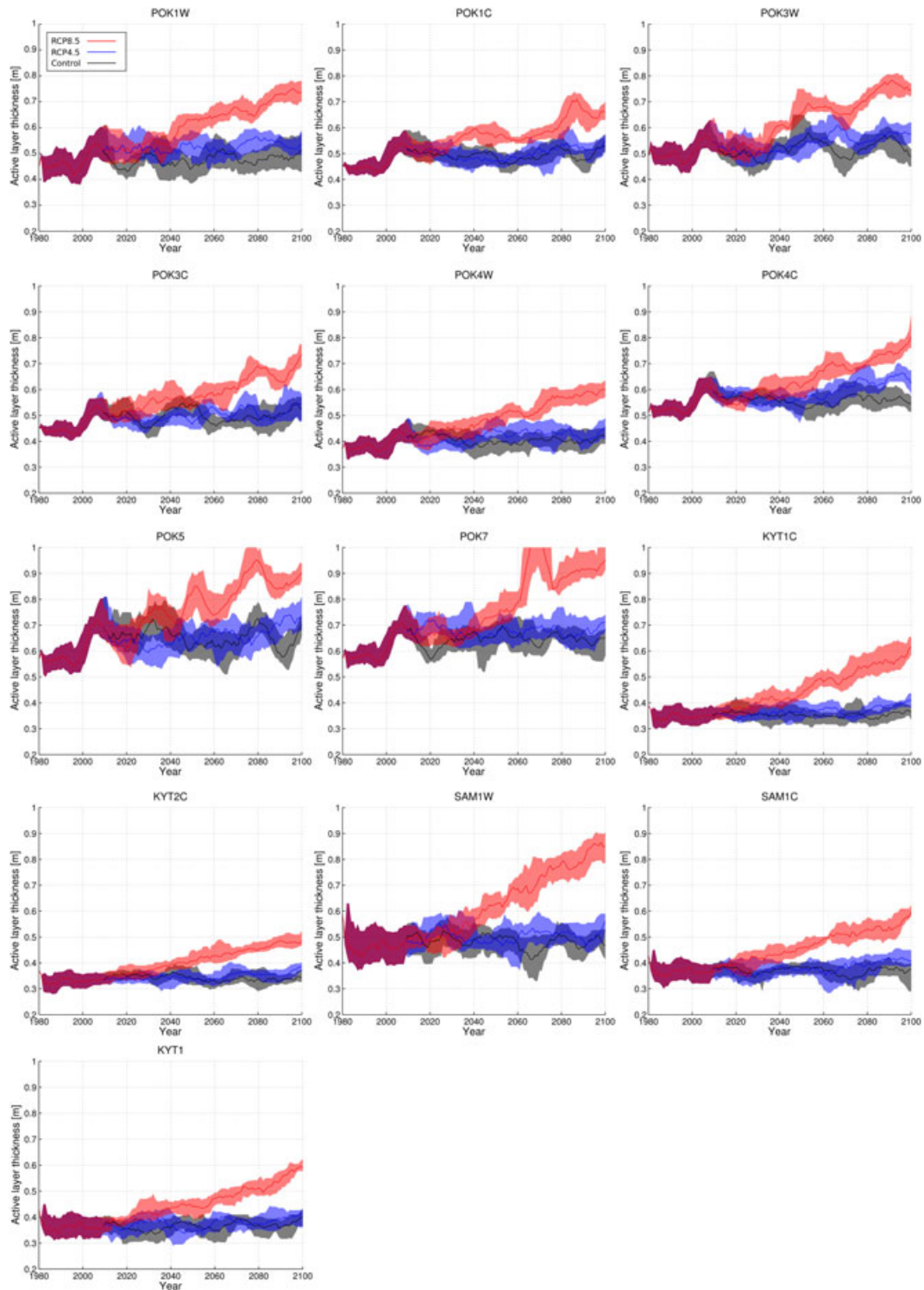
Figure 3 Modelled active-layer thickness (ALT) for all soil profiles in the Kolyma Delta (KOL), Indigirka lowlands (IND) and Lena Delta (LEN). The ALT simulations were performed for two climate warming scenarios following the representative concentration pathways RCP4.5 and RCP8.5. A control run without warming trend is shown for comparison. The shaded areas indicate the range of high-frequency ALT variations within a 5-year averaging window. [Colour figure can be viewed at wileyonlinelibrary.com]

Table 4 Increase of active-layer thickness (ALT) in the three study areas until 2100 (RCP8.5) and annual N liberation in this period. The results from the Kolyma Delta (KOL) are based on three and two soil profiles, respectively. Significant differences are indicated by superscript lower case letters and the results of the respective ANOVA are presented. The results from the study areas in the Lena Delta (LEN) and the Indigirka lowlands (IND) are each based on one soil profile.

—	Site	n	ALT increase (cm)	N liberation (mg year^{-1} m^{-2})
LEN	Polygon ridge	1	35 ± 6	22 ± 4
	Polygon centre	1	19 ± 6	8 ± 3
IND	Polygon ridge	1	19 ± 3	17 ± 3
KOL	Polygon ridge	3	22 ± 3[b]	41 ± 6[b]
	Polygon centre	3	22 ± 5[b]	34 ± 8[b]
	Floodplain	2	29 ± 5[a]	81 ± 14[a]
—	—	—	$F_{(2,6)} = 5.9, p < 0.05$	$F_{(2,6)} = 13.5; p < 0.01$

In contrast, pronounced increases in ALT (between 14 ± 3 and 35 ± 6 cm) were observed for the RCP8.5 scenario. Overall, the highest ALT increases were observed for the polygon ridge on Samoylov (35 ± 6 cm) and the floodplain soils in Pokhodsk (29 ± 5 cm). By contrast, with average ALT increases between 19 and 22 cm, the polygon ridge in Kytalyk, the polygon centre on Samoylov Island and the polygonal undra soils in Pokhodsk showed only minor differences (Table 2). A distinct increase in ALT outside of the short-term variability of ALT was simulated to occur as early as 2040 for most of the investigated soil profiles. The results of the ALT modelling show that local differences in ALT evolution can be expected despite the same climate forcing (Figure 3).

Based on the ALT simulations and the measured N concentrations, we estimated the mean annual liberation of N until the year 2100 for the RCP8.5 scenario (Table 4). The highest N liberation rates were estimated for the soils on the Kolyma floodplain (81 ± 14 mg N year^{-1} m^{-2}). The soils on the polygon ridges and in the polygon centres at the Pokhodsk site showed mean annual N liberation rates between 58 and 48 mg N year^{-1} m^{-2}. The annual N liberation rates for the soils on Samoylov Island and in Kytalyk were substantially lower (between 8 and 22 mg N year^{-1} m^{-2}).

DISCUSSION

Nitrogen Contents

Our study reveals for the first time significant stores of ammonium frozen within Siberian permafrost soils. The 11 soil profiles from three study sites across the Siberian Arctic contain different lacustrine and fluvial sediments as well as peat and pure ice. Similar accumulations of ammonium were previously reported from permafrost-affected soils in Sweden and Greenland (Elberling et al., 2010; 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 perennially frozen ground is a general feature of permafrost-affected soils in arctic tundra lowlands.

The availability of inorganic nitrogen in arctic soils varies substantially between seasons. The highest availability directly follows snowmelt (Hobbie and Chapin, 1996) and lowest coincides with the peak of the growing season in mid-July, when plant growth and competition are highest (Weintraub and Schimel, 2005b). However, the pool of inorganic nitrogen refills towards the end of the growing season, due to microbial mineralisation throughout this 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 ammonium contents in the active layer and permafrost.

Microbial organisms in arctic soils are adapted to low temperatures and are active down to −15°C (Panikov, 2009; Mykytczuk et al., 2013; Jansson and Taş, 2014), although their temperature optima are above 0°C (Thamdrup and Fleischer, 1998; Mikan et al., 2002). Despite the overall frozen state of the soil, some unfrozen pore water persists in permafrost soils and is essential for microbial activity (Ershov, 1998; Jessen et al., 2014). On a timescale of 10^3–10^4 years, even limited microbial activity under subzero conditions can substantially influence the geochemical composition of arctic permafrost-affected soils (Panikov, 2009). In soil cores from the Lena River Delta, high amounts of methane were found in depths to 4 m because of Holocene methanogenesis within frozen soil (Wagner et al., 2007). Evidence for the buildup of biodegradable dissolved organic carbon under anoxic and subzero conditions has also been found in arctic permafrost soils (Abbott et al., 2014; Ewing et al., 2015). Thus, we assume that the observed accumulation of ammonium in permafrost results from the coupled microbial mineralisation of organic carbon and nitrogen under low temperature and anoxic conditions.

The increase in the ammonium contents in the permafrost was highest in soils of the Kolyma Delta and lowest in those of the Lena Delta. These differences could result partly from differences in the soil temperatures between the three study areas. The soil profile in the Kolyma Delta showed minimum temperatures that were almost 10°C higher than in

the two other study sites. At 25 cm b.s., the temperatures were even higher and showed less variation, indicating reduced influence of air temperature on soil temperature and a strong insulation of the soil, respectively. By contrast, soil temperatures in the Lena Delta were nearly identical between 6 and 38 cm b.s., indicating less pronounced winter insulation. These continuously higher soil temperatures throughout the year in the Kolyma Delta probably provided better conditions for the accumulation of ammonium than in the two other study areas. Furthermore, reduced insulation of the soil, especially in the soils in the Lena Delta, allows for deeper thawing during warm periods, mobilising previously accumulated stores of ammonium.

The mineral composition of the soils could also influence the amount of ammonium accumulation in them. The highest amounts of ammonium in the permafrost were found in the floodplain cores from the Kolyma Delta, which were characterised by a significantly lower amount of organic material and a finer soil texture than on the polygon ridges and in the polygon centres (*silty clay*). These fine-grained soils tend to have a high pore volume, high water pressure during freezing and thus a high amount of unfrozen pore water (Eigenbrod *et al.*, 1996). As unfrozen pore water is the main prerequisite for subzero microbial activity, the fine soil texture of fluvial origin in the soil cores of the floodplain of the Kolyma River could explain the high amounts of ammonium in the permafrost.

ALT Evolution

In general, the model simulated the ALT realistically for all soil profiles under current climate conditions with the climate forcing datasets used. This gave confidence about future projections of ALT increases. Nevertheless, the model and the forcing data are highly simplified. In particular, possible changes in soil moisture and the snow thermal properties are not taken into account. Langer *et al.* (2013) have demonstrated that uncertainties in soil moisture can result in uncertainties in the modelled ALT of about ±15 cm, whereas uncertainties in snow properties had only a minor impact on ALT. Therefore, all model results must be considered first-order estimates of possible ALT changes due to the assumed warming rates. Furthermore, permafrost modelling studies (including this one) usually do not consider all permafrost degradation processes, including thermokarst subsidence and thermo-erosion (van Huissteden and Dolman, 2012; Lee *et al.*, 2014). As these processes are assumed to be highly sensitive to small changes in warming rates (Grosse *et al.*, 2011; Westermann *et al.*, 2016), we consider our estimated rates of permafrost degradation and nitrogen liberation to be conservative.

A significant increase in ALT for all soil profiles was observed only 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 depends strongly on the local soil composition

(cf. Langer *et al.*, 2013). In particular, the ALTs at the floodplain sites were highly sensitive to increased temperatures, probably related to the lower contents of ice and higher mineral contents of the soils compared with the soils from the polygonal tundra.

Nitrogen Liberation

Our ALT model predicts significant permafrost thaw under the RCP8.5 scenario: we expect a mean increase in ALT between 0.35 and 0.44 cm year^{-1}. Thawing permafrost will liberate formerly frozen N stores. The calculated annual liberation of NH_4^+-N across all soil cores until the year 2100 is between 8 and 81 mg N m^{-2} year^{-1}. The highest rates of N liberation were calculated for the soil cores from the Kolyma floodplain, where ammonium contents in permafrost are highest and the modelled increase of ALT is greatest. A slightly greater amount of N release than in the present study was projected from thawing permafrost soils in Swedish peatlands (30–130 mg N m^{-2} year^{-1}; Keuper *et al.*, 2012). Our estimated annual N liberation from thawing permafrost reaches values up to the amount of annual N fixation rates in arctic surface soils (80–130 mg N m^{-2}; Hobara *et al.*, 2006).

Thaw-induced liberation of N, however, represents only a small flux compared with the overall ecosystem N cycling. Although annual net N mineralisation in arctic tundra ecosystems accounts for 50–500 mg N m^{-2} year^{-1} (Nadelhoffer *et al.*, 1992; Schmidt *et al.*, 1999; Schimel *et al.*, 2004), gross N mineralisation is much higher, with reported daily rates between 130 and 1500 mg N m^{-2} (Kaiser *et al.*, 2005; Buckeridge *et al.*, 2010). Plants can also take up organic N forms such as amino acids (Schimel and Bennett, 2004; Näsholm *et al.*, 2009) and the gross release of amino acids from proteins far exceeds gross N mineralisation rates in arctic tundra soils (Wild *et al.*, 2013). Thus, the amount of N liberated by permafrost thaw is unlikely to have a major impact on the overall ecosystem N availability. On the other hand, substantial amounts of potentially biodegradable N will also be released as permafrost thaws. Keuper *et al.* (2012) projected that the amount of annually mineralised N from thawing permafrost will reach between 300 and 1300 mg N m^{-2} year^{-1} in the tenth year after permafrost thaw. Considering the high amounts of total N in our samples, the amount of N released by mineralisation of previously frozen organic matter will strongly exceed the amount of inorganic N liberated upon permafrost thaw in the long term.

Independent of the total amount of liberated N, it is also important to know if plants can access this N. As the thaw depth peaks at the end of the growing season, when competition is low (cf. Kutzbach *et al.*, 2004), a substantial part of liberated N may be immobilised temporarily due to a high sink capacity for N of the microbial biomass (Churchland *et al.*, 2010). On the other hand, the roots of different Graminoid species are known to grow down to the bottom of the active layer (Callaghan *et al.*, 1991), and *Larix*

species have been shown to have access to meltwater from the permafrost (Sugimoto *et al*., 2002). Thus, particularly deep-rooting species will benefit from the liberation of deep N, and the thaw-induced liberation of frozen N can influence the plant-species composition of arctic tundra ecosystems.

Due to the high water contents and probable anaerobic conditions in the soils, the freshly liberated nitrogen can also be released as atmospheric N by denitrification (Repo *et al*., 2009; Elberling *et al*., 2010; Abbott *et al*., 2014). Furthermore, permafrost degradation can also export inorganic N in water (McClelland *et al*., 2007; Abbott *et al*., 2015; Tanski *et al*., 2017). Thus, increased temperatures can also lead to permanent removal of N from these soils by denitrification and hydrological export, despite increased mineralisation of organic N released by permafrost thaw.

CONCLUSIONS

Our study shows that permafrost thaw can liberate substantial amounts of inorganic N, reaching values up to the order of magnitude of the annual fixation of atmospheric N. Although the flux of liberated inorganic N is small compared to the overall ecosystem N budget, the impacts of releasing additional N cannot be foreseen, because thawing will affect large areas of the northern permafrost ecosystem and permafrost thaw can also lead to increased mineralisation of organic N. On the other hand, we also demonstrate that the permafrost in arctic riverine landscapes is probably less sensitive to climate change than currently expected, because temperature increases under the RCP4.5 scenario may not lead to significant changes in ALT by the year 2100.

Follow-up studies should determine whether the accumulation of inorganic N is a general characteristic of arctic permafrost soils. Furthermore, analysis of the seasonal cycle of the contents of inorganic N in the active layer could elucidate the accumulation of ammonium in the seasonally frozen layer and thus would also help to estimate the pace of ammonium accumulation in the permafrost.

SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

Figure S1. Cryolithological data of soil cores from the study sites.
Figure S2. Time series of soil temperatures and soil moisture in the study sites.
Figure S3. Total carbon (TC), total nitrogen (TN), ammonium and nitrate contents, and thaw depth in the soil cores.
Table S1. Summary of the input data for the ALT modelling.

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