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Thermo-erosion gullies increase nitrogen available for hydrologic export

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Abstract Formation of thermokarst features, ground subsidence caused by thaw of ice-rich permafrost, can result in increased export of inorganic nitrogen (N) from arctic tundra to downstream ecosystems. We compared physical characteristics, N pools, and rates of N transformations in soils collected from thermo-erosion gullies, intact water tracks (the typical precursor landform to thermo-erosion gullies), and undisturbed tundra to test potential mechanisms contributing to export of inorganic N. Subsidence exposes mineral soils, which tend to contain higher abundance of inorganic ions relative to surface soils, and may bring inorganic N into contact with flowing water. Alternatively, physical mixing may increase aeration and drainage of soils, which could promote N mineralization and nitrification while suppressing denitrification. Finally, some soil types are more prone to formation of thermokarst, and if these soils are relatively N-rich, thermokarst features may export more N than surrounding tundra. Inorganic N pools in thermo-erosion gullies were similar to the mean for all tundra types in this region, as well as to water tracks when integrated across two sampled depths. Thus, soils prone to thermo-erosion are not intrinsically N-rich, and increased N availability in thermokarst features is apparent only at sub-regional spatial scales. However, vertical profiles of N pools and transformation rates were homogenized within thermo-erosion gullies compared to adjacent intact tundra, indicating that physical mixing brings inorganic N to the surface, where it may be subject to hydrologic export. Increased inorganic N availability caused by formation of thermo-erosion gullies may have acute, localized consequences for aquatic ecosystems downstream of positions within drainage networks that are susceptible to thermo-erosion.

Keywords Arctic tundra · Denitrification · Mineralization · Nitrification · Nitrogen · Permafrost · Thermo-erosion gully · Thermokarst

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Introduction

Tundra landscapes are characterized by strong nitrogen (N) limitation that results in a closed N cycle, with little export of inorganic N to aquatic ecosystems and the atmosphere (Buckeridge and Grogan 2010; Yano et al. 2010). However, warming climate and loss of permafrost may disrupt the mechanisms regulating arctic N cycling and cause significant export of N (Frey et al. 2007; McClelland et al. 2007). Experimental warming of arctic tundra results in elevated inorganic N availability (Buckeridge and Grogan 2010; Natali et al. 2011; Shaver et al. 1998), which may be subject to leaching, particularly from deep soils (Mack et al. 2004). Such patterns may result from introduction of previously frozen N into the cycling pool due to gradual degradation of permafrost that deepens the zone of seasonally thawed soils, or from direct effects of temperature on microbial processes. Further, loss of ice-rich permafrost can cause rapid ground subsidence, termed thermokarst (Jorgenson and Osterkamp 2005), which has resulted in elevated concentrations of N in plant tissue (Schuur et al. 2007), and hydrologic export of ammonium (NH_4^+) (Bowden et al. 2008).

Seasonally thawed soils, termed the active layer, typically encompass organic soils in the arctic, and biological activity as well as flow of water is largely restricted to the active layer (Hinzman et al. 1991). In undisturbed tundra, plants and micro-organisms compete intensely for nutrients available within the active layer, including organic forms (Jonasson and Shaver 1999; Schimel and Chapin 1996). For N, typically the limiting nutrient, such competition results in low net rates of N mineralization and nitrification, small pools of inorganic N, and minimal gaseous and hydrologic losses of inorganic N (Buckeridge et al. 2010; Giblin et al. 1991; Yano et al. 2010).

Strong stratification of mineral and organic horizons in tundra soils is commonly disrupted by cryoturbation, vertical mixing of soil resulting from repeated freeze–thaw cycles (Ping et al. 1998). Cryoturbation incorporates surface-derived organic matter into mineral horizons below the permafrost table, preserving significant stocks of organic carbon (Bockheim 2007; Kaiser et al. 2007; Ping et al. 1998). Retention of nutrients in surface soils of tundra is sustained by input of high-quality organic matter, which stimulates heterotrophic uptake (DeMarco et al. 2011; Lavoie et al. 2011), and incorporation of surface-derived organic matter at depth may likewise promote nutrient retention at depth. The consequences of moving mineral soils toward the surface, such as caused by thermokarst formation, however, are less well studied. Mineral soils of arctic tundra contain larger pools of inorganic N than overlying organic soils as well as higher potential rates of N mineralization and nitrification (Hobbie and Gough 2002; Keuper et al. 2012; Nadelhoffer et al. 1991). In other ecosystems, physical mixing of soils can speed rates of N cycling, including increasing net rates of nitrification (Booth et al. 2006).

Thermokarst formation can occur through several modes. Herein we address thermo-erosion gullies, a common type of thermokarst on hillslopes (Jorgenson and Osterkamp 2005), which often develop from water tracks and therefore connect disturbed soils to stream networks. Thermo-erosion gullies form when heat transfer from water flowing across the soil or vegetation surface deepens the active layer in an area underlain by ice-rich permafrost (Jorgenson and Osterkamp 2005). A combination of ice-volume loss and mechanical erosion causes subsidence and channel incision through a process of thermo-erosional tunneling and surface collapse (Fortier et al. 2007; Godin and Fortier 2012; Fig. 1), which results in mixing of soil horizons and significant erosion of adjacent hillslope soils into the feature. This process can occur rapidly in a single season, but may continue over several years depending on the depth of ice-rich permafrost and the extent of the ice-wedge network (Fortier et al. 2007; Godin and Fortier 2012). Once a depression has formed, thermo-erosion is accelerated by accumulation of windblown snow, which insulates underlying soil, reducing heat loss in winter (Osterkamp et al. 2009). During the thaw season, collection of surface water by the depression facilitates heat transfer, further promoting development of the feature (Jorgenson and Osterkamp 2005).

We hypothesize several mechanisms by which thermokarst formation influences N cycling in tundra soils. First, thermokarst-associated mixing brings mineral soils, which are relatively rich in inorganic N, to the surface where the N may be exported in flowing water. Second, physical mixing may result in increased aeration and drainage of soils, which could promote N mineralization and nitrification, or restrict capacity for N loss via denitrification. Third, some soil types are more prone to formation of thermokarst because of high ice content (Jorgenson and Osterkamp 2005; Walker and Everett 1991), and these soils can have elevated concentrations of exchangeable ions (Kokelj and Burn 2005). If thermokarst-prone soils are also N-rich relative to other soil types, thermokarst features may export more N than surrounding tundra. Finally, although increased N availability has been observed in some thermokarst soils, erosion activity has potential to result in increased retention or removal of inorganic N by altering relative rates of biological processes because mixing of organic soil horizons with mineral soils at depth brings a potentially labile source of carbon together with inorganic N from mineral soils.

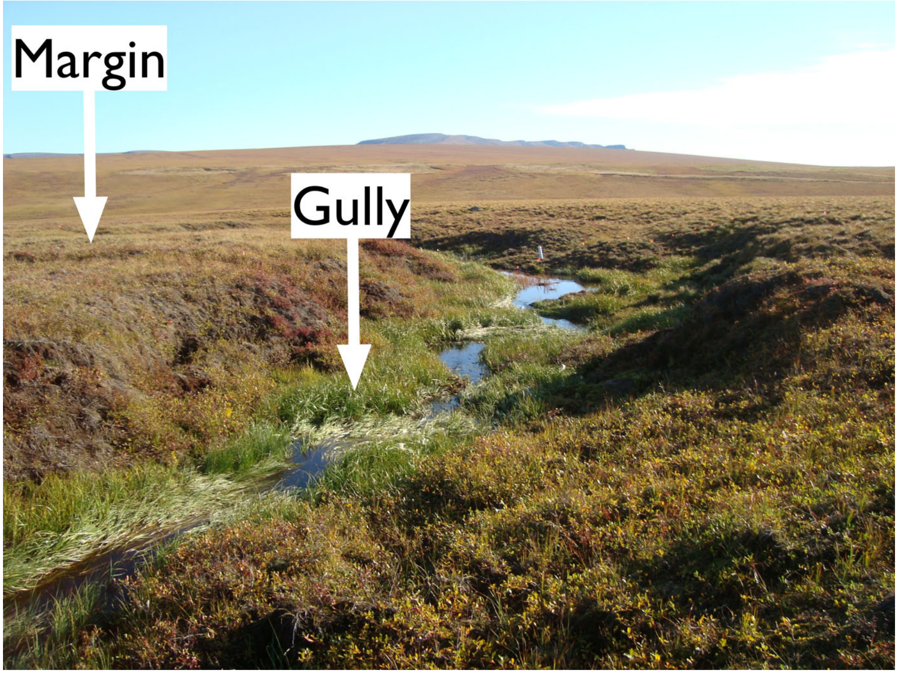

Fig. 1 Ground view of a thermo-erosion gully (Site 3)

We tested these hypotheses by measuring soil N pools and rates of N transformations in thermo-erosion gullies, water tracks, and undisturbed tundra soils in northern Alaska. We contrasted two soil depths to evaluate hypotheses associated with physical mixing, comparing inorganic N pools and rates of N mineralization, nitrification, and denitrification assayed in the laboratory. Contrasts between undisturbed tundra and gully soils were used to evaluate the effects of thermokarst formation on N pools and processes. Comparison of gully soils with water tracks, which are often the precursor landform to thermo-erosion gullies, and data describing regional N content of soils was used to evaluate whether sites prone to thermokarst formation differ in N cycling relative to surrounding tundra. These comparisons provide an assessment of the potential for thermokarst features to contribute to increased N availability in warming arctic tundra.

Methods

Study sites

Soils were collected from seven thermo-erosion gullies in arctic tundra near the Toolik Field Station in the northern foothills of the Brooks Range, Alaska, USA (Table 1; Fig. 2). Thermokarst features were selected from those identified by Bowden et al. (2008) using aerial photography. One additional feature (site 8) was sampled that was not previously identified. Toolik Field Station is located 254 km north of the Arctic Circle and 180 km south of the Arctic Ocean. The average annual temperature is −10 °C and average monthly temperature ranges from −25 °C in January to 11.5 °C in July. The region receives 320 mm of precipitation annually with 200 mm falling between June and August (Toolik Environmental Data Center Team 2011). Parent materials consist of glacial till and loess with thermo-erosion gullies occurring on landscapes of various glacial ages. Substrate age affects soil pH, which creates distinct vegetation groups including moist, acidic tussock tundra on older surfaces and non-acidic tundra on young substrates (Walker et al. 2010).

Soil collection and analysis

Soils were collected in August 2010 from seven thermo-erosion gullies and three undisturbed water tracks using a manual auger (5 cm diameter). The living moss layer was discarded and cores were separated to 0–10 and 10–20 cm depths. These depths corresponded to organic and mineral horizons, or the transition between

Table 1 Feature-level attributes of thermo-erosion gullies and water tracks

Site ID	Type	Coordinates (UTM)	Glacial geology	Surface age (ka)[a]	Tundra vegetation	Activity index[b]	Elevation	Bearing (°)	Slope (°)	Max width (m)	Feature depth (m)	Length (m)	pH (10 cm)	pH (20 cm)
1	Gully	N68.7223 W149.7505	Drift of Sag river late advance[c]	150–60	Low shrub[d]	1	800	76	4	15	2	89	4.55	4.20
2	Gully	N68.8716 W149.5789	Sag age outwash[c,e,f]	400–250	Erect shrub[d]	3	560	316	3	15	4	190	4.03	3.96
3	Gully	N68.6923 W149.2067	Drift of older Sag age[g]	150	Tussock[h]	2	780	33	3	18	3	238	3.68	4.42
5	Gully	N68.6192 W149.4251	Sag River age drift overlain by thin solifluction sheet[g]	modern, overlying 150	Low shrub[h]	2	838	13	2	5	2	90	4.11	4.37
6	Gully	N68.5435 W149.5225	Drift of latest Itkillik readvance[g]	12.8–11.4	Low shrub[h]	2	885	9	4	20	1	206	4.09	4.17
7	Gully	N68.5524 W149.5652	Drift of Itkillik phase II[g]	25–11.5	Tussock[h]	5	841	2	4	3	4	20	4.42	4.23
8	Gully	N68.5875 W149.7942	Undifferentiated lacustrine deposits[c]	12–10	Low shrub[h]	3	654	307	4	11	2	30	5.21	4.70
3	Water track	N68.6911 W149.2084	Drift of older Sag age[g]	150	Sedge, moss, dwarf shrub[h]	0	792	10	3	8	<1	864	3.76	3.79
4	Water track	N68.6447 W149.3944	Drift of older Sag age[g]	150	Tussock[h]	0	758	247	3	10	<1	445	3.75	4.04
7	Water track	N68.5527 W149.5663	Drift of Itkillik phase II[g]	25–11.5	Tussock[h]	0	830	334	4	4	<1	110	4.93	ND

ND no data

[a] Data sources same as for glacial geology

[b] Activity index: (0) No apparent current or past thermo-erosion activity, (1) Stabilized with complete revegetation, (2) Limited thermo-erosion activity but with coarse sediment in stream bottom (clear outflow), (3) Moderate thermo-erosion activity with somewhat turbid outflow, (4) Active thermo-erosion with turbid outflow and some lateral growth, (5) Very active thermo-erosion (lateral growth and deepening) with turbid outflow

[c] Hamilton (2003b)

[d] This study

[e] USGS/NPS (1999)

[f] Karlstrom 1964

[g] Hamilton (2003a)

[h] Walker et al. (2010)

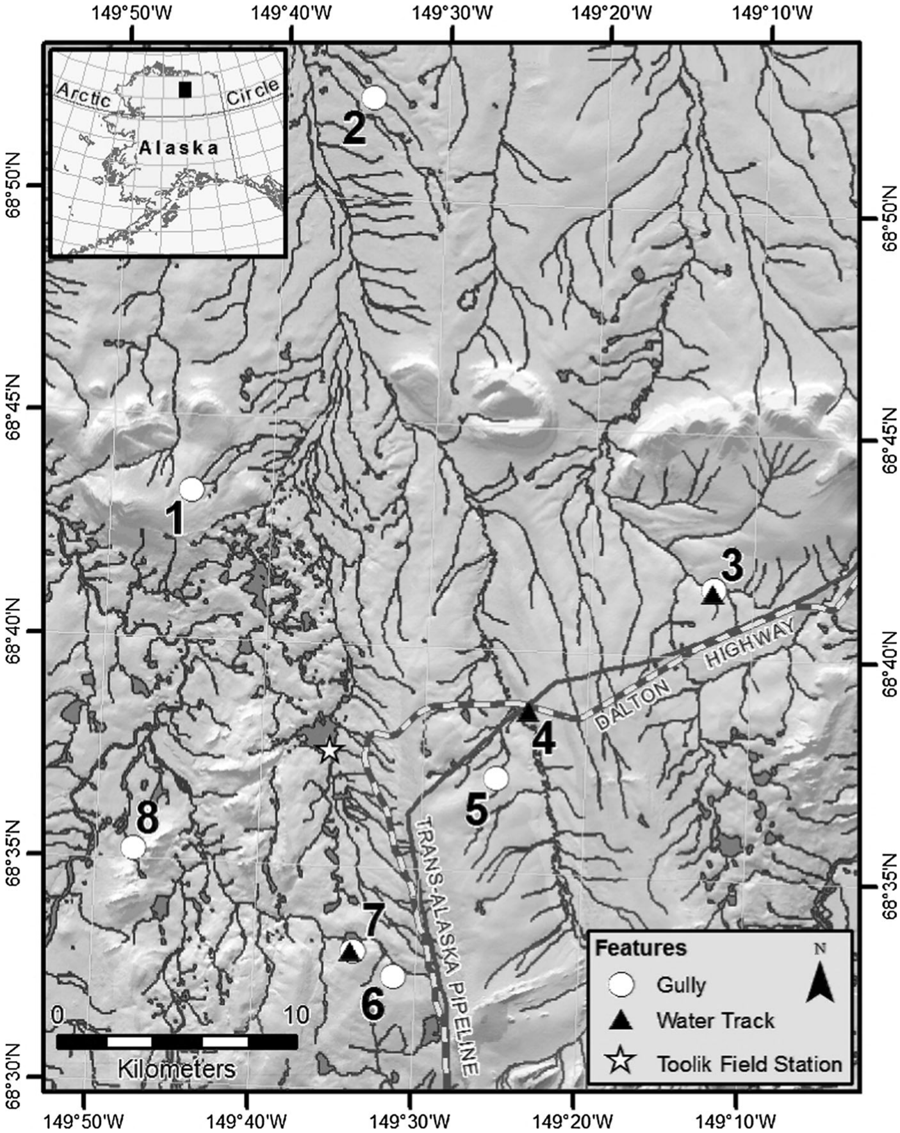

Fig. 2 Thermo-erosion gullies and water tracks were sampled near the Toolik Field Station. Site-level attributes are summarized in Table 1

them at most undisturbed tundra sites. Soils were collected from three replicate locations within each feature (hereafter referred to as gully), and three adjacent locations in undisturbed tundra, within 2 m from the edge of the collapse (hereafter referred to as margin). Soil temperature is not affected at the margin of gullies, but soil moisture is lower at the margin of features compared to undisturbed tundra at greater distances from the collapse (B.A. Abbott and J.B. Jones, unpublished data). Here we chose reference sites near the gully to minimize variation in soil and permafrost type within and adjacent to the gully. Water tracks were sampled only within the track. Three to six replicate cores were aggregated at each sampling location and replicate sampling locations within each feature were at least 20 m apart. Samples were transported to the laboratory where they were refrigerated for up to 24 h before processing for extractable pools of inorganic N and incubated for net mineralization and nitrification rates. Remaining soils were refrigerated for one week before potential nitrification and denitrification assays.

Soil assays

The composited sample for each location was thoroughly homogenized, removing rocks by hand before soil analyses. Soil moisture was determined by mass after drying at 105 °C for 3 days, and organic matter as mass loss following combustion at 550 °C. Extractable pools of inorganic N were determined by extraction in 2 M KCl (Robertson et al. 1999). NH_4^+ concentration was determined using the phenol-hypochlorite method, and NO_3^- via cadmium reduction on a Bran+Luebbe Autoanalyzer 3. Soil pH was determined on slurries in deionized water that had equilibrated with the atmosphere for 30 min. Total C and N were measured following acidification of samples to remove inorganic C on a Costech 4010 elemental analyzer.

Net rates of N mineralization and nitrification were estimated as net change in inorganic N or NO_3^- pools, respectively, following aerobic incubation for 7 days at 20 °C (Robertson et al. 1999). Potential rate of nitrification was measured in aerobic slurries supplemented with 0.5 mM NH_4^+ and 1 mM PO_4^{3-} (Robertson et al. 1999) that were sub-sampled four times in 24 h. $CaCl_2$ was added to each sub-sample as a flocculant, and solids were separated using a centrifuge. NO_3^-concentration of the supernatant was analyzed as previously described. Potential rate of nitrification was calculated as the change in NO_3^- concentration over the incubation time. We assayed potential denitrification enzyme activity using the acetylene block method (Yoshinari et al. 1977). Media containing 722 mg NO_3^--N/L, 100 mg dextrose/L, and 10 mg chloramphenicol/L was purged of O_2 using N_2 and added to soils in gas-tight jars equipped with a stopcock, followed by purging with N_2 for 2 min. Acetylene was added to the sample headspace (10 % v/v) to prevent the reduction of N_2O to N_2, and samples were vented to bring pressure to ambient. Following vigorous shaking, headspace gas was sampled and stored in evacuated containers. Headspace was sampled again after 4 h of incubation at 20 °C. Headspace N_2O concentration was analyzed on a Varian CP-3800 gas chromatograph via electron-capture detection. Bunsen coefficients were applied to determine the mass of N_2O dissolved in the slurry, and total N_2O produced by each sample was used to calculate production of N_2O over the incubation period.

Statistical methods

To assess the contribution of thermokarst and water track soils to regional N pools, we calculated regional means of soil moisture, organic matter, and inorganic N pools using data collected by the Arctic Long-Term Ecological Research Program and the Department of Energy R4D Program. These datasets spanned a 15–120 ka gradient in land surface age and encompassed the major habitat types present within this tundra region: non-acidic tussock tundra, acidic tussock tundra, wet sedge tundra, riverside willow, heath/hillslopes, and footslopes. We calculated regional means of soil moisture and N pools based only on samples collected in August, to compare with our dataset. The regional dataset reports values for whole soil cores, rather than depth-specific values, so we compared these to the mean of 0–10 and 10–20 cm values determined in this study. We determined the potential for formation of thermokarst to increase regional-scale heterogeneity in soil N pools by comparing the 95 % confidence intervals of mean values across the sampled thermo-erosion gullies to the regional mean. We also assessed the potential for particular gully features to contribute to spatial heterogeneity at the regional scale by using Z-scores to compare each gully to the regional mean. These analyses were repeated for water tracks, to determine whether pre-existing conditions may contribute to enhanced N availability in thermo-erosion gullies. We supplemented data collected in water tracks as part of this study with additional data available in the literature.

We used randomized block analysis of variance (ANOVA) to compare soil attributes and N processes in gullies and undisturbed margins. Position (gully and margin), soil depth, and their interaction were included as fixed effects, and site was applied as a random block, resulting in comparison of depths and positions within each site. Tukey's HSD was applied to determine significant differences among groups following significant ANOVAs. Assumptions of ANOVA were assessed for the residuals of the analysis. Normality was evaluated using normal probability plots and variance was visually assessed with plots of observed values compared to residuals. Response variables were ln-transformed when necessary to meet these assumptions. All statistical tests were evaluated with $\propto = 0.1$.

Results

Comparison to regional patterns

Soils of thermo-erosion gullies differed from regional mean values of soil moisture and organic matter, but not inorganic N pools, as determined by comparing overlap in confidence intervals about the means describing regional soils and gully features (Table 2). Gully soils were drier than the regional mean, and were also drier than water tracks. Both water track and gully soils tended to contain less organic matter than the regional mean in the top 20 cm. Total N pool size was not significantly different when comparing mean values for water tracks and thermokarst gullies observed in this study to the regional mean. Pools of extractable soil NH_4^+ and NO_3^- also did not differ from the regional mean, and were similar when comparing water tracks and thermo-erosion gullies (Table 2). At the feature scale, only one gully had significantly elevated extractable NH_4^+ (site 2) and two sites had elevated NO_3^- pools compared to the regional mean (sites 2 and 3; Z-score > 1.65). Several gullies (sites 2, 3, and 6) and one water track (site 3) had total N pools significantly larger than the regional mean.

Median N processing rates in the sampled water tracks were qualitatively similar to intact, margin soils. Net N mineralization rate spanned positive to negative values in soils 0–10 cm (median: −0.24 mg N/kg dry soil day), with a range similar to margin soils (data not shown). Net immobilization occurred in all samples collected from 10 to 20 cm (median: −0.37 mg N/kg dry soil day), a pattern that was unique to water tracks. Net nitrification occurred in only 2 samples from water tracks, both collected at 0–10 cm, with median values of 0 at both depths, similar to margin soils. Median rate of denitrification in water track soils was lower than in margin or gully soils for both depths (0–10: 30.5, 10–20: 9.4 μg N/kg dry soil h).

Feature-level patterns

Soil attributes differed significantly between intact margins and disturbed soils within the gully, as well as between soil depths. Soil moisture was significantly higher in gullies compared to margin soils (ln-transformed; $F_{1,74} = 4.3$, $P = 0.04$; Fig. 3), and in the surface layer compared with deeper soils ($F_{1,74} = 24.9$, $P < 0.01$; Fig. 3). Organic matter also differed between positions (ln-transformed; $F_{1,74} = 3.7$, $P = 0.06$) and depths ($F_{1,74} = 21.0$, $P < 0.01$). Whereas organic matter was significantly greater at 0–10 cm than 10–20 cm depths in margin soils, this difference was not significant in gullies, where organic matter content of both depths was similar to surface soils of the margin (Fig. 3). Soil pH did not differ significantly between depths or positions (Table 1; $P > 0.1$).

Total N tended to be greater in shallow soils ($F_{1,71} = 12.7$, $P < 0.01$), although this effect was driven by strong stratification of intact margin soils (Fig. 4). Extractable NH_4^+ was greater in gully compared to margin soils (ln-transformed; $F_{1,73} = 6.8$, $P = 0.01$), but differences between depths were not significant ($F_{1,73} = 2.8$, $P = 0.1$). These patterns result from larger pools of extractable NH_4^+ in gully soils at both depths compared to the deep margin soils (Fig. 4). Non-normal distributions caused by

Table 2 Means and 95 % confidence intervals for tundra soils, water tracks, and thermo-erosion gullies from the Toolik Lake Region

	n	Moisture (%)	Organic matter (%)	Total N (%)	NH_4^+ (mg N/kg dry soil)	NO_3^- (mg N/kg dry soil)
Regional	344–425[a]	67.1 (66.3–67.9)	37.8 (33.3–42.2)	0.51 (0.48–0.54)	7.1 (6.4–7.7)	0.2 (0.2)
Water tracks	3–5	64.6 (44.6–84.6)	24.0 (10.1–37.8)	0.57 (−1.67–2.8)	5.5 (−0.7–11.8)	0.3 (−0.2–0.9)
Thermo-erosion gullies	7	51.2 (45.4–57.0)	26.7 (16.1–37.2)	0.73 (0.41–1.1)	8.2 (−0.6–16.9)	1.0 (−0.6–2.6)

Regional means calculated from samples collected from the Sagavanirktok and Toolik areas in Aug 1987-2002 (ARC-LTER) and organic matter from Walker and Barry (1991). The regional means represent non-acidic tussock tundra, acidic tussock tundra, wet sedge tundra, riverside willow, heath/hillslopes, and footslopes, and are weighted by spatial extents calculated for the Upper Kuparuk region by Walker et al. (2008); thermokarst gullies are not included in the cover classes analyzed by Walker et al., and we have attributed 0.5 % cover to gullies. Values are integrated over 0–20 cm. Water track data include samples collected in this study, supplemented with data from Chapin et al. (1988) and Cheng et al. (1998)

[a] For organic matter, *n* = 86; for total N, *n* = 100

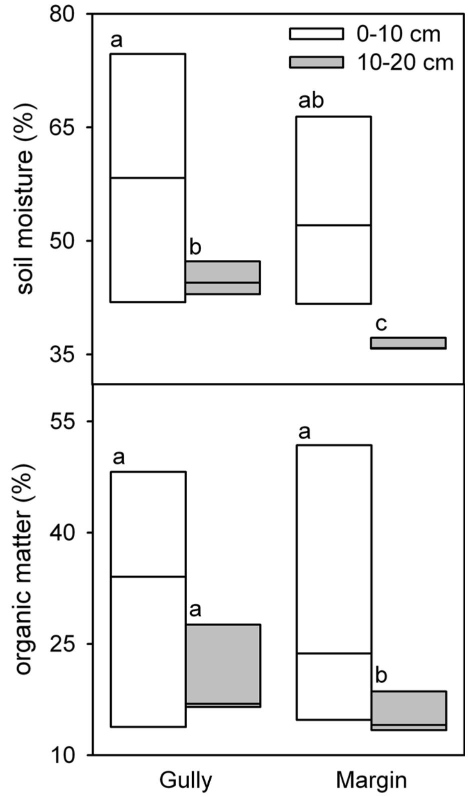

Fig. 3 Soil moisture and organic matter content of soils within (*gully*) and adjacent to (*margin*) thermo-erosion gullies. *Letters* designate significant ($P < 0.1$) differences determined by Tukey's HSD. Boxes designate 25 and 75 percentiles of data and the center bar corresponds to the median value, $n = 7$

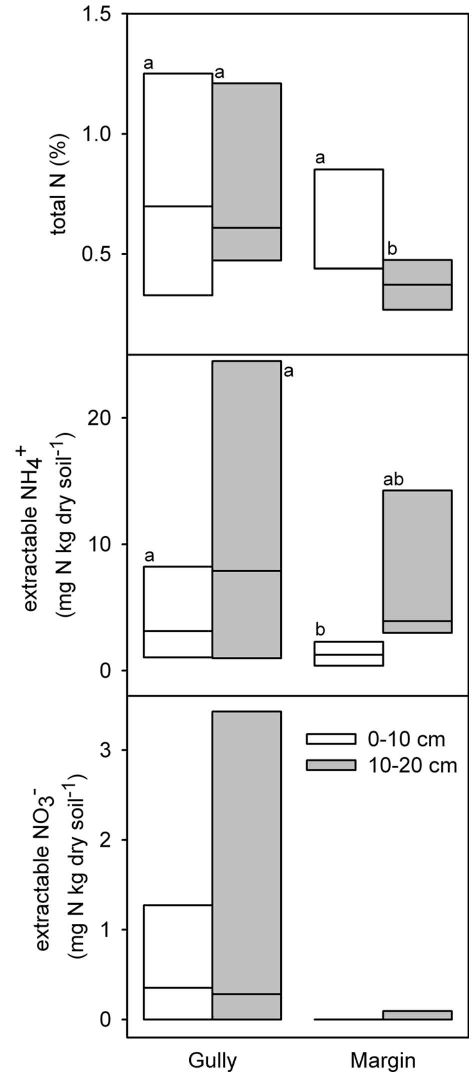

Fig. 4 Inorganic N pools in soils of thermokarst gullies. *Letters* designate significant differences ($P < 0.1$) determined by Tukey's HSD, $n = 7$. Symbology as in Fig. 3

numerous samples with NO_3^- concentration below detection limits constrained application of statistical tests. Nitrate was typically not detectable in the intact margin soils, but occurred in 43 % (0–10 cm) to 50 % (10–20 cm) of all samples from gullies (Fig. 4).

Some nitrogen transformations also contrasted between intact margins and disturbed gullies. Denitrification potential was significantly greater in surface compared with deeper soil ($F_{1,74} = 19.8$, $P < 0.01$), and there was a significant interaction between position and depth ($F_{1,74} = 3.1$, $P = 0.09$), which can be seen as a strong contrast between shallow and deeper soils of intact margins, but no contrast between depths in gullies (Fig. 5). Net nitrification and nitrification potential were not detectable in a large number of samples, constraining application of statistical tests. However, net nitrification occurred in 30 % of gully soils, at each of the sampled depths, whereas only 1 % of all margin soils supported nitrification (Fig. 5). Potential nitrification was distributed more evenly across gully and margin soils, but highest potential nitrification occurred in gully soils at both depths, and potential rates were greater than net rates. No significant differences were observed in net N mineralization rates.

Variation among thermo-erosion gullies

N pools and process rates varied up to 20-fold across gully sites. Randomized block ANOVA revealed a

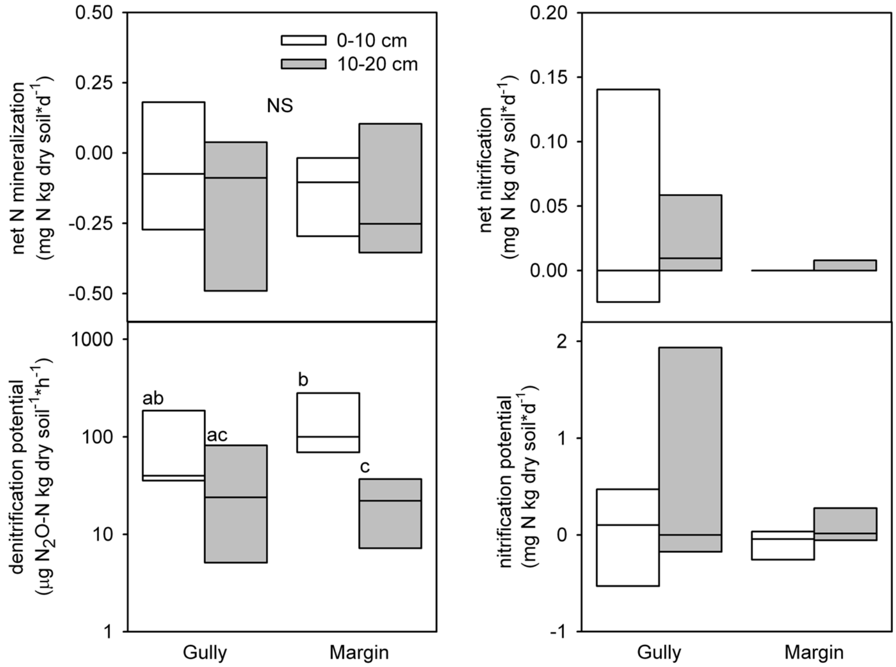

Fig. 5 Transformation rates of inorganic N. *Letters* designate significant differences ($P < 0.1$) determined by Tukey's HSD. *Note* log scale for denitrification, $n = 7$. Symbology as in Fig. 3

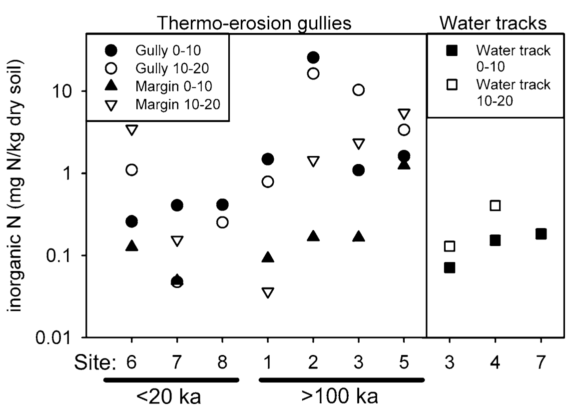

Fig. 6 Inorganic N pools of soils within and adjacent to thermo-erosional gullies, and intact water tracks. Sites, denoted by numbers listed in Table 1, are categorized by geological substrate age. Note that inorganic N is displayed on a log scale. Pools of inorganic N were below the detection limit for margin soils of gully site 8

significant effect of site on moisture, organic matter, pH, NH_4^+, and denitrification ($P < 0.01$), indicating significant heterogeneity among sites. Sites with largest inorganic N pools within the gully tended to occur on the oldest substrates, and mean depth-integrated N pools were significantly different between sites on surfaces <20 ka and those >100 ka (one factor ANOVA, ln-transformed; $F_{1,10} = 2.7$, $P = 0.04$; Fig. 6).

Discussion

Regional heterogeneity in tundra soils

We investigated soil inorganic N pools and transformations in thermo-erosion gullies to determine how formation of thermokarst may result in increased flux of inorganic N previously observed downstream of thermo-erosion in arctic tundra. We hypothesized that thermokarst soils may contain elevated N pools either because soils prone to permafrost degradation have inherently high N content relative to stable tundra, or because physical processes leading to subsidence alter the distribution of N or abiotic conditions that influence biological processing of N. Both thermo-erosion gullies and water tracks contained similar total and inorganic N pools to other tundra landforms, indicating that on average, neither gullies nor the undisturbed landform constitute hot spots for N storage at the regional scale. However, thermo-erosion appeared to alter the vertical distribution of inorganic N relative to adjacent undisturbed soils, which may promote export of dissolved N.

Influence of thermo-erosion on N cycling

Despite similarity in depth-integrated soil N between thermo-erosion gullies and intact tundra, we observed significant differences in the vertical distribution of N between gullies and adjacent undisturbed soils. This pattern could result from altered rates of N transformations following subsidence or physical changes to the soil profile within gullies. Pools of N and N transformation rates were similarly distributed between the two sampled depths in undisturbed margin and water track soils. Whereas intact profiles of margin soils had significant vertical structure, nearly all measured soil attributes were vertically homogenized in gullies, providing support for the hypothesis that physical processes associated with thermokarst formation contribute to elevated N export from thermo-erosion gullies. As gullies form, thermo-erosion causes the soil from the margins to collapse inward and move downslope within the feature, repeatedly overturning the soil profile and incorporating fresh hillslope-derived soil into the gully (Godin and Fortier 2012; Jorgenson and Osterkamp 2005). This mixing effect can be seen in soil organic matter content that is greater at depth within gullies compared to margins, indicating that burial of surface-derived organic matter has occurred during formation of the thermokarst features. Significantly larger inorganic N pools in mineral compared to organic horizons is characteristic of tundra soils (Hobbie and Gough 2002; Keuper et al. 2012), and indicates mineral soils as the source of inorganic N observed in shallow gully soils following mixing.

In addition to pool sizes, vertical patterns in N transformation rates indicate that NO_3^- dynamics differed between intact and disturbed soils. Higher rates of nitrification in gully soils, coupled with a dampening of denitrification in surface soils likely contribute to the larger pools of NO_3^- observed in gullies compared to adjacent margins. Nitrate is infrequently observed in the active layer of tundra soils, and accordingly rates of nitrification are typically low or undetectable (Giblin et al. 1991; Hobbie et al. 2002; Lavoie et al. 2011). Increased available NH_4^+ in aerated, surface soils may support nitrification activity in thermo-erosion gullies. Indeed, higher rates of nitrification when NH_4^+ was added to laboratory assays of nitrification potential compared to unamended net rate supports the notion that substrate availability limits nitrification in tundra soils.

Similar rates of net N mineralization between margins and gullies and between surface and subsurface soils suggest that differences in N processing do not account for homogenization of NH_4^+ within the soil profile of gully soils. Further, similar rates of net N mineralization across landscape positions and soil depths suggest that differences in quality of organic N do not contribute to observed patterns in NH_4^+ from thermo-erosion gullies. Experimental warming of tundra soils results in enhanced proteolytic activity (Brzostek et al. 2012), which could produce larger pools of labile organic N following thermo-erosion. However, our observations combined with previous work that documented no change in production of dissolved organic N following experimental warming (Neff and Hooper 2002) suggest that warming and thermo-erosion have little net effect on production of organic N.

The source of inorganic N for hydrologic export appears to be mineral soils, which are brought into contact with surface water as a consequence of thermo-erosion. Whereas increased nitrification and decreased denitrification may alter the form of N available for export, a physical mechanism that results in N export is constrained by the size of the soil N pool and therefore the effect of thermo-erosion on N export may be short-lived. However, active thermo-erosion gullies continuously erode adjacent intact tundra and the effect of thermo-erosion on N export from gullies is likely determined by the intensity and duration of thermo-erosion activity. In contrast to increased inorganic N availability that may occur as a result of increased thaw depth in intact tundra (Keuper et al. 2012), thermo-erosion renews the supply of N by turbation of intact tundra, and subjects it to export in shallow flow.

Characteristics of thermo-erosion gullies contributing to N export

Although our observations provide evidence in support of a common physical mechanism explaining vertical distribution of inorganic N across sites, we observed significant variation in N pools and process rates among the sampled gullies, suggesting differences in the underlying drivers of N availability. At a regional scale, landscape age is correlated with the size of N pools, with larger pools in soils developed on older surfaces, particularly in mineral horizons (Hobbie and Gough 2002), and this pattern was detected across the sites investigated in the present study (Fig. 6). Older, acidic soils leach more dissolved organic N than younger soils (Whittinghill and Hobbie 2011) and support faster rates of decomposition and N mineralization (Hobbie et al. 2002). The relationship between substrate age and soil N may have significant consequences for N export from thermokarst terrain, because thermo-erosion gullies are more likely to form on older, acidic substrate where ice wedges are larger and more abundant (Bockheim and Hinkel 2012).

Strong contrasts in NO_3^- pools among the surveyed thermo-erosion gullies suggest that in addition to substrate age, characteristics of individual sites contribute to the capacity for thermokarst soils to serve as a source or sink for NO_3^-. Our survey of seven thermo-erosion gullies does not present sufficient statistical power to quantify relationships of N dynamics with potential site-level explanatory variables. We hypothesize that several site-level attributes may influence N pools, including depth of the gully, slope, aspect, and position within the drainage network. Deeper gullies accumulate more snow, providing insulation to soils through winter, which promotes more rapid net N mineralization in intact tundra (DeMarco et al. 2011; Schimel et al. 2004). Similarly, deeper or larger water tracks may transport more heat, resulting in deeper permafrost thaw, and subjecting deeper mineral horizons to cryoturbation upon development of thermokarst. Both water track and gully soils were significantly drier than the regional mean for tundra soils, which is counterintuitive given that both contain advective flow. However, deeper thaw in water tracks (Chapin et al. 1988) and thermo-erosion gullies (SE Godsey, personal comm.) compared to other tundra types allows for deeper infiltration. Therefore, sampling surface soils late in the active season perhaps did not capture saturated depths (Cheng et al. 1998) and deeper pools of inorganic N that may be an important source of N subject to hydrologic export late in the thaw season. Finally, ground subsidence increases heterogeneity of soil characteristics at scales smaller than whole features, due to redistribution of soil moisture caused by changes in topography (Lee et al. 2010), which may introduce small scale hot spots of N availability or transformation within features.

Previous studies have linked N pools in thermokarst features to shifts in vegetation communities. Older, revegetated retrogressive thaw slumps contained larger NO_3^- pools than younger thermokarst features, likely due to colonization by N-fixing plants (Lantz et al. 2009). However, thermo-erosion gullies rarely result in substantial shifts in plant communities (Jorgenson and Osterkamp 2005). Although the gullies observed in the present study contained revegetated islands, and spanned a range of thermo-erosion activity, N-fixing plant species were not observed at high densities, suggesting that N inputs did not change following subsidence.

Implications of thermo-erosion for N export

Despite a small spatial extent (~1 % of continuous permafrost in Alaska; Jorgenson et al. 2009), thermo-erosion gullies occupy a focal point for transport of water and solutes, which may propagate the effects of permafrost thaw and soil disturbance to valley bottoms or stream networks. Enrichment of shallow soils with inorganic N due to physical mixing and subsequent changes to biological transformations of N could contribute to observed export of inorganic N and fertilization of oligotrophic ecosystems downstream of thermo-erosion gullies. This fertilization may be acute (Bowden et al. 2008), but it remains unclear whether elevated nutrient concentrations persist while thermokarst features stabilize and are revegetated, which occurs over a timescale of years (Godin and Fortier 2012). Thus, the direct consequences of thermo-erosion gullies for receiving waters may be significant, but relatively short-lived. However, about a third of all permafrost has medium or high ice-content (Zhang et al. 1999) and is therefore susceptible to formation of thermokarst, and the incidence of thermo-erosion is increasing (Jorgenson et al. 2009; Lantz and Kokelj 2008). The effects of multiple individual gullies may therefore cumulatively increase the intensity of N fertilization in downstream ecosystems.

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