



This discussion paper is/has been under review for the journal Biogeosciences (BG).
Please refer to the corresponding final paper in BG if available.

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault^{1,2}, E. Lévesque^{1,2}, D. Fortier^{2,3}, and L. J. Lamarque^{1,2}

¹Département des Sciences de l'environnement, Université du Québec à Trois-Rivières, Trois-Rivières, QC, G9A 5H7, Canada

²Centre d'études nordiques, Université Laval, Québec, QC, G1V 0A6, Canada

³Département de géographie, Université de Montréal, Montréal, QC, H2V 2B8, Canada

Received: 29 June 2015 – Accepted: 5 July 2015 – Published: 5 August 2015

Correspondence to: E. Lévesque (esther.levesque@uqtr.ca)

Published by Copernicus Publications on behalf of the European Geosciences Union.

BGD

12, 12191–12228, 2015

Thermo-erosion
gullies boost the
transition from wet to
mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

Continuous permafrost zones with well-developed polygonal ice-wedge networks are particularly vulnerable to climate change. Thermo-mechanical erosion can initiate the development of gullies that lead to substantial drainage of adjacent wet habitats. How vegetation responds to this particular disturbance is currently unknown but has the potential to strongly disrupt function and structure of Arctic ecosystems. Focusing on three major gullies of Bylot Island, Nunavut, we aimed at estimating the effects of thermo-erosion processes in shaping plant community changes. Over two years, we explored the influence of environmental factors on plant species richness, abundance and biomass studying 197 polygons that covered the whole transition from intact wet to disturbed and mesic habitats. While gullying decreased soil moisture by 40 % and thaw front depth by 10 cm in breached polygons, we observed a gradual vegetation shift within five to ten years with mesic habitat plant species such as *Arctagrostis latifolia* and *Salix arctica* replacing wet habitat dominant *Carex aquatilis* and *Dupontia fisheri*. This transition was accompanied by a five time decrease in graminoid above-ground biomass in mesic sites. Our results illustrate that wetlands are highly vulnerable to thermo-erosion processes that may rapidly promote the decrease of food availability for herbivores and reduce methane emissions of Arctic ecosystems.

1 Introduction

Warming in the Arctic is occurring twice as fast as the global average (USGCRP, 2009; New et al., 2011; NOAA, 2014). Perennially frozen ground (permafrost) has consequently warmed by 2 °C over the last 20 to 30 years (Christiansen et al., 2010; Romanovsky et al., 2010), and there is now evidence of a decrease in both permafrost area extent across the Northern Hemisphere and permafrost thickness at the local scale (Beilman and Robinson, 2003; Payette et al., 2004; Couture and Pollard, 2007; Smith, 2011).

BGD

12, 12191–12228, 2015

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Permafrost is tightly associated with biophysical components such as air temperatures, soil conditions, surface water, groundwater, snow cover and vegetation (Jorgenson et al., 2010; Sjöberg, 2015). For instance, permafrost impedes water to drain to deeper soil layers maintaining a perched water table and saturated soils across the Arctic (Woo, 2012; Natali et al., 2015). These wet habitats are dominated by highly productive graminoid species which offer abundant high quality food for arctic herbivores (Manseau and Gauthier, 2003; Doiron, 2014) while significantly contributing to methane emission (Brummel et al., 2012; Bouchard et al., 2014). Permafrost degradation that would increase subsurface drainage and reduce the extent of lakes and wetlands at high latitudes (Avis et al., 2011; Jorgenson et al., 2013; Beck et al., 2015) would have major consequences on ecosystem structure and function (Collins et al., 2013; Jorgenson et al., 2013). This would also strongly influence variations of active layer depths (Wright et al., 2009; Shiklomanov et al., 2010; Gangodagamage et al., 2014) as illustrated by long-term monitoring sites throughout the circumpolar North (Tarnocai et al., 2004; Nelson et al., 2008; Smith et al., 2009; Shiklomanov et al., 2010).

Several forms of ground and massive ice can be found within permafrost (Rowland et al., 2010), especially ice-wedges in regions where winter temperatures enable thermal contraction cracking (Fortier and Allard, 2005; Ewertowski, 2009; Kokelj et al., 2014). Continuous permafrost zones with well-developed polygonal ice-wedge networks are particularly vulnerable to climate change because ice-wedges are usually found near the top of permafrost (Smith et al., 2005; Jorgenson et al., 2006; Woo et al., 2008; Vonk et al., 2013). In these regions, thawing permafrost can result in ground ice erosion and displacement of sediments, carbon and nutrients by drainage (Rowland et al., 2010; Godin et al., 2014; Harms et al., 2014). This thermo-erosion process has especially been observed across North-America (Grosse et al., 2011), in Siberia (Günther et al., 2013) and in the Antarctic Dry Valleys (Levy et al., 2008). On Bylot Island in Nunavut, thermo-mechanical erosion by water has initiated internal tunneling and the development of gully networks in both aeolian and organic depositional environments which cover about 20 000 m² (Fortier et al., 2007; Godin and Fortier, 2010, 2012a).

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



A fine-scale spatio-temporal monitoring study of the six largest gullies showed that their development rate ranges from 14 to 25 myr⁻¹, going up to 80 myr⁻¹ during their inception (Godin and Fortier, 2012b), leading to substantial changes in the drainage network and increased eroded area throughout the valley (Godin et al., 2014).

The extent to which vegetation is affected by thermo-erosion gullying is currently unknown, and contrasts with the extensive literature that has documented increased plant abundance, growth and biomass as well as shrub expansion northward in response to climate warming (Hudson and Henry, 2010; Epstein et al., 2013; Boulanger-Lapointe et al., 2014; Naito and Cairns, 2015). This information is urgently needed as vegetation plays an important role in structuring Arctic ecosystems and regulating permafrost response to climate change (Jorgenson et al., 2010; Gauthier et al., 2011; Legagneux et al., 2012). Wetlands, which serve as preferred grounds for Arctic herbivores (Gauthier et al., 1996; Massé et al., 2001; Doiron et al., 2014), are expected to produce more methane compared to shrub-dominated areas (Olefeldt et al., 2013; Nauta et al., 2015; Treat et al., 2015), which on the other hand may reduce active layer thickness and permafrost thaw rate (Blok et al., 2010).

The present study aimed at examining plant community patterns following thermo-erosion processes. Bylot Island, where geomorphological and ecological processes in response to climate change have been monitored for over two decades (Gauthier et al., 1995; Allard, 1996; Fortier and Allard, 2004), offered a unique opportunity to specifically assess the response of wetlands to gullying. The following questions were addressed: (1) to what extent thermo-erosion gullying modifies environmental conditions of low-centered wetland polygons? (2) how do plant communities cope with these geomorphological changes, i.e. do we observe shifts in plant diversity, abundance and productivity?

2 Methods

2.1 Study area

This study took place in the Qarlikturvik valley of Bylot Island, Nunavut, Canada (73°09' N, 79°57' W; Fig. 1a). Bound to the North and South by plateaus < 500 m a.s.l., it connects C-79 and C-93 glaciers to the Navy Board Inlet sea via a proglacial river that passes through the plain. The valley (ca. 50 km²) is characterized by a polygon-patterned landscape that results from ice-wedge development during the late Holocene (Ellis and Rochefort, 2004; Fortier and Allard, 2004; Ellis et al., 2008). It is defined by elevated ridges that enclose a central depression usually flooded by snowmelt water (Woo and Young, 2006; Minke et al., 2007).

Two main plant communities can be recognized at the study site. Wetlands, often associated with low-centered polygons, represent ca 23 % of the valley area (Hughes et al., 1994) and are dominated by sedges (*Carex aquatilis*, *Eriophorum scheuchzeri*, *Eriophorum angustifolium*), grasses (*Arctagrostis latifolia*, *Dupontia fisheri*, *Pleurypogon sabinei*; Gauthier et al., 1995) and fen mosses (*Drepanocladus* spp., *Aulocomnium* spp.; Ellis et al., 2008). Low-centered polygon rims, sloping terrain and hummocky tundra support mesic species such as *Salix* spp., *Vaccinium uliginosum*, *Arctagrostis latifolia*, *Poa arctica* and *Luzula confusa* (Zoltai et al., 1983). As a result, the valley houses many herbivores during summer, in particular snow geese, brown and collared lemmings (Gauthier et al., 1995; Gruyer et al., 2008), and thus represent a critical environment for tundra food web (Gauthier et al., 2011; Legagneux et al., 2012).

2.2 Field sites

Our work was conducted along three gullies that were selected among the 36 identified in the valley (Fig. 1b; Godin and Fortier, 2012b). All three were located in the low-centered polygon complex of the Qarlikturvik valley. Gullies A and B, respectively 835 and 717 m long, are characterized by substantial thermo-erosion processes (Fortier

BGD

12, 12191–12228, 2015

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



et al., 2007; Godin and Fortier, 2012b) whilst gully C, 180 m long, has not been active in recent years. A total of 197 sampling sites (i.e. polygons) were randomly selected along the three gullies (Fig. 1b; $n = 95$, 79 and 21 for gully A, B and C, respectively). They were classified into one of four polygon categories (referred hereafter as habitats) that were defined by the following characteristics: polygon rim integrity, drainage observation and polygon location along the gully (Fortier et al., 2007; Godin and Fortier, 2012b). The habitats were sorted as follows: (i) undisturbed wet polygons ($n = 62$), encompassing sites that were not affected by gullying, i.e. with intact rims and non-apparent ice wedges; less than five year disturbed polygons ($n = 44$), characterizing sites located along the gully most recent sections and that have been recently perturbed, i.e. with partially degraded rims, ongoing drainage and apparent ice wedges; more than five year disturbed polygons ($n = 43$), representing sites where rims are heavily degraded and drainage is almost complete; mesic environments ($n = 48$), characterizing sites located along the oldest gully sections and where rims have entirely collapsed.

2.3 Environmental condition monitoring

Daily precipitation was recorded with a manual rain gauge throughout summer 2010 at the base camp, located 700 m west of the gully A (Gauthier et al., 2010). Soil (top 10 cm) moisture content was recorded at the center of each polygon using ECH₂O EC-5 moisture sensors connected to Em5b dataloggers (Decagon Devices, WA, USA). Measurements were carried out in 2010, both 5 July (early season) and 30 July (late season) in polygons located along gullies A and B, and 30 July only in gully C polygons. Thaw front depth was recorded at the center of each polygon using a steel rod graduated in centimetre and driven in the active layer. This was done late July 2009 and 2010 in polygons located along gullies A and B, and mid-July 2010 in those situated along gully C. One measure was taken per polygon, except for the mesic sites where three measurements were randomly conducted. In this case, means per site were calculated prior to analyses.

2.4 Plant community characterization

Species richness and abundance were determined in each polygon in July 2009 or 2010 using randomly placed 70 cm × 70 cm quadrats within areas that were representative of habitats. Abundance of vascular plants, lichens, mosses, *Nostoc*, fungi, cryptogamic crust, bare ground, litter, standing dead, standing water, signs of grubbing, and geese feces was evaluated as cover percentages using photography analyses. Three quadrats were vertically photographed at each site at ca 1.3 m from the ground (see detailed protocols in Chen et al., 2010 and the IPY CiCAT, 2012). Daubenmire cover class method (Daubenmire, 1959) was then applied on each quadrat picture to evaluate species cover as the projection on the ground of all species above-ground parts.

Five polygons per habitat were also randomly selected to measure above-ground biomass of graminoid species. At each site, an enclosure of 1 m × 1 m was made of chicken wire 30 cm high and supported by wooden stakes at each corner (see Gauthier et al., 1995). Enclosures were set up in early July 2012 to avoid any significant grazing by geese. Above-ground biomass was harvested inside the enclosures near peak production in early August 2012, using imaginary grids of 25 cm × 25 cm for wet and recently disturbed polygons and of 50 cm × 20 cm for long-time disturbed polygons and mesic environments. All vegetation present in the enclosures was cut to a standard height, i.e. at an average of 1 cm below the moss surface (Gauthier et al., 1995). Live vascular species were sorted as follows: *Carex aquatilis*, *Eriophorum angustifolium* and *Eriophorum scheuchzeri* (Cyperaceae); *Luzula arctica* and *Luzula confusa* (Juncaceae); *Anthoxanthum arcticum*, *Arctagrostis latifolia*, *Dupontia fisheri* and *Festuca brachyphylla* (Poaceae). Biomass was then oven-dried at 65 °C until constant dry weight and further weighed to ±0.0001 g using an electronic weighing scale.

BGD

12, 12191–12228, 2015

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



2.5 Statistical analyses

Differences in soil moisture content and thaw front depth between habitats were tested with a generalized linear model (procedure GLM in SAS, version 9.4, SAS Institute, Cary, NC, USA). Soil moisture content, thaw front depth as well as date or year of measurements and the interaction terms were the factors included in the model. Type III sums of squares were used for the calculation of F statistics. SNK post hoc contrasts were performed to ascertain specific differences at $\alpha < 0.05$. Differences in graminoid above-ground biomass between habitats were tested using a one-way analysis of variance (procedure ANOVA). Distributions of variables were tested for normality prior to analyses using Shapiro–Wilk test (procedure UNIVARIATE). Contrary to graminoid above-ground biomass ($W = 0.95$, $P = 0.42$), soil moisture content ($W = 0.96$, $P < 0.001$) and thaw front depth ($W = 0.98$, $P = 0.002$) did not meet normal distribution assumptions, therefore analyses were performed on log-transformed data for these two variables (Tabachnik and Fidell, 1996; Quinn and Keough, 2002). Canonical Correspondence Analyses (CCA) were conducted to test unimodal relationships between eco-terrain sites and environmental variables (ter Braak, 1986; Zuur et al., 2007) using the “vegan” package in R 3.1.3. Two matrices were elaborated: one of 197 sites $\times$ 66 species using species mean cover per site (i.e. polygon), and another of 197 sites $\times$ 8 environmental characteristics comprising the following continuous variables: soil moisture content, thaw front depth, litter cover, bare ground, grubbing, standing dead, standing water and geese feces. Soil moisture measurements obtained on 30 July 2010 were used in the analyses.

BGD

12, 12191–12228, 2015

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3 Results

3.1 Environmental conditions

In 2009, above-average spring temperatures led to a rapid snowmelt (16 June) while summer was one of the driest ones on record (Gauthier et al., 2009). In 2010, despite a relatively warm spring (0.26 °C above normal), the high snow pack at the end of the winter (41.6 cm on 31 May) delayed the snowmelt in the lowlands, which was a week later than normal (28 June). Summer was characterized by warm and sunny conditions as well as below-average precipitations (cumulative rain of 84 mm vs. long-time average of 92 mm; Gauthier et al., 2010). However, the 36 mm received in only five days in mid-July were an important water input for the polygons and explain the significant difference observed in soil moisture between the two monitoring dates ($df = 1$, $F = 55.50$, $P < 0.001$; Fig. 2). There was also a significant difference in soil moisture content among habitats ($df = 3$, $F = 38.02$, $P < 0.001$; Fig. 2), which was driven both in early and late July by differences between wet polygons and the other habitats (early July: $F = 18.72$, $P < 0.001$, late July: $F = 19.34$, $P < 0.001$; Table 1). Throughout the summer, soil moisture was approximately 40 % higher in wet sites compared to disturbed and mesic ones. There was no significant habitat x date interaction ($df = 3$, $F = 0.06$, $P = 0.98$).

We found a significant difference in thaw front depth among habitats ($df = 3$, $F = 51.51$, $P < 0.001$; Fig. 3), which was also driven by significant differences between wet polygons and the other habitats (2009: $F = 20.51$, $P < 0.001$, 2010: $F = 33.09$, $P < 0.001$; Table 1). Thaw front depth of wet polygons was approximately 10 cm deeper than in disturbed and mesic sites (35–36 vs. 25–27 cm). There was no significant difference between years of thaw front depth monitoring ($df = 1$, $F = 0.46$, $P = 0.50$; Fig. 3) and no significant habitat x year interaction ($df = 3$, $F = 0.14$, $P = 0.94$).

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀◀	▶▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



3.2 Plant community characterization

A total of 18 vascular plant families encompassing 59 species were sampled throughout the study (Table A1). The greatest species richness was found in polygons that were disturbed 5 years ago and where both hydrophilic and mesic species were present (Table 2). The transition from wet polygons to mesic environments was accompanied by significant changes in plant community composition, especially with the decline in Cyperaceae and Poaceae cover and the emergence of Salicaceae species (Table 2). *Carex aquatilis* and *Dupontia fisheri* were respectively present in 100 and 93 % of the wet polygons sampled, where they accounted for 52 and 26 % of the total vascular plant cover. They were found in only 47 and 16 % of mesic sites and accounted for 9 and 0.45 % of the total vascular plant cover. In contrast, *Salix arctica* and *Arctagrostis latifolia*, which were found in approximately half of the wet polygons accounting for 3 % of the total plant cover, were present in 98 % of the mesic sites where they accounted for 50 and 14 % of the total plant cover. Vegetation changes were also observed through the decline of graminoid above-ground biomass which varied significantly among habitats (df = 3, F = 11.59, P < 0.001; Table 1; Fig. 4a). Graminoid biomass was nearly five times greater in wet than in mesic sites (29.2 vs. 5.9 g m⁻²; Figs. 4a and B1). Differences were mainly driven by the decline of hydrophilic *Carex aquatilis*, *Eriophorum scheuchzeri*, *Anthoxanthum arcticum* and *Dupontia fisheri* from wet polygons to mesic environments (28.8, 19.7, 3.6 and 2.5 g m⁻² in wet, recently disturbed, disturbed 5 years ago and mesic polygons, respectively; Fig. 4b). Above-ground biomass of *Luzula* spp., *Arctagrostis latifolia* and *Festuca brachyphylla* was contrastingly fifteen times greater in mesic than in wet habitats (4.45 vs. 0.29 g m⁻²).

3.3 Relationships between plant communities and environmental variables

The first two axes of the Canonical Correspondence Analysis retained 14 % of the vegetation data variance and 80 % of the vegetation–environment relationship variance (Table 3). Five of the eight environmental variables tested were significant within the

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀	▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



canonical model ($P < 0.05$, 999 permutations), but only three – litter cover, thaw front depth and soil moisture – showed high correlations with the canonical axes (Table 4). Thaw front depth and soil moisture were strongly related to the first axis, while litter cover was mainly associated with the second axis (Table 4). Altogether, these variables discriminated well the eco-terrain units defined in the polygon-patterned landscape of the Qarlikturvik valley. Wet polygons were mainly related to high soil moisture content and substantial thaw front depth (i.e. active layer thickness) whilst mesic environments were associated with greater litter cover (Fig. 5). A transition from less to more than five year disturbed polygons was also observed along the soil moisture gradient (Fig. 5).

4 Discussion

Sustainability of wetlands at high latitudes relies on perennial frozen ground that prevents drainage and allows wet soil moisture conditions (Woo and Young, 2006; Ellis et al., 2008). However, snowmelt water run-off through ice-wedge polygon landscapes can initiate permafrost thermo-erosion and the development of gullies (Fortier et al., 2007; Godin et al., 2014). We show here that thermo-erosion significantly alters wetlands by rapidly decreasing soil moisture content and thaw front depth of polygons adjacent to gullies. More importantly, vegetation was sensitive to this process, and mesic habitat plant species replaced gradually hydrophilic ones within a five to ten year span. This vegetation turn-over has substantial consequences on wildlife biology, permafrost stabilization and ecosystem-level greenhouse gas emissions (Blok et al., 2010; Doiron et al., 2014; McEwing et al., 2015).

4.1 Transition in environmental conditions

Thermo-erosion gullying led to a significant decrease of soil moisture content of disturbed polygons, which is consistent with what has been previously observed in gullied areas (Seppälä 1997; Poesen et al., 2003; Godin and Fortier, 2012a; Godin et al.,

Title Page	
Abstract	Introduction
Conclusions	References
Tables	Figures
◀◀	▶▶
◀	▶
Back	Close
Full Screen / Esc	
Printer-friendly Version	
Interactive Discussion	



2014; Harms et al., 2014). While intact wet sites store important quantities of water during spring snowmelt and summer rainfalls, gully formation rapidly reduces water conservation capacity of breached polygons due to polygon ridge erosion and water runoff through frost cracks leading to increased hydrological connectivity (Fortier et al., 2007; Godin et al., 2014). However, disturbed polygons still responded positively to summer rainfalls, and their summer volumetric water content was much more dependent of these rainfalls than in wet sites (data not shown). This is in line with the work of Godin et al. (2015) at the polygon scale, who found that soil moisture content variability in disturbed sites is significantly greater than in undisturbed polygons.

Decreasing soil moisture content in disturbed polygons came with decreasing thaw front depth. While this result was expected given that active layer thickness is closely related to local hydrological processes (Nelson et al., 1999; Hinzman et al., 2005; Minke et al., 2009; Wright et al., 2009; Gangodagamage et al., 2014), it contrasts with the active layer thickening generally observed in response to climate change (Tarnocai et al., 2004; Woo et al., 2007; Akerman and Johansson, 2008; Smith et al., 2009; Nauta et al., 2015). In addition, the values of thaw front depth obtained at our sampled sites are of similar order of magnitude than those measured by Godin et al. (2015) in their intact and disturbed polygons. Within five years of drainage, thaw front depth in disturbed polygons decreased by 37 % compared to that in intact wet sites. This is mainly explained by the greater heat transfer from water and higher thermal conduction rates in wetter polygons that provide substantial melt energy to the frost table (Nelson et al., 1997; Hinzman et al., 2005; Wright et al., 2009; Romanovsky et al., 2010). This effect is also sharpened by the low thermal conductivity of moss carpets in disturbed sites (Wright et al., 2009).

4.2 Vegetation changes

Gully development in the Qarlikturvik valley and subsequent drainage of adjacent low-centered polygons has led to a radical change in plant communities, thus illustrating the standard plant succession following climatic and/or geomorphic variations (Billings and

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Peterson, 1980; Ellis and Rochefort, 2006; Woo and Young, 2006). In the canonical ordination analysis, soil moisture gradient discriminated wet polygons from the other sites as well as recently disturbed from long-time disturbed habitats. The influence of soil moisture content in separating plant community types at high latitudes has been previously well documented (Hinzman et al., 2005; Daniëls and de Molenaar, 2011; Daniëls et al., 2011; Sandvik and Odland, 2014). This is particularly the case of Duclos (2002), who surveyed mesic and dried habitats of Bylot Island, and Mann et al. (2002), who reported that vegetation community changes in Alaska over the past 8–13 000 years mostly relied on soil moisture changes. Four other variables significantly influenced the distinction among habitats: (i) thaw front depth discriminated habitat types in the same direction than soil moisture, which was expected since these two factors are closely related to each other (see Sect. 4.1), (ii) litter cover separated mesic polygons from the others, which can be explained by increased organic matter related to greater shrub abundance in mesic environments (Zamin et al., 2014), (iii) standing dead separated wet and recently disturbed polygons from the other habitats, which can be explained by the greater abundance and biomass of *Cyperaceae* species at these sites (Fig. 4), (iv) geese feces were mainly associated with long-time disturbed and mesic sites. While this may suggest a higher use of these habitats by geese, the slower degradation of feces in dryer habitats cannot be ruled out; this has yet to be tested.

Overall, the floristic composition of our sampled sites is in line with previous field surveys conducted in the same area (Gauthier et al., 1996; Duclos, 2002; Doiron, 2014). The presence of *Carex aquatilis*, *Eriophorum scheuchzeri* and *Dupontia fisheri* also characterizes well the typical vegetation of Arctic wetlands (Jorgenson et al., 2013; Sandvik and Odland, 2014; Lara et al., 2015). While the highest in disturbed polygons, species richness increased from wet and mesic environments, which is concordant with previous work showing changes in species richness in response to climate change (Britton et al., 2009; Pauli et al., 2012; Ross et al., 2012; Sandvik and Odland, 2014). More interestingly, we highlight here the rapidity of vegetation transition in response to gully development, which can be surprising given that Arctic plant

that this species mostly relies on wetlands for food resources (Gauthier et al., 1995, 2011), especially because graminoids are easily digested thanks to their low fiber concentration and rich nutritive elements (Sedinger and Raveling, 1989; Manseau and Gauthier, 1993; Audet et al., 2007). For instance, geese removed respectively 40 and 31 % of the total annual production of *Dupontia fisheri* and *Eriophorum scheuchzeri* during the period 1990–2007 (Cadieux et al., 2008). Thus, the degradation of wetland habitat following thermo-erosion gullying will probably limit the availability of high-quality food to geese since mesic habitats have a lower carrying capacity than wetlands (Massé et al., 2001). Moreover, climate warming can speed up the seasonal decline in nutritive quality of forage plants, eventually impacting goose gosling size and conditions (Doiron, 2014). In addition, the presence of ponds in wetlands provides geese refuges from predators such as arctic fox (Hughes et al., 1994; Lecomte et al., 2009), and their disappearance might also change predator-prey interactions.

Effects of gullying-induced vegetation changes may finally be visible on variations of greenhouse gas emissions. There is evidence for a strong vegetation control on methane emission from wetlands (Olefeldt et al., 2013; McEwing et al., 2015; Tveit et al., 2015). In wet polygonal tundra of Northern Siberia, Kutzbach et al. (2004) found for instance that dense *Carex aquatilis* stands emitted more methane than sites with low *Carex* densities. Overall, wetlands and lakes expansion are thought to increase methane emission but also carbon storage (Myers-Smith, 2005; Nauta et al., 2015; Treat et al., 2015; Bouchard et al., 2015). We can therefore expect that the reverse transition from wet to mesic environments observed within our low-centered polygon landscape would lead to reduced methane emission and greater carbon release through enhanced decomposition. However, no general pattern on ecosystem responses to decreased water table position and subsequent gas emissions has emerged to date (see Grosse et al., 2011 for review). It will thus be crucial to determine in the near future the specific evolution of *Salix* and *Luzula* spp. primary production in mesic sites in order to accurately predict the effects of wetland retreat on methane and soil organic carbon cycles.

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



5 Conclusions

This study illustrates that changes the shift in the hydrological and thermal regimes following the induction of thermo-erosion boost the transition of wet to mesic plant communities within low-centered polygon landscapes, providing evidence that permafrost degradation is a critical component of vegetation modifications at high latitudes. More importantly, gully effects such as increasing drainage and wetland degradation go in the opposite direction to what is generally observed in response to climate warming. Ecological studies should consequently start using an approach that integrates disturbed permafrost monitoring if one wants to more efficiently document climate change effects on arctic terrestrial ecosystems. In addition, while surface warming is expected to alter the ground's thermal regime (Couture and Pollard, 2007), more work should be devoted to the understanding of the feedbacks plant communities and vegetation succession may have on the thermal and mechanical stabilization dynamics of permafrost terrains disturbed by thermo-erosion gully. This is especially needed since plant community differences between disturbed and undisturbed sites can last several centuries (Cray and Pollard, 2015).

**The Supplement related to this article is available online at
doi:10.5194/bgd-12-12191-2015-supplement.**

Acknowledgements. The authors would like to thank Parks Canada – Sirmilik National Park, Northern Studies Center (CEN) and Gilles Gauthier (Laval University) for the access to the field camp during summers 2009, 2010 and 2012. We also thank Alexandre Guertin-Pasquier, Etienne Godin, Jonathan Lasnier, Stephanie Coulombe and Coralie Henry-Brouillette for their fieldwork support as well as Alexandre Moreau, Stephan Ouellet, Noémie Boulanger-Lapointe for their help with statistical analyses. This project was made possible by the excellent logistic contribution of Polar Continental Shelf Program (PCSP) as well as the financial support of the International Polar Year (IPY) program of the Government of Canada, Natural Sciences and Engineering Research Council of Canada (NSERC), Fonds québécois de la recherche sur la

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



nature et les technologies (FQRNT), Northern Scientific Training Program (NSTP) of the Department of Indian Affairs and Northern Development, the network of centers of excellence of Canada ArcticNet, NSERC CREATE training program in northern environmental sciences (EnviroNorth) and Groupe de recherche en biologie végétale (GRBV) of the Université du Québec à Trois-Rivières.

References

- Akerman, H. J. and Johansson, M.: Thawing permafrost and thicker active layer in sub-arctic Sweden, *Permafrost Periglac.*, 19, 279–292, 2008.
- Allard, M.: Geomorphological changes and permafrost dynamics: key factors in changing arctic ecosystems. An example from Bylot Island, Nunavut, Canada, *Geosci. Can.*, 23, 205–212, 1996.
- Audet, B., Lévesque, E., and Gauthier, G.: Seasonal variation in plant nutritive quality from Greater Snow Goose goslings in mesic tundra, *Can. J. Bot.*, 85, 457–462, 2007.
- Avis, C. A., Weaver, A. J., and Meissner, K. J.: Reduction in areal extent of high-latitude wetlands in response to permafrost thaw, *Nat. Geosci.*, 4, 444–448, 2011.
- Baldwin, A. H., Jensen, K., and Schönfeldt, M.: Warming increases plant biomass and reduces diversity across continents, latitudes, and species migration scenarios in experimental wetland communities, *Glob. Change Biol.*, 20, 835–850, 2014.
- Beck, I., Ludwig, R., Bernier, M., Lévesque, E., and Boike, J.: Assessing permafrost degradation and land cover changes (1986–2009) using remote sensing data over Umiujaq, sub-Arctic Québec, *Permafrost Periglac.*, 26, 129–141, doi:10.1002/ppp.1839, 2015.
- Beilman, D. W. and Robinson, S. D.: Peatland permafrost thaw and landform type along a climate gradient, in: *Proceedings, Eighth International Conference on Permafrost*, edited by: Phillips, M., Springman, P. M., and Arenson, S. U., A. A. Balkema, Zurich, Switzerland, 1, 61–65, 2003.
- Billings, W. D. and Peterson, K. M.: Vegetational change and ice-wedge polygons through the thaw-lake cycle in Arctic Alaska, *Arctic Alpine Res.*, 12, 413–432, 1980.
- Blok, D., Heijman, M. M. P. D., Schaepman-Strub, G., Kononov, A. V., Maximov, T. C., and Berendse, F.: Shrub expansion may reduce summer permafrost thaw in Siberia tundra, *Glob. Change Biol.*, 16, 1296–1305, 2010.

BGD

12, 12191–12228, 2015

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



[Back](#)

Close

Full Screen / Esc

[Printer-friendly Version](#)

Interactive Discussion



- Bouchard, F., Francus, P., Pienitz, R., Laurion, I., and Feyte, S.: Subarctic thermokarst ponds: investigating recent landscape evolution and sediment dynamics in thawed permafrost of Northern Québec (Canada), *Arct. Antarct. Alp. Res.*, 46, 251–271, 2014.
- Bouchard, F., Laurion, I., Preskienis, V., Fortier, D., Xu, X., and Whiticar, M. J.: Modern to millennium-old greenhouse gases emitted from freshwater ecosystems of the eastern Canadian Arctic, *Biogeosciences Discuss.*, 12, 11661–11705, doi:10.5194/bgd-12-11661-2015, 2015.
- Boulanger-Lapointe, N., Lévesque, E., Boudreau, S., Henry, G. H. G., and Schmidt, N. M.: Population structure and dynamics of Arctic willow (*Salix arctica*) in the High Arctic, *J. Biogeogr.*, 41, 1967–1978, 2014.
- Britton, A. J., Beale, C. M., Towers, W., and Hewison, R. L.: Biodiversity gains and losses: evidence for homogenization of Scottish alpine vegetation, *Biol. Conserv.*, 142, 1728–1739, 2009.
- Brummel, M. E., Farrell, R. E., and Siciliano, S. D.: Greenhouse gas soil production and surface fluxes at a high arctic polar oasis, *Soil Biol. Biochem.*, 52, 1–12, 2012.
- Cadieux, M.-C., Gauthier, G., Gagnon, C. A., Lévesque, E., Bêty, J., and Berteaux, D.: Monitoring the environmental and ecological impacts of climate change on Bylot Island, Sirmilik National Park, Université Laval, Centre d'études nordiques, Université Laval, Québec, 113 pp., 2008.
- Chen, Z. H., Chen, W. J., Leblanc, S. G., and Henry, G. H. R.: Digital photograph analysis for measuring percent plant cover in the Arctic, *Arctic*, 63, 315–326, 2010.
- Christiansen, H. H., Eltzelmueller, B., Isaksen, K., Juliussen, H., Farbro, H., Humlum, O., Johansson, M., Ingeman-Nielsen, T., Kristensen, L., Hjort, J., Holmlund, P., Sannel, A. B. K., Sigsgaard, C., Åkerman, H. J., Foged, N., Blikra, L. H., Pernosky, M. A. and Ødegård, R.: The thermal state of permafrost in the Nordic Area during the International Polar Year 2007–2009, *Permafrost Periglac.*, 21, 156–181, 2010.
- Collins, Knutti, R., Arblaster, J., Dufresne, J.-L., Fichet, T., Friedlingstein, P., Gao, X., Gutowski, W. K., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A. J., and Wehner, M.: Long-term climate change: projections, commitments and irreversibility, in: *Climate Change 2013: the Physical Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, UK, 1029–1136, 2013.

- Couture, N. J. and Pollard, W. H.: Modelling geomorphic response to climatic change, *Climatic Change*, 85, 407–431, 2007.
- Cray, H. A. and Pollard, W. H.: Vegetation recovery patterns following permafrost disturbance in a Low Arctic setting: case study of Herschel Island, Yukon, Canada, *Arct. Antarct. Alp. Res.*, 47, 99–113, 2015.
- Daniëls, F. J. A. and de Molenaar, J. G.: Flora and vegetation of Tasiilaq, formerly Angmagssalik, southeast Greenland: a comparison of data between around 1900 and 2007, *Ambio*, 40, 650–659, 2011a.
- Daniëls, F. J. A., de Molenaar, J. G., Chytrý, M. and Tichý, L.: Vegetation change in southeast Greenland? Tasiilaq revisited after 40 years, *Appl. Veg. Sci.*, 14, 230–241, 2011b.
- Daubenmire, R.: A canopy-coverage method of vegetation analysis, *Northwest Sci.*, 33, 43–64, 1959.
- Doiron, M.: Impacts des changements climatiques sur les relations plantes-herbivores dans l'Arctique, PhD thesis, Université Laval, Québec 123 pp., 2014.
- Doiron, M., Gauthier, G., and Lévesque, E.: Effects of experimental warming on nitrogen concentration and biomass of forage plants for an arctic herbivore, *J. Ecol.*, 102, 508–517, 2014.
- Duclos, I.: Milieux mésiques et secs de l'Île Bylot, Nunavut (Canada): caractérisation et utilisation par la Grande Oie des Neiges, M.S. thesis, Université du Québec à Trois-Rivières, Trois-Rivières, 113 pp., 2002.
- Ellis, C. J. and Rochefort, L.: Century-scale development of polygon-patterned tundra wetland, Bylot Island (73° N, 80° W), *Ecology*, 4, 963–978, 2004.
- Ellis, C. J. and Rochefort, L.: Long-term sensitivity of a High Arctic wetland to Holocene climate change, *J. Ecol.*, 94, 441–454, 2006.
- Ellis, C. J., Rochefort, L., Gauthier, G., and Pienitz, R.: Paleoeological evidence for transitions between contrasting landforms in a polygon-patterned High Arctic wetland, *Arct. Antarct. Alp. Res.*, 40, 624–637, 2008.
- Epstein, H. E., Myers-Smith, I., and Walker, D. A.: Recent dynamics of arctic and sub-arctic vegetation, *Environ. Res. Lett.*, 8, 015040, doi:10.1088/1748-9326/8/1/015040, 2013.
- Ewertowski, M.: Ice-wedge pseudomorphs and frost-cracking structures in Weichselian sediments, Central-West Poland, *Permafrost Periglac.*, 20, 316–330, 2009.
- Fortier, D. and Allard, M.: Late Holocene syngenetic ice-wedge polygons development, Bylot Island, Canadian Arctic Archipelago, *Can. J. Earth Sci.*, 41, 997–1012, 2004.

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Fortier, D. and Allard, M.: Frost-cracking conditions, Bylot Island, Eastern Canadian Arctic archipelago, *Permafrost Periglac.*, 16, 145–161, 2005.
- Fortier, D., Allard, M., and Shur, Y.: Observation of rapid drainage system development by thermal erosion of ice wedges on Bylot Island, Canadian Arctic Archipelago, *Permafrost Periglac.*, 18, 229–243, 2007.
- Gangodagamage, C., Rowland, J. C., Hubbard, S. S., Brumby, S. P., Liljedahl, A. K., Wainwright, H., Wilson, C. J., Altmann, G. L., Dafflon, B., Peterson, J., Ulrich, C., Tweedie, C. E., and Wullschleger, S. D.: Extrapolating active layer thickness measurements across Arctic polygonal terrain using LiDAR and NDVI data sets, *Water Resour. Res.*, 50, 6339–6357, doi:10.1002/2013WR014283, 2014.
- Gauthier, G., Hughes, R. J., Reed, R., Beaulieu, J., and Rochefort, L.: Effect of grazing by greater snow geese on the production of graminoids at an arctic site (Bylot Island, NWT, Canada), *J. Ecol.*, 83, 653–664, 1995.
- Gauthier, G., Rocheford, L., and Reed, A.: The exploitation of wetland ecosystems by herbivores on Bylot Island, *Geosci. Can.*, 23, 253–259, 1996.
- Gauthier, G., Cadieux, M.-C., Lefebvre, J., Bêty, J., and Berteaux, D.: Population study of Greater Snow Geese and its nesting habitat on Bylot Island, Nunavut, in 2009: a progress report, 31 pp., 2009.
- Gauthier, G., Cadieux, M.-C., Lefebvre, J., Bêty, J., and Berteaux, D.: Population study of Greater Snow Geese and its nesting habitat on Bylot Island, Nunavut, in 2010: a progress report, 32 pp., 2010.
- Gauthier, G., Berteaux, D., Bêty, J., Tarroux, A., Therrien, J.-F., McKinnon, L., Legagneux, P., and Cadieux, M.-C.: The tundra food web of Bylot Island in a changing climate and the role of exchanges between ecosystems, *Ecoscience*, 18, 223–235, 2011.
- Gauthier, G., Cadieux, M.-C., Lefebvre, J., Bêty, J., and Berteaux, D.: Population study of Greater Snow Geese and its nesting habitat on Bylot Island, Nunavut, in 2012: a progress report, 36 pp., 2012.
- Godin, E. and Fortier, D.: Geomorphology of thermo-erosion gullies – case study from Bylot Island, Nunavut, Canada, in: *Proceedings, 6th Canadian Permafrost Conference and 63rd Canadian Geotechnical Conference*, Calgary, 2010.
- Godin, E. and Fortier, D.: Fine scale spatio-temporal monitoring of multiple thermo-erosion gullies development on Bylot Island, eastern canadian archipelago, in: *Proceedings, Tenth International Conference on Permafrost (TICOP)*, Salekhard, Russia, 2012a.

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Godin, E. and Fortier, D.: Geomorphology of a thermo-erosion gully, Bylot Island, Nunavut, Canada, *Can. J. Earth Sci.*, 49, 979–986, 2012b.
- Godin, E., Fortier, D., and Coulombe, S.: Effects of thermo-erosion gullying on hydrologic flow networks, discharge and soil loss, *Environ. Res. Lett.*, 9, 105010, doi:10.1088/1748-9326/9/10/105010, 2014.
- Godin, E., Fortier, D., and Lévesque, E.: Nonlinear thermal and moisture dynamics of high Arctic wetland polygons following permafrost disturbance, *Biogeosciences Discuss.*, 12, 11797–11831, doi:10.5194/bgd-12-11797-2015, 2015.
- Grosse, G., Harden, J., Turetsky, M., McGuire, A. D., Camill, P., Tarnocai, C., Froking, S., Schuur, E. A. G., Jorgenson, T., Marchenko, S., Romanovsky, V., Wickland, K. P., French, N., Waldrop, M., Bourgeau-Chavez, L., and Striegl, R. G.: Vulnerability of high-latitude soil organic carbon in North America to disturbance, *J. Geophys. Res.*, 116, G00K06, doi:10.1029/2010JG001507, 2011.
- Gruyer, N. G., Gauthier, G., and Berteaux, D.: Cyclic dynamics of sympatric lemming populations on Bylot Island, Nunavut, Canada, *Can. J. Zool.*, 86, 910–917, 2008.
- Günther, F., Overduin, P. P., Sandakov, A. V., Grosse, G., and Grigoriev, M. N.: Short- and long-term thermo-erosion of ice-rich permafrost coasts in the Laptev Sea region, *Biogeosciences*, 10, 4297–4318, doi:10.5194/bg-10-4297-2013, 2013.
- Harms, T. K., Abbott, B. W., and Jones, J. B.: Thermo-erosion gullies increase nitrogen available for hydrologic export, *Biogeochemistry*, 117, 299–311, 2014.
- Hinzman, L. D., Bettez, N. D., Bolton, W. R., Chapin III, F. S., Dyurgerov, M. B., Fastie, C. L., Griffith, B., Hollister, R. D., Hope, A., Huntington, H. P., Jensen, A. M., Jia, G. J., Jorgenson, T., Kane, D. L., Klein, D. R., Kofinas, G., Lynch, A. H., Lloyd, A. H., McGuire, A. D., Nelson, F. E., Oechel, W. C., Osterkamp, T. E., Racine, C. H., Romanovsky, V. E., Stone, R. S., Stow, D. A., Sturm, M., Tweedie, C. E., Vourlitis, G. L., Walker, M. D., Walker, D. A., Webber, P. J., Welker, J. M., Winker, K. S., and Yoshikawa, K.: Evidence and implications of recent climate change in northern Alaska and other arctic regions, *Climatic Change*, 72, 251–298, 2005.
- Hollister, R. D., Webber, P. J., and Tweedie, C. E.: The response of Alaskan arctic tundra to experimental warming: differences between short- and long-term responses, *Glob. Change Biol.*, 11, 525–536, 2005.
- Hudson, J. M. G. and Henry, G. H. R.: High Arctic plant community resists 15 years of experimental warming, *J. Ecol.*, 98, 1035–1041, 2010.

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Hughes, R. J., Reed, A., and Gauthier, G.: Space and habitat use by greater snow goose broods on Bylot Island, Northwest Territories, *J. Wildlife Manage.*, 58, 536–545, 1994.
- IPY, International Polar Year: Climate Change Impact on Canadian Arctic Tundra, Protocols for taking vertical photographs and field measurements of plant height for biomass and LAI estimation in Arctic tundra (for vegetation height < 0.5 m), available at: <http://ipytundra.ca/protocols> (last access: June 2015), 2012.
- Jonsdottir, I. S., Magnusson, B., Gudmunsson, J., Elmarsdottir, A., and Hjartarson, H.: Variable sensitivity of plant communities in Iceland to experimental warming, *Glob. Change Biol.*, 11, 553–563, 2005.
- Jorgenson, M. T., Shur, Y. T., and Pullman, E. R.: Abrupt increase in permafrost degradation in Arctic Alaska, *Geophys. Res. Lett.*, 33, L02503, doi:10.1029/2005GL024960, 2006.
- Jorgenson, M. T., Romanosky, V., Harden, S., Shur, Y., O'Donnell, J., Schuur, E. A. G., Kanevskiy, M., and Marenko, S.: Resilience and vulnerability of permafrost to climate change, *Can. J. Forest Res.*, 40, 1219–1236, 2010.
- Jorgenson, M. T., Harden, S., Kanevskiy, M., O'Donnell, J., Wickland, K., Ewing, S., Manies, K., Zhuang, Q., Shur, Y., Striegl, R., and Koch, J.: Reorganization of vegetation, hydrology and soil carbon after permafrost degradation across heterogeneous boreal landscapes, *Environ. Res. Lett.*, 8, 035017, doi:10.1088/1748-9326/9/10/035017, 2013.
- Kokelj, S. V., Lantz, T. C., Wolfe, S. A., Kanigan, J. C., Morse, P. D., Coutts, R., Molina-Giraldo, N., and Burn, C. R.: Distribution and activity of ice wedges across the forest-tundra transition, western Arctic Canada, *J. Geophys. Res.-Earth*, 119, doi:10.1002/2014JF003085, 2014.
- Kutzbach, H. J., Wagner, D., and Pfeiffer, E. M.: Effect of microrelief and vegetation on methane emission wet polygonal tundra, Lena Delta, Northern Siberia, *Biogeochemistry*, 69, 341–362, 2004.
- Lara, M. J., McGuire, A. D., Euskirchen, E. S., Tweedie, C. E., Hinkel, K. M., Skurikhin, A. N., Romanovsky, V. E., Grosse, G., Bolton, W. R., and Genet, H.: Polygonal tundra geomorphological change in response to warming alters future CO₂ and CH₄ flux on the Barrow Peninsula, *Glob. Change Biol.*, 21, 1634–1651, 2015.
- Lecomte, N., Gauthier, G., and Giroux, J.-F.: A link between water availability and nesting success mediated by predator-prey interactions in the Arctic, *Ecology*, 90, 465–475, 2009.
- Legagneux, P., Gauthier, G., Berteaux, D., Bêty, J., Cadieux, M.-C., Bilodeau, F., Bolduc, E., McKinnon, L., Tarroux, A., Therrien, J.-F., Morissette, L., and Krebs, C. J.: Disentangling

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



trophic relationships in a High Arctic tundra ecosystem through food web modeling, *Ecology*, 93, 1707–1716, 2012.

Levy, J. S., Head, J. W., and Marant, D. R.: The role of thermal contraction crack polygons in cold-desert fluvial systems, *Antarct. Sci.*, 20, 565–579, 2008.

5 Manseau, M. and Gauthier, G.: Interactions between greater snow geese and their rearing habitat, *Ecology*, 74, 2045–2055, 1993.

Massé, H., Rochefort, L., and Gauthier, G.: Carrying capacity of wetland habitats used by breeding greater snow geese, *J. Wildlife Manage.*, 65, 271–281, 2001.

10 McEwing, K. R., Fisher, J. P., and Zona, D.: Environmental and vegetation controls on the spatial variability of CH₄ emission from wet-sedges and tussock tundra ecosystems in the Arctic, *Plant Soil*, 338, 37–52, 2015.

Minke, M., Donner, D., Karpov, N. S., de Klerk, P., and Joosten, H.: Distribution, diversity, development and dynamics of polygon mires: examples from Northeast Yakutia (Siberia), *Peatlands Int.*, 1, 36–40, 2007.

15 Minke, M., Donner, D., Karpov, N. S., de Klerk, P., and Joosten, H.: Patterns in vegetation composition, surface height and thaw depth in polygon mires in the Yakutian Arctic (NE Siberia): a microtopographical characterisation of the active layer, *Permafrost Periglac.*, 20, 357–368, 2009.

Myers-Smith, I. H.: Carbon exchange and permafrost collapse: implications for a changing climate, M.S. thesis, University of Alaska Fairbanks, Fairbanks, 66 pp., 2005.

20 Myers-Smith, I. H., Harden, J. W., Wilmking, M., Fuller, C. C., McGuire, A. D., and Chapin III, F. S.: Wetland succession in a permafrost collapse: interactions between fire and thermokarst, *Biogeosciences*, 5, 1273–1286, doi:10.5194/bg-5-1273-2008, 2008.

Naito, A. T. and Cairns, D. M.: Patterns of shrub expansion in Alaskan arctic river corridors suggest phase transition, *Ecol. Evol.*, 5, 87–101, 2015.

25 Natali, S. M., Schuur, E. A. G., Mauritz, M., Schade, J. D., Celis, G., Crummer, K. G., Johnston, C., Krapek, J., Pegoraro, E., Salmon, V. G., and Webb, E. E.: Permafrost thaw and soil moisture driving CO₂ and CH₄ release from upland tundra, *J. Geophys. Res.-Biogeo.*, 120, doi:10.1002/2014JG002872, 2015.

30 Nauta, A. L., Heijmans, M. M. P. D., Blok, D., Limpens, J., Elberling, B., Gallagher, A., Li, B., Petrov, R. E., Maximov, T. C., van Huissteden, J., and Berendse, F.: Permafrost collapse after shrub removal shifts tundra ecosystem to a methane source, *Nature Clim. Change*, 5, 67–70, 2015.

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Nelson, F. E., Shiklomanov, N. I., and Mueller, G. R.: Variability of active-layer thickness at multiple spatial scales, North-central Alaska, U.S.A., *Arct. Antarct. Alp. Res.*, 31, 179–186, 1999.
- Nelson, F. E., Shiklomanov, N. I., Hinkel, K. M., and Brown, J.: Decadal results from the Circumpolar Active Layer Monitoring (CALM) program, *Proceedings, Ninth International Conference on Permafrost*, edited by: Hinkel, K. M. and Kane, D. L., University of Alaska Press, Fairbanks, Alaska, 1273–1280, 2008.
- New, M., Liverman, D., Schroder, H., and Anderson, K.: Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications, *Philos. T. R. Soc. A*, 369, 6–19, 2011.
- NOAA (National Oceanic and Atmospheric Administration), Arctic Research Program: Arctic Report Card, edited by: Jeffries, M. O., Richter-Menge, J., and Overland, J. E., available at: <http://www.arctic.noaa.gov/reportcard> (last access: June 2015), 2014.
- Olefeldt, D., Turetsky, M. R., Crill, P. M., and McGuire, A. D.: Environmental and physical controls on northern terrestrial methane emissions across permafrost zones, *Glob. Change Biol.*, 19, 589–603, 2013.
- Payette, S., Delwaide, A., Caccianiga, M., and Beauchemin, M.: Accelerated thawing of subarctic peatland permafrost over the last 50 years, *Geophys. Res. Lett.*, 31, L18208, doi:10.1029/2004GL020358, 2004.
- Pauli, H., Gottfried, M., Dullinger, S., Abdaladze, O., Akhalkatsi, M., Benito Alonso, J. L., Coldea, G., Dick, J., Erschbamer, B., Fernandez Calzado, R., Ghosn, D., Holten, J. I., Kanka, R., Kazakis, G., Kollar, J., Larsson, P., Moiseev, P., Moiseev, D., Molau, U., Molero Mesa, J., Nagy, L., Pelino, G., Puscas, M., Rossi, G., Stanisci, A., Syverhuset, A. O., Theurillat, J.-P., Tomaselli, M., Unterluggauer, P., Villar, P., Vittoz, P., and Grabherr, G.: High Arctic vegetation after 70 years: a repeated analysis from Svalbard, *Polar Biol.*, 33, 635–639, 2012.
- Poesen, J., Nachtergaele, J., Verstraeten, G., and Valentin, C.: Gully erosion and environmental change: importance and research needs, *Catena*, 50, 91–133, 2003.
- Pouliot, R., Rochefort, L., and Gauthier, G.: Moss carpets constrain the fertilizing effects of herbivores on graminoid plants in arctic polygon fens, *Botany*, 87, 1209–1222, 2009.
- Ross, L. C., Woodin, S. J., Hester, A. J., Thompson, D. B. A., and Birks, H. J.: Biotic homogenization of upland vegetation: patterns and drivers at multiple spatial scales over five decades, *J. Veg. Sci.*, 23, 755–770, 2012.

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Rowland, J. C., Jones, C. E., Altmann, G., Bryan, B., Crosby, B. T., Geernaert, G. L., Hinzman, L. D., Kane, D. L., Lawrence, D. M., Mancino, A., Marsh, P., McNamara, J. P., Romanosky, V. E., Toniolo, H., Travis, B. J., Trochim, E., and Wilson, C. J.: Arctic landscapes in transition: responses to thawing permafrost, *EOS T. Am. Geophys. Un.*, 91, 229–236, 2010.
- 5 Romanovsky, V. E., Smith, S. L., and Christiansen, H. H.: Permafrost thermal state in the polar Northern Hemisphere during the international polar year 2007–2009: a synthesis, *Permafrost Periglac.*, 21, 106–116, doi:10.1002/ppp.689, 2010.
- Sandvik, S. M. and Odland, A.: Changes in alpine snowbed-wetland vegetation over three decades in northern Norway, *Nord. J. Bot.*, 32, 377–384, 2014.
- 10 Sedinger, J. S., White, R. G., Mann, F. E., Burris, F. A., and Kedrowski, R. A.: Apparent metabolizability of alfalfa components by yearling Pacific Black Brant, *J. Wildlife Manage.*, 53, 726–734, 1989.
- Seppälä, M.: Piping causing thermokarst in permafrost, Ungava Peninsula, Quebec, Canada, *Geomorphology*, 20, 313–319, 1997.
- 15 Sheard, J. W. and Geale, D. W.: Vegetation studies at Polar Bear Bass, Bathurst Island, N.W.T., I. Classification of plant communities, *Can. J. Bot.*, 61, 1618–1636, 1983.
- Shiklomanov, N. I., Streletskiy, D. A., Nelson, F. E., Hollister, R. D., Romanovsky, V. E., Tweedie, C. E., Bockheim, J. G., and Brown, J.: Decadal variations of active-layer thickness in moisture-controlled landscapes, Barrow, Alaska, *J. Geophys. Res.*, 115, G00104, doi:10.1029/2009JG001248, 2010.
- 20 Sjöberg, Y.: Linking water and permafrost dynamics, PhD thesis, Stockholm University, Stockholm, Sweden, 27 pp., 2015.
- Smith, S.: Trends in permafrost conditions and ecology in northern Canada: Ecosystem Status and Trends 2010, Technical Thematic Report No. 9, Canadian Councils of Resource Ministers, Ottawa, ON, iii + 22 pp., 2011.
- 25 Smith, S. L., Burgess, M. M., Riseborough, D., and Nixon, F. M.: Recent trends from Canadian Permafrost Thermal Monitoring network sites, *Permafrost Periglac.*, 16, 19–30, 2005.
- Smith, S. L., Wolfe, S. A., Riseborough, D. W., and Nixon, F. M.: Active-layer characteristics and summer climatic indices, Mackenzie Valley, Northwest Territories, Canada, *Permafrost Periglac.*, 20, 201–220, 2009.
- 30 Tarnocai, C., Nixon, F. M., and Kutny, L.: Circumpolar-Active-Layer-Monitoring (CALM) sites in the Mackenzie Valley, Northwestern Canada, *Permafrost Periglac.*, 15, 141–153, 2004.

- ter Braak, C. J. F.: Canonical correspondence analysis: a new eigenvector technique for multi-variate direct gradient analysis, *Ecology*, 67, 1167–1179, 1986.
- Treat, C. C., Natali, S. M., Ernakovitch, J., Iversen, C. M., Lupascu, M., McGuire, A. D., Norby, R. J., Chowdhury, T. R., Richter, A., Santruckova, H., Schadel, C., Schuur, E. A. G., Sloan, V. L., Turetsky, R., and Waldrop, M. P.: A pan-Arctic synthesis of CH₄ and CO₂ production from anoxic soil incubations, *Glob. Change. Biol.*, 21, 2787–2803, doi:10.1111/gcb.12875, 2015.
- Tveit, A. T., Urich, T., Frenzel, P., and Svenning, M. M.: Metabolic and trophic interactions modulate methane production by Arctic peat microbiota in response to warming, *P. Natl. Acad. Sci. USA*, 112, 2507–2516, doi:10.1073/pnas.1420797112, 2015.
- USGCRP: Global Climate Change Impacts in the United States, edited by: Karl, T. R., Melillo, J. M., and Peterson, T. C., United States Global Change Research Program, Cambridge University Press, New York, NY, 2009.
- Vonk, J. E., Mann, P. J., Dowdy, K. L., Davydova, A., Davydov, S. P., Zimov, N., Spencer, R. G. M., Bulygina, E. B., Eglinton, T. I., and Holmes, R. M.: Dissolved organic carbon loss from Yedonna permafrost amplified by ice wedge thaw, *Environ. Res. Lett.*, 8, 035023, doi:10.1088/1748-9326/8/3/035023, 2013.
- Woo, M.-K.: *Permafrost Hydrology*, Springer, New York, NY, 564 pp., 2012.
- Woo, M.-K. and Young, K. L.: High Arctic wetlands: their occurrence, hydrological characteristics and sustainability, *J. Hydrol.*, 320, 432–450, 2006.
- Woo, M.-K., Kane, D. L., Carey, S. K., and Yang, D.: Progress in permafrost hydrology in the new millennium, *Permafrost Periglac.*, 19, 237–254, 2008.
- Woo, M.-K., Mollinga, M., and Smith, S. L.: Climate warming and active layer thaw in the boreal and tundra environments of the Mackenzie Valley, *Can. J. Earth Sci.*, 44, 733–743, 2007.
- Wright, N., Hayashi, M., and Quinton, W. L.: Spatial and temporal variations in active layer thickness and their implication on runoff generation in peat-covered permafrost terrain, *Water Resour. Res.*, 45, W05414, doi:10.1029/2008WR006880, 2009.
- Zamin, T. Z., Brett-Harte, M. S., and Grogan, P.: Evergreen shrubs dominate responses to experimental summer warming and fertilization in Canadian mesic low arctic tundra, *J. Ecol.*, 102, 749–766, doi:10.1111/1365-2745.12237, 2014.
- Zoltai, S. C., McCormick, K. J., and Scotter, G. W.: A natural resource survey of Bylot Island and adjacent Baffin Island, Northwest Territories, Parks Canada, Ottawa, ON, 176 pp., 1983.

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Zuur, A. F., Ieno, E. N., and Smith, G. M.: Analysing Ecological Data, edited by: Gail, M., Krickeberg, K., Samet, J., Tsiatis, A., and Wong, W., Springer, New York, 672 pp., 2007.

BGD

12, 12191–12228, 2015

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Table 1. Sample sizes and means ($\pm$ SE) of soil moisture content, thaw front depth and graminoid above-ground biomass in the four low-centered polygon habitats studied in the Qarlikturvik valley of Bylot Island, Nunavut. Letters refer to SNK post hoc contrasts. For a given variable, different letters indicate significant differences among habitats.

Habitat	Soil moisture 5 Jul 2010 (%)		Soil moisture 30 Jul 2010 (%)		Thaw front depth Jul 2009 (cm)		Thaw front depth Jul 2010 (cm)		Above-ground biomass (g m ⁻²)	
	<i>n</i>	Mean $\pm$ SE	<i>n</i>	Mean $\pm$ SE	<i>n</i>	Mean $\pm$ SE	<i>n</i>	Mean $\pm$ SE	<i>n</i>	Mean $\pm$ SE
Wet polygons	53	36.3 $\pm$ 1.7 a	54	48.0 $\pm$ 1.3 a	52	36.0 $\pm$ 0.9 a	62	34.6 $\pm$ 0.8 a	5	29.2 $\pm$ 5.2 a
< 5 year disturbed polygons	39	21.9 $\pm$ 1.2 b	39	31.0 $\pm$ 1.5 b	39	25.5 $\pm$ 1.5 b	44	25.0 $\pm$ 1.1 b	5	22.3 $\pm$ 1.4 a
> 5 year disturbed polygons	33	22.0 $\pm$ 1.1 b	33	31.2 $\pm$ 1.2 b	32	25.3 $\pm$ 1.1 b	43	24.9 $\pm$ 0.8 b	5	9.3 $\pm$ 4.0 b
Mesic polygons	46	19.6 $\pm$ 1.3 b	50	28.4 $\pm$ 1.4 b	44	27.6 $\pm$ 1.1 b	48	26.5 $\pm$ 0.7 b	5	5.9 $\pm$ 2.6 b

BGD

12, 12191–12228, 2015

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Table 3. Information of the Canonical Correspondence Analysis. CCA-1: first canonical axis; CCA-2: second canonical axis.

	CCA-1	CCA-2
Eigenvalues	0.2208	0.1911
Cumulative % of vegetation data	7.29	13.60
Cumulative % of vegetation–environment relationship	42.8	79.8
Total inertia	3.0295	

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Table 4. Canonical correspondence analysis for vegetation in the Qarlikturvik valley of Bylot Island, Nunavut. CCA-1: first canonical axis; CCA-2: second canonical axis. Statistically significant values ($P < 0.05$) after 999 permutations are shown in bold.

Environmental variables	df	χ^2	F	P	CCA-1	CCA-2
Litter cover	1	0.1524	11.4008	0.004	0.0212	−0.8682
Thaw front depth	1	0.1768	13.2230	0.001	−0.8607	−0.1439
Soil moisture	1	0.0430	3.2157	0.006	−0.7341	0.2425
Standing dead	1	0.0715	5.3467	0.007	−0.2393	0.2580
Bare ground	1	0.0067	0.4983	0.640	0.0209	−0.0529
Standing water	1	0.0090	0.6728	0.549	−0.2365	0.0829
Grubbing	1	0.0240	1.7932	0.088	−0.1052	0.1982
Geese feces	1	0.0330	2.4608	0.025	0.4769	−0.0768
Residual	188	2.5133				

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Table A1. List of the vascular plant species inventoried in the Qarlikturvik valley, Bylot Island, Nunavut during the 2009 and 2010 field seasons. Species names are from the integrated taxonomic information system (ITIS 2011).

Family	Species
Asteraceae	<i>Erigeron uniflorus</i> var. <i>eriocephalus</i> (Vahl) Boivin, <i>Taraxacum hyparcticum</i> Dahlst., <i>Tephroseria palustris</i> (L.) Reichenbach
Brassicaceae	<i>Cardamine bellidifolia</i> L., <i>Cardamine nymanii</i> Gand., <i>Draba cinerea</i> Adams, <i>Draba corymbosa</i> R. Br., <i>Draba glabella</i> Pursh, <i>Draba lactea</i> Adams, <i>Draba nivalis</i> Lilj., <i>Draba</i> sp. ^{ast} , <i>Eutrema edwardsii</i> R. Br.
Caryophyllaceae	<i>Cerastium alpinum</i> L. s. lat., <i>Minuartia rubella</i> (Wahlenb.) Hiern., <i>Silene involucrata</i> (Cham. & Schlecht.) Bocquet subsp. <i>involucrata</i> , <i>Silene uralensis</i> (Rupr.) Bocquet subsp. <i>uralensis</i> , <i>Stellaria longipes</i> Goldie subsp. <i>longipes</i>
Cyperaceae	<i>Carex aquatilis</i> var. <i>minor</i> Boott, <i>Carex marina</i> Dewey, <i>Eriophorum angustifolium</i> Honck subsp. <i>angustifolium</i> , <i>Eriophorum scheuchzeri</i> Hoppe s. lat./ <i>russeolum</i> subsp. <i>leiocarpum</i> Novos.
Equisetaceae	<i>Equisetum arvense</i> L. s. lat.
Ericaceae	<i>Cassiope tetragona</i> var. <i>tetragona</i> (L.) Don
Fabaceae	<i>Astragalus alpinus</i> var. <i>alpinus</i> L. <i>Oxytropis maydelliana</i> ssp. <i>Melanocephala</i> (Hook.) Porsild
Juncaceae	<i>Juncus biglumis</i> L., <i>Luzula arctica</i> Blytt, <i>Luzula confusa</i> Lindebl.
Onagraceae	<i>Epilobium arcticum</i> Sam.
Papaveraceae	<i>Papaver</i> sp. (including <i>P. dahlianum</i> , <i>P. cornwalisense</i> , <i>P. lapponicum</i> ssp. <i>occidentale</i>)
Poaceae	<i>Alopecurus borealis</i> Trin., <i>Anthoxanthum arcticum</i> Veldkamp, <i>Arctagrostis latifolia</i> subsp. <i>latifolia</i> (R. Br.) Griseb., <i>Deschampsia brevifolia</i> R. Br., <i>Dupontia fisheri</i> R. Br., <i>Festuca brachyphylla</i> ssp. <i>Brachyphylla</i> Schult. & Schult. f., <i>Phippsia algida</i> (Sol.) R. Br., <i>Pleuropogon sabinei</i> R. Br., <i>Poa arctica</i> R. Br. s. lat.
Polygonaceae	<i>Bistorta vivipara</i> (L.) Delarbre, <i>Oxyria digyna</i> (L.) Hill
Pyrolaceae	<i>Pyrola grandiflora</i> Radius
Ranunculaceae	<i>Ranunculus hyperboreus</i> Rottb., <i>Ranunculus nivalis</i> L.
Rosaceae	<i>Dryas integrifolia</i> Vahl subsp. <i>integrifolia</i> , <i>Potentilla hyparctica</i> Malte subsp. <i>hyparctica</i>
Salicaceae	<i>Salix arctica</i> Pall., <i>Salix herbacea</i> L., <i>Salix reticulata</i> L., <i>Salix richardsonii</i> Hook.
Saxifragaceae	<i>Chrysosplenium tetrandrum</i> (Lund) Th. Fries, <i>Micranthes foliolosa</i> (R. Br.) Gornall, <i>Micranthes hieraciifolia</i> (Waldst. & Kit.) Haworth, <i>Micranthes nivalis</i> (L.) Small, <i>Saxifraga cernua</i> L., <i>Saxifraga cespitosa</i> L., <i>Saxifraga hirculus</i> L., <i>Saxifraga oppositifolia</i> L.
Scrophulariaceae	<i>Pedicularis langsдорffii</i> subsp. <i>arctica</i> (R. Br.) Pennell, <i>Pedicularis sudetica</i> subsp. <i>albolabiata</i> Hult.

^{ast} *Draba* sp. was not counted as a distinct species because it is probably one of the five species already mentioned.

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

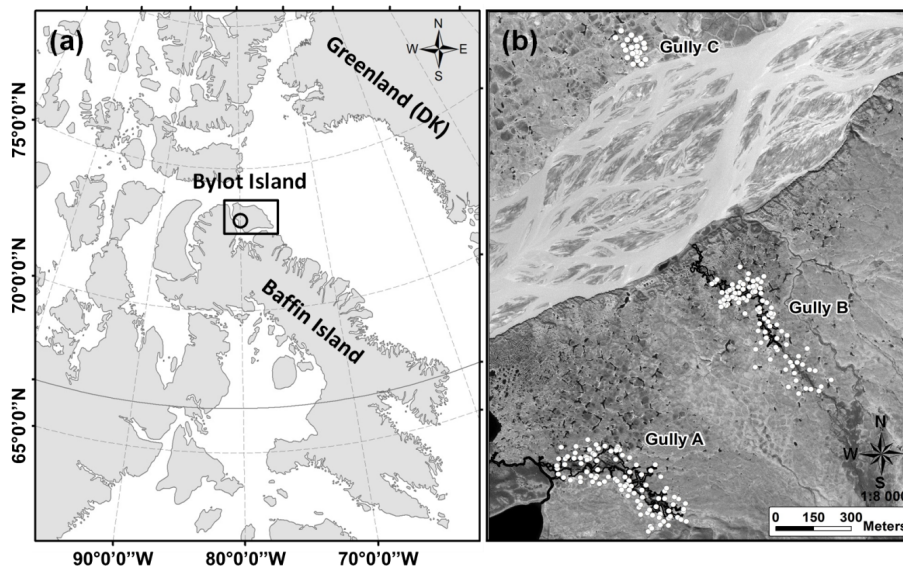


Figure 1. Location of the study area. **(a)** The Qarlikturvik valley (black circle) of Bylot Island, Nunavut (black rectangle), **(b)** the three gullies and the 197 sampling polygons (white dots) located in the Qarlikturvik valley.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

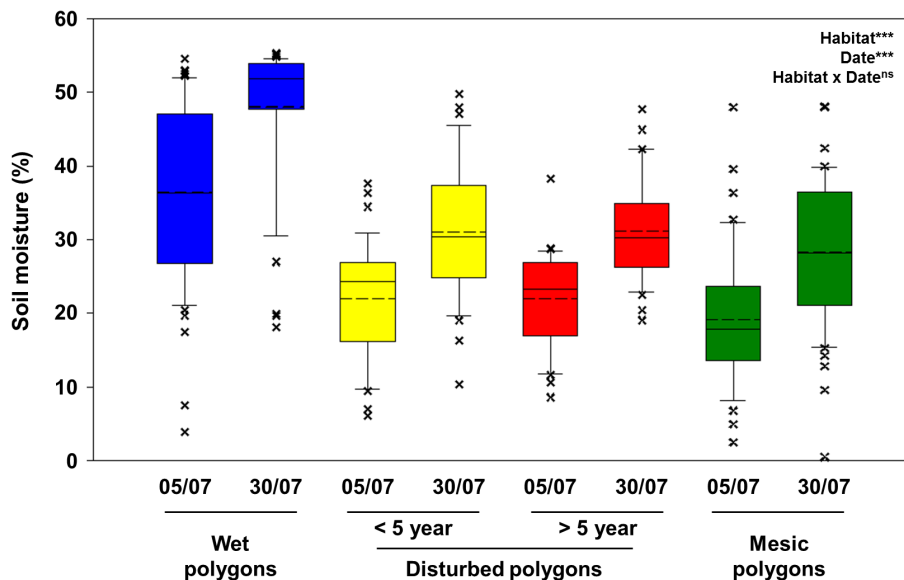


Figure 2. Soil moisture content monitored early and late July in the four low-centered polygon habitats studied in Bylot Island, Nunavut. 10th percentiles, lower quartile, median, mean (dash line), upper quartile and 90th percentiles are shown. See Table 1 for sample sizes and SNK post-hoc contrasts. *** $P < 0.001$, ns: statistically non-significant effect.

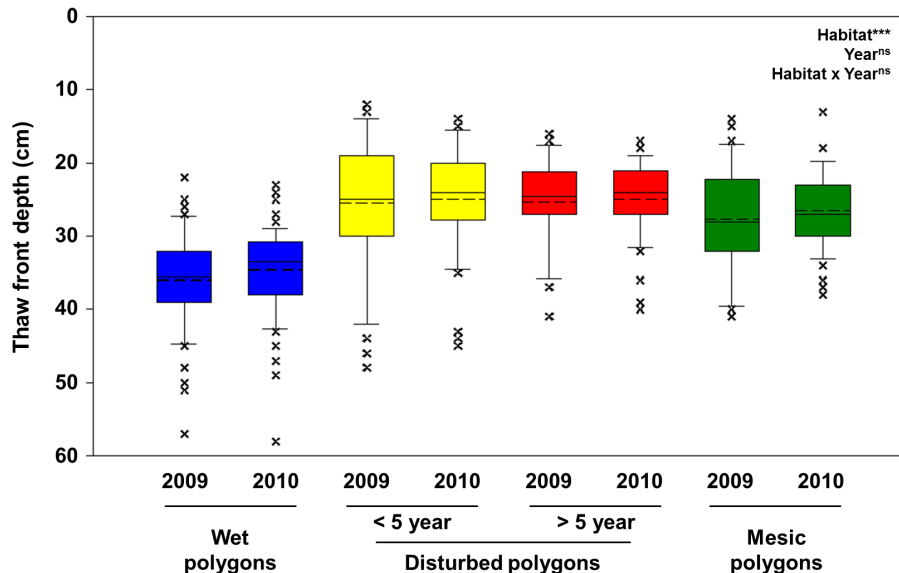


Figure 3. Thaw front depth monitored in July 2009 and 2010 in the four low-centered polygon habitats studied in Bylot Island, Nunavut. 10th percentiles, lower quartile, median, mean (dash line), upper quartile and 90th percentiles are shown. See Table 1 for sample sizes and SNK post-hoc contrasts. *** $P < 0.001$, ns: statistically non-significant effect.

BGD

12, 12191–12228, 2015

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

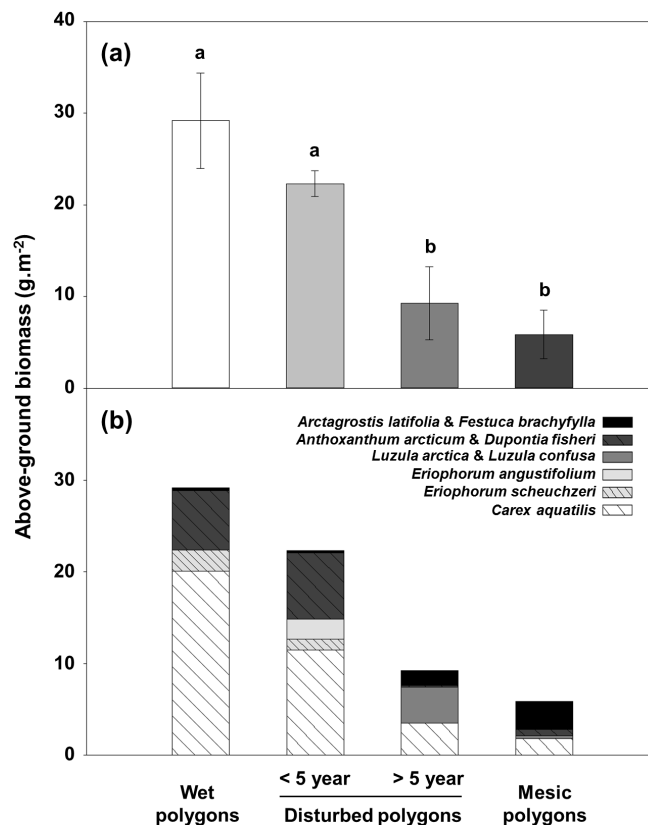


Figure 4. Above-ground biomass of graminoids in the four low-centered polygon habitats studied in Bylot Island, Nunavut. **(a)** Mean total biomass ($\pm$ SE), and **(b)** mean biomass per species. In **(b)**, dashes represent hydrophilic species. $n = 5$ per habitat. Species aforementioned belong to the following families: Cyperaceae (*Carex aquatilis*, *Eriophorum angustifolium* and *Eriophorum scheuchzeri*), Juncaceae (*Luzula arctica* and *Luzula confusa*), and Poaceae (*Anthoxanthum arcticum*, *Arctagrostis latifolia*, *Dupontia fisheri* and *Festuca brachyphylla*).

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[◀](#)
[▶](#)
[◀](#)
[▶](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

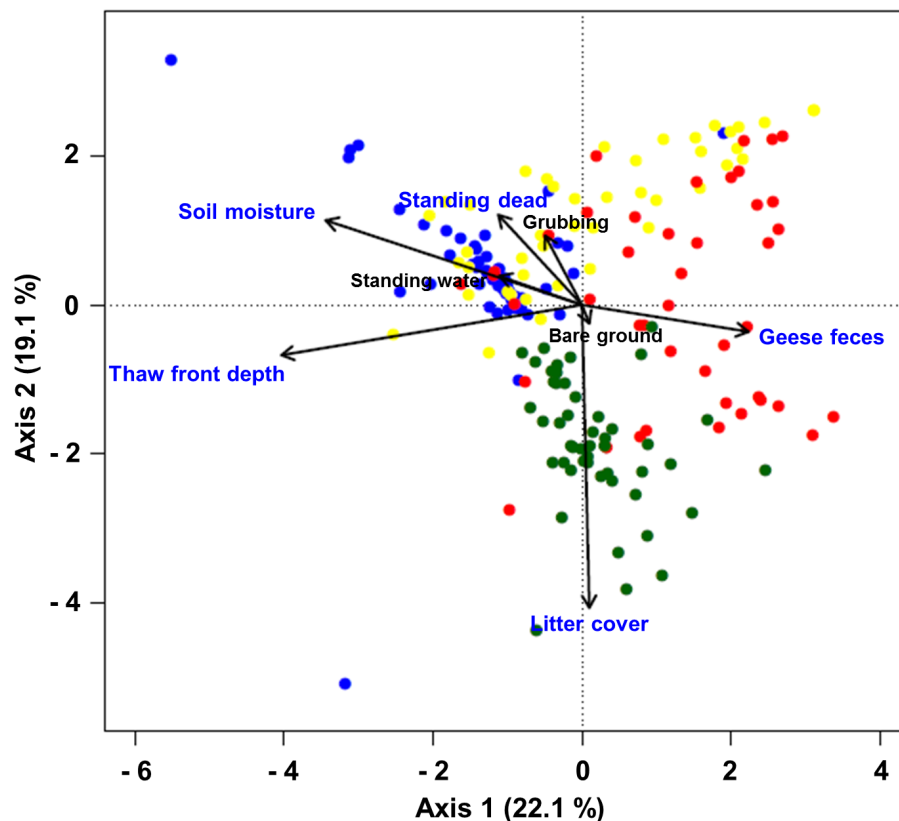



Figure 5. Canonical correspondence analysis (CCA) ordination of the 197 polygons sampled in the Qarlikturvik valley of Bylot Island, Nunavut. Wet polygons ($n = 62$): blue circles; < 5 year disturbed polygons ($n = 44$): yellow circles; > 5 year disturbed polygons ($n = 43$): red circles; mesic environments ($n = 48$): green circles. Blue font indicates statistically significant environmental variables (see Table 4).

Thermo-erosion gullies boost the transition from wet to mesic vegetation

N. Perreault et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

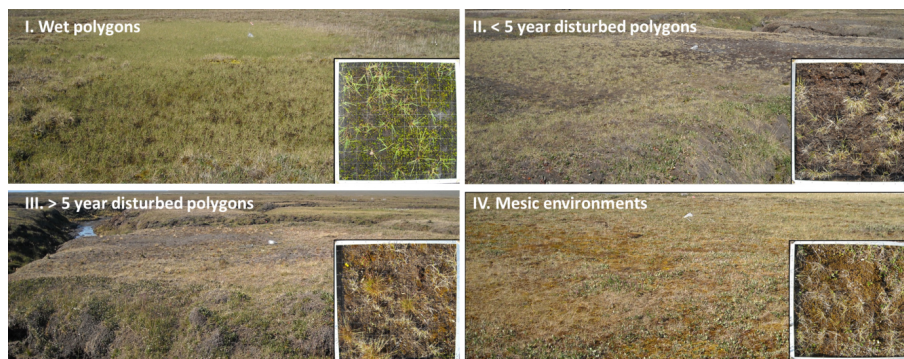


Figure B1. Illustration of the four low-centered polygon habitats studied in the Qarlikturvik valley of Bylot Island, Nunavut.