Microtopographic patterns in an arctic baydjarakh field: do fine-grain patterns enforce landscape stability?

John A Gamon¹,², G Peter Kershaw¹, Scott Williamson² and David S Hik²

¹ Department of Earth and Atmospheric Sciences, University of Alberta, 1-26 Earth Sciences
Building, Edmonton, AB, T6G 2E3, Canada
² Department of Biological Sciences, University of Alberta, CW 405, Biological Sciences
Building, Edmonton, AB, T6G 2E9, Canada

E-mail: jgamon@gmail.com

Received 2 August 2011
Accepted for publication 1 November 2011
Published 4 January 2012
Online at stacks.iop.org/ERL/7/015502

Abstract
Recent observations suggest that while some arctic landscapes are undergoing rapid change, others are apparently more resilient. In this study, we related surface cover and energy balance to microtopography in a degraded polygonal peat plateau (baydjarakh field) near Churchill, Manitoba in mid-summer 2010. The landscape consists of remnant high-centered polygons divided by troughs of varying widths. Historical aerial photos indicate these topographical features have been stable for over 80 years. Our goal was to explore patterns that might explain the apparent stability of this landscape over this time period and to evaluate remote sensing methods for characterizing microtopographic patterns that might resist change in the face of climate warming. Summertime surface albedo measurements were combined with several years of winter snow depth, snow heat flux, summer thaw depth and annual surface temperature, all of which had striking contrasts between wet troughs and high polygon centers. Measurements of albedo and the snowpack heat transfer coefficient were lowest for wet troughs (areas of standing water) dominated by graminoids, and were significantly higher for high polygon centers, dominated by dwarf shrubs and lichens. Snow depth, surface temperature and thaw depth were all significantly higher for wet troughs than high polygon centers. Together these patterns of cover and energy balance associated with microtopographic variation can contribute to the stability of this landscape through differential heat transfer and storage. We hypothesize that local thermal feedback effects, involving greater heat trapping in the troughs than on the baydjarakh tops, and effective insulation on the baydjarakh edges, have ensured landscape stability over most of the past century. These results suggest that high-resolution remote sensing, combined with detailed field monitoring, could provide insights into the dynamics or stability of arctic landscapes, where cover often varies over short distances due to microtopographic effects.

Keywords: arctic tundra, microtopography, baydjarakh, high-centred polygons, permafrost, vegetation cover, landscape stability, remote sensing, albedo, thermal properties

Online supplementary data available from stacks.iop.org/ERL/7/015502/mmedia

1. Introduction

Many arctic regions are warming rapidly, leading to changes in surface temperature (Allison et al 2011), surface hydrology (Smith et al 2005), thaw depth (Schuur et al 2008), vegetation cover (Sturm et al 2005) and surface-atmosphere feedbacks (Euskirchen et al 2009). The Hudson Bay lowlands around Churchill, Manitoba, located at the ‘treeline’ boundary
between boreal and arctic biomes, has been warming at a rate of about 0.5 °C/decade since 1970. (Gagnon and Gough 2005), leading to vegetation change in this region (Mamet and Kershaw 2011). Common predictions of future arctic warming are that tree and shrub cover will continue to expand into tundra (e.g. northward movement of the boreal biome), and community compositional changes will occur. However, while these predictions are often observed, not all arctic landscapes show the same pace or degree of change (Callaghan et al. 2011), causing us to consider factors that might resist change in arctic landscapes.

High-centered polygons are a common feature in coastal arctic landscapes, including the Hudson Bay lowlands around Churchill (Kershaw 2008), and are characterized by raised centers bisected by low troughs. These landscape features are formed by the alternating thermal expansion and contraction that form cracks. With spring snowmelt, these cracks collect water to form ice wedges (MacKay 2000). Melting of ice wedge causes ground subsidence (thermokarst formation) to form deeper troughs, leaving isolated polygon centers, which are termed baydjarakh (Soloviev 1962, as cited in French 1974). Even in the face of warming, polygons can be surprisingly stable over many decades, or they can exhibit measurable changes over short time spans (Kershaw 2008). In some cases, ice wedges in baydjarakh fields have been dated to many thousands of years (Sannel and Kuhry 2008, Vasil’chuk and Vasil’chuk 2008), suggesting remarkable longevity for these landscapes. Possible explanations for the stability of these landscapes include ‘self-organizing’ properties (Kessler and Werner 2003) or the underlying freeze-thaw dynamics, which can be inferred from temperature profiles (Kershaw 2008). A further possibility explored in this study is that thermal effects involving interacting geomorphology and surface cover (vegetation and standing water) could reinforce landscape patterns. For example, differential heat transfer and storage, along with the insulating properties of moss cover, could play an important role in stabilizing these landscapes. The potential for surface cover to enforce the stability of these landscape features is the focus of this study.

The site chosen for this study has appeared in aerial photos of the region as an apparently stable landscape feature for over 80 years (figure 1), despite considerable warming over that period. A previous study (Kershaw 2008) has classified this landscape as a polygonal peat plateau with ‘degrading’ ice wedges. Photographic comparisons spanning 63 years reveal little evidence of any changes in the primary landscape features over this time period, although changes in surface hydrology and associated vegetation cover are visible (arrows, figure 1).

In this study, we explored links between microtopography, surface cover, productivity and energy balance at this site. The contrast between high and low regions provided a ‘natural experiment’ for studying the effects of microtopographic variation on vegetation cover, productivity, and thermal and moisture regimes. Our starting assumption was that vegetation cover reflects hydrology, which is in turn determined by microtopography, a perspective that is consistent with previous studies demonstrating moisture effects on arctic vegetation distribution (Bliss et al. 1984, Chapin et al. 1995). On the other hand, vegetation cover is known to exert feedback on larger ecosystem, landscape and atmospheric processes through altered energy balance and gas exchange (Callaghan et al. 2004, Cutler 2011, Euskirchen et al. 2009, Sturm et al. 2005, Swann et al. 2010), so an additional hypothesis is that vegetation change or stability can, in itself, lead to further dynamics or stasis in geomorphology through localized feedbacks involving surface energy balance. Our goal was to understand factors that might explain the apparent stability of high-centered polygon landscapes in the face of warming climate.

2. Methods

The field site is located east of Churchill, Manitoba, on the southern border of Ramsay Lake Road, approximately 1 km to the southeast of the Churchill Northern Studies Centre. This site has been the focus of previous studies, including measurements of snow depth, temperature profiles and other thermal properties related to energy balance (Kershaw 2008). For the current study, we added surface albedo (reflectance) measurements to explore the additional role microtopography and vegetation cover might play in landscape thermal properties and stability. On 27 July 2010 (one day prior to measurement), a 100 m transect was
calculated for several sample locations (indicated by non-italic type). When standard deviation was calculated treating each year as a separate sample (indicated by italics); otherwise, the standard deviation was measured with a 2 m probe.

established in a roughly E–W direction (figure 1), immediately adjacent to locations of ongoing thermal monitoring (Kershaw 2008). The next day (28 July 2010), we sampled surface reflectance within 1 h of solar noon at each meter along the transect, using a field spectrometer (UniSpecDC, PP Systems, Amesbury, MA, USA). This instrument simultaneously sampled downwelling radiation (uncalibrated irradiance) and upwelling reflected radiation (uncalibrated surface radiance). To sample irradiance, we used a 2 m straight fiber optic attached to a leveled cosine receptor (UNI435, PP Systems, Amesbury, MA, USA). To sample surface radiance, we used a 3 m straight fiber optic with a field-of-view (FOV) restrictor (UNI688, PP Systems, Amesbury, MA, USA) that reduced the FOV to approximately 20°. Sampling at a 3 m height led to a sample on the ground of approximately 1 m diameter.

Reflectance was calculated by dividing the surface radiance by the irradiance, and then correcting this ratio by the same measurements made over a white reference standard (Spectralon, Labsphere, North Sutton, NH, USA). This ‘cross-calibration’ corrected for changing sky illumination, and yielded unitless reflectance readings as a function of wavelength (see Gamon et al. 2006 for further information).

To calculate broadband albedo, reflectance spectra were interpolated to 1 nm intervals, and values were then corrected to energy units, then summed between 400 and 1100 nm (the usable range of the spectrometer). This yielded a unitless measure of albedo over the visible–NIR region.

At each sampling point, relative elevation was determined by sighting a horizontal line along the sampling transect with a transit and measuring the height to the ground surface with a meter stick. The standing water surface in wet troughs was used as a reference (0 m) elevation. For further information, please see the supplementary data (available at stacks.iop.org/ERL/7/015502/mmedia).

Cover and species composition were estimated from digital photos of each meter along the transect. From these observations, we were able to ascertain the dominant plant cover for elevational positions along the transect.

At this site, measurements of snow depth, surface temperature and thaw depth have been made on contrasting landscape positions (troughs and polygon centers) for several years (Kershaw 2008). Additionally, using winter snow data the snow heat transfer (HT) coefficient was calculated for different landscape positions by dividing snowpack thermal conductivity (C) by snowpack depth (d) (see Abel’s 1893, as cited in Kershaw 2001 and 2008).

These data were first analyzed for time trends, and finding no significant trends over the sampling period, we calculated averages for multiple years and added these values to the summertime albedo measurements (see table 1). For this purpose of evaluating microtopographic differences, the landscape was categorized into two primary landscape units or ‘types’ based on elevation: (1) baydjarakhs (high polygon centers) ranging in height from approximately 50–100 cm and (2) wet troughs (with standing water).

Because thaw depth in baydjarakhs was too deep to be measured with frost probes (see table 1), we also examined ground-penetrating radar (GPR) for this landscape. The Pulse EKKO IV unit (Sensors & Software, Mississauga, ON, Canada) was used with a 100 MHz antenna at 1 m separation and a 0.25 m step. Radar surveys were conducted over several years at different times in the thaw season, and we present data from the most recent sampling in October 2006, during maximum seasonal thaw depth.

### Table 1. Summary measurements showing mean albedo, summer thaw depth, winter snow depth, snow heat transfer coefficient and annual average surface temperature for representative baydjarakh and trough locations.

| Location       | Mean (st.dev.) | n  | Sampling year(s) |
|----------------|---------------|----|------------------|
| Baydjarakh     |               |    |                  |
| Albedo         | 0.155 (0.006) | 3  | 2010             |
| Thaw depth (cm)| 45.56 (3.66)  | 1  | 2002, 2004, 2007–10 |
| Snow depth (cm)| 5.24 (1.08)   | 1  | 2002–11          |
| HT coefficient (W m⁻² K⁻¹) | 5.62 (2.63) | 1  | 2002–11          |
| Surface temperature (°C) | −3.75 (1.72) | 2  | 2004–8          |
| Trough         |               |    |                  |
| Mean (st.dev.) | 0.107 (0.02)  | 3  |                  |
| >200 (N/A)    | 49.74 (4.71)  | 1  |                  |
| 0.54 (0.10)   | 1.96 (0.061, 0.082) | 4  |                  |

Different cover types were associated with different landscape features. For example, the highest areas (baydjarakhs) were dominated by lichens and small, prostrate shrubs (mostly *Ledum sp.*, *Rubus sp.*, and *Empetrum sp.*). Wet troughs (subsided ice wedge locations) were dominated by standing water and graminoids (e.g. *Carex* sp.), with high levels of moss cover on the moist edges. The variation in cover types with elevation and landscape position can be seen in photos of the site (figure 2), showing the transition from a baydjarakh (plateau, on left) to a wet trough dominated by graminoids (right). The moss-dominated transition zone, with its relatively high albedo, is visible as a yellowish band in the middle of the photo.

Wet troughs with standing water and high graminoid cover had the lowest albedo. By contrast, polygon centers (baydjarakhs) that were dominated by dwarf shrubs and lichens tended to have higher albedo (figures 3 and 4).
Active layer (thaw) depth and snowpack depth roughly mirrored the albedo patterns. During the 2002–10 period, average mid-summer active layer depth for the baydjarakhs (plateaus) was 45.6 cm, whereas in the wet troughs, the active layer depth was >2 m (beyond the depth of the frost probe (table 1)). Average winter snow depth for baydjarakhs was 5.24 cm and for troughs was 49.74 cm. This difference in snowpack led to similar contrasts in winter heat loss, with mean HT coefficient values 5.62 W m⁻² K⁻¹ for baydjarakhs and 0.54 W m⁻² K⁻¹ for troughs (table 1). As a result of these contrasting values, annual surface temperatures were significantly different for baydjarakhs and troughs, with troughs exhibiting above-freezing mean annual surface temperatures (1.96 °C) and baydjarakhs maintaining below-freezing average surface temperatures (−3.75 °C).

Because thaw depth in troughs could not be determined with a 2 m probe, we also examined GPR profiles for the landscape. While direct measurement of permafrost depth is not possible with this method, radar returns for baydjarakhs and wet troughs revealed a pattern consistent with melted ice wedges and a deep (>2 m) active layer in the troughs (figure 5).

4. Discussion

Given the pace of temperature change in this region (Gagnon and Gough 2005), the apparent stability of this landscape is striking, particularly when compared to seemingly widespread surface cover change reported over similar time periods for other arctic sites (e.g. Sturm et al 2005, Bhatt et al 2010, Callaghan et al 2011). However, stability in surface cover has been reported at a handful of other arctic sites (e.g. Prach et al 2010, Callaghan et al 2011), leading us to speculate on the processes that might enforce stability.

When combining albedo patterns with additional measurements of this landscape spanning a 10 year period (table 1),
a picture of striking contrasts in landscape thermal properties between high and low microtopographic regions emerges. Based on the observations reported here, we propose a model (figure 6) for how microtopography, moisture and vegetation cover interact to maintain a stable landscape, which was originally formed by melting of ice wedges to form troughs and residual high plateaus (baydjarakhs). In summer, the wet troughs have the lowest albedo, and consequently the highest heat gain and deepest active layer (>2 m deep). The standing water (with its high heat capacity) helps store this heat into the winter. In winter, the deeper snowpack of the troughs helps retain this heat in these low regions, preventing the ice wedges from reforming (Kershaw 2008), thus reinforcing the deep trough structure. By contrast, the higher summer albedo of the baydjarakhs and edges maintains cooler sub-surface temperatures and preserve the near-surface permafrost and structural integrity of the elevated regions. The dense moss cover on the baydjarakh edges also helps insulate against surface thermal transfer between the warmer troughs and cooler plateaus. Surface insulation has been invoked as a possible factor supporting the remarkable longevity of some arctic permafrost (Froese et al. 2008). We propose that the contrasting thermal transfer and storage between the high and low landscape regions, along with the insulating moss layer common in the transition zone, promote the stability of the landscape and associated cover types.

The striking contrasts in vegetation cover associated with microtopography are similar to vegetation patterns reported for other arctic landscapes (Brown et al. 1980, Bliss and Gold 1994, Engstrom et al. 2005). Arctic vegetation is known to respond to resource gradients in nutrients and moisture (Bliss et al. 1984, Chapin et al. 1995, Engstrom et al. 2008, Huemmrich et al. 2010a, 2010b), and it is likely these factors were involved in the surface cover patterns observed here. Albedo (reflectance) measurements can help contribute to an understanding of how surface cover might contribute to landscape structure through energy balance. Clearly, there is a potential role for fine-scale remote sensing in describing and monitoring landscape patterns related to surface–atmosphere feedbacks, but these measurements will need to be coupled with additional long-term monitoring of vegetation and below-ground thermal properties. While such ‘snapshots’ provided by remote sensing cannot directly assess processes, they can help infer a process, particularly when combined with other information or collected over time.

Mathematical models have been used to describe the ‘self-organizing’ properties of patterned arctic landscapes based on physical properties involving freeze-thaw dynamics and sorting of particle sizes (Kessler and Werner 2003). These physical models generally do not consider the role of surface cover in maintaining the equilibrium of such landscapes. Our results suggest a role for surface albedo associated with different cover types and moisture levels in maintaining the structural stability and vegetation cover of baydjarakh fields characterized by high-centered polygons, which are common arctic landscape features. The remarkable insulating properties of surface vegetation could be additional biological factors supporting landscape structure and stability (Froese et al. 2008). Further study is needed to integrate vegetation dynamics into existing physical models, and the optical sampling methods used here could contribute to the development of such a revised model, particularly if sampled repeatedly over time and combined with other thermal measurements. High-resolution remote sensing could extend sampling of surface vegetation patterns associated with microtopography to larger arctic regions, and help identify areas warranting detailed field monitoring.

Based on the thermal data presented here (table 1), we speculate that an unusually warm pulse of several degrees or strong erosional effects are required to overcome the stability of this landscape. It is likely that the Churchill region has experienced such warm periods before (Mamet and Kershaw 2011), and this could explain the origin of this or similar baydjarakh landscapes in the region. On the other hand, some polygonal landscapes have been dated to over 40 thousand years (Vasil’chuk and Vasil’chuk 2008) and to over 4000 years in Canadian regions emerging from recent glaciation (Sannel and Kuhry 2008), so a much older age for many baydjarakh fields is likely. The Churchill landscape is the result of recent isostatic rebound (for this site dated to about 1500 years), and ice wedges for this particular location have been dated to 1340 + 60 years (Kershaw, unpublished data). Consequently, this landscape is much younger than many similar features reported for other arctic regions. It may take another substantially warmer period to cause further noticeable change in the structure of this particular landscape.

Alternatively slight changes in surface hydrology (figure 1) or the gradual incursion of shrubs and trees may, over time, alter the thermal properties to allow further geomorphological change to occur, as observed in other sites.
Studies of baydjarakh fields offer unique insights into the factors that determine change or stability in arctic landscapes. The apparent stability of these landscape features is remarkable considering the rapid pace of change for other arctic landscapes, and may provide insights into the basic processes causing stability and change in a future warming and drying arctic.

Acknowledgments

We thank NSERC, iCORE (AITF), the Churchill Northern Studies Centre, and Wapusk National Park (Parks Canada) for supporting this research. Earthwatch Institute volunteers contributed to the fieldwork. Rick Bello (York University), Glenn Schneider and Beverly Riel (Manitoba Hydro), and Joanne Tremblay (Natural Resources Canada) were instrumental in providing access to airborne imagery. Craig Tweedie and Donnette Thayer provided helpful discussion and suggestions.

References

Allison I et al 2011 The Copenhagen Diagnosis: Updating the World on the Latest Climate Science (Oxford: Elsevier) (available at http://eprints.ifm-geomar.de/11839/)
Bhatt U S et al 2010 Circumpolar arctic tundra vegetation change is linked to sea ice decline Earth Interact. 14 doi:10.1175/2010EI315.1
Bliss L C and Gold W G 1994 The patterning of plant communities and edaphic factors along a high arctic coastline—implication for succession Can. J. Bot.-Revue Can. Bot. 72 1095–107
Bliss L C, Svodoba J and Bliss D I 1984 Polar deserts and their plant communities Environ. Res. Lett. 7 2011
Brown J, Everett K R, Webber P J, MacLean S F Jr and Murray D F 1980 The coastal tundra at Barrow Holoact. Ecol. 7 305–24
Brown J, Everett K R, Webber P J, MacLean S F Jr and Murray D F 1980 The coastal tundra at Barrow An Arctic Ecosystem: The Coastal Tundra at Barrow, Alaska (US/IBP Synthesis Series vol 12) ed J Brown, P C Miller, L L Ticszen and F L Bunnell (Stroudsburg, PA: Dowden, Hutchinson & Ross) pp 1–29
Callaghan T V et al 2004 Effects of changes in climate on landscape and regional processes, and feedbacks to the climate system Ambio 33 459–68
Callaghan T V et al 2011 Multi-decadal changes in tundra environments and ecosystems: synthesis of the International Polar Year—back to the future project (IPY-BTF) Ambio 40 705–16
Chapin F S III, Hobbie S E, Bret-Harte M S and Bonan G 1995 Causes and consequences of plant functional diversity in arctic ecosystems Arctic and Alpine Biodiversity: Patterns, Causes and Ecosystem Consequences ed F S Chapin III and C Korner (Berlin: Springer) pp 225–37
Cutler N 2011 Vegetation-environment interactions in a sub-arctic primary succession Polar Biol. 34 693–706
Engström R, Hope A, Kwon H and Stow D 2008 The relationship between soil moisture and NDVI near Barrow, Alaska Phys. Geogr. 29 38–53
Engström R, Hope A, Kwon H, Stow D and Zamolodchikov D 2005 Spatial distribution of near surface soil moisture and its relationship to microtopography in the Alaskan Arctic coastal plain Nor. Hydrol. 36 219–34
Euskirchen E S et al 2009 Changes in vegetation in northern Alaska under scenarios of climate change, 2003–2100: implications for climate feedbacks Ecol. Appl. 19 1022–43
French H M 1974 Active thermokarst processes, eastern Banks Island, Western Canadian Arctic Canadian J. Earth Sci. 11 785–94
Groves D G, Westgate J A, Reyes A V, Enkin R J and Preece S J 2008 Ancient permafrost and a future, warmer Arctic Science 321 1648
Gagnon A S and Gough W A 2005 Trends in the dates of ice freeze-up and breakup over Hudson Bay, Canada Arctic 58 370–82
Gamon J A, Cheng Y, Claudio H, MacKinney L and Sims D 2006 A mobile tran system for systematic sampling ecosystem optical properties Remote Sens. Environ. 103 246–54
Huemmrich K F et al 2010a Remote sensing of tundra gross ecosystem productivity and light use efficiency under varying temperature and moisture conditions Remote Sens. Environ. 114 481–9
Huemmrich K F et al 2010b Tundra carbon balance under varying temperature and moisture regimes J. Geophys. Res.—Biogeosci. 115 G00020
Kershaw G P 2001 Snowpack characteristics following wildfire on a simulated transport corridor and adjacent subarctic forest, Tulita, N.W.T, Canada Arctic, Antarct., Alpine Res. 33 131–9
Kershaw G P 2008 Snow and temperature relationships on polygonal peat plateaus, Churchill, Manitoba, Canada Proc. 9th Int. Conf. on Permafrost vol 1 ed D L Kane and K M Hinkel (Fairbanks, Alaska) pp 925–30
Kershaw G P unpublished data
Kessler M A and Werner B T 2003 Self-organization of sorted patterned ground Science 299 380–3
MacKay J R 2000 Thermally induced movements in ice-wedge polygons, western arctic coast: a long-term study Géogr. Phys. Quat. 54 41–68
Mamet S D and Kershaw G P 2011 Radial-growth response of forest-tundra trees to climate in the Western Hudson Bay Lowlands Arctic 64 446–58
Myers-Smith I H 2011 Shrub encroachment in arctic and alpine tundra: patterns of expansion and ecosystem impacts PhD Thesis University of Alberta
Prach K, Kosnar J, Klimesova J and Hais M 2010 High Arctic vegetation after 70 years: a repeated analysis from Svalbard Polar Biol. 33 635–9
Sannel A B K and Kuhry P 2008 Long-term stability of permafrost in subarctic peat plateaus, west-central Canada Holocene 18 589–601
Schuur E A G et al 2008 Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle BioScience 58 701–41
Smith L C, Sheng Y, MacDonald G M and Hinzman L D 2005 Disappearing Arctic lakes Science 308 1429
Sturm M et al 2005 Changing snow and shrub conditions affect albedo with global implications J. Geophy. Res.—Biogeosci. 110 G01004
Swann A L et al 2010 Changes in Arctic vegetation amplify high-latitude warming through the greenhouse effect Proc. Natl Acad. Sci. USA 107 1295–300
Vasil’chuk Y K and Vasil’chuk A C 2008 Dansgaard-Oeschger events on isotope plots of Siberian ice wedges Proc. 9th Int. Conf. on Permafrost ed D L Kane and K M Hinkel (Fairbanks: Institute of Northern Engineering, University of Alaska Fairbanks) pp 1809–14