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Sixty-year legacy of human impacts on a high Arctic ecosystem

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Summary

1. The high Arctic is the world's fasting warming biome, allowing access to sections of previously inaccessible land for resource extraction. Starting in 2011, exploration of one of the Earth's largest undeveloped coal seams was initiated in a relatively pristine, polar desert environment in the Canadian high Arctic. Due to the relative lack of historic anthropogenic disturbance, significant gaps in knowledge exist on how the landscape will be impacted by development.

2. At an abandoned airstrip located near the area of current exploration, we used a disturbance case–control approach to evaluate the long-term ecological consequences of high Arctic infrastructure disturbance to vegetation and sensitive, ice-rich permafrost. We quantified: (i) long-term effects on vegetation diversity, soil nutrients and abiotic ground conditions and (ii) the alteration of the ground surface topography and legacy of subsurface thermal changes.

3. We found that in over 60 years since abandonment, the disturbed landscape has not recovered to initial conditions but instead reflects a disturbance-initiated succession towards a different stable-state community.

4. Microtopography greatly influenced recovery patterns in the landscape. The terrain overlaying buried ice (ice-wedge polygon troughs) was the most sensitive to disturbance and had a different species composition, decreased plot-level species richness, significant increases in vegetation cover and a drastically reduced seasonal fluctuation in subsurface temperatures. In contrast, disturbed polygon tops showed resiliency in vegetation recovery, but still had remarkable increases in depth of seasonal soil thaw (active layer).

5. *Synthesis and applications*. Our results indicate that disturbance effects differ depending on microtopographic features, leading to an increased patchiness of the landscape as found elsewhere in the Arctic. Managers who wish to lessen their impact on high Arctic environments should avoid areas of sensitive, ice-rich permafrost, constrain the geographic scale of near-surface ground disturbance, limit vegetation removal where possible and reseed disturbed areas with native species.

Key-words: biodiversity, climate change, disturbance, ground temperature, ice wedges, infrastructure, permafrost, polar desert, species richness, thermokarst

Introduction

The high Arctic is warming, allowing access to large sections of previously isolated or logistically unfeasible land for development (IPCC 2013). Much of the Arctic is considered a 'storehouse of resources' (ADHR 2004), while at the same time governments of circumpolar nations have introduced new regulatory changes and policies to encourage further exploration and increased land use (Haley *et al.* 2011). Arctic Canada, a resource frontier region, has recently expanded the development of mining in its far north (Prowse *et al.* 2009), despite significant industry concerns over the threat of future climate change and the lack of adaptation plans (Ford *et al.* 2010; Pearce *et al.* 2011). Starting in 2011, exploration of one of the largest undeveloped coal seams in the world was initiated on the Fosheim Peninsula of Ellesmere Island, Canada

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(O'Donnell 2012). The region is a rather pristine, polar desert environment, and significant gaps in knowledge exist on how this landscape will respond to increased human activity.

High Arctic environments are thought to be particularly sensitive to anthropogenic disturbance, given the slow rate of vegetation growth as well as the presence of large amounts of thermally sensitive ice-rich permafrost (Reynolds & Tenhunen 1996; Forbes, Ebersole & Strandberg 2001). The coal-rich Fosheim Peninsula is estimated to have 1456·8 km^2 of ground ice within the permafrost (equalling about 30% of the upper 5·9 m of permafrost) (Couture & Pollard 1998), with roughly 700 km^2 of it composed as wedge ice. Ice wedges are vertical, v-shaped bodies of ice that extend downwards into the ground for three to four metres and can comprise up to 50% of the near-surface ground volume (Pollard & French 1980). Their presence creates a network of high-centred polygon tops, surrounded by low-relief troughs (generally 10–30 cm deep) under which the ice wedges lay. Due to their sensitivity to warming air temperatures, their melting changes surface moisture regimes throughout the water-scarce polar desert (Edlund, Woo & Young 1990). These bodies of ice are especially prone to disturbance as any increase in the seasonal depth of thaw (active layer), through the removal of an insulating vegetation cover for instance, results in topographic subsidence and the collapse of the ground surface (Edlund, Woo & Young 1990). This change in surface relief even at very small (decimetre) scales due to melting ground ice (termed thermokarst) substantially alters vegetation, hydrology and near-surface soil characteristics (Zona *et al.* 2011).

It is important to assess the range of potential landscape impacts prior to increasing large-scale mining operations, in order to minimize and mitigate impacts (ACIA 2004). Impacts include those on coastal marine biota (Larsen *et al.* 2001), freshwater ecosystems (Laperrière *et al.* 2008), permafrost thaw/thermokarst (Sharkhuu 2003; Weaver & Kulas 2003), soil contamination (Elberling *et al.* 2007; Yakovlev *et al.* 2008) and plant community composition (Forbes 1997; Forbes, Ebersole & Strandberg 2001). One such way to evaluate the impacts of future high Arctic industrial development is to assess outcomes of historical disturbance. Due to the remote location and recent occurrence of human activity in the high Arctic, examples of historic disturbance are few and generally small scale, with most non-industrial anthropogenic activities creating disturbances in the range of 100 m^2–1 km^2 (Walker & Walker 1991; Forbes 1993). One of the oldest industrial human disturbances in the high Arctic is a network of high Arctic weather stations established in the 1940s and 1950s (Department of Transport – Canada, M.D. & Department of Commerce – US, W.B. 1951). These stations required several forms of infrastructure – tundra airstrips, buildings and seashore loading zones – all essential to industrial work. The Eureka Weather Station, situated on the Fosheim Peninsula, is directly adjacent to the area of current mining interest.

During Eureka's establishment in 1947, a tundra runway was created and used until 1951, when it was abandoned in favour of a new airstrip 3 km closer to base. This abandoned runway provides a rare opportunity to examine the long-term land surface impacts from a form of infrastructure essential to future mining development. Over the last several decades, research has qualitatively described both the vegetation changes and geomorphic disturbances to arise from historic anthropogenic impact at this site (Beschel 1963; Couture & Pollard 2007). Ecosystem impacts that are visible today were noted as little as 2 years after the disturbance stopped in 1951 by Bruggemann, P.F. (Beschel 1963). This suggests that colonizing plants rapidly filled available niche space and showed marked stability, similar to other Arctic locations where disturbance-induced community composition changes demonstrated consistency and resiliency over time (Forbes 1993; Jorgenson, Ver Hoef & Jorgenson 2010).

The high Arctic's vegetation (Forbes, Ebersole & Strandberg 2001) and permafrost (Woo & Young 2003, 2006) responses to disturbance are distinct from elsewhere in the Arctic, and few examples of long-term studies exist. In this study, we evaluate the following hypotheses: (i) infrastructure disturbance to the high Arctic environment creates long-term changes to vegetation, soil nutrients and abiotic ground conditions and (ii) the alteration of the ground surface and removal of vegetation result in a legacy of subsurface thermal changes. We highlight the aspects of the ecosystem that are most sensitive to disturbance and provide managers and industry professionals with clear ways to minimize and mitigate impacts to high Arctic landscapes.

Materials and methods

STUDY SITE

Eureka was established in 1947 through a joint US–Canadian partnership. The crew developed an area of flat tundra to create a winter ice runway, located at 80·0175°N 85·7340°W approximately 5 km from the current weather station (Figs 1 and S1, Supporting Information). The airstrip was constructed in 1947 by grading and removal of vegetation, and the infilling of uneven polygonal ground using nearby fine-grained marine clay soils into a flat, compacted 1·2-km-long × 50-m-wide tundra runway. While primarily used as an ice runway for winter transport, the yearly removal of vegetation continued from 1947 until its abandonment in 1951. Since 1951, the airstrip has had no further development, but vegetation and geomorphic differences between the disturbed and undisturbed areas are still easily visible. Since its abandonment, the area has been without human activity, aside from a few scientific observational studies, and has been allowed to 'recover' along its own trajectory.

The region is characteristic of a polar desert environment with scarce annual precipitation, low snow depth and low water-equivalent snow (Edlund, Woo & Young 1990). There are intense

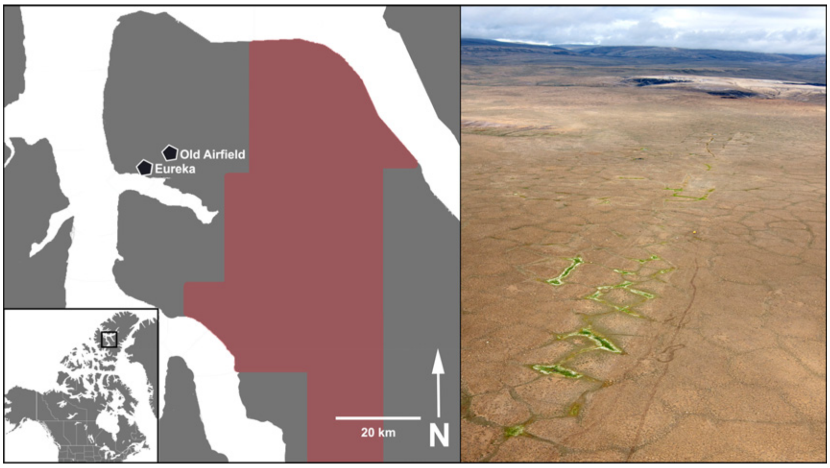

Fig. 1. Map of the Fosheim Peninsula, Ellesmere Island, Nunavut, Canada. The old airstrip is located ~5 km away from the Eureka Weather Station. The red highlighted area shows the sections of the Fosheim Peninsula currently leased for mining interests (O'Donnell 2012). The aerial image of the airstrip on the right was taken in 2012. The zone of airstrip disturbance is clearly visible with marked differences in vegetation and more greatly expressed polygon features.

seasonal fluctuations of temperature with a mean annual air temperature (MAAT) of −19·6°C, a February mean of −37·4°C and a July mean of 6·1°C. Soils consist of nitrogen-poor, fine-grained marine clay sediments, typical of the region (Hodgson, St-Onge & Edlund 1991). In addition to the very distinct nature of the grading disturbance, easy visualization of location and discrete time frame of occurrence, there is the added benefit of daily records written by Eureka staff that catalogued landscape alterations (Department of Transport – Canada, M.D. & Department of Commerce – US, W.B. 1951).

DATA COLLECTION

A 400 × 400 m subsection of the area was selected near the middle of the runway to eliminate edge effects from either end. A network of transects were overlaid on the site of disturbance with a significant border area of undisturbed, control terrain on the east and west sides of the runway. Plot-level vegetation, soil and abiotic data were collected during June and July 2012. Vascular plant percentage cover was visually estimated within 0·5-m^2 quadrats placed at alternating polygon tops and troughs (roughly 5–10 m apart) along five transects running 400 m east to west, as well as one additional transect running north to south along the airstrip. We conducted a stratified random sampling approach, recording compositional data within 80 quadrats divided into the following microtopographical groups: 22 control tops, 23 control troughs, 18 disturbed tops and 17 disturbed troughs. Quadrats were assigned as disturbed or control based on whether they fell within the airstrip-grading zone, and the category of polygon top or trough was obvious as troughs delineate the edges of tops. Plots were marked by GPS and stakes for relocating in the future.

Vascular vegetation was identified to the species level, and specimen vouchers were submitted to the Marie-Victorin Herbarium in Montreal, QC (Table S1). Vascular plant nomenclature follows Saarela *et al.* (2013). Additional measures of percentage moss cover, leaf litter and bare ground were taken. Elevation of the 400 × 400 m site was mapped by taking 471 surveying measurements using a laser level, plus measurements at each quadrat. Active layer depth was ascertained by pounding a permafrost probe into the four corners of the quadrat and calculating the average depth of penetration. Snowpack measurements were taken the following year on 5 June 2013 prior to the spring melt period. This measure represents the maximum total accumulated snow for the winter season and is therefore a good general measure of the bulk of annual water input for the system because summer rain is scant (Rydén 1977). Additionally, this measure provides an idea of the snow insulation layer influencing soil temperate data.

Plot-level soil temperature data were collected for a period of 1 year from 20 June 2013 to 18 June 2014. iButton data loggers were buried at 12 cm depth (maximum rooting depth) at the locations of all quadrat plots and set to record ground temperature data every 4 hours. Thirteen data loggers, all at disturbed trough locations, were unable to be buried on 20 June 2013 as the ground at these locations was still frozen. Instead, these sites were revisited on 23 July and all successfully buried. Seventy-four of the eighty data loggers were recovered on 19 June 2014 and none malfunctioned.

SOIL CHEMISTRY

At each plot, soil samples were collected by taking 12-cm-deep slices from the four corners of the quadrat, homogenizing, air drying for several days and then pulverizing. Wet/dry weight ratios were taken in the field for soil moisture content (%H_2O).

Laboratory soil chemistry was conducted as follows: pH using a 1 : 2 soil-to-solution ratio using H_2O and then measured by pH meter (Hendershot, Lalande & Duquette 1993). Extractable NO_3- and NH_4+ were obtained using a 2 M KCl extraction ratio of 1 : 10 soil-to-solution and shaken for 1 hour. The filtrate was analysed by colorimetry for the determination of N on a multichannel Lachat Quikchem auto-analyser (Lachat Methods 13-107-06-1-A, 13-107-06-2-B, 10-107-06-2-C; Maynard & Kalra 1993). Available P and K were determined by a multielement extraction using Mehlich III solution and then measured by flow injection analysis (Lachat Instruments; Tran & Simard 1993). Percentage organic matter was measured by loss-on-ignition, and the difference in weight is attributed to the loss of organic matter (Schulte, Kaufmann & Peter 1991).

STATISTICAL ANALYSIS OF VEGETATION, SOIL AND TEMPERATURE DATA

Vegetation differences between the four classes of microtopography were analysed using the following techniques: community differences were examined by ordinating plot composition and percentage cover using non-metric multidimensional scaling (NMDS) of a Bray–Curtis distance matrix calculated from plant species percentage cover in the r-library *vegan* (Oksanen *et al.* 2013), and quantified using a permutational multivariate analysis of variance (PERMANOVA) set for 1000 randomizations. Mean plot species percentage cover (of vascular vegetation), richness (alpha diversity) and evenness (Shannon's H) were compared between classes of microtopography using two-way, type III ANOVAS for imbalanced designs to account for the unequal number of sample sizes, followed by Tukey's tests for post hoc significance testing. Soil chemistries were tested in a similar fashion, using two-way, type III ANOVAS for imbalanced designs followed by Tukey's tests for post hoc analysis.

Temperature analysis was divided into two measures: thawing degree-days (TDD) and freezing degree-days (FDD). TDD and FDD are measures of the magnitude of annual warming above 0°C or freezing below 0°C, respectively. For TDD, each plot had its daily mean temperature calculated, and then, mean temperatures for all days greater than 0°C were summed. For FDD, all mean temperatures for days less than 0°C were summed. For group means testing of TDD, all data from before 23 July 2013 were removed as a large portion of the thermokarst trough loggers were not yet buried. Therefore, the TDD metric should be viewed as the *relative* differences of TDD experienced between microtopographies for the yearly period, rather than the absolute TDD for the summer period. Since all loggers were successfully buried for the winter season, FDD represents the true values experienced through the winter season.

All analyses were done in R version 3.0.2 (R Core Team 2014).

Results

VEGETATION

The vegetation patterns of disturbed troughs have followed a distinct trajectory compared to polygon tops and undisturbed troughs. The NMDS ordination of communities (Fig. 2a) and species vectors (Fig. 2b) shows that disturbed troughs have a vegetation composition distinct from the other three microtopographies, supported by the PERMANOVA results (Table S2). These plots have changed into wet-sedge-dominated communities, compared to the willow-dominated communities present in the other three microtopographies.

The study site included 23 of the estimated 140 species indigenous to the Fosheim Peninsula (Edlund, Woo & Young 1990) (Table S1), with control and disturbed zones having a gamma diversity (pooled species richness) of 18 and 17, respectively. The control top and trough had 12 and 15 species, respectively, with *Salix arctica* dominating and *Poa glauca* and *Dryas integrifolia* the next greatest in cover. Five species, *Saxifraga oppositifolia*, *Pedicularis hirsuta*, *Cerastium arcticum*, *Bistorta vivipara* and *Poa pratensis*, were unique to control terrain and completely absent from disturbed terrain.

Disturbed tops had a species pool of 13 and were dominated by *S. arctica*, with *P. glauca* and *Deschampsia brevifolia* the next most common. Disturbed troughs had a species pool of 14 and were the only microhabitat not dominated by *S. arctica*, instead being dominated by the grass *Alopecurus magellanicus*, with secondary dominance split between the sedge *Eriophorum scheuchzeri* and *S. arctica*. *E. scheuchzeri* tended to entirely cover the wettest plots (Fig. S2). Four species were unique to disturbed plots: *Juncus arcticus*, *Pleuropogon sabinei*, *Elymus alaskanus* and *Dupontia fisheri*.

In addition to pronounced compositional differences, disturbance significantly affected both species richness and evenness (Fig. 3 and Table S3). Significant interaction effects between disturbance and microtopography showed that disturbance lowered species richness (Fig. 3a) and evenness (Fig. 3b) in troughs, but not tops. Conversely, disturbance significantly increased percentage cover on troughs, and not tops.

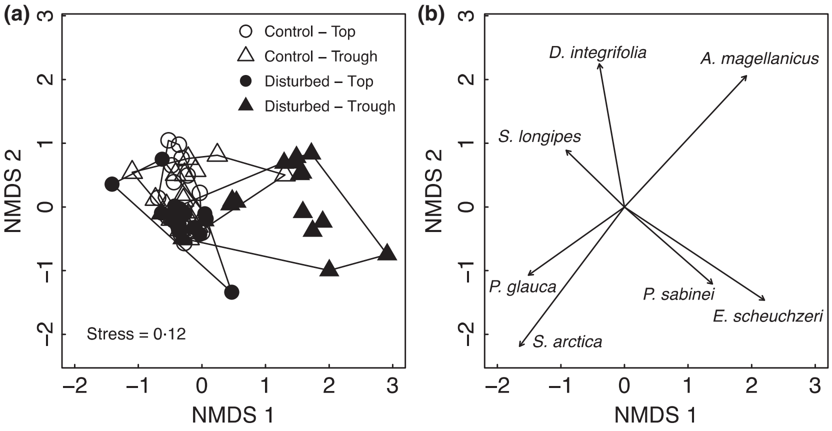

Fig. 2. NMDS ordination using a Bray–Curtis dissimilarity matrix generated from plant community composition. (a) Hulls connect the outermost points of each microtopography to show spread of the community composition data. Only the disturbed troughs show clear separation from the other microtopographies, reflected in the strong interaction effect from PERMANOVA results (Table S2). Additionally, disturbed troughs show greater variability in community composition than other microtopographies. (b) Species vectors as they correlate with NMDS ordination; only vectors statistically significant at $P \leq 0{\cdot}01$ are shown.

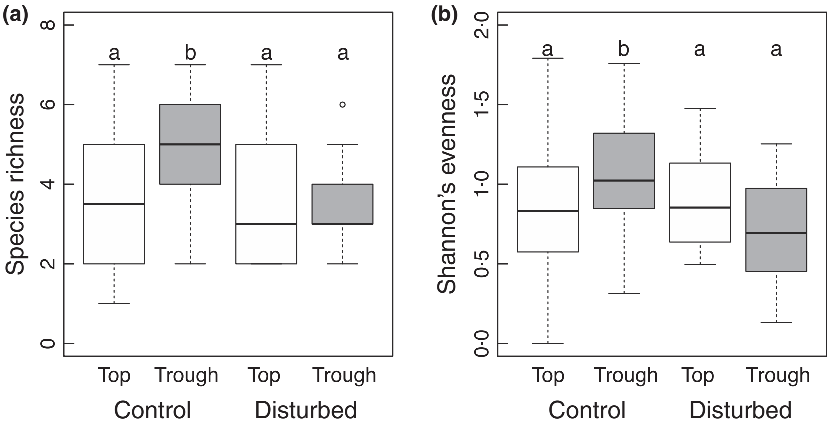

Fig. 3. Measures of plant species richness (alpha diversity) (a) and evenness (b) of the four microtopographies. Box–whiskers represent 1·5 interquartile range (IQR) boundaries. Different letters above boxes represent significantly different values ($P < 0{\cdot}01$, ANOVA and Tukey's post hoc test).

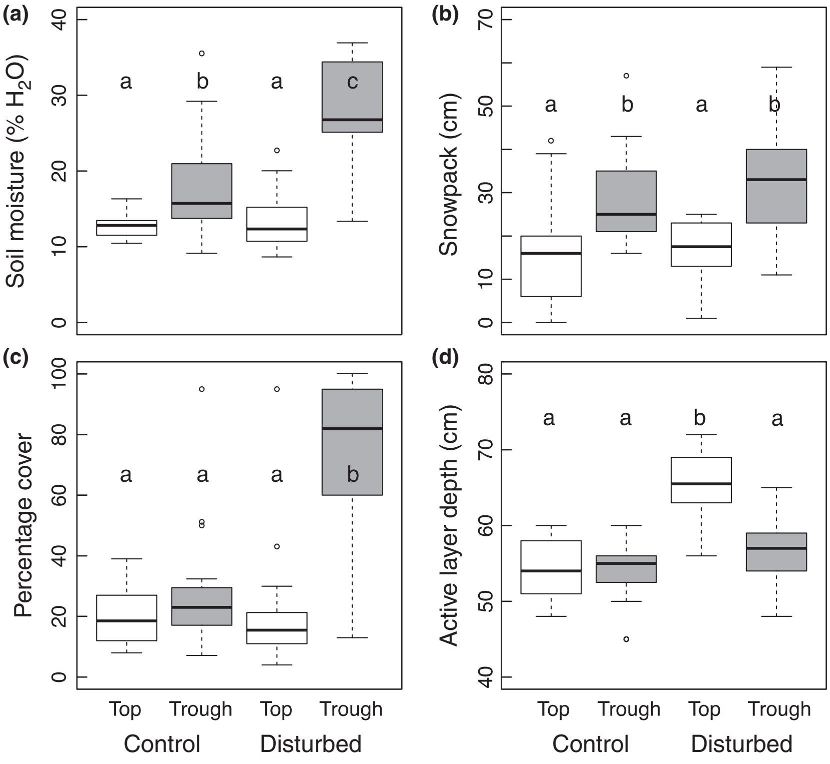

Fig. 4. Measures of soil moisture (a), snowpack depth (b), vegetation percentage cover (c) and active layer depth (d) of the four microtopographies. Box–whiskers represent 1·5 interquartile range (IQR) boundaries. Different letters above boxes represent significantly different values ($P < 0{\cdot}01$, ANOVA and Tukey's post hoc test).

ABIOTIC

Disturbance altered soil chemistry in a similar manner as vegetation, whereby the effect of disturbance was much more pronounced on troughs than on tops (Fig. S3 and Table S4). Disturbance significantly increased amounts of NH_4, while lowering levels of P, K and decreasing soil pH. Disturbance had no significant effect on organic matter accumulation, and NO_3 levels were generally at detection limit.

The most prominent effect of disturbance to abiotic soil conditions was the marked increase in soil moisture of disturbed troughs (Fig. 4 and Table S5). The effect of disturbance increased soil moisture far more in troughs than in tops, with a significant interaction effect (Fig. 4a). This comes despite no significant difference between disturbed and undisturbed troughs for the depth of winter snowpack – the largest annual input of moisture to the system (Fig. 4b). There was also no significant difference in soil subsidence between undisturbed and disturbed troughs. However, disturbance increased vegetation percentage cover in troughs and not tops (Fig. 4c), with a strong interaction effect mirroring trends found with soil moisture. Opposite to most other measures, disturbance greatly increased active layer depth in tops, but not troughs (Fig. 4d), with a significant interaction effect present.

We found substantial annual differences in soil temperature between the disturbed and control quadrats (Table S6). Figure 5 shows that disturbed troughs have lower summer soil temperatures and warmer winter soil temperatures. Significant interaction effects between disturbance and microtopography result in greatly reduced

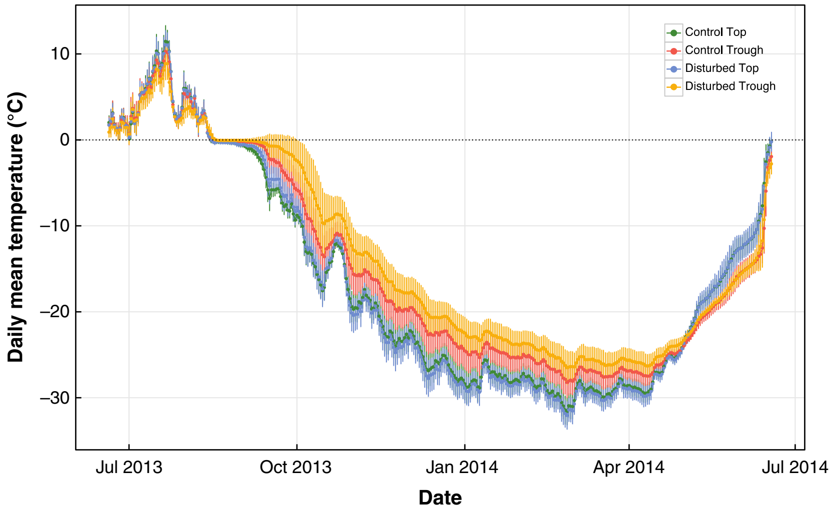

Fig. 5. Averaged daily soil temperatures at 12 cm depth, bars denote standard deviation. Disturbed troughs clearly demonstrate lowest summer temperatures and warmest winter temperatures, with reduced fluctuations throughout the year.

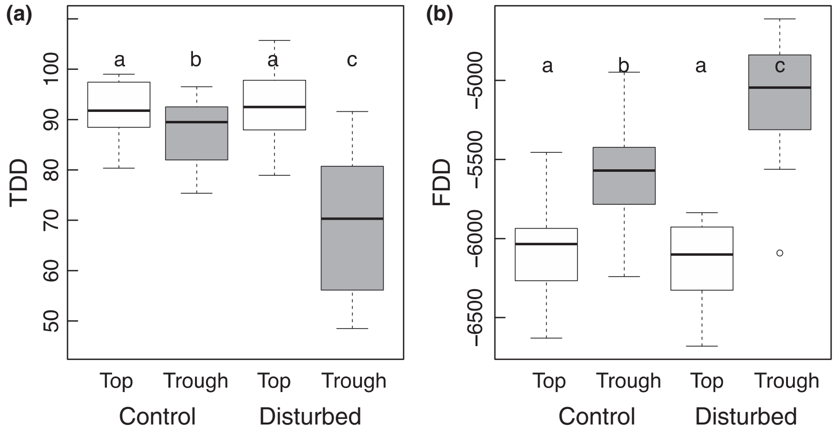

Fig. 6. Measures of thawing degree-days (TDD) (a) and freezing degree-days (FDD) (b) of the four microtopographies. Box–whiskers represent 1·5 interquartile range (IQR) boundaries. Different letters above boxes represent significantly different values ($P < 0{\cdot}01$, ANOVA and Tukey's post hoc test).

TDD (Fig. 6a) and FDD (Fig. 6b) in troughs, but not tops. The overall effect of disturbance resulted in less seasonal variation in soil temperature for troughs throughout the year, with no significant effect on tops.

Discussion

In over 60 years after abandonment of an airstrip on high Arctic tundra, the disturbed landscape has not recovered to a state comparable to surrounding terrain. The disturbed ground does not appear to be on a recovery trajectory towards the control conditions, but instead reflects a disturbance-initiated succession towards a different stable-state community due to altered soil conditions (Forbes, Ebersole & Strandberg 2001; Kemper & Macdonald 2009). The terrain overlaying ice wedges within the polygon networks are the most sensitive to disturbance, with altered species compositions and the largest impact on abiotic soil conditions and subsurface temperatures. Disturbed tops also preserve a thermal legacy of impact with the largest active layer depth changes, despite having vegetation that appears to have returned to normal. We attribute these active layer increases to the increased compaction of the disturbed soils, whereby compaction decreases the insulative properties of soil (Forbes 1993; Kevan *et al.* 1995), allowing a similar thermal signal (TDD/FDD) as experienced by the undisturbed tops to propagate deeper into the subsurface. These results indicate that both types of microtopography can bear the hallmarks of disturbance long after human activity has stopped. These effects differ depending on microtopographic feature, leading to an increased patchiness of the landscape as found elsewhere in the Arctic (Forbes, Ebersole & Strandberg 2001). We therefore recommend that developers avoid areas of sensitive, ice-rich permafrost, constrain the geographic scale of near-surface disturbance and limit vegetation removal.

VEGETATION

The vegetation community's response to disturbance differs greatly depending on microtopography. Disturbed polygon troughs, underlain by ice wedges, have followed a unique trajectory. Rather than track a vegetation recovery pattern like tops, the troughs appear to have stabilized into a different stable state – a wetland very similar to naturally induced thermokarst (Forbes, Ebersole & Strandberg 2001; Jorgenson, Shur & Pullman 2006). The dominant type of vegetation has changed from willow in undisturbed troughs to wet-sedge/graminoid in disturbed troughs, with a plot-level decrease in species richness and evenness. This results from incoming, rapidly growing clonal species (such as *E. scheuchzeri* and *A. magellanicus*) that leave very little space for additional colonization or further diversity (Forbes 1996). Recruitment to disturbed sites generally comes from local soil seed bank stores rather than freshly dispersed seeds or vegetative runners (Cooper *et al.* 2004). This means that species richness may be kept low by both a dearth of microsite space availability and a limited number of efficient colonizers in the Arctic (Forbes 1996). In contrast to studies where diversity was lowered for the entire disturbance area (Forbes, Ebersole & Strandberg 2001), in our study species richness remained unchanged for disturbed tops. This shows resiliency for polygon top vegetation to recover from disturbance and removal.

The effects of differential and increased vegetation growth in disturbed troughs are mirrored in the impacts on soil nutrients, primarily the consumption of K and the increase in pH and organic matter through increased plant activity. Low nitrogen concentrations are typical for high Arctic ecosystems (McKane *et al.* 2002). However, NH_4 concentrations in disturbed troughs may increase over decadal or century time-scales from greater microbial fixation due to more favourable (increased moisture) soil conditions (Mengel *et al.* 2001) and may act as localized nutrient pools. While soil nutrient conditions do not yet greatly differ for disturbed locations, it is likely that over time the altered vegetation communities will produce increasingly divergent soil conditions (Edlund & Alt 1989).

ABIOTIC

A major impact of increased vegetation cover in the disturbed troughs has been the alteration of abiotic soil conditions – primarily the drastically higher soil moisture content (Woo & Young 2006). Given that troughs in both control and disturbed locations are receiving roughly the same amount of water input (i.e. no significant difference in snowpack), we believe that the increased vascular plant cover in disturbed troughs is helping to retain moisture when compared to higher proportion of bare ground found in control troughs. Interestingly, the lack of significant difference between undisturbed and disturbed trough depths means that the once graded and infilled airstrip troughs have subsided since abandonment, allowing for the catchment of surface water run-off (Kevan *et al.* 1995). Wet-sedge species such as *E. scheuchzeri* rely on greater soil water content to persist but also need this greater water content to successfully colonize. Edlund, Woo & Young (1990) found that in hot years, melting ice wedges provided increased soil moisture. In our case, we posit that the removal of vegetation decreased the insulation of the ground (Babb & Bliss 1974; Shur & Jorgenson 2007), increased the seasonal depth of thaw, resulting in melted ground ice that contributed the essential moisture needed for sedge colonization. As sedge growth continued, further moisture was retained, and successive years reinforced the wet-sedge ecosystem (Jorgenson, Ver Hoef & Jorgenson 2010).

This wet-sedge ecosystem has significantly dampened annual ground temperature fluctuations. These plots are colder in the summer, and warmer in the winter, due partly to the insulating effects of a greatly increased vegetation cover (Shur & Jorgenson 2007). Additionally, the retention of soil moisture due to increased plant cover should contribute to greater soil ice content, which dampens the seasonal warming of the active layer (Woo & Young 2003). This cooling effect happens for two reasons: a larger amount of heat is required to thaw-frozen ice content due to the latent heat flux during the phase change from ice to water, and the seasonally differing thermal conductivities of thawed/frozen organic layers (Osterkamp & Romanovsky 1997). We doubt that the decrease in FDD plays much of a role in the annual development of the active layer – yet – as the mean annual air temperature of the region is so cold the active layer completely refreezes by winter. However, the significantly less TDD experienced during the summer means that active layer depth is reduced, and it is possible that the disturbed troughs are now more resistant to further thermal change (i.e. from climate change) when compared to control plots. Jorgenson, Shur & Pullman (2006) found that the expansion of thermokarst terrain during six decades of climate warming was due primarily to the initiation of new thermokarst, rather than the expansion of old. Indeed, older thermokarst showed only gradual change and the stabilization of new thermokarst could be achieved within 20–30 years through stimulated vegetation growth. Thus, while the vegetation biotic composition has shifted completely for disturbed troughs, the greater biomass of clonal species is a stabilizing feedback that may help with the overall resistance to further change of the underlying permafrost (Walker & Walker 1991).

RECOMMENDATIONS FOR MANAGEMENT

We emphasize the following points for decreasing the physical and biotic effects of infrastructure on high Arctic environments:

- Avoid areas of ice-rich soils. Areas with disturbed ice wedges showed the most pronounced plant diversity and compositional changes. It is likely that any operations that affect the ground surface will cause thermal changes to underlying wedge ice causing ground subsidence with long-term biotic effects. However, as the dominant recovery vegetation is likely to be thick, clonal wet-sedge cover, we recommend facilitating colonization in ice-wedge troughs as early as possible as this growth should insulate the ground to further subsidence. Stripping ice-rich permafrost of vegetation cover and not promoting recovery growth would likely leave these areas extraordinarily susceptible to further melt and disturbance (Shur & Jorgenson 2007).

- Keep impacts spatially confined: the disturbance we measured appears to be confined to the area of the airstrip, with very little adjacent effects. Other areas of high Arctic ground disturbance also show highly constrained impacts (Forbes, Ebersole & Strandberg 2001).
- Remove as little vegetation as possible. Given the abiotic changes and the creation of bare ground, there is danger of colonization by non-native species, for example from soil attached to industrial machinery transported from the south. We recommend thorough cleaning of incoming machinery, as the establishment of non-native species may act as further dispersal points to other nearby human disturbances or even to naturally bare ground (Kearns *et al.* 2015). Additionally, we recommend industry-assisted revegetation of disturbed ice-wedge troughs using native varieties of *Eriophorum* and *Carex* species – as they have been shown to be successful colonizers (Chapin & Chapin 1980), there is likely additional seed bank of *E. scheuchzeri* (Forbes 1993) already present, and success rates of revegetation in wet areas are relatively high (Forbes & Jefferies 1999). Chapin & Chapin (1980) showed that fertilization of adjacent, existing patches of vegetation next to the disturbance site could provide a local seed bank at a cost-effective level. While it is likely that there is already sufficient resident seed bank for colonization, recolonizers are unlikely to be the original *Salix* community because of the altered growing conditions (Cooper *et al.* 2004). Thus, while 'recovered' disturbed troughs will not resemble the original vegetation community, they would at least comprise natively derived species and help to prevent further thermal damage to the subsurface.

In the Arctic, it appears that early recolonizing communities of disturbed terrain are self-perpetuating and fairly stable over time in altered soil conditions (Forbes 1993, 1996; Forbes, Ebersole & Strandberg 2001). The distinct patches that have been created through landscape disturbance create wetlands in the high Arctic environment with novel biotic and abiotic feedbacks that persist over a long time-scale. As the mining development of the Fosheim Peninsula, and indeed much of the high Arctic, looks set to rapidly expand in the coming decades, it is imperative that managers take heed of the few historical precedents in the region. Both small- and large-scale disturbances from increased anthropogenic activity in the Arctic should be planned with great caution and foresight, keeping in mind the legacy we impart on the environment long after we have left.

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Data accessibility

Data on vegetation composition, soil chemistry and abiotic variables are available from the Dryad Digital Repository at doi: 10.5061/dryad.t0k5k (Becker & Pollard 2015).

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Figure S1. Historical photo of airfield disturbance taken in 1960.

Table S1. Species list and presence/absence at the four different microtopographies.

Table S2. PERMANOVA results testing differences in community structure.

Figure S2. Photographs of undisturbed troughs and disturbed troughs.

Table S3. ANOVA results testing differences in vegetation species richness and evenness of different microhabitats.

Figure S3. Soil chemistry variables measured at the four different microtopographies.

Table S4. ANOVA results testing differences in soil chemistry.

Table S5. ANOVA results testing differences in soil abiotic factors.

Table S6. ANOVA results testing differences in soil temperature (TDD and FDD).