Ecosystem Impacts of High Arctic permafrost disturbances

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GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

ABSTRACT
Active layer detachment slides located at Hot Weather Creek, Ellesmere Island, were studied during the growing season of 1994 and revisited during 2012 to determine the short- and long-term impacts on vegetation and ecosystem processes. Distinct vegetation communities exist in differently aged disturbances with unique species defining various zones and ages of disturbance. Zonal differences illustrate the varying responses of the ecosystem to disturbance and differing modes of recovery. Disturbances affect site soil characteristics over the long-term, exemplified through soil nutrients (specifically nitrate), soil moisture, and active layer depths measured during the 2012 sampling period.

RÉSUMÉ
Des détachements de couches actives situées à Hot Weather Creek sur l'ile d'Ellesmere furent étudiés en 1994 et revisités en 2012 durant la saison de croissance afin de déterminer l'impact à court et long terme des perturbations sur la végétation et le fonctionnement des écosystèmes. Des communautés végétales distinctes vivent dans des perturbations d'âges variés, dont la composition unique d'espèces associées à des stades de colonisation, définissent les zones et l'âge de la perturbation. Les différences mesurées à l'intérieur d'un même détachement de couche active illustrent le spectre de réponses des écosystèmes face aux perturbations, ainsi que les différents processus de régénération. Les résultats démontrent que les perturbations affectent les sols à long terme notamment par des changements dans la concentration des nutriments (surtout le nitrate), l'humidité du sol, ainsi que la profondeur de la couche active.

1 INTRODUCTION

Land surface disturbances are predicted to increase in frequency and extent with global climate change and increased ground temperatures (ACIA, 2005; Vincent et al., 2011). In the High Arctic, these disturbances commonly take the form of active layer detachment slides (ALDS). ALDS occur when the thawed (or active) layer breaks away from the underlying ice-rich permafrost resulting in a mass movement of soil and vegetation downslope. With predicted changes in the rates of occurrence of ALDS, it becomes essential to determine both the short- and long-term impacts of disturbance on the landscape and underlying processes.

The objectives of this study include 1) to determine the impact of permafrost disturbances, specifically ALDS, on tundra vegetation, across multiple temporal scales, using historical and modern data; 2) to contrast recovery among different modes of recovery (those subject to primary vs. secondary succession); and 3) to analyze environmental characteristics influencing vegetation recovery.

2 STUDY SITE

Research was conducted during 1994 and 2012 at Hot Weather Creek (79° 58' N, 84° 27' W), located on the Fosheim Peninsula, Ellesmere Island. The nearest weather station is located at Eureka, approximately 30 km west. The Fosheim Peninsula contains 140 vascular plants on uniform, weakly alkaline to neutral cryosols (Edlund et al., 1989) Geology of the region is comprised of sandstones of the Eureka Sound group (Bell, 1996). The marine limit is located at approximately 140 m above sea level; areas above the marine limit are dominated by bedrock and till and contain minimal vegetation. Hot Weather Creek (HWC) is located below the marine limit, and vegetation here is characterized as prostrate dwarf shrub tundra (Cannone et al., 2011). The dominant plant community at HWC is Salix-Dryas hummocky tundra, occurring across moderately drained sites as continuous communities and across drier polar desert areas as isolated patches (Edlund et al., 1989). Slope and valley bottoms are comprised of wet sedge communities.

Due to the presence of ice rich permafrost throughout this region and increased summer temperatures and precipitation over the past twenty years, active layer detachment activity is widespread at Hot Weather Creek. When the ice rich permafrost degrades these slides can transition into another form of disturbance, retrogressive thaw slumps (RTS) thus lengthening the duration of active disturbance activity and delaying landscape recovery and revegetation (Lewkowicz, 1990).

Ecosystem recovery was analyzed at multiple ALDS at Hot Weather Creek in 1994 (Desforges, 2000). Several (25%) of these originally studied ALDS had transitioned into active retrogressive thaw slumps when revisited in 2012. The ages of historical disturbances were determined using air photo analysis and past field sampling (Desforges, 2000); these include young, moderate, and old age categories (Table 1). These original sites were revisited and resampled during the 2012 summer season to determine the role of time in recovery processes. As a space for time substitution method is usually used to determine the impacts of disturbance over time, this method allows us to compare data collected over a twenty-year period and compare disturbances of varying ages across an additional time variable.

Desforges (2000) identified multiple vegetation classes associated with vegetation recovery of ALDS. The young disturbances are colonized by ruderal grasses and forbs (e.g. *Puccinellia, Braya* spp). This is followed by the mid to late sere of grass and forbs (moderate disturbances colonized by *Poa, Taraxacum, Oxyria*, *Melandrium, Potentilla* spp.) and the shrub grass forb vegetation class of old disturbances dominated by *Salix arctica*. The undisturbed and oldest disturbances are characterized by shrub and cushion plants dominated by *Dryas*, *Salix*, and *Cassiope* species.

Table 1: Age characteristics of ALDS, Hot Weather Creek

ALDs	Number	Age (1994)	Age(2012)
Young	3	6	24
Moderate	1	6-20	24-38
Old	3	20 +	38 +

Research on these disturbances (ALDS and RTS) has predominantly focused on geomorphological characteristics (Lewkowicz & Harris, 2005) and impacts on soil temperature, water quality, and soil nutrients (Lamoureux & Lafrenière, 2009, Lantz et al., 2009, Kokelj & Lewkowicz*,* 1998, Kokelj & Lewkowicz, 1999). Vegetation studies have been limited to one year of sampling and no analysis over time has been completed to date (Desforges, 2000; Cannone et al., 2011), thus returning to these previously studied ALDS allows us to re-evaluate vegetation recovery of these sites.

3 METHODS

3.1 Vegetation sampling (1994 and 2012)

ALDS were sampled during the 1994 and 2012 growing seasons. ALDS that transitioned into RTS (N=4) were omitted from this analysis and only sites sampled within both years are included. Within each disturbance, three transects across undisturbed and disturbed terrain were situated perpendicular to the slide direction (Figure 1). Separate transects were established to include the three zones found within ALDS; 1) the upper scar zone, from which material is removed, 2) the track zone, where material is transported and 3) the toe zone, located furthest downslope, where material is deposited and compressed. Transects were extended beyond the edge of the disturbance to allow for undisturbed plots to be located on both sides of the ALDS; these controls were placed at least 1 m away from the edge to prevent any influence of edge effects. Material is removed from the scar area therefore this area is characteristic of primary succession whereas material is deposited in the toe thereby initiating secondary succession. Plots were located using haphazard stratified sampling, with a trowel thrown every 2-3 m along each transect and plots established where the trowel fell. Percent cover of vascular plants, mosses, lichens, and litter was estimated using a 50 cm x 50 cm quadrat, subdivided into 5 cm x 5 cm sections. Vascular plants were identified to the species level, and total cover was estimated for mosses and lichens.

3.2 Comprehensive site characterization (2012 only)

3.2.1 Soil moisture and active layer depth

Soil moisture was measured using a HydroSense II Soil Water Time Domain Reflectometry (TDR) sensor with 12 cm rods weekly throughout July 2012 at all plots (consistent with vegetation plots). Following precipitation events, measurements were delayed for 24 hours. Active layer depth was measured by inserting a thin metal probe into the ground until the depth of permafrost is reached, was measured in conjunction with soil moisture measurements.

3.2.2 Soil nutrient availability

Ion exchange membranes (PRS Probes, Western Ag, Saskatoon, SK) were installed 28 June 2012 and retrieved 6 August 2012. Nutrient probes (N=48) were installed in select recovered active layer detachments (ALD1, ALD3, ALD4) throughout the scar, track, and toe with 4 probes placed across each zone. Control probes were placed adjacent to the disturbance scar, track, and toe locations (N=4). During 2013, nutrient probes were installed at one site, ALD 1, in the same areas as the previous year to determine inter-annual differences. Probes were installed on 28 June 2013 and retrieved on 26 July 2013. Nutrient availabilities (including Total N, NO3, NH4, Mg, Ca, and K) were calculated for each burial period in micrograms/10 cm2/burial length.

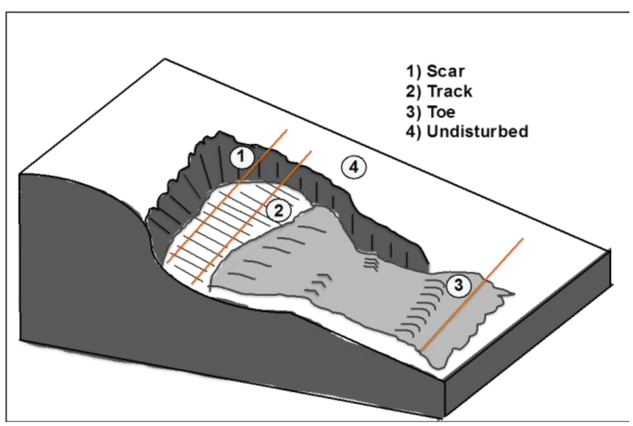

Figure 1: Schematic diagram with distinct zones of active layer detachment slide (scar, track, toe, and undisturbed) and corresponding transects used for vegetation and site sampling. Adapted from Desforges (2000).

3.3 Statistical analysis

3.3.1 Time Comparison

All disturbances were pooled based on age classification. To compare data from 1994 and 2012, the two extremes were analyzed, specifically age of disturbance (young and old) and mode of succession (primary succession in the scar vs. secondary succession in the toe). Multiple sites (4) were omitted as ALDS in 1994 had transitioned into RTS in 2012 and as these disturbances were active, vegetation was minimal inside the exposed mud slumps and difficult to access. Analysis was constrained to focus on active layer detachments slides, to allow for a comparison between the historical and current dataset.

3.3.2 Vegetation Composition

All data analysis and graphing was completed using R statistical language, Version 3.1.2 (R Core Team, 2014). Dissimilarity matrices were computed based on the Bray-Curtis distances method. Ordinations were plotted using the metaMDS function in the vegan package (version 2.2). Environmental vectors significant at the $\alpha = 0.05$ level are plotted on the ordination plots.

For the 2012 dataset, we used indicator species analysis (ISA) to identify vegetation found in each zone of disturbance and age. ISA combines specificity and fidelity to find species that are located in a single zone or group and are present at most of these sites, thereby being indicators of different groups of sites (Legendre and Legendre, 1998). ISA was determined using the Indval function proposed by Dufrene and Legendre (1997) using the labdsv package (version 1.6).

3.3.3 Total Vegetation Cover & Soil Characteristics

Total cover was computed based on individual values of species cover for the 1994 and 2012 datasets. Fixed effect 2-way analyses of variance (ANOVAs) were used to test for differences and interactions across all sites and levels of disturbance for total cover and nutrient concentrations. Soil moisture and active layer depth were compared using 1-way ANOVAs with grouping cluster as the variable incorporating disturbance classification, site age, and zone. Soil moisture measurements were aggregated to calculate an average soil moisture and variability throughout the season. Early season (late June) active layer depth and maximum active layer depth (early August) were compared across sites. Any datasets that did not meet statistical assumptions were log-transformed. Post hoc Tukey tests with Bonferroni correction were used to determine differences when significant.

4 RESULTS

4.1 Time Comparison

4.1.1 Vegetation Community Composition Across Time

Ordination analysis (NMDS) revealed compositional differences between disturbed and undisturbed plots (Figure 2). Significant differences in vegetation communities exist based on zone of disturbance (scar and toe), age of disturbance (young and old) and year (sampled in 1994 and 2012). Vectors represent factors that significantly differ in vegetation composition; age, year of data collection, zone, and disturbance level, were found to be significant (NMDS1=0.99, NMDS2=0.09, r^2=0.28, p<0.001). When these categories were examined individually, each were found to be significant, including year of data collection (NMDS1=-0.09, NMDS2=-0.99, r^2=0.04, p=0.009), age of disturbance (NMDS1=0.87, NMDS2=0.50, r^2=0.23, p<0.001), zone (NMDS1=0.43, NMDS2=-0.90, r^2=0.23, p<0.001), and disturbance level (NMDS1=0.34, NMDS2=-0.93, r^2=0.05, p=0.003). Additional vectors that were found to be significant were total bare ground (NMDS1=-0.96, NMDS2=-0.27, r^2=0.04, p=0.007) and total plant cover (NMDS1=0.91, NMDS2=0.42, r^2=0.18, p<0.001). Amount of total litter was found not to differ across all plots (NMDS1=0.70, NMDS2=0.72, r^2=0.0007, p=0.90).

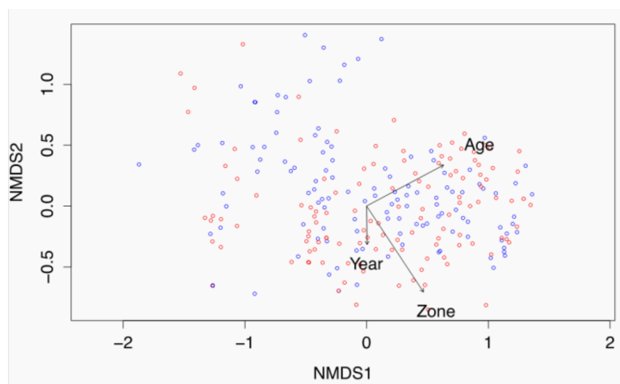

Figure 2: NMDS ordination of sites comparing 1994 and 2012 vegetation data (Year) from all ALDS (stress=0.16, k=2, nonmetric R^2=0.97, linear R^2=0.88). Red circles represent disturbed plots and blue represent undisturbed plots. Significant variables (α<0.05) are plotted as vectors (Age, Zone, and Year).

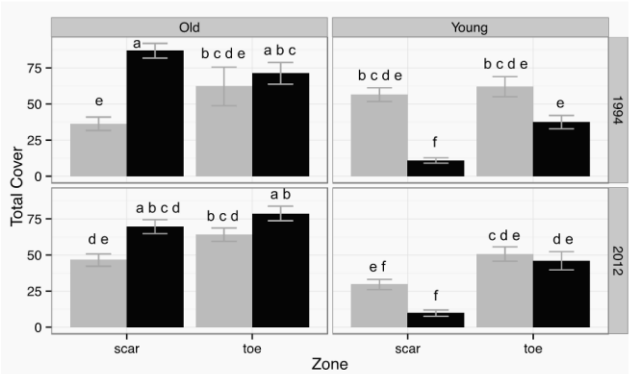

Figure 3: Total vegetation cover based on zone (scar and toe), age (young and old), and year (1994 and 2012). Different letters indicate significant differences. Grey bars represent undisturbed tundra and black bars represent disturbed tundra.

4.1.2 Total Vegetation Cover Across Time

Total cover was calculated within the scar and toe of ALDS and in undisturbed zones for 1994 and 2012 (Figure 3). Results from 2-way ANOVA indicate significant differences based on zone ($F_{250,1}$ = 35.68, p<0.001) and the interaction between zone and year ($F_{250,7}$ = 3.73, p<0.001). Within the oldest age category samples, cover estimates from both 1994 and 2012 indicate increased cover in disturbed zones (in both the scar and the toe). This differs from the youngest age category, with vegetation cover decreasing in the scar and toe compared to undisturbed tundra found in similar zones. Post hoc Tukey tests reveal vegetation cover in the scar of old disturbances was greater than controls in 1994, while cover was lower in the scar of young disturbances. In 2012, resampled sites still showed increased cover in old disturbances and decreased cover in young disturbances, however, these cover differences were not significant.

4.2 Community comparison of 2012 disturbances

Disturbances sampled in 2012 of all age categories (young, moderate, and old) and all zones (scar, track, toe, and corresponding controls) were compared using ordination analysis. NMDS revealed compositional differences between disturbed and undisturbed plots (Fig. 4). Significant differences in cover exist based on zone of disturbance ((NMDS1=0.99, NMDS2=0.13, r^2=0.04, p=0.016), age of disturbance ((NMDS1=0.98, NMDS2=-0.21, r^2=0.09, p<0.001) and whether the plot represented disturbed or undisturbed tundra (NMDS1=-0.42, NMDS2=-0.91, r^2=0.05, p=0.003).

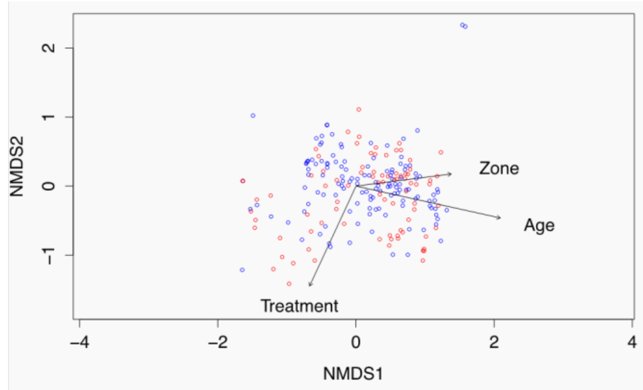

Figure 4: NMDS ordination of data collected in 2012 (stress=0.16, k=2, nonmetric R^2=0.97, linear R^2=0.89). Red circles represent disturbed plots and blue represent undisturbed plots. Additional age category (moderate) and zone (track) included in this analysis. Significant variables (α<0.05) are plotted as vectors (Age = Young/Moderate/Old, Zone=Scar/Track/Toe, and Treatment=Disturbed/Undisturbed).

Indicator species were found for disturbed and undisturbed areas. Within 2012 disturbances, in the youngest age category of disturbance, the scar and toe were found to have distinct indicator species (IS), *Puccinaella* spp., and *Potentila hyparctica*, respectively. Within the moderate age category, only the disturbed track and toe were found to have unique IS, *Pedicularis capitata* and *Carex rupestris*. In the old age category disturbed toe was characterized by *Stellaria longipes*, *Cassiope tetragona*, and *Alopecurus alpinus*. Only two undisturbed areas contained indicator species, *Erigeron compositus* next to the moderate scar and *Minuartia rubella* and *Lesquerella arctica* beside the moderate toe. The location of species across this slope and disturbance gradient is likely in response to microenvironmental conditions that arise following ALDS.

Table 1: Indicator Species Analysis (2012) data (Σ probabilities=8.701, ΣIV=4.23, # Significant IV = 11)

Species	Cluster*	Indicator Value	p value
Puccinellia spp.	2	0.1483	0.046
Potentilla hyparctica	6	0.1566	0.033
Erigeron compositus	7	0.2378	0.015
Pedicularis capitata	10	0.1789	0.032
Potentila vahliana	11	0.2150	0.006
Minuartia rubella	11	0.1346	0.041
Lesquerella arctica	11	0.1311	0.047
Carex rupestris	12	0.1385	0.034
Stellaria longipes	18	0.2365	0.005
Cassiope tetragona	18	0.1765	0.010
Alopecurus alpinus	18	0.1517	0.032

*Cluster codes as follows: 1) young scar undisturbed, 2) young scar disturbed, 3) young track undisturbed, 4) young track disturbed, 5) young toe undisturbed, 6) young toe disturbed, 7) moderate scar undisturbed, 8) moderate scar disturbed, 9) moderate track undisturbed, 10) moderate track disturbed, 11) moderate toe undisturbed, 12) moderate toe disturbed,

13) old scar undisturbed, 14) old scar disturbed, 15) old track undisturbed, 16) old track disturbed, 17) old toe undisturbed, 18) old toe disturbed.

4.3 Site characteristics of 2012 disturbances

4.3.1 Soil Moisture

One way ANOVA revealed differences in mean soil moisture based on group (see clusters listed below Table 1) ($F(17,217)=15.95$, $p<0.001$). Soil moisture was greatest in the scar area of young disturbances and differed from the undisturbed scar as revealed by post hoc Tukey tests. Disturbances of the moderate and old age category had lower mean soil moisture values, although disturbed and undisturbed areas had similar values. Deviation in soil moisture was analyzed through standard deviation of the mean soil moisture throughout the season ($F(17,217)=9.90$, $p<0.001$), and greater variability was found in the young disturbances, specifically within the scar and toe areas.

4.3.2 Active Layer Depth

Early season active layer depth differed based on cluster grouping, including disturbance, age, and zone ($F(17,210)=5.35$, $p<0.001$). Post hoc Tukey tests show the shallowest depth occurs in the disturbed scar of the youngest age category ($\mu=45.6\pm4.5$), however this is not significantly different from the corresponding undisturbed plots. The younger disturbed areas were shallower than older more recovered disturbances and undisturbed areas had deeper active layer depths than disturbed plots.

When the maximum active layer depth (measured at the end of the field season) was analyzed, differences between clusters were found ($F(17,210)=2.80$, $p<0.001$). Post hoc tests reveal the younger track of ALDS to be deeper ($\mu=88.2\pm10.3$) than corresponding undisturbed areas. The scar of the oldest disturbances contained the shallowest overall depth ($\mu=71.5\pm8.5$). No zonal differences were found between young and moderate disturbances.

The magnitude of thaw (calculated as the difference in thaw depth between early season and late season thaw) was also compared to determine if disturbance acts to impact seasonal thaw. No differences in thaw depths were found ($F(17,210)= 1.65$, $p=0.054$).

4.3.3 Soil Nutrients

A two-way ANOVA was used to determine differences based on location (scar, track, toe, control) and treatment (disturbed and undisturbed tundra) for each nutrient (NH_4^+, NO_3^-, Ca^{2+}, K^+, and Mg^{2+}) (Table 3). Undisturbed probes placed adjacent to scar, track, and toe areas were pooled as no significant differences were found in nutrient concentrations from each undisturbed set (undisturbed scar, undisturbed track, undisturbed toe).

Table 3: Statistical results of nutrient availability

Nutrient	F	p value
NO_3^-		
treatment	$F(1,42) = 31.939$	<0.001
zone	$F(4,42) = 12.303$	<0.001
NH_4^+		
treatment	$F(1,42) = 1.2136$	0.277
zone	$F(4,42) = 1.4222$	0.243
Ca^{2+}		
treatment	$F(1,42) = 0.5649$	0.456
zone	$F(4,42) = 2.5361$	0.0541
Mg^{2+}		
treatment	$F(1,42) = 8.4394$	0.0058
zone	$F(4,42) = 0.6657$	0.619
K^+		
treatment	$F(1,42) = 3.9948$	0.0521
zone	$F(4,42) = 0.5264$	0.717

4.3.4 Zonal Comparison

Data were pooled to determine if spatial differences exist within recovered ALDS (Table 3). Total N (calculated as the sum of NO_3^- and NH_4^+) differed significantly based on location within disturbed and undisturbed tundra (treatment) and based on location within the slide (zone) (see Table. 1 above). Post hoc Tukey tests revealed differences based on scar location, as Total N within the scar differed from nutrient concentrations in the toe, track, and undisturbed zones. When separated into component nutrients, NO_3 also differed based on location in the slide and treatment, and identical differences were found using post hoc tests. However, no significant differences were found in NH_4 based on treatment and zone, indicating that elevated Total N concentrations are due to elevated NO_3 values. No differences were found in the availability of Ca^{2+}. Mg^{2+} and K^+ concentrations differed between disturbed and undisturbed tundra. Variability also increased for K^+ and Mg^{2+} from disturbed areas.

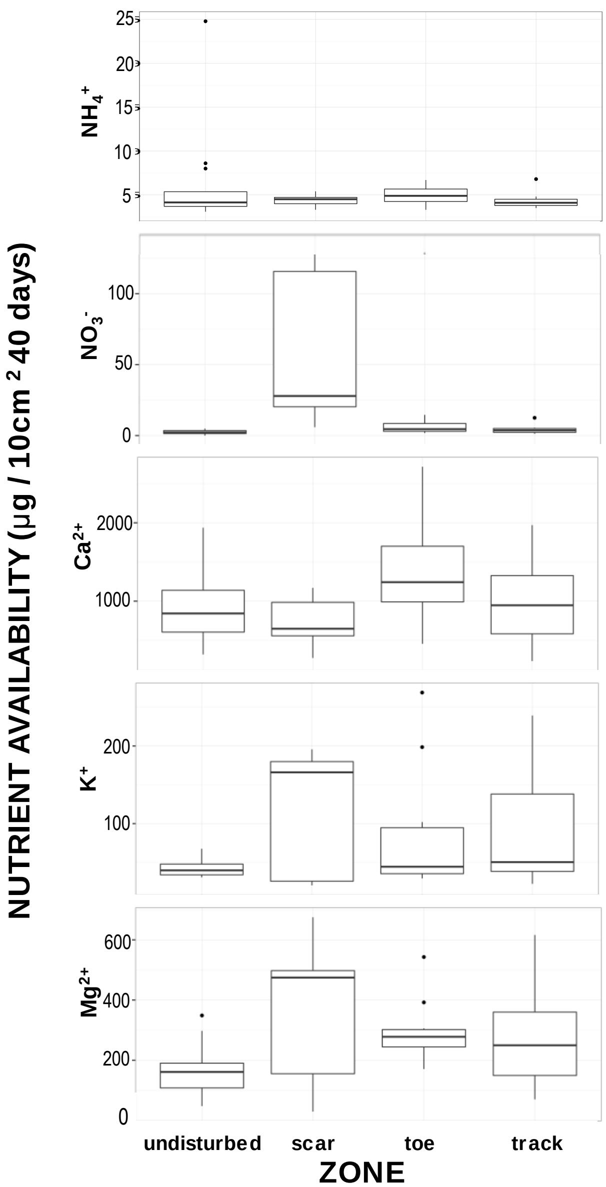

Figure 5: Soil nutrients across zones. Availabilities of all nutrients are in µg/ $10cm^2$ 40 days.

4.3.5 Inter-annual comparison of nutrient concentrations

Nutrient probes that were installed the following season (2013) at one ALDS (ALD1) for approximately the same burial period were compared with 2012 values from this ALDS. Values were consistent with those measured in 2012 and no significant differences in any nutrient concentrations were found. Significant differences in the disturbed zones were also found in 2013, supporting the 2012 results.

5 DISCUSSION

5.1 Time Comparison (1994 and 2012)

Vegetation found in disturbed zones of ALDS in 1994 differed from vegetation resampled nearly 20 years later. Despite the progression in site recovery, exemplified by reduced differences in total cover, unique species were still present within different zones and ages of disturbance. As these communities differ in composition from nearby areas, disturbances are acting to enhance spatial heterogeneity of the landscape. In addition, unique microclimatic conditions created by the distinct morphology that results following active layer detachment activity reinforces this spatial variation. Lantz et al. (2009) found that disturbances alter the microclimate, allowing for recolonization and altered community composition of areas impacted by disturbance.

Our follow-up analysis of vegetation recovery is supported by other disturbance work that find permafrost disturbances have long-lasting impacts on ecosystems as the ground thermal regime returns to pre-disturbance levels up to a century following disturbance, and thereby influencing vegetation due to these unique soil characteristics (Bartleman et al., 2001; Burn and Friele, 1989).

5.2 Microsite conditions

Nutrients, including NO3, Mg, and K were elevated in scar zones of the ALDS. Previous nutrient analysis from other permafrost disturbances reveal increased nutrient concentrations (Kokelj et al., 1999; Lantz et al., 2009; Ukraintseva, 2000; Ukraintseva & Leibman, 2007). In the Low Arctic, retrogressive thaw slumps were associated with elevated sulphate, calcium, and nitrate availability (Lantz et al., 2009). In Siberia, Ukraintseva (2000) found increased concentrations of K, Ca, Mg, Cl, S, and P in soil water that interact with root systems of plants in ALDS. Enrichment of soil, water and vegetation resulted in enhanced productivity enabling the spread of Salix species (Ukraintseva, 2008). Increased nitrogen and potassium concentrations have also been associated with increased soil fertility (Ukraintseva and Leibman, 2007). Across the Fosheim Peninsula, Kokelj and Lewkowicz (1999) noted the presence of salt efflorescence (surface salt accumulations) in areas impacted by ALDS and other forms of disturbance, as soluble materials previously stored in permafrost are released upon thaw. These concentrations can result in decreased plant growth and increased plant mortality (Srivastava and Jefferies, 1995). Despite the presence of graminoids able to tolerate highly saline soils (including *Puccinellia* spp.) these salinity levels found across the landscape are too elevated to be beneficial to salt tolerant species.

Based on our findings, as soil nutrients were measured only in select disturbances, and sites contain much variability in nutrient concentrations, potential long-term impacts of disturbance on soil characteristics may be muted.

5.3 Permafrost thaw implications

Due to the transition of sites from ALDS to RTS over the past 18 years (4 of the originally sampled 16 ALDS), 25% of sites that were characterized and sampled in 1994 were omitted from this analysis. As these sites are currently active, ecosystem recovery is delayed and recovery trajectories may deviate from those of ALDS due to the differing morphologies of these two forms of disturbance. Active RTS border Hot Weather Creek, therefore material that may have been deposited in the toe area of ALDS is actively removed from these RTS. Due to the large amount of material removed, succession would be similar to that in the scar of ALDS. Vegetation recovery would be predicted to follow the trajectory of recovery in the scar of ALDS. This determination of reactivated disturbances and transition to RTS was only possible due to the re-measurement of sites after 18 years.

Lewkowicz and Harris (2005) predict an increase in ALDS across the Fosheim Peninsula if increased temperatures occur in conjunction with low cloud cover. As ALDS transition into RTS, the implications of increased disturbance potential and positive climate feedbacks are significant. Organic carbon currently stored within the permafrost could be released, and with greater permafrost thaw, more carbon has the potential to be released and available for microbial decomposition (Schuur et al., 2008). As depth of permafrost thaw increases, so too does ecosystem respiration (Hicks Pries et al., 2013). ALDS and RTS are likely to modify the carbon balance in many Arctic ecosystems.

6 CONCLUSION

Vegetation was measured nearly 20 years after initial measurements on the recovery of vegetation following active layer detachment slide activity. Unique species are still present within different locations (scar and toe) reflecting differing modes of succession and different ages of disturbance. Even the oldest age category toe location, likely to have undergone the greatest degree of recovery contains differing vegetation from the surrounding undisturbed environment indicating compositional differences exist following 20 years of recovery. When species were pooled to evaluate the effect on total cover, differences were found in the initial 1994 dataset with decreased cover found in young disturbances in both the scar and toe zones, but increased cover found in the older disturbances. However, when these were analyzed within the 2012 data, similar trends in cover differences were not significant. Despite the effects on individual species, cover values are similar to the undisturbed tundra. When soil characteristics were analyzed, soil nutrients, including total nitrogen (based on NO_3) and Mg contain disturbance effects, with concentrations found in the scar zone elevated compared to other zones. Differences also exist in soil moisture measurements and active layer depths, indicating long-lasting impacts of disturbance on tundra ecosystems. Thus, if predicted increases in disturbances occur across the Fosheim Peninsula, their impacts will be widespread, with permafrost thaw impacting both ecosystem structure and ecosystem functioning.

ACKNOWLEDGEMENTS

Funding for this project was provided by ADAPT (a NSERC Discovery Frontiers project), ArcticNet, and the Northern Scientific Training Program. We thank Polar Continental Shelf Program for logistical support. Andrew Baylis assisted in the field.

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