Natural Recovery of Tundra Vegetation Following Exploration Drilling at Meliadine, Nunavut

Prepared for Agnico Eagle Mines Limited

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Preface

On June 1, 2018 Agnico Eagle Mines and the University of Saskatchewan were successful in receiving a Natural Sciences and Engineering Research Council (NSERC) Collaborative Research and Development grant. The grant entitled "Tundra Restoration: Niche construction in early successional plant-soil systems" will support on-site and laboratory research from June 2018 to June 2022. The primary objective of this research is to address Term and Condition no. 41 of the Project Certificate for the Meliadine site: *"Prior to the commencement of operations, the Proponent shall develop a progressive re-vegetation program for disturbed areas that are no longer required for operations, such program to incorporate measures for the use of test plots, reseeding and replanting of native plants as necessary."* Several additional scientific objectives that support this primary objective will also be examined: i) Characterization of initial and realized niches of biological soil crusts and tundra vascular plants across a chronosequence of naturally recolonized drilling waste dumps; ii) Characterization of initial and realized niches of actively restored biological soil crusts on disturbed substrates iii) Characterization of initial and realized niches of actively restored tundra vascular plants on disturbed substrates. In addition to the scientific work, the project will include the development of a youth education program and local community engagement in Rankin Inlet and Baker Lake, NU.

Below is a summary timeline for key project activities and deliverables. For a timeline including all activities and deliverables see Appendix A.

Milestone	Description of activities	Anticipated starting date	Anticipated completion date
Natural recolonization of drilling wastes	Study natural recolonization of drilling waste dumps 2-17 yrs old by biological soil crusts and vascular plants. Specific recommendations of species for restoration will be developed.	2018-06-01	2019-08-31
Active restoration with tundra surface layers	Transplanting of tundra plugs, shredded surface layers and biological soil crusts onto disturbed substrates. Specific recommendations of restoration practice and species for restoration will be developed.	2019-06-01	2021-08-31
Youth education program	Collaboratively develop and deliver an education program on-site for one week in 2019 and 2020 for youth from Rankin Inlet and Baker Lake, NU. The program will focus on arctic ecology, restoration and skills in environmental monitoring and research.	2019-01-31	2021-01-31
Community meetings	We will hold community meetings in Rankin Inlet and Baker Lake. Working with Agnico's community relations department we will identify key groups to host. Our research and restoration of tundra environments will be presented and discussed.	2019-06-01	2021-08-31
Website development	Creation of project website providing information to restoration practitioners and the public on general arctic ecology and restoration practice in the North, as well as key findings from the research.	2019-08-31	2022-06-01

Technical reports for Agnico Eagle	Detailed technical reports for AEM on the restoration techniques examined. Guidelines and standard operating procedures for on-going monitoring will be included. Preliminary report January 2021, final report January 2022. Yearly progress reports November 2018-2021.	2018-11-30	2022-06-01

Executive Summary

This technical report directly addresses the first of several objectives associated with a Natural Sciences and Engineering Research Council (NSERC) Collaborative and Research Development grant held by Agnico Eagle Mines and the University of Saskatchewan. The grant entitled "Tundra Restoration: Niche construction in early successional plant-soil systems" will support on-site and laboratory research from June 2018 to June 2022. The primary objective of this research is to address Term and Condition no. 41 of the Project Certificate for the Meliadine site: "*Prior to the commencement of operations, the Proponent shall develop a progressive re-vegetation program for disturbed areas that are no longer required for operations, such program to incorporate measures for the use of test plots, reseeding and replanting of native plants as necessary.*" The specific objective addressed in the following technical report is the characterization of initial and realized niches of biological soil crusts and tundra vascular plants across a chronosequence of naturally recolonized drilling waste dumps. This work was completed in summer 2018.

A total of 25 drilling waste sites were examined across a range of ecotypes including low-lying hummock-hollow complexes dominated by sedges, upland hummock-hollow complexes dominated by heath and upland lichen-heath often with frost boil features. Following delineation of each drilling waste site, a transect was placed along the long axis of the waste site and three survey plots ($1m^2$) were placed at the center of this transect. In addition, at each site a control transect was placed at least 10 m from the edge of the drilling waste and three adjacent 1 m^2 plots were placed in undisturbed vegetation of the same type, slope and aspect as the disturbed area. The percent cover of all vegetation species present was estimated by eye and the drilling waste and organic matter depth was measured in the center of each plot.

We found that natural revegetation of drilling wastes is occurring at the Meliadine site. The community composition between drilling wastes and the paired undisturbed tundra was similar 20-25 years post disturbance and species richness recovered within 6 years. Due to the different life history characteristics of tundra plants, individual species responses to disturbance were observed. While sedges and mosses may recover more rapidly on these drilling wastes, dwarf shrubs and lichens may require longer to recover. These trends in natural recovery are important for guiding future restoration efforts and techniques. Specifically, targeting sedge and moss species for transplanting and/or seeding of disturbed substrates may be a highly effective strategy for initiating the development of early successional tundra communities.

Based on our findings we provide the following suggestions to improve and/or maintain the relatively rapid natural revegetation of the drilling wastes: i) Placement of drilling wastes on the landscape that allow for remnant patches or islands of intact tundra throughout the disturbed area; ii) Apply drilling wastes in thin layers to allow for vegetative establishment; and iii) Promote establishment of bryophyte communities in the early stages of revegetation to support long-term ecosystem recovery.

Given the findings of this study we suggest that active restoration of the drilling wastes is likely not required for the recovery of the tundra plant communities, if the timeline for recovery is ~20 years. Therefore, in our on-going work to develop tundra restoration techniques, we suggest developing active restoration trials at other disturbed areas on the Meliadine site.

Drilling Waste Site Description

Ecotypes

A total of 25 drilling waste sites were examined across a range of ecotypes including low-lying hummock-hollow complexes dominated by sedges, upland hummock-hollow complexes dominated by heath and upland lichen-heath often with frost boil features. Low-lying hummock-hollow complexes dominated by sedges were characterized by high soil moisture, often with standing water surrounding hummock-hollow complexes of approximately 30 cm in height. The primary vegetation found in this ecotype was *Dryas integrifolia*, *Carex aquatilis*, and *Scorpidium scorpioides*. Upland hummock-hollow complexes were similar in size to low-lying complexes, however due to a high landscape position had drier soil conditions and were dominated by *Rhododendron lapponicum, Loiseleuria procumbens, Cassiope tetragona,* and species of *Cetraria* lichen. The upland heath ecotype were typically associated with upper slope locations and well developed frost boil features. The primary vegetation in the upland heath ecotype was *Alectoria ochroleuca*, *Cassiope tetragona, Tomentupnum nitens,* and species of *Cetraria* lichen.

Drilling waste sites were grouped by time since drilling and included sites created in 1993, 1997-1998, 2008, 2012-2013 and 2017 (n=5 per age group) (Figure 1). Of the sites surveyed, 5 were low-lying sedge, 9 upland heath, 7 transitional between low-lying sedge and upland heath, and 4 lichen-heath ecotypes (Figures 2 and 3, Table 1). Ecotypes were not equally represented across age categories because drilling tended to be localized within the landscape for a given year. Older sites (1993, 1997-1998) occurred more frequently in low-lying sedge and sedge-heath transitions, while four of the five 2017 sites were in lichen-heath tundra. Due to the nature of drilling, some sites we sampled were spatially clustered together (i.e. 2008 and 2017 sites).

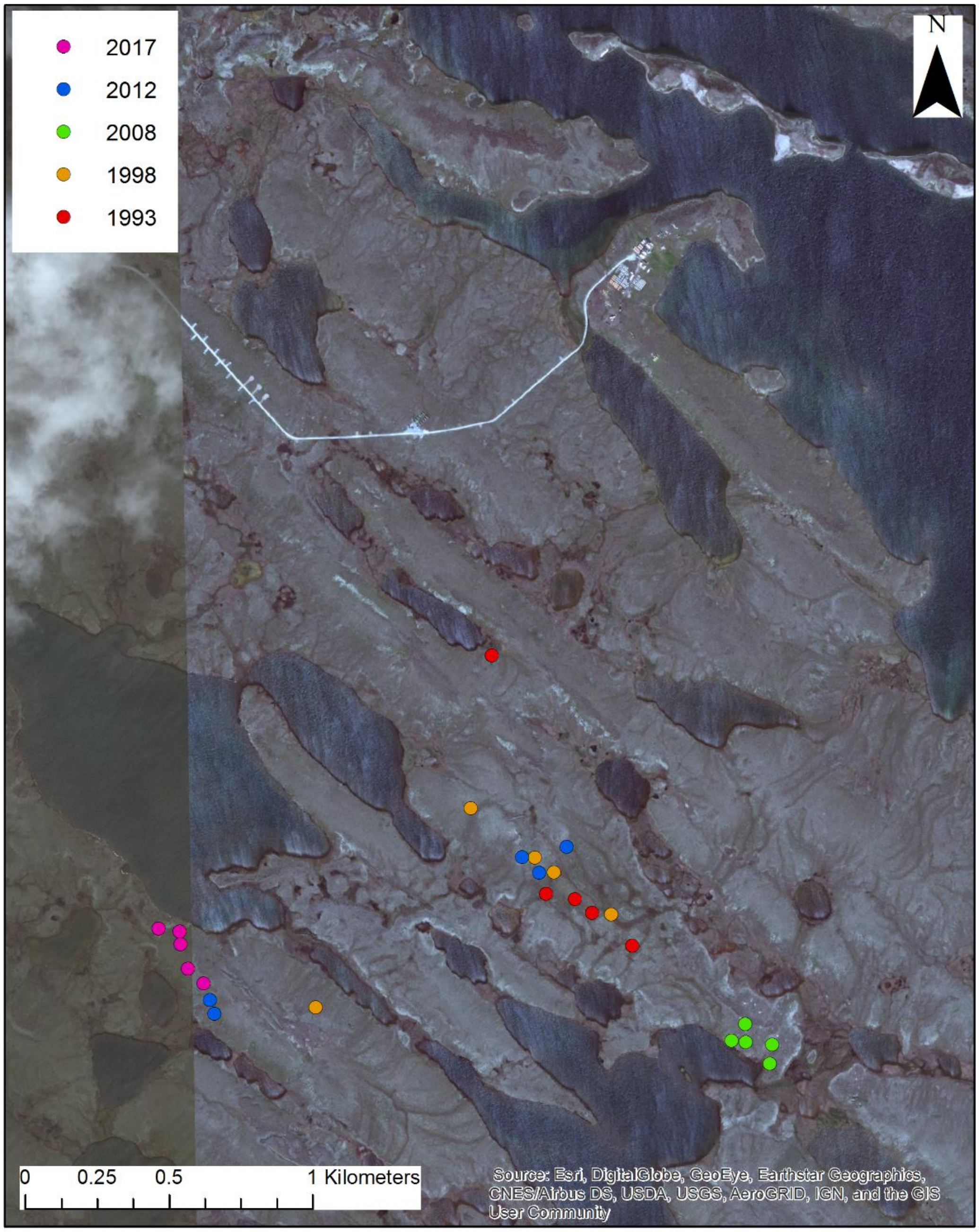

Figure 1. Map of drilling waste areas sampled in 2018. The year of drilling is given for each of the sites surveyed. The Meliadine site is shown for reference and all drilling waste sites were outside of the mine footprint.

Table 1. Drilling waste areas surveyed for natural revegetation. Site name, location, year and ecotype of each area surveyed is included. Ecotypes are described as low-lying sedge hummock-hollow (SH), upland heath hummock-hollow (HH) and upland lichen-heath (LH). Some drilling waste areas were in transitional areas between ecotypes (SH/HH).

Site	Location (UTM)	Year	Ecotype
W93-29	15V 0541749 6986813	1993	SH
W93-30	15V 0541809 6967640	1993	SH
W93-32	15V 0541948 6986649	1993	SH
W93-40	15V 0541439 6987661	1993	SH/HH
W93-44	15V 0541647 6986830	1993	SH
M97-155	15V 0540844 6986435	1997	HH
M98-230	15V 0541609 6986957	1998	HH
M98-242	15V 0541675 6986906	1998	SH/HH
M98-243	15V 0541385 6987129	1998	SH/HH
M98-244	15V 0541874 6986759	1998	SH
M08-729	15V 0542342 6986377	2008	HH
M08-734	15V 0542295 6986320	2008	SH/HH
M08-735	15V 0542344 6986314	2008	SH/HH
M08-740	15V 0542435 6986305	2008	HH
M08-741	15V 0542427 6986240	2008	HH
M12-1528	15V 0541565 6986959	2012	HH
M12-1860	15V 0541625 6986905	2012	HH
M12-1863	15V 0541720 6986994	2012	HH
M13-1948	15V 0540492 6986413	2012	SH/HH
GT13-71	15V 0540477 6986460	2013	SH/HH
M17-2394	15V 0540298 6986710	2017	LH
M17-2395	15V 0540375 6986656	2017	LH
M17-2396	15V 0540500 6986571	2017	LH
M17-2398	15V 0540455 6986519	2017	LH
M17-2415	15V 0540371 6986700	2017	HH

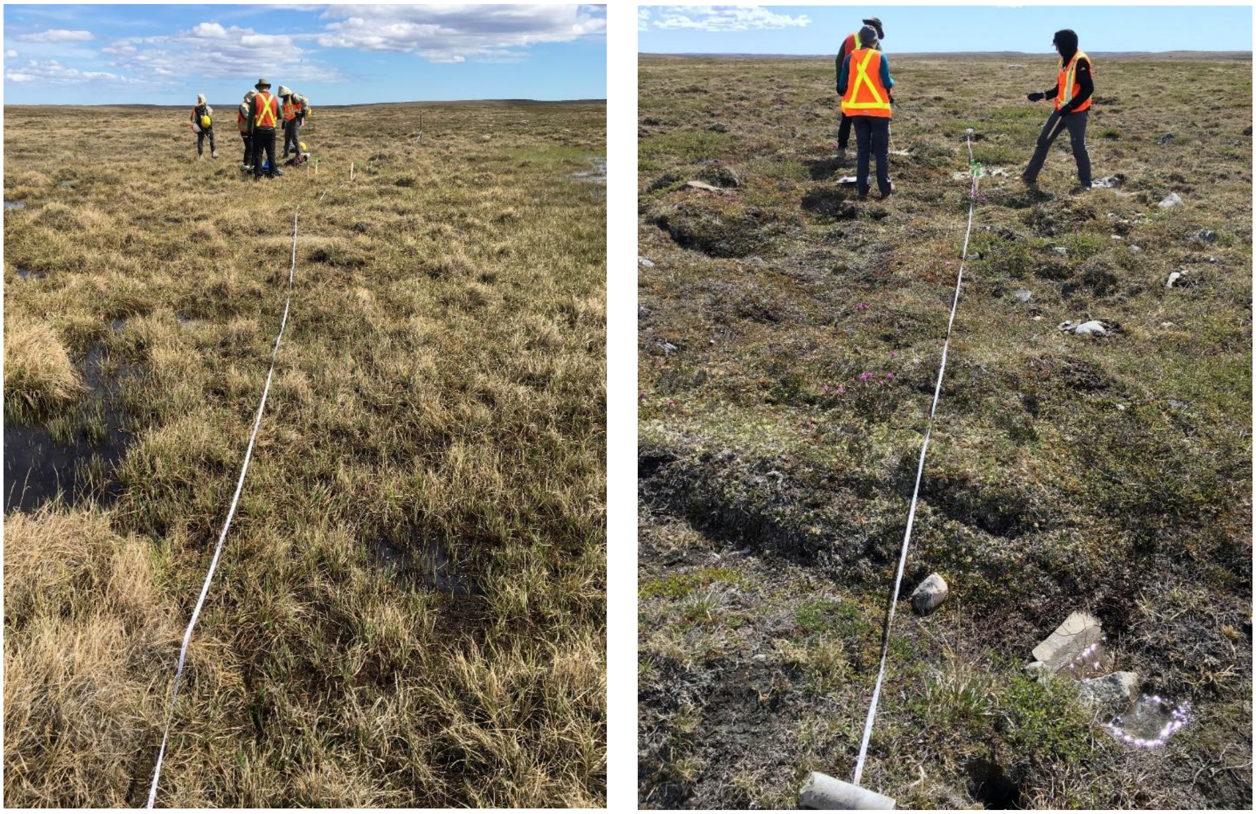

Figure 2. Low-lying sedge hummock-hollow (M93-30) (left) and upland heath hummock-hollow (M12-1860) (right).


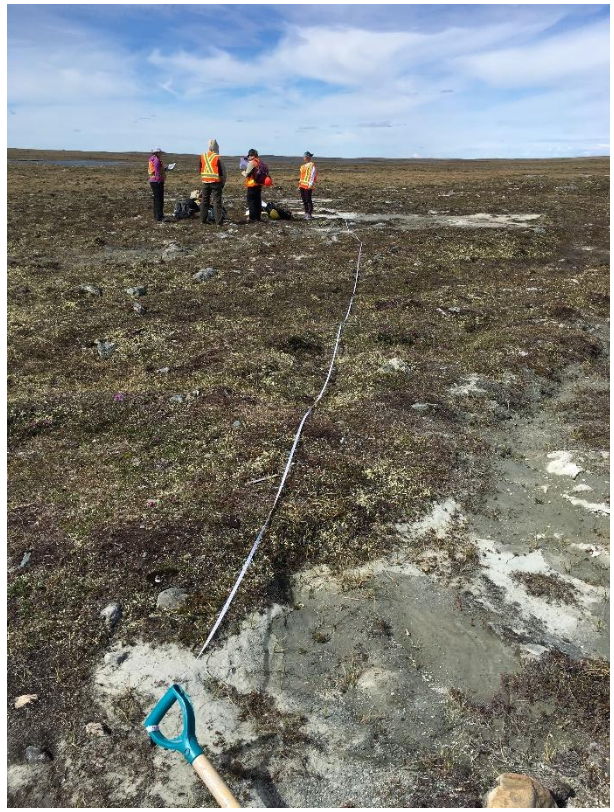

Figure 3. Transitional form low-lying sedge hummock-hollow to upland heath (M08-735) (left) and upland lichen heath (M17-2396) (right).

Delineation of Drilling Waste Sites

The approximate area of each drilling waste site was delineated by determining the extent of drilling waste at each location. The presence of drilling waste was either observed on the surface or below the surface by digging up to ~15 cm in depth. The average size of the drilling waste sites was 21 m x 9 m or 189 m^2. The largest drilling waste area sampled was from 1993 (W93-32) with an area of 1472 m^2. On average the 2008 drilling waste sites surveyed had the smallest area (77 m^2). In general, older drilling waste sites were covered with more vegetation and at times were difficult to locate. However, even at sites created in 1993 small patches of drilling waste were present at the surface (Figure 4). Newer drilling waste sites (i.e. 1-5 years old) generally had large patches of waste visible at the surface (Figure 5).

Figure 4. Small pockets of drilling waste evident at the surface of older sites (Left M93-30, Above M93-40).

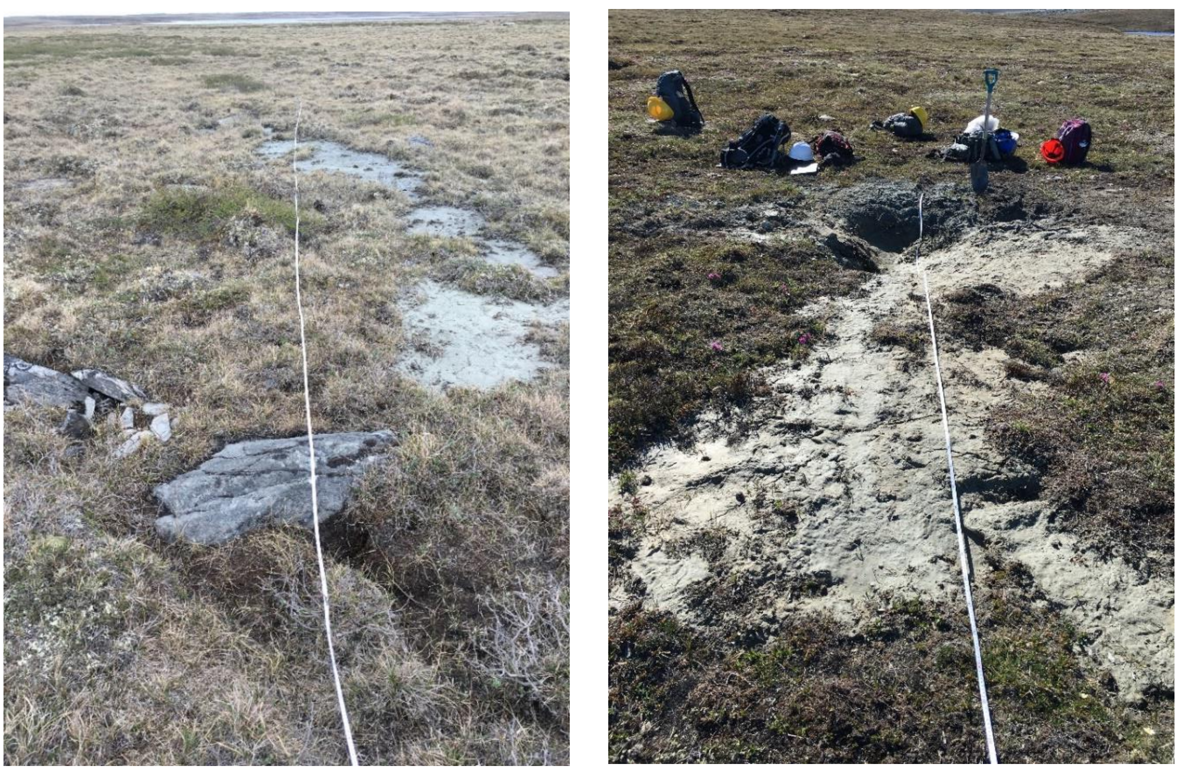

Figure 5. Larger patches of drilling waste evident at the surface on newer drilling sites (left M12-1863; right M17-2398).

Sampling Design

Following delineation of each drilling waste site (see description above), a transect was placed along the long axis of the waste site and three survey plots were placed at the center of this transect (Figure 6). The three plots were each 1 m^2 and were placed immediately adjacent to one another. In each plot percent cover was estimated by eye for all species present. Following completion of the vegetation survey, a soil/drilling waste sample was taken in the center of each plot and the depth of both drilling waste and organic matter were measured.

At each drilling waste site a control transect was placed at least 10 m from the edge of the drilling waste. Along the transect three adjacent 1 m^2 plots were placed in undisturbed vegetation of the same type, slope and aspect as the disturbed area. In control plots, percent cover was estimated by eye for all species present and a soil sample was taken in the center of each plot to determine the depth of the organic matter. For all statistical analyses the average across the three plots either on the drilling wastes or in the control plots was used for each site.

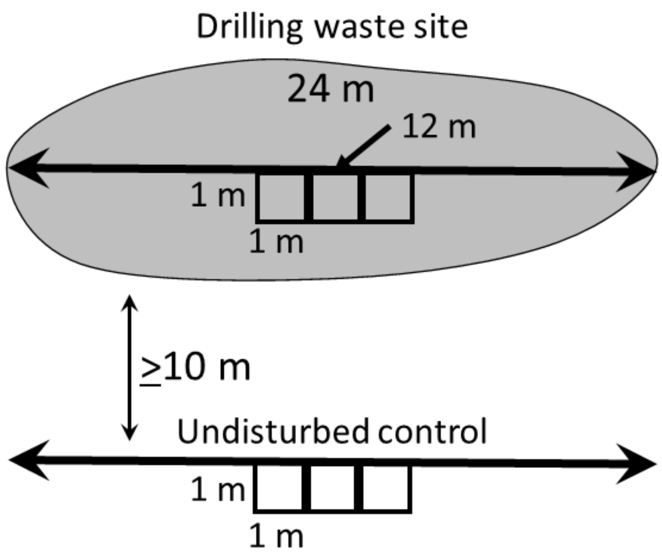

Figure 6. Sampling design at each drilling waste site. Three 1 m^2 plots were placed directly adjacent to one another at the center of the long axis of the delineated drilling waste area (ex. at a drilling waste area 24 m long, the center sampling plot would be placed from 11.5-12.5 m). At each site an undisturbed control transect was placed at least 10 m from the edge of the drilling wastes and 3 control plots (1m^2 each) were placed in undisturbed vegetation.

Vegetation Community Recovery

Community-level Differences

Recovery of the tundra vegetation at the drilling waste sites was examined through comparison of vegetation in disturbed and undisturbed survey plots at each site, as well as, examination of vegetative recovery over time (i.e. across time since disturbance). Community differences between drilling wastes and undisturbed controls over time were explored using non-metric multidimensional scaling ordination (NMDS). NMDS provides an ordination based on a distance or dissimilarity matrix, therefore objects that are ordinated closer to one another are more similar than those that are far apart (McCune and Grace, 2002). Overlap between drilling sites from 1993 and 1998 and their respective controls were evident (i.e. overlapping black and red squares and circles) suggesting that 20-25 years following disturbance the plant communities on drilling wastes are similar to undisturbed tundra (Figure 7). More recently disturbed sites from 2008, 2012 and 2017 had distinct communities (i.e. black and red triangles, crosses and x's are separated along the axes) suggesting that >10 years is required for disturbed tundra communities to naturally recover.

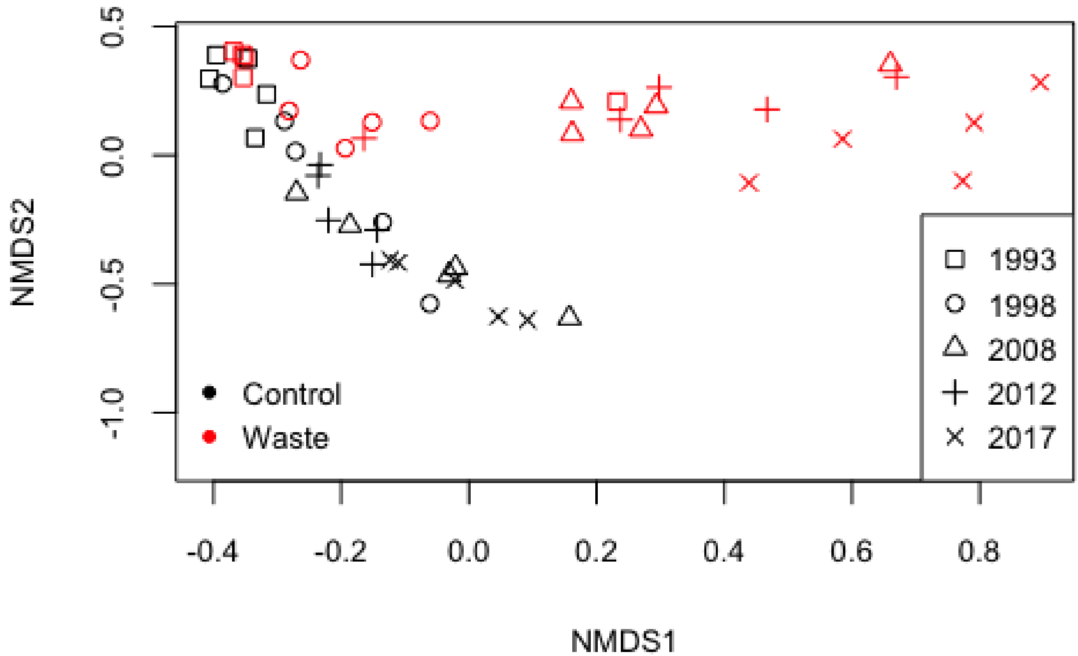

Figure 7. Non-metric multidimensional scaling ordination of species percent cover data on drilling wastes (red) and undisturbed control sites (black) in the disturbance years of 1993 (squares), 1998 (circles), 2008 (triangles), 2012 (crosses) and 2017 (x's). A stress value of $\leq$ 0.05 indicates a good fit. The stress value for the above ordination was 0.047.

To test for the effect of drilling wastes on community composition over time a PERMANOVA with Euclidean distances was used (Okasanen et al., 2015). PERMANOVA is a non-parametric multivariate analysis of variance that uses distance matrices. Treatment (i.e. drilling waste or control), year (i.e. 1993, 1998, 2008, 2012, 2017) and the interaction of treatment and year were fixed effects in the analysis and species cover was the response. All fixed effects were significantly different indicating that the plant communities are different between drilling wastes and control sites, as well as with time since disturbance ($p < 0.05$). A significant interaction between treatment and year is consistent with the NMDS since we observed that plant communities at older sites (1993, 1998) were similar between the drilling waste and control sites, but more recently disturbed communities were not.

Species Richness

Species richness was compared between the disturbed drilling wastes and the undisturbed control plots for each year included in the study. There were significant differences in species richness over time (df=4, F=2.96, p=0.03), between drilling waste and undisturbed controls (df=1, F=19.763 p <0.001), and the interaction between time and drilling waste/control (df=4, F=3.24, p=0.02). Sites disturbed in 2017 had significantly lower species richness compared to their respective controls (p <0.001), however, there were no significant differences in species richness between disturbed and undisturbed plots for sites from 1993, 1998, 2008 and 2012 (Figure 8). Natural recovery of the tundra ecosystem results in similar species richness within 6 years. This trend is encouraging as it suggests that species richness can recover quickly and similar numbers of species are able to colonize the disturbed area. However, individual species may still be excluded on these recovering drilling wastes due to differences in the life history traits (i.e. growth form, reproduction and growth rate) of arctic vegetation.

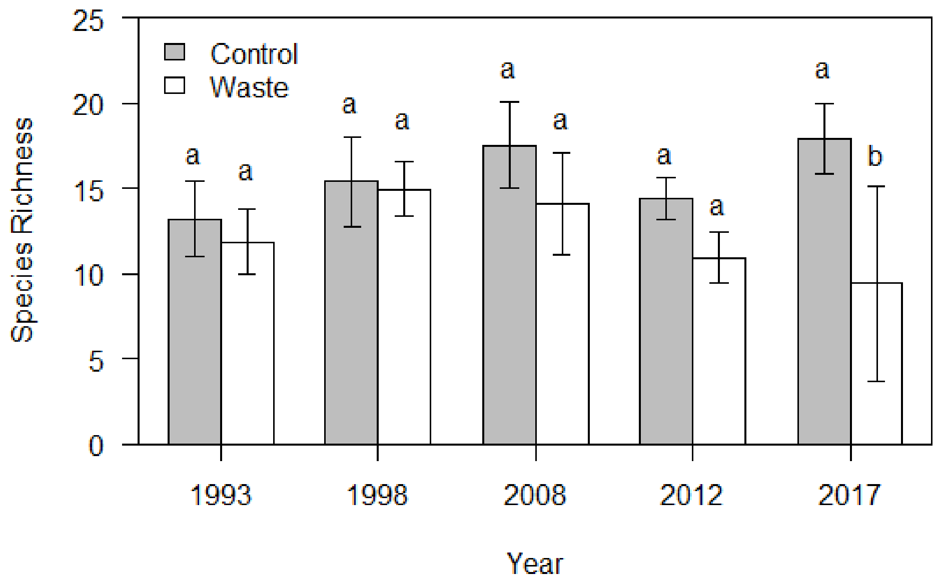

Figure 8. Species richness of drilling wastes and undisturbed control plots in different disturbance years. Both treatment (drilling waste and control) and year (1993, 1998, 2008, 2012, 2017) were significantly different (ANOVA, p<0.0f). Different letters represent significant differences (p <0.05) between control and waste sites within each year from a Tukey HSD post-hoc test. Bars present means with standard deviation (n=5).

Individual Species Response

Delayed dwarf shrub establishment was observed in recently disturbed sites, with the three most abundant ericaceous dwarf shrubs (*Cassiope tetragona, Dryas integrifolia* and *Loiseleuria procumbens*) having lower cover 1-2 years following disturbance (Table 2). Although there was variability across years since disturbance, in general, low-lying shrub cover increased over time with similar dwarf shrub cover present following 20 years of natural recovery.

Table 2. Difference in the percent cover of species between the drilling waste and paired undisturbed control plots. Values are the average % differences with standard error across all sites within a given year and only species with >5% differences in at least one year are included. Negative values indicate lower cover on the drilling wastes compared with the control and positive values indicate higher cover on the drilling waste compared to the control.

Year	Difference in Species percent cover (average % difference)				
	Dwarf Shrubs			**Sedge**	
	Cassiope tetragona	*Dryas integrifolia*	*Loiseleuria procumbens*	*Carex aquatilis*	
2017	**-9.0 (3.4)**	-4.3 (1.7)	-1.2 (1.2)	**8.6 (0.8)**	
2012	**5.3 (1.8)**	-2.4 (1.6)	0 (0)	1.5 (0.7)	
2008	1.6 (1.0)	2.9 (1.4)	**-9.6 (4.6)**	-0.7 (1.4)	
1998	4.1 (3.7)	**8.4 (3.8)**	0 (0)	-0.3 (3.0)	
1993	-0.6 (0.5)	-1.3 (2.4)	-1.2 (0)	0 (4.5)	
	Mosses		**Lichens**		
	Bryum spp.	*Scorpidium scorpioides*	*Cetraria* sp.	*Alectoria ochroleuca*	Fruticose Lichen
2017	-1.3 (1.2)	-0.3 (0.3)	**-20 (7.7)**	**-6.3 (1.3)**	**-8.7 (4.2)**
2012	4.1 (4.3)	-0.1 (0.1)	**-7.2 (3.1)**	0 (0.6)	-0.4 (0.4)
2008	**8.3 (2.3)**	0 (0)	**-14 (4.7)**	**-7.7 (3.0)**	**-4.1 (0.8)**
1998	**5.3 (2.9)**	-0.3 (0.2)	**-6.4 (3.2)**	-2.2 (1.4)	-1.9 (1.7)
1993	0.9 (1.5)	**-13 (5.4)**	-1.5 (1.1)	0.1 (0.1)	-0.9 (0.4)

Higher cover of *Carex aquatalis* in the early years of recovery are not surprising since sedges can often rapidly establish on disturbed arctic sites. Previous revegetation studies from Alaskan tundra found that native sedges established on disturbed sites in 5-10 year and had an aboveground biomass equal to undisturbed tundra (Chapin and Chapin, 1980). Sedges are often more dominant in lower-lying landscape positions in tundra ecosystems. Higher sedge cover on drilling wastes were observed only in 2012 and 2017. The 2012 sites were located in sedge (n=2) or heath (n=3) dominated hummock-hollow complexes, whereas, 2017 sites were in heath dominated hummock-hollow (n=1) and lichen heath (N=4) ecotypes. Therefore, sedge establishment of disturbed substrates may be occurring naturally across ecotypes indicating that these species could be useful for active restoration efforts.

One to two years following disturbance both mosses and lichens had a lower cover on the drilling wastes than the undisturbed controls. However, some moss species, such as *Bryum* spp. appear to recover quickly and establish at higher percentages on drilling wastes than the undisturbed tundra. *Bryum* sp. are acrocarpous, or carpet forming, are tolerant of high levels of solar radiation and are known to establish on disturbed substrates, especially slightly alkaline substrates (McKnight et al., 2013). Other moss species, such as *Scorpidium scorpioides*, have lower establishment on the disturbed substrates. *S. scorpioides* are pleurocarpous, or branched, and tend to be found in moist depressions in the landscape. In addition, saline conditions are known to inhibit or prevent growth of S. *scorpioides* (Vitt et al., 1993). Salinity associated with the drilling waste materials may be inhibiting the establishment of *S. scorpioides* over time. Lichen cover was lower across almost all ages of drilling wastes which is not surprising as lichens are commonly regarded as slow-growing (Werner, 1990; Seminara et al., 2018). Despite the lower percent cover of lichens on the drilling wastes there was a clear trend of increasing cover over time. This is exemplified by *Cetraria* sp. that had 20% less cover on the drilling wastes 1-2 years following disturbed but only 1.5% less cover 25 years following disturbance.

Sedges and mosses may be important early colonizers and appear to establish relatively rapidly under natural recolonization. Dwarf shrubs and lichens are likely to require more time for natural recolonization and these growth forms may require active restoration efforts if shorter revegetation timelines (i.e. < 20 years) are required.

Presence/absence of plant species had similar trends to those observed for the percent cover differences (Table 3). Investigating presence/absence data is critical to understanding specific species response, because it reveals species that could be excluded from the disturbed sites. Dwarf shrubs (*Cassiope tetragona* and *Dryas integrifolia)* including *Salix* spp. were absent from 60-80% of recently disturbed drilling waste sites (i.e. 2012, 2017) (Table 3). Similarly, several moss and lichen species were absent from 60-100% of drilling waste sites that were disturbed within the last 10 years. As discussed above the slow-growing nature of these species likely accounts for the slow rates of colonization. It also appears that there may be some *Carex* spp. that are absent from the drilling wastes even after 25 years of natural recovery.

Table 3. Species presence/absence on the drilling wastes compared with paired undisturbed control plots. Negative values represent the total percentage of sites where a species was present in the paired control plots but not on the drilling waste. Positive values represent the total percentage of sites where a species was present on the drilling waste but not the paired control plots. All values are expressed as a percentage of sites where a species was present/absent (i.e. x/5*100). Only species where presence/absence differences were found at > 2 sites (>40%) are included.

Year	Presence/absence of species on drilling wastes vs. paired controls (% of sites)						
	Shrubs	**Dwarf Shrubs**				**Sedge**	**Forb**
	Betula glandulosa	*Cassiope tetragona*	*Dryas integrifolia*	*Salix spp.*	*Salix reticulata*	*Carex spp.*	*Pedicularis sp.*
2017	0	**-80**	**-80**	20	-20	-20	0
2012	20	**-60**	0	**-60**	**-80**	0	0
2008	0	0	40	0	-20	0	-20
1998	**60**	-40	0	40	-40	-20	**60**
1993	0	-40	20	0	40	**-60**	-40
	Mosses		**Lichens**				
	Tomenthypnum nitens	*Distichium spp.*	*Alectoria ochroleuca*	*Dactylina arctica*	*Thamnolia spp.*	*Xanthoparmelia spp.*	
2017	**-60**	-40	0	**-100**	**-60**	**-60**	
2012	**-60**	-40	-20	-20	-40	-20	
2008	**-60**	**-60**	**-80**	**-60**	**-80**	-20	
1998	0	0	-40	-40	20	-20	
1993	-20	20	0	-0	-20	-20	

Only two species were found to occur on the majority of drilling waste sites in comparison to the paired control plots: *Betula glandulosa and Pedicularis sp* (Table 3). Both species were found on 60% of the drilling waste at sites disturbed in 1998, and *B. glandulosa* was also found on 20% of the drilling waste sites in 2012. It is possible that both of these species benefit from the exposed substrate and high light conditions on the drilling waste surfaces. A survey of more sites across the landscape is needed to support these initial results, but it is clear that there are species that may be excluded from the drilling wastes and others that may benefit from the disturbance.

Overall tundra disturbed by the deposition of drilling wastes at the Meliadine site appears to recover relatively rapidly (i.e. within 20 years) without any active restoration. The community composition between drilling wastes and the paired undisturbed tundra was similar 20-25 years post disturbance and species richness recovered within 6 years. Due to the different life history characteristics of tundra plants, individual species responses to disturbance were observed. While sedges and mosses may recover more rapidly on these drilling wastes, dwarf shrubs and lichens may require longer to recover. These trends in natural recovery are important for guiding future restoration efforts and techniques. Specifically, targeting sedge and moss species for transplanting and/or seeding of disturbed substrates may be a highly effective strategy for initiating the development of early successional tundra communities.

Invasive Species

We examined 25 drilling wastes sites ranging in age from 1-25 years across the landscape at Meliadine, NU (Figure 1). At each of these sites we surveyed all species present in six $1m^2$ plots (3 on drilling wastes, 3 in undisturbed tundra). Within these 150 survey plots no invasive species were detected. In addition, no invasive species were noted at any other location on site, however, no systematic survey was conducted.

The University of Saskatchewan will conduct invasive plant surveys once a year during the summers of 2019, 2020, and 2021. We will provide and implement "*protocols for reducing Project-related effects to plant populations and communities, primarily through the mitigation and management of invasive species, and includes both environmental and follow-up monitoring"* as required by the Project Certificate (No.006, Condition 37) for the Meliadine site. These surveys will allow for early detection of any non-native invasive species present on the Meliadine site and provide the distribution and abundance of any invasive species found. A targeted monitoring approach, which focuses on high probability sites of initial invasive species establishment will be used.

Invasive plant monitoring will follow the survey protocol outlined by Oldham 2006 for exotic plants along Northwest Territories highways. Our survey study area will include the footprint of the Meliadine mine, as well as, the main access road from Rankin to the Meliadine site. Road surveys will consist of driving at a low speed (30km/hr on the road into site, and posted speed limits within the mine footprint) along all roadways in the study area. During road surveys, we will be looking for any invasive plants. All roads will be driven twice, to ensure both roadsides are surveyed.

On the main access road, we will stop every 2km for an informal roadside walking survey. At each informal roadside survey, we will record latitude and longitude, walk 50 meters along both sides of the road and record if any invasive species are encountered (location, pictures). Within the mine footprint, areas of high likelihood of invasive species colonization, such as intersections, will be surveyed through formal roadside surveys. At each formal roadside survey location, we will record the latitude and longitude, describe the local habitat with reference to native species nearby, and walk 50m in all directions looking for invasive species. Additional locations with a high likelihood of invasive species colonization within the mine footprint, such as the exploration camp and main camp, will also be surveyed by the formal approach with a focus on the perimeter of the disturbed area. We will consult with the AEM environment team for other targeted locations (storage buildings, gravel pits) while ensuring we are only conducting surveys in safe areas clear of mining related activity.

Based on a 2010 report from the Canadian Endangered Species Conservation Council, there are 14 non-native plant species that have been recorded in Nunavut (Table 4). While looking for species previously recorded as invasive in Nunavut, we will take samples of any plants we cannot identify in the field to confirm their identification.

Table 4. Non-native invasive plant species identified by the Canadian Endangered Species Conservation Council that have been found in Nunavut.

Scientific name	**Common name**
Carum carvi	Wild Caraway
Taraxacum officinale	Common Dandelion
Sonchus arvensis	Field Sow Thistle
Leucanthemum vulgare	Oxeye Daisy
Thlaspi arvense	Field Pennycress
Capsella bursa-pastoris	Shepherd's Purse
Barbarea vulgaris	Yellow Rocket
Amaranthus retroflexus	Green Amaranth
Hordeum vulgare	Common Barley
Puccinellia distans	Spreading Alkali Grass
Vicia cracca	Tufted Vetch
Papaver somniferum	Opium Poppy
Plantago major	Common Plantain
Polygonum aviculare	Prostrate Knotweed

Colonization of Drilling Wastes

Bryophytes played an important role in the initial and early colonization of drilling wastes across the landscape. Moss species, particularly *Bryum* spp. were found on 88% of the drilling waste sites and were only absent at three sites all of which were disturbed in 2017. In addition, *Bryum* spp. had higher cover on the drilling wastes compared with the paired undisturbed tundra controls 10-20 years following disturbance. These early colonizing acrocarpous moss species appear to be the first macro biological soil crust component to establish. Biological soil crusts (BSCs) are communities of mosses, liverworts, lichens, bacteria, cyanobacteria and fungi that are commonly found throughout the arctic, especially on recently disturbed soils (Bowker et al, 2018). Mature BSCs appear to naturally develop approximately 10 years following disturbance with BSCs present on all but one drilling waste site from the disturbance years 1993-2008. These early colonizers and the subsequent development of mature biological soil crusts (Figure 9) likely play an important role in increasing water hold capacity and maintaining soil moisture at the surface, which is critical for soil nutrient cycling processes and germination of vascular plants from seed (Forbes and Jefferies 1999; Stewart et al. 2011a,b,c). In addition, early bryophyte colonizers provide surface roughness that can trap wind blown seed (Belnap and Harper, 2003). Through wetting and drying cycles moss mats can also provide a significant input of carbon, nitrogen and phosphorus that in turn promote key ecosystem processes, such as carbon and nitrogen cycling (Stewart 2011a,b).


Figure 9. Early acrocarpous moss establishment on 4-5-year-old drilling waste (left GT13-70) and mature biological soil crust 20-year-old drilling wastes (right M98-230).

On-going work is being completed in the laboratory at the University of Saskatchewan to examine the development and function of BSC assemblages in relation to soil physical, chemical and microbial properties. We are also working to develop successional models of BSCs based on the realized niche of primary macro and micro BSC phyla. This will allow us to assess the primary factors that determine the initial colonization of the disturbed substrates and the subsequent development and function of these critical early successional communities.

BSC and underlying substrate samples were collected from three drilling waste sites for each of the following disturbance years: 1998, 2008 and 2013. Five samples of crust and the underlying substrate were collected by pushing a 7 cm diameter by 6.5 cm deep cylindrical sampling cup into the ground, cutting around it with a knife and extracting the sample. Samples were then tapped out of the sample jar, turned upright and returned to the cup and closed tightly. Samples were stored in coolers until brought to the university, where they were then housed in the PhytoTRON (Diurnal cycle of 18.5 hrs light/5.5 hrs dark with 15°C during light and 5°C during dark with relative humidity ~50%) and watered regularly with approximately 125 ml of water (MilliQ ®Ultra-Pure). Subsamples of each crust surface (~ 2.5 cm) and underlying substrate (> 2.5 cm to depth of sample) were collected within 1 week of return from the field and were stored at -80°C until analysis. DNA will be extracted (DNeasy PowerPlant Pro Kit, Qiagen) from these BSCs and underlying substrate. Molecular analysis will be conducted using Illumina MiSeq sequencing. Bryophytes and lichens, bacteria (16S) and fungal ITS will be examined for each BSC and underlying soil sample. In addition, BSC and substrates immediately underlying BSCs will be characterized for pH, ammonium (NH_4), nitrate (NO_3), dissolved organic nitrogen and dissolved organic carbon.

To better understand the role these early colonizing communities have in driving recovery of ecosystem function, gas flux measurements and enzyme assays have and will be completed. Gas flux measurements of all sampled BSCs were measured in August 2018. A Fourier Transform InfaRed-Multicomponent Gas Analyzer was used to determine carbon dioxide (CO_2), methane (CH_4) and nitrogen dioxide (N_2O) flux under both dark and light conditions. Measurements of N_2 fixation were made using acetylene reduction assays (Stewart et al., 1967). For the subsequent years of sampling (2019 and 2020), a series of enzyme assays to measure mineralization (chitinase and protease assays, following Hendel & Marxsen (2005)), nitrification (potential nitrification assay, following Hoffman et al. 2007)) and denitrification (potential denitrification assay, following Luo et al., 1996)) will be performed.

Finally, two microclimate monitoring stations were deployed on drilling wastes from 2013. At each site, two zones were established; one with exposed drilling waste and no BSC establishment and the other colonized by BSCs. In each zone, soil surface temperature is being monitored with fine wire copper constant thermocouples, BSC moisture is being monitored with impedence clips (Coxson, 1991) and soil moisture sensors were inserted to measure below surface moisture conditions. PAR (Photosynthetically Active Radiation) sensors were installed to measure light intensity and Leaf Wetness Smart sensors were deployed to provide the percent wetness just above the surface of the BSCs. These instruments were connected to a dataloggers (CR1000X Campbell Scientific Inc or HOBO loggers) and hourly means are being recorded until 2020. Additionally, an inventory of BSC was conducted by use of $5cm^2$ grids in a $25cm^2$ quadrats to measure surface cover by visual estimates. This will allow us to examine the microclimatic conditions associated with these developing BSC communities.

Substrate Characterization

The average depth of drilling waste and organic matter in impacted sites was 3.7 ± 3.2 and 2.4 ± 3.2 respectively (Figure 10). The average depth of organic matter in control sites across the landscape was 7.7 ± 2.9 cm. The deepest deposits of drilling waste were > 15 cm and found at 1993 sites, M93-40 and M98-230. The deepest organic layer depth was found in a control site at 20 cm. While drilling waste depth was similar across the differently aged sites, higher organic matter accumulation was evident at older sites (Figure 11).

Figure 10. Drilling waste ~3 cm in depth underlain by an organic soil horizon (left) and organic matter accumulation over drilling waste (right).

The depth of drilling waste and organic matter (OM) was assessed at each site by measuring the depth of each substrate type within the center of each 1 m^2 vegetation survey plot. Drilling waste depth was similar across all disturbance years and OM in undisturbed control plots was also similar across the landscape (Figure 11). The highest amount of OM found on drilling wastes was found in sites >25 years old (i.e. 1993), while very low to no OM was found on recently disturbed sites (i.e. 2017).

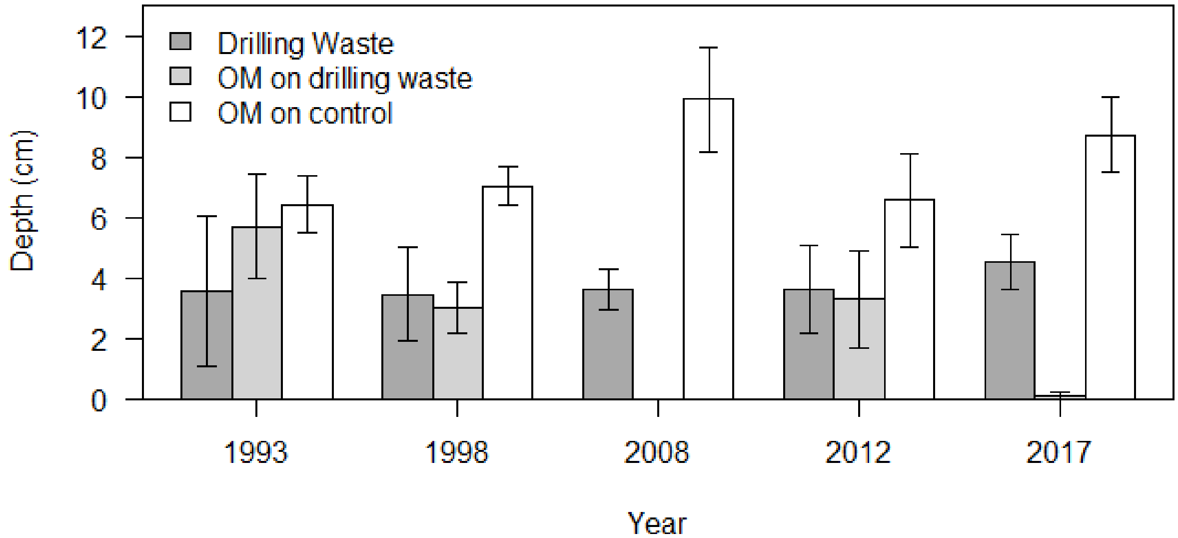

Figure 11. Depth of drilling waste, organic matter found over drilling waste and depth of organic matter in undisturbed controls plots. Bars are means with standard error (n=5).

Sites surveyed in 2008 were an anomaly with no OM depth detected (Figure 11). It possible that our sampling design biased placement of survey plots to areas with exposed drilling waste. However, we also found lower percent cover of several species (Table 2) and the highest number of absent species on drilling wastes (Table 3) at 2008 sites. The lack of organic matter accumulation could be due to the physicochemical properties of the drilling wastes inhibiting vegetative establishment or may be associated with the landscape position of 2008 sites. All 2008 sites were in close proximity to one another and were the most south-easterly sites sampled (Figure 1). Differences in landscape conditions (i.e. moisture, aspect, soil properties) in this area may impact natural revegetation. The 2008 sites were classified as heath hummock-hollow or transitional sites between heath hummock-hollow and sedge hummock-hollow. The mid-slope position of these sites would likely contribute to drier soil conditions, which may be limiting vegetative growth and hence OM accumulation. To confirm if/why lower OM accumulation is occurring in 2008, further survey of 2008 drilling waste sites in other landscape locations and assessment of the physicochemical characteristics of these drilling wastes is needed.

The relatively high OM depth measured at 2012 sites is also unexpected (Figure 11). Accumulation of OM in tundra ecosystems is generally considered to occur very slowly due to the short growing season and relatively low biomass production each year (Hobbie et al. 2002; Hugelius et al. 2010). It is very unlikely that approximately 4 cm of OM would accumulate within 6 years. We noted that on several drilling waste sites, wastes were found in depressions or hollows, with hummocks remaining intact above the level of the wastes. It is highly possible that some slumping is occurring in these hummock-hollow landscapes that could result in the burial of drilling wastes and appearance of OM accumulation on the drilling waste surface. These results should be interpreted with caution both due to the possible biasing of measurement due to the sampling design and the low numbers of replication (i.e. n=5) in each age category.

Best Practices to Promote Natural Recovery on Drilling Wastes

Based on the characterization of drilling waste sites and the tundra vegetation present on drilling wastes ranging from 1-25 years it is evident that natural revegetation is occurring on these wastes. Sources of vegetative materials for recolonization and depth of drilling waste appear to be two of the primary driving factors in determining the extent of recovery. Given these driving factors we suggest the following practices to promote natural revegetation processes.

1. Leaving areas of intact tundra vegetation dispersed throughout the area where drilling wastes are contained is essential. In hummock-hollow tundra, dispersal of drilling wastes into hollows, allows for hummocks to stay intact and act as source population for revegetation. Hummocks provide not only aboveground islands for revegetation but also maintain connectivity with intact belowground soil systems.

2. Thinly spread drilling wastes appear to undergo revegetation processes more quickly. In general, a depth of ~3 cm allowed for natural recolonization to proceed. Whereas depth of drilling waste > 15 cm can impede ecosystem recovery with little recovery observed even 20 years after disturbance. Underlying microtopography of drilling waste sites should be considered in managing wastes with an emphasis placed on limiting drilling wastes.

3. Direct colonization of drilling wastes in the first ~5 years is primarily driven by the colonization of acrocarpous mosses. Establishment of these early colonizing moss communities appears to facilitate the development of cohesive and diverse biological soil crusts in later years (~10-20 years). Mature biological soil crusts may act to further stabilize exposed drilling wastes and promote establishment of vascular plant species. **Promoting bryophyte cover in early stages may be beneficial to long-term tundra vegetation establishment.** Surface moisture is essential for establishment of early bryophyte communities and therefore practices that promote retention of surface moisture may assist in recovery.

Conclusions

Natural revegetation of drilling wastes is occurring at the Meliadine site. In our initial project proposal, we had proposed to examine active restoration on drilling waste sites. The first step in preparing to conduct active restoration was to examine a chronosequence of drilling waste sites across the landscape. This approach allows us to determine patterns of natural recolonization and use this information to inform active restoration practice. From the 25 drilling waste sites with paired undisturbed controls that were examined, we found that the community composition between drilling wastes and the paired undisturbed tundra was similar 20-25 years post disturbance and species richness recovered within 6 years. Due to the different life history characteristics of tundra plants, individual species responses to disturbance were observed. While sedges and mosses may recover more rapidly on these drilling wastes, dwarf shrubs and lichens may require longer to recover. These trends in natural recovery are important for guiding future restoration efforts and techniques. Specifically, targeting sedge and moss species for transplanting and/or seeding of disturbed substrates may be a highly effective strategy for initiating the development of early successional tundra communities.

Drilling waste depth was similar across all disturbance years and OM in undisturbed control plots was also similar across the landscape. The highest amount of OM found on drilling wastes was found in sites >25 years old (i.e. 1993), while very low to no OM was found on recently disturbed sites (i.e. 2017). However, we found surprisingly large depths of OM on the drilling wastes in a short time period (ex. ~4 cm in 6 years). This trend warrants further investigation to determine the source and cause of this OM.

Based on our findings we provide suggestions to improve and/or maintain the relatively rapid natural revegetation of the drilling wastes. Placement of drilling wastes on the landscape that allow for remnant patches or islands of intact tundra throughout the disturbed area are essential for recolonization. Applying drilling wastes in thin layers may also assist with more rapid vegetative establishment. Finally, promotion of bryophyte communities in the early stages of revegetation may have long-term benefits for ecosystem recovery. Over the next three summers we will continue to monitor, survey and conduct laboratory trials to better understand the initial colonization and succession of species on these drilling wastes, particularly by bryophytes, lichens and biological soils crusts.

Finally, given the findings of this study we suggest that active restoration of the drilling wastes is likely not required for the recovery of the tundra plant communities, if the timeline for recovery is ~20 years. Therefore, in our on-going work to develop tundra restoration techniques, we suggest developing active restoration trials at other disturbed areas on the Meliadine site.

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Appendix A

Project Timeline and Deliverables

Dates have been modified to reflect that the grant was not awarded until June 1, 2018. Modification of research activities and additional reporting are also indicated.

4 (RPP)

Personal identification no. (PIN)	Family name of applicant
441262	Stewart

ACTIVITY SCHEDULE
(Refer to instructions to see if this section applies to your application. Use additional page(s) if necessary.)

Milestone	Description of activities	Anticipated starting date	Anticipated completion date
Milestone 0.1: Hiring HQP and field season preparation	All HQP will be hired and preparation for the field season completed. Preparations will include start-up meetings with the project team including AEM representatives. Planning of project logistics for year 1 and development of field plans.	2018-01-01 2018-06-01	2018-05-31 2018-07-01
Milestone 1.1: Natural recolonization of drilling wastes	Study natural recolonization of drilling waste dumps 2-17 yrs old by biological soil crusts and vascular plants. Specific recommendations of species for restoration will be developed.	2018-06-01 2018-07-01	2019-08-31 2018-11-30 Initial Technical report
Milestone 1.2: Development of HOF models	Hierarchical logistic regression modelling or Huisman Olff Fresco (HOF) models will be applied to examine optima and niche ranges of key naturally recolonizing foundational and early successional tundra species.	2018-09-01	2019-09-01
Milestone 1.3: Belowground niche ranges on waste dumps	Root density of key naturally recolonizing vascular plants will be plotted against key physicochemical parameters to determine niche ranges. This information will be used to further define HOF models in Milestone 1.2.	2018-09-01	2019-09-01
Milestone 0.3: Youth Education program	Collaboratively develop and deliver an education program on-site for one week in 2019 and 2021 for youth from Rankin Inlet and Baker Lake, NT. The program will focus on arctic ecology, restoration and skills in environmental monitoring and research.	2019-01-31	2020-01-31
Milestone 3.3: Assesment soil propagules in donor materials	The soil propagule bank in homogenized and plugs for transplant with be assessed. Specific recommendations on species present for restoration in local tundra will be developed.	2019-06-01	2020-01-01
Milestone 2.1: Active restoration with BSCs waste dumps	Transplanting of biological soil crusts on 10 drilling waste dumps. Specific recommendation of restoration practice and species for restoration will be developed. Active restoration of drilling wastes not required. Site of active restoration TBD. BSC development on drilling wastes will be examined through a chronosequence but not active restoration.	2019-06-01	2021-08-31

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ACTIVITY SCHEDULE
(Refer to instructions to see if this section applies to your application. Use additional page(s) if necessary.)

Milestone	Description of activities	Anticipated starting date	Anticipated completion date
Milestone 2.4: Active restoration with BSCs Waste Rock	Transplanting of biological soil crusts on 5 waste sites. Specific recommendation of restoration practice and species for restoration will be developed. This will be included in active restoration trial, location TBD.	2019-06-01	2021-08-31
Milestone 3.1: Active restoration with vascular plants	Transplanting of tundra plugs on 25 drilling waste dumps. Specific recommendation of restoration practice and species for restoration will be developed. This will be included in active restoration trial, location TBD.	2019-06-01	2021-08-31
Milestone 3.2: Belowground niches ranges at donor sites	The belowground niches ranges at undisturbed donor sites will be determined for key tundra vascular plants.	2019-06-01	2021-08-31
Milestone 2.3: Recovery of ecosystem function restored BSCs	Role of BSCs in recovery of key ecosystem services will be determined through examining community composition of actively restored BSCs with indicators of ecosystem function (ex. N and C fixation).	2019-06-14	2021-09-01
Milestone 0.4: Community meetings	We will hold community meetings in Rankin Inlet and Baker Lake. Working with Agnico's community relations department we will identify key groups to host. Our research and restoration of tundra environments will be presented and discussed	2019-08-01	2021-08-31
Milestone 2.2: Niche ranges of restored BSCs	Initial and realized niches of actively restored BSCs will be determined on drilling waste dumps and waste rock.	2019-09-01	2021-09-01
Milestone 0.6: Technical reports for Agnico Egale	Detailed technical reports for AEM on the restoration techniques examined. Guidelines and standard operating procedures for on-going monitoring will be included. Preliminary report January 2021, final report January 2022. Additional dates of yearly updates/technical reports on project progress.	2020-01-01 2018-11-30 2019-11-30	2022-01-01

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ACTIVITY SCHEDULE
(Refer to instructions to see if this section applies to your application. Use additional page(s) if necessary.)

Milestone	Description of activities	Anticipated starting date	Anticipated completion date
Milestone 0.5: Website development	Creation of project website providing information to restoration practitioners and public on general information on arctic ecology and restoration practice in the North, as well as key findings from the research.	2020-01-31 2019-06-01	2022-01-31
Milestone 3.4: Belowground niche ranges restored vasculars	The belowground niches of transplanted tundra species will be delineated on drilling waste dumps that were actively restored. Specific recommendation of restoration practice and species for restoration will be developed.	2020-06-01	2022-01-01