doi:10.36487/ACG_repo/2515_98

Five-year performance review of a mine rock stockpile cover trial in the Canadian Shield

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Abstract

Progressive reclamation during mine operations allows for the development and refinement of techniques over time. At the Detour Lake Mine in Canada (50°N, 80°W), the planned end land use for mine rock stockpiles is dense mature coniferous forest to re-establish pre-mine ecosystems. The site-specific reclamation design elements that would lead to better reclamation outcomes were initially unknown, so a 10-hectare cover trial was constructed to assess the relative performance of different cover and revegetation prescriptions toward achieving the planned end land use. The trial was divided into plots considering a range of slope angle, aspect, cover thickness, surface grading and revegetation prescriptions.

This paper presents a review of the cover trial performance after five years of monitoring. Large-scale slope instabilities have not been observed in the silt-rich reclamation cover. Most erosional and depositional features are interpreted to have stabilised three to four years following construction. The primary factors influencing erosion are variability in surface water run-on from the upstream bench and surface grading on slopes, with lesser influence from slope angle and cover thickness. Erosion performance is improved by limiting surface water run-on to slopes by using a microtopography surface grading of offset hummocks and hollows plus rapidly establishing vegetation. The density of conifers is within the range required to achieve the planned end land use, although it is nearing the lower end of that range, with some ongoing mortality. Green alders are growing well and reaching heights greater than 2 m. The presence of peat was the key driver of seedling survival and vigour, where survival was approximately 25% higher in areas with increased peat. A 0.7 m cover thickness was suitable for promoting vegetation growth and managing erosion. Insights into operational-scale construction methods and the relative performance of cover characteristics are being applied to ongoing progressive reclamation activities.

Keywords: *soil cover, peat, erosion, deposition, seedling survival, seedling vigour, run-on*

1 Introduction

Progressive reclamation and site rehabilitation conducted during mine operations are advantageous to improve early-stage reclamation performance, reduce closure activities required at the end of operations and distribute costs across the mine life. These activities develop site-specific operational experience and initiate adaptive management of reclamation techniques which can be applied to improve the design of landforms (International Network for Acid Prevention 2014, 2017). Developing progressive reclamation techniques can be challenging if the design elements are unknown or if experience with onsite materials is limited. As a mine progresses from construction to operations, field-scale reclamation testing programs can provide key observations and data to support better reclamation outcomes.

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The Detour Lake Mine (DLM) is a gold mine located in northeastern Ontario, Canada (50°N, 80°W). DLM currently has two operational mine rock stockpiles (MRS) and three more planned MRS. Two MRS will store ore that will be removed and processed at the end of mine life, and the remaining three MRS will be reclaimed by the end of the mine life. Reclamation activities are guided by the mine closure plan, end land-use plan and commitments related to the restoration of habitat for boreal woodland caribou. To advance the state of knowledge of progressive reclamation for the MRS and to develop guidance for mine-scale progressive reclamation prescriptions, an MRS cover trial, referred to as the ‘test cover’, was designed and constructed as part of a broader multi-disciplinary research program (Raizman & Lyle 2022).

2 Site conditions, design and construction

The test cover design was initiated in 2018 and construction occurred in fall 2018 through to spring 2019. The test cover was constructed using conventional mining equipment on 10 hectares of run-of-mine waste rock. The test cover area included bench and slope area geometry representative of typical MRS. The goal of the test cover was to compare different strategies and potential designs for progressive reclamation of the MRS, with consideration of hydrological, geotechnical and ecological performance. This section provides an overview of test cover design and construction; details and design drawings are provided in Cash et al. (2022).

2.1 Regional setting and climate

DLM is located in Canada’s eastern boreal forest region within the Abitibi Uplands, an eroded upland that forms a drainage divide between the Hudson Bay and St Lawrence River watersheds in the Canadian Shield. Topography at DLM is subdued, with elevations ranging from approximately 255 to 315 m.

The local area has a complex glacial history (Gao 2013), with exposed flat-lying bedrock ridges, glacial sediments and a surficial blanket of organic soils. The typical surficial sediment profile consists of peat underlain by discontinuous glaciolacustrine sediments, with glacial outwash (or drift) sediments and till, overlying bedrock. The drift deposit was formed from an ice shelf environment with materials ranging from silty sand to sandy silt with trace gravel. The till deposits have similar gradation, consisting primarily of silt and fine sand with some gravel and cobbles. In general, the drift/till materials are cohesionless and fine-grained, with 30 to 50% silt-sized material.

DLM has a warm-summer humid continental climate (Köppen–Geiger classification Dfb; Kottek et al. 2006). The average annual air temperature is 1°C. Average annual precipitation is 800 mm, with 540 mm rain and 260 mm snow water equivalent. Average monthly precipitation ranges from 37 mm in February to 93 mm in July and September. The estimated one-in-10-year 24-hour rainfall event is 71 mm.

2.2 End land use, design basis and objectives

Developed in consultation with partnered Indigenous communities, the target end land use for the MRS is a contiguous landscape of dense mature coniferous forest with smaller areas of open upland coniferous forests to provide habitat for boreal woodland caribou. The DLM end land-use plan indicates that the re-established ecosystems should be similar to pre-mine ecosystems, consider the effects of the mine topography and surficial materials, and support Indigenous land uses. The projected revegetated ecosites for the MRS slopes are characteristic of upland ecosystems representative of a black spruce (*Picea glauca*), jack pine (*Pinus banksiana*) and feathermoss (*Pleurozium* spp.) upland forest on peat and mineral soils.

A design basis was established for the test cover program with the goal of evaluating the performance of different cover system characteristics to support progressive reclamation of the MRS. Several objectives were established as part of the design basis, including to:

- Determine the steepest slope that can reliably maintain a cover.
- Evaluate the relative performance of different reclamation cover prescriptions.
- Assess the establishment, biodiversity, growth trajectories and performance of planted species.

- Evaluate the partitioning of the water balance between evapotranspiration, net percolation and overland flow.

This paper is focused on the first three objectives listed above and includes some discussion of instrumentation that is also used to support the fourth objective. The reader is referred to Harrington et al. (2022) for details regarding the cover water balance.

The design team included multi-disciplinary specialists from DLM and external partners with expertise in ecology, hydrotechnical design, geotechnical design, landform design, mine planning and geochemistry. The team also included university research partners investigating additional physical, meteorological, geochemical, microbiological, and ecological characteristics of the MRS. These research programs are ongoing and are not described herein.

2.3 Cover materials and cover design

The available cover materials at DLM are stripped overburden from the open pit or other construction activities. Overburden stripping and stockpiled material typically include an unsegregated mix of geologic units (i.e. a mix of peat, glaciolacustrine, drift and till materials), where the dominant particle size distribution and properties are similar to the drift and till units. Due to the high proportion of silt in the drift and till materials, the design required consideration of mechanisms and methods to mitigate erosion (i.e. rills and gullies) and the potential for slip-off failures of the cover. Acid-base accounting and whole rock elemental analysis identified that the cover materials are unlikely to be acid generating and are not enriched in metals that may affect post-closure drainage chemistry.

The test cover design considered a range of characteristics to be assessed, including slope angle, slope aspect and exposure, cover thickness, cover material composition and grading methods, and revegetation prescriptions (Section 2.4; Cash et al. 2022). The trial area was one bench- (approximately 10 to 15 m-) high and was subdivided into 12 bench slope plots and one large plateau plot. Each slope plot included the upper bench crest, bench slope and lower bench. Each plot was large enough to be constructed with mine-scale equipment, with consideration of the edge effects between plots.

The test cover design included the following variations in cover design components:

- Slope angles of 2H:1V, 2.5H:1V, 3H:1V, 4H:1V and flat (plateau). The slope angles were selected based on a range of operational and volume constraints.
- North, northeast and east slope aspects. The slope aspects were selected to represent the full range of aspects within the constraints of the test cover area.
- Cover thicknesses of 0, 0.3, 0.7 and 1.0 m. The cover thicknesses were selected to range above and below the initial target thickness while also evaluating a no-cover option.
- Cover composition of peat-mineral mix (i.e. 10 to 30% peat by volume mixed with mineral soil) via dump-and-blending or layering and ripping.
- Corrugated or microtopography surface grading. Corrugated grading was intended to limit erosion to individual rills and prevent rill erosion coalescing into larger gullies. Microtopography grading was intended to interrupt surface water flow pathways, resulting in reduced erosion.

2.4 Revegetation design

The test cover revegetation design aimed to support long-term establishment of contiguous closed-canopy conifer forest for caribou habitat. Projected ecosites from the DLM end land-use plan were used to develop revegetation prescriptions and species selection for the test cover. Rapid establishment of vegetation was encouraged to limit erosion and reduce net percolation through the cover via evapotranspiration.

The test cover design included the following methods of revegetation:

- Hydraulic seeding: native grasses in combination with fertiliser, mulch and tackifier
- Broadcast seeding: native grasses in combination with fertiliser
- Conifer planting: planting of container seedlings of white spruce (*Picea glauca*) and jack pine
- Deciduous trees and shrubs: interplanting with the conifer planting prescription in select areas.

In addition to native grasses, an agronomic species 'nurse crop' of fall rye or oats was included in the hydroseed and broadcast seed mix for initial rapid vegetation establishment.

2.5 Instrumentation design

The instrumentation program for the test cover was designed to provide data to assess water flow, water budget, vegetative demand and moisture conditions affecting slope stability in the soil cover. These data allow examination of changes to the cover over time, such as from vegetation establishment, freeze-thaw processes and weather events. The instrumentation network comprised a meteorological station, time lapse cameras, soil-moisture stations (continuous measuring of soil moisture content, soil-water tension and soil temperature) and standpipe piezometers.

2.6 Construction

Test cover construction included waste rock regrading, cover placement, ditch construction, instrumentation installation, and vegetation seeding and planting. The test cover was constructed in general accordance with the design and specifications presented above; however, some deviations from the design occurred. Deviations of note were: (a) the peat content in the as-constructed cover material was limited (i.e. <10% peat by volume in the peat-mineral mix); and (b) the surface grading methods were modified to reduce cover bulk densities by ripping where densities exceeded design specifications. The test cover was constructed in summer 2019. Vegetation seeding and planting occurred in the late summer and early fall of 2019, respectively, after cover placement, to allow for vegetation establishment before winter. Additional infill planting of deciduous species was completed on the plateau in fall 2020.

3 Monitoring program

The test cover monitoring program was initiated after construction was completed in 2019 and is ongoing. Monitoring has been conducted primarily during semi-annual or annual field visits, supplemented by instrumentation recording continuous data. The test cover monitoring program includes snow surveys, soil-moisture station test pits, a meteorological station, geotechnical plot observations and rankings, soil cover density and hydraulic conductivity testing, leaf-area index (LAI) measurements, seedling stem counts and vigour rankings, and vegetation composition surveys. Additional detail is provided on these methods in the following sub-sections.

3.1 Geotechnical monitoring

Observations of erosional and associated depositional features were recorded for interpretation of factors affecting the relative geotechnical performance of the different cover prescriptions. Observations of erosional features included both qualitative descriptions (e.g. shape, location) and quantitative measurements (e.g. approximate width, depth and spacing) of rills and gullies. Observations of depositional features included the description of the apparent transport or accumulation of cover material across the plots, including the relative size, shape and location of cover soil deposition, and descriptions of the deposited material. General observations of the test cover, such as locations with evidence of water ponding, large-scale drainage patterns and observations related to surface grading, were also recorded.

Additionally, erosion and deposition performance was evaluated by using a qualitative ranking scale from one (lowest) to five (highest) for the relative performance of sub-plots defined by unique combinations of design characteristics (Sections 2.3 and 2.4). Qualitative ranks were based on the degree of erosion and deposition, stability and regularity of erosional and depositional features, degree of pavement development, retention of original surface grading, and a qualitative estimate of vegetation cover as indicators of the above.

3.2 Ecological monitoring

Observations of vegetation cover, growth and diversity were recorded to understand revegetation trajectories and the relative performance of different vegetation prescriptions. Vegetation observations were recorded at 84 permanent sample plots (PSPs), with each PSP having an area of 100 m^2.

LAI was used as a proxy measurement of plant productivity and biomass, and was measured manually at a subset of PSPs using a plant canopy analyser. Larger-scale estimates of LAI were derived by correlating manual LAI measurements with remotely sensed vegetation indices. The vegetation indices were obtained from spectral reflectance data recorded by a remotely piloted aircraft system (i.e. drone). The relationship between LAI and vegetation indices at the test cover was explored for three vegetation indices. The 90th percentile of the simple ratio, i.e. the ratio between near-infrared and red wavelengths, was selected as the best considered predictor of LAI.

At each PSP, stem counts of individual living jack pine, white spruce and other species of interest (e.g. green alder [*Alnus alnobetula*], willow [*Salix* spp], trembling aspen [*Populus tremuloides*]) were recorded to provide information on forest stand density and survival rates. Visual estimates of per cent cover by species within each PSP were conducted to track changes in vegetation composition within PSPs. The vigour of selected seedlings was assessed using a qualitative vigour ranking scale from one to four to provide information on the overall condition and growth of seedlings.

4 Results and interpretation

The test cover has changed substantially between the time of construction in 2019 (Figure 1) and the most recent monitoring visit (in 2024) (Figure 2). This section describes the results and interpretation of test cover geotechnical and vegetation monitoring, along with selected instrumentation data.

Figure 1 Test cover in May 2019 showing construction and cover material placement. Dashed outline represents the test cover project area

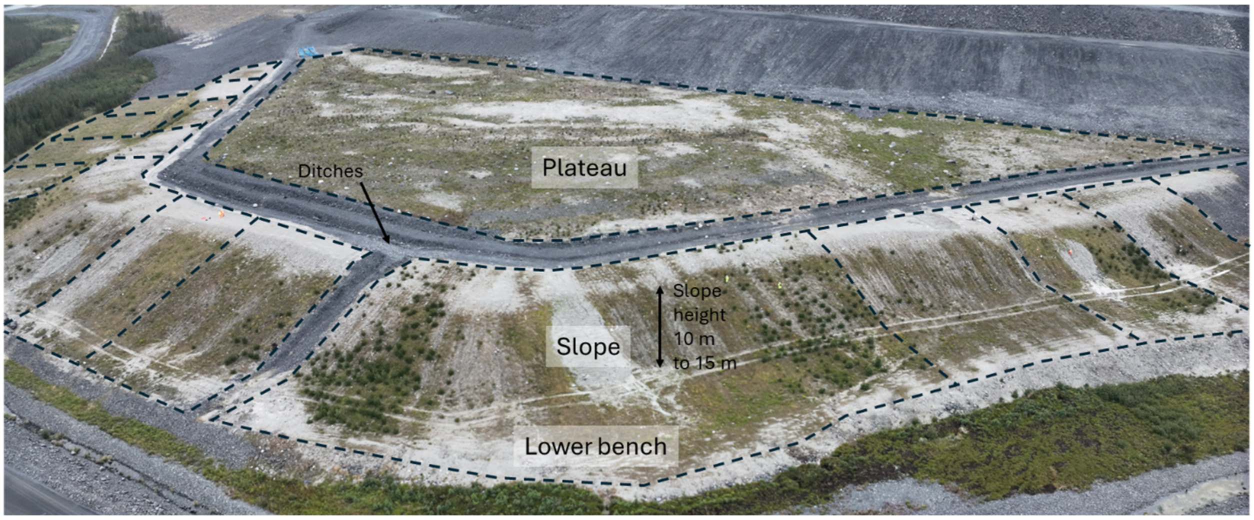

Figure 2 Test cover in September 2024 showing observed erosion, deposition and revegetation. Dashed lines show extents of cover design plots described in Section 2.3. Large barren areas on slopes and excavator tracks across the lower bench are from recent test pit excavation and re-covering

4.1 Geotechnical observations

4.1.1 Stability, erosion and deposition

Geotechnical instability within the cover material, such as slip-off failure (i.e. infinite slope failure mechanism) or large-scale flow or slumping, was identified as a key potential hazard during the design process due to the challenging geotechnical properties of the silt-rich drift/till cover material. However, such geotechnical instabilities have not been observed in the reclamation cover material during the first five years of monitoring.

Instead, the dominant processes observed to affect cover stability are erosion of cover material and deposition of transported material. Erosion and deposition of the cover material are hazards to cover performance. Erosion may alter or remove surface grading and may lead to the development of rills and gullies, erosion pavement and small sinkholes. Where erosional features penetrate through the cover, waste rock becomes exposed, allowing increased net percolation into waste rock and increased air exchange. Deposition of transported cover material can bury surface gradings, developing soils and young vegetation. Conversely, erosion and deposition contribute to topographic variability and, where rates are modest, may contribute to vegetation establishment. These erosion and deposition mechanisms are complex, requiring an empirical approach to design, aided by trials such as the test cover.

The main erosional features at the test cover are rills and gullies (Figure 3). These erosional features developed largely during the first two years following construction, then broadly stabilised over the next three years. Erosion rates were interpreted to have declined over these last three years based on increased amounts of non-planted vegetation in rills and gullies, and no apparent increase in size of most depositional features. The ongoing development of vegetation is also interpreted to contribute to decreased rates of erosion through interception of rainfall, increased resistance to flow (Woo et al. 1997) and stabilisation by roots (Gyssels & Poesen 2003). Decreased erosion rates may also result in a positive feedback loop where vegetation development is improved, thereby further limiting erosion and promoting the end land-use goal of established vegetation.

Since the test cover was constructed, annual precipitation at DLM has ranged from 683 to 1,002 mm and the annual maximum 24-hour rainfall event at the test cover has ranged from 28 to 69 mm, with the last two years being notably drier than the first three years. These trends in rainfall may contribute to the observed trends in erosion; however, erosion rates began decreasing prior to the onset of drier years, and the development of vegetation over time is still interpreted to have reduced erosion rates.

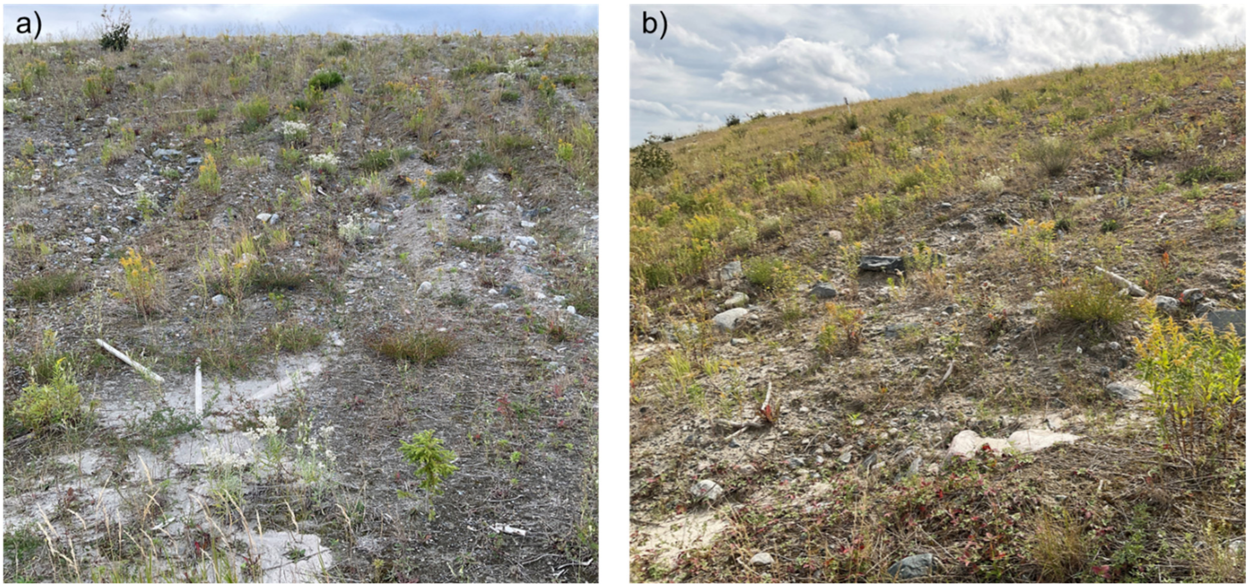

Figure 3 (a) Slope with corrugated surface grading, showing rill and gully erosion, and a small depositional fan at the base of the central gully; (b) Slope with microtopography surface grading, showing widely spaced irregular rills and a gully

Depositional features have developed below many of the larger erosional features on the test cover (Figure 3). Similarly to erosion, depositional features developed mainly during the two years following construction. During the following three years, most fans were interpreted to have no appreciable volumes of additional material deposited, with many areas of existing fans having established vegetation. Some fans showed signs of downcutting with rills less than 0.1 m deep. These observations are interpreted to indicate stabilisation of most depositional features, corresponding to a decrease in erosion of the slopes above the deposition areas.

Wind and water erosion of fines from the surface, leaving behind a coarser fraction, leads to the formation of a surficial crust that stabilises the remaining material and decreases subsequent erosion rates, sometimes referred to as 'erosion pavement' (Lowdermilk & Sundling). Many areas of silt-rich cover material with low peat content and with no to limited vegetation growth have well-developed erosion pavement on the test cover (e.g. Figure 4a).

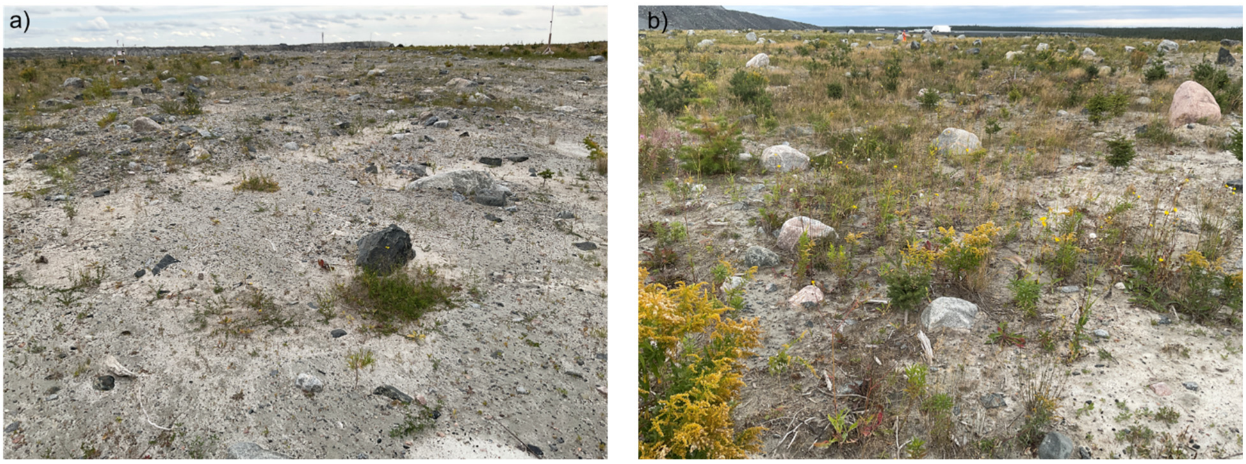

Figure 4 Areas of plateau showing: (a) Development of erosion pavement on cover material with low peat content; (b) Lack thereof on cover material with high peat content

Minimal erosion pavement was noted during the first two years of monitoring, followed by an increasing extent of erosion pavement over the last three years of monitoring. Erosion pavement may reduce infiltration of water, particularly for higher intensity rainfall and snowmelt events, promoting overland flow, which may lead to further erosion. This promotion of overland flow may lead to decreased infiltration and net percolation. Erosion pavement may also limit the ability of vegetation to grow and may prevent new vegetation from becoming established, limiting the ability to meet end land-use goals.

Sinkholes have been observed in limited areas of the test cover. Most sinkholes were small (i.e. less than 0.5 m across) and located at the slope crest, while one larger sinkhole developed in an area where ponded water is often observed. Sinkholes are interpreted to have formed when water flowed from the surface through the cover and into the relatively large void spaces of the underlying waste rock, transporting some cover material. These features are undesirable because they may promote rapid infiltration directly into the underlying waste rock, decreasing water availability for plants and leading to increased contact water discharging from the MRS. However, sinkholes are a relatively minor erosional feature at the test cover compared to rill and gully erosion, and can be repaired under routine maintenance if necessary.

4.1.2 Surface grading

Surface grading methods influence the development of erosion features on slopes and benches. Based largely on the degree of erosion, microtopography grading performed better than corrugated grading (Figure 3). Microtopography grading, especially where hummocks and hollows were staggered, limited erosional features to shorter rills. Corrugated grading promoted the formation of gullies, extending the length of slopes.

4.1.3 Surface water run-on

Local changes in topography and surface grading, while often quite subtle, can have appreciable impacts on surface water run-on from the crest onto slopes and the resulting erosion. Focused run-on or larger volumes of water likely result in more erosion than diffuse run-on or small volumes of water. Primary run-on controls appeared to be the local gradient of the crest and the surface grading of cover material near the crest.

A local gradient toward the crest promotes run-on, while a local gradient away from the crest either diverts water elsewhere or promotes infiltration. A third situation occurs where the gradient of the crest is parallel to the crest. This results in flow along the bench surface, parallel to the crest, and accumulation of water until it reaches a barrier feature (e.g. trough, depression or ridge in the cover material). The barrier feature results in either ponding that promotes infiltration or diversion of the accumulated flow onto the plot slope as focused run-on, resulting in the largest erosion features on the test cover (Figure 5).

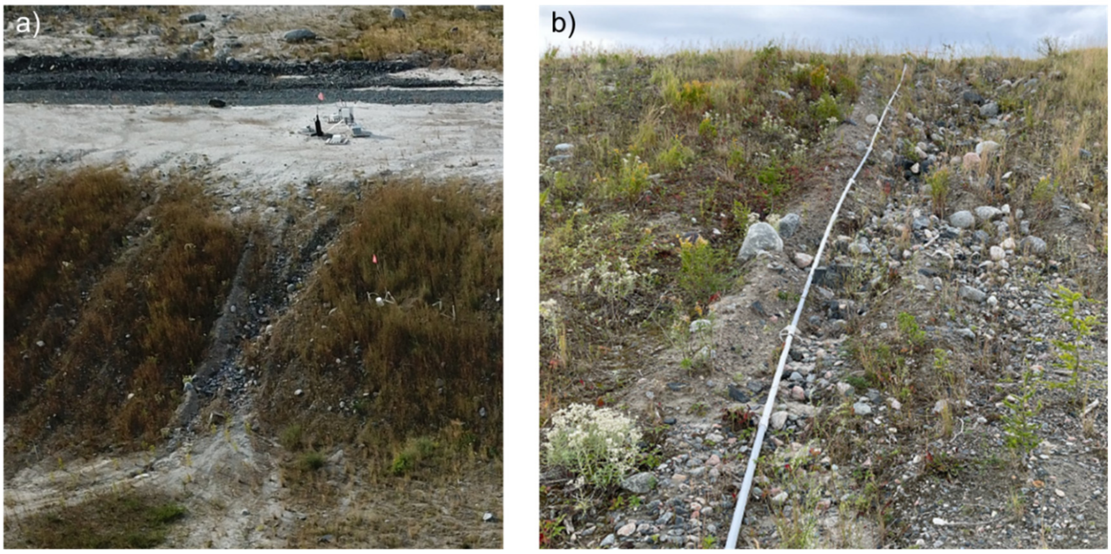

Figure 5 Largest erosion gully observed on the test cover, created by focused run-on from the crest at the intersection between two cover plots: (a) Overview; (b) Close-up

On the crest, corrugated surface grading can provide direct pathways for water to flow over the crest, whereas microtopography surface grading can impede water flow over the crest. However, microtopography may not be effective at impeding water flow over the crest where the bench gradient is parallel to the crest.

4.1.4 Slope angle

Determining the steepest slope that could reliably maintain a cover was identified as a key objective during the design basis (Section 2.2). As noted in Section 4.1.1, no large-scale geotechnical instabilities were observed within the covers. In terms of erosion, steeper 2.0H:1.0V and shallower 4.0H:1.0V slopes generally exhibited a greater degree of erosion than the intermediate 2.5H:1.0V and 3.0H:1.0V slopes. Greater erosion on steeper slopes was attributed to higher overland flow velocities, while greater erosion on shallower slopes was attributed to larger overland flow volumes due to a larger slope catchment area. Thus, intermediate slope angles are preferred for limiting erosion and allowing for the development of vegetation. Overall, the effects of slope angle on erosion performance were interpreted to be less important compared to surface grading and surface water run-on.

4.1.5 Cover thickness

Most test cover plots have a 0.7 m thick cover, and differences in erosion performance are attributed to other factors noted above. Waste rock has been observed in gullies on a plot with a 0.3 m thick cover, indicating that erosion is expected to expose waste rock on relatively thin covers. The plot with a 1.0 m thick cover did not show improved erosion performance due to cover thickness compared to plots with 0.7 m thick covers. Uncovered areas remain largely bare and unvegetated, and they are unlikely to develop the vegetation required to achieve the end land use.

The plot observations indicate that a cover thickness of 0.7 m is suitable for accommodating erosion while keeping waste rock covered. Erosion may expose waste rock on thinner covers and thicker covers do not provide erosion advantages.

4.1.6 Qualitative ranks

Only one sub-plot received a rank of five, with a slope of 3.0H:1.0V, microtopography surface grading, a conifer-deciduous vegetation prescription and minimal run-on features on the upstream crest. A rank of four was limited to sub-plots on the slope and lower bench. These sub-plots had microtopography surface grading, with a small number also being cross-ripped or on peat-mineral mix soils. A rank of one or two was generally assigned for sloped sub-plots with corrugated surface grading and areas on the crest showing widespread pavement development. A limited number of sub-plots with microtopography surface grading also received a rank of one or two, and either showed appreciable erosion attributed to run-on from the crest above or were below slopes with appreciable erosion.

Statistical analyses were used to evaluate the importance of observed differences between sub-plots and to test the confidence of empirical interpretations of cover performance. Linear regression models were used to assess the statistical significance of the effects of various factors on cover performance. The results of the qualitative ranks analysis that were judged to be statistically significant given the size and variability of the input dataset were:

- The plateau crest areas showed significantly poorer performance than both the slopes ($p < 0.001$) and lower bench ($p < 0.01$).
- A 0.7 m thick cover showed significantly better performance than a 0.3 m cover ($p < 0.05$).
- Cross-ripped microtopography performed significantly better than the other surface grading methods ($p < 0.05$).
- An initial rye seeding prescription may provide better performance compared to other seeding mixes ($p < 0.15$).

4.2 Ecological observations

4.2.1 Leaf-area index and revegetation

Site-wide vegetation abundance was quantified using LAI estimates. September 2024 LAI values, averaged by plot, ranged from 0.2 to 1.0 m^2/m^2. These values are below those typical of mature conifer forests (i.e 2 to 5 m^2/m^2; Pope & Treitz 2013). This result is expected given the young age of the reclaimed forest on the test cover. On the slopes, LAI was highest where deciduous (green alder) and coniferous seedlings were planted together, and the cover thickness is at least 0.7 m. On the plateau, LAI was typically highest in areas of relatively high peat content, which is discussed further in Section 4.2.2.

4.2.2 Effects of peat on seedling survival and health

Peat content of the reclamation cover material is interpreted to be the key driver of seedling survival and health. The original design for the test cover specified cover materials with a peat content of 10 to 30% by volume, but as-built conditions showed a range of peat contents. Sloped areas received little to no peat in the cover materials, while the cover material has highly variable peat content in the plateau area. Visible spectra from drone imagery were manually classified to delineate higher-peat and lower-peat pixels to evaluate the relationship between peat content and conifer survival and vigour.

Mean survival rates for jack pine and white spruce in areas of high and low peat content are shown in Figure 6. Initial decreases in survival rates were due to seedling pulling by birds and mortality during the first winter. Analysis with a binomial generalised linear model found that conifer survival was significantly higher in areas with higher peat content for white spruce (26% higher survival; $p < 0.01$) and jack pine (22% higher survival; $p < 0.01$). Where peat contents are high, survival rates of both species stabilised after two growing seasons. Comparing the two conifer species, white spruce survival rates are higher than those of jack pine where peat contents are high; where peat contents are low, jack pine survival continues to decline over time while spruce survival is relatively stable.

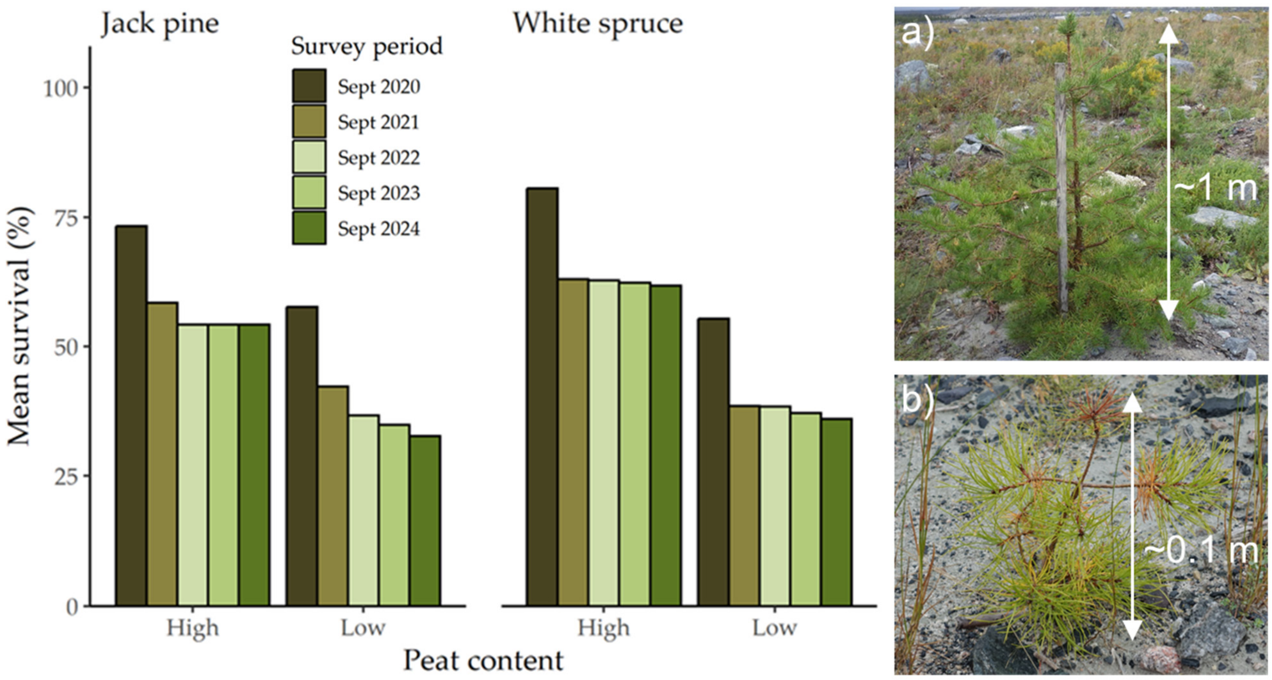

Figure 6 Survival of jack pine and white spruce by peat content: (a) Example of healthy (high vigour) jack pine in high peat content area; (b) Example of chlorotic (low vigour) jack pine in low peat content area

While the overall survival rates of jack pine are lower than white spruce, surviving jack pine generally had higher vigour rankings. Higher vigour in jack pine was observed in areas with higher peat contents (Figure 6). Larger jack pine seedlings growing in high peat areas are now reproductively mature (i.e. producing cones), though there is no evidence of the establishment of new seedlings from these cones.

There are several benefits of incorporating peat into reclamation cover materials. Peat contains nutrients (primarily nitrogen) beneficial to plant growth and has a higher nutrient- and water-holding capacity than mineral soil. In addition, peat reduces the overall growth medium bulk density, making it easier to plant seedlings with larger plugs. If seedlings are installed properly (i.e. the entirety of their rooting structure is buried beneath the soil surface and the root plug is not deformed) they have a higher chance of survival. Benefits of peat can be seen in the higher survival rates and vigour of those seedlings growing in areas with higher peat content.

4.2.3 Green alder success

Surviving green alders are growing well, with many individuals reaching heights greater than 2 m after five growing seasons (Figure 7). Although the initial survival rate of alders was substantially lower than that of the conifer species, apparently due to preferential pulling of alder seedlings by animals, remaining alder seedlings are growing vigorously and with a stable survival rate that is higher than jack pine after five years. This survival rate is strong evidence supporting the continuing use of relatively high densities of alder in the reclamation planting program at DLM.

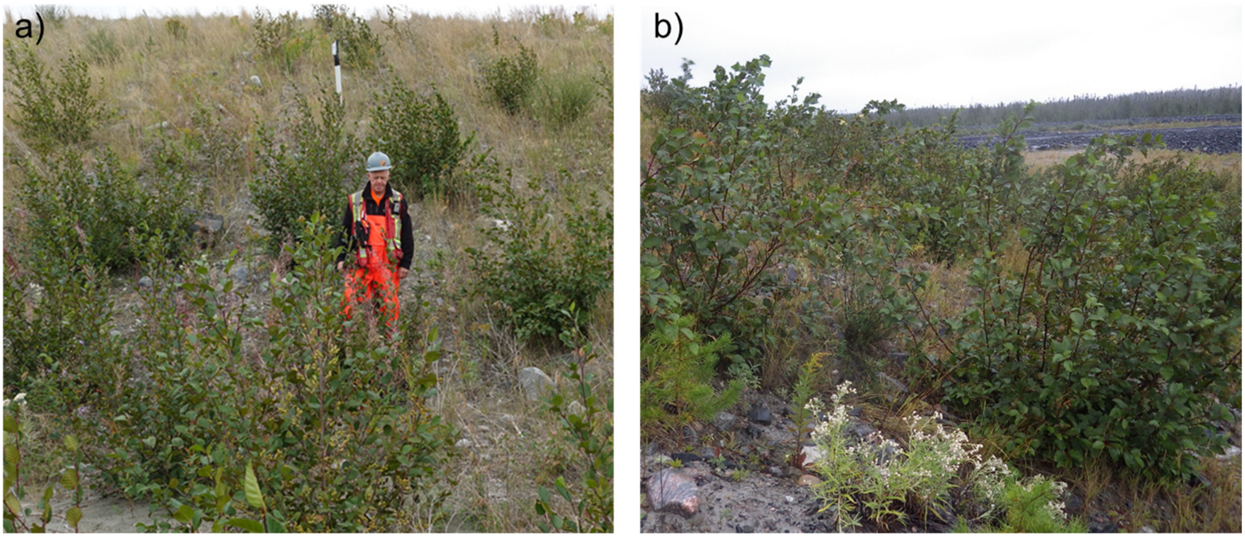

Figure 7 Green alder with: (a) A person for scale; (b) Jack pine (front left and centre)

Green alders support the end land-use goal of providing caribou habitat through the establishment of conifer forest. Alder has a symbiotic fixation of atmospheric nitrogen, which supports high growth rates and annual deposition of relatively large amounts of nutrient-rich leaf litter. In addition, taller alders provide some shade to conifers and some protection from wind. Alders are less affected by winter desiccation than conifers, as they do not have leaves during frozen conditions with low water vapour concentrations in the air. In addition, alders are not particularly palatable to browsing ungulates and are not an attractant to moose that would be counteractive to the caribou habitat goal.

4.2.4 Plot characteristics

While peat content is interpreted to be the most important factor for revegetation success (Section 4.2.2, cover thickness, surface grading and topography also affect seedling survival and health as follows:

- Cover thickness: seedling survival rates were significantly higher in areas with 0.7 m thick covers compared to those with 0.3 m thick covers (approximately 20% higher survival; $p < 0.001$). Additionally, uncovered areas remain largely bare and unvegetated
- Surface grading: seedling survival was significantly higher ($p < 0.01$) in areas that received additional excavator ripping than in corresponding plots that were not ripped after cover placement (Section 2.6). This higher survival is primarily attributable to better performance over the first winter, with mortality similar after this period. This finding of higher survival on ripped plots aligns with fine-fraction density being lower at the time of planting in plots that received additional excavator ripping (Cash et al. 2022). This effect could be due both to reduced soil densities in these areas facilitating plant establishment and making high-quality planting easier
- Slope position and aspect: survival rates are higher in topographical conditions that provide protection from snow scouring and winter desiccation, such as flat and lower-slope areas and east-facing aspects. The edges of the plateau, north- and northeast-facing slopes, and upper-mid slope positions have the lowest survival rates due to the high levels of wind exposure. The predominant northerly wind decreases accumulation of protective, insulating snow cover on seedlings, exposing them to harsh winter conditions and desiccation.

Vegetation establishment was poor along the crest. This is likely related to the observed widespread development of erosion pavements and soil crusts in these areas (Section 4.1.1).

4.3 Instrumentation

An example of typical soil moisture conditions on a test cover plot is shown in Figure 8. Cover material soil-moisture content generally ranged from 0.10 to 0.35 m^3/m^3 and soil-water tension was generally less than 100 kPa during non-winter months. Soil moisture conditions show expected responses to wet and dry periods. Spatial variability in soil moisture conditions was primarily driven by snow redistribution, where the east aspect had substantially more snow than other areas, leading to limited soil freezing and increased moisture availability on this aspect (not shown).

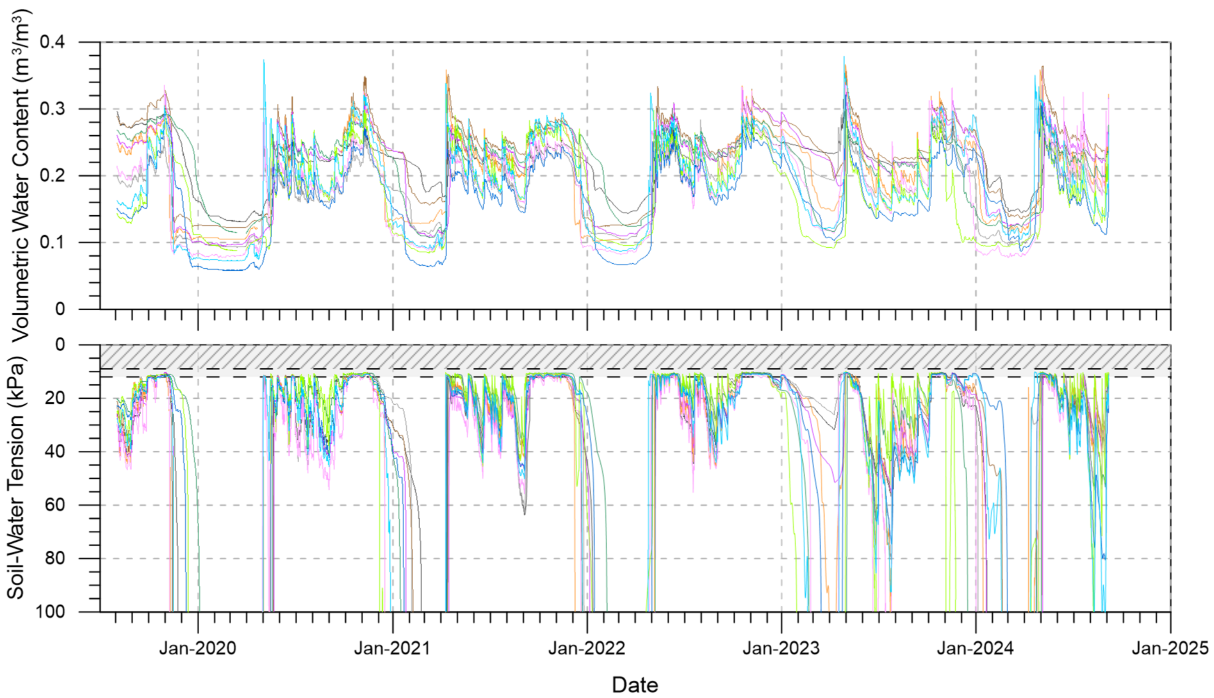

Figure 8 Soil-moisture content and soil-water tension data from a north-facing plot. Coloured lines represent 12 different sensors, with lighter colours at 0.2 m depth and darker colours at 0.5 m depth. The hatched area on the soil-water tension plot is outside the measurement range of the sensor. The sensors do not provide representative data for winter periods

Spikes in soil-moisture content coupled with soil-water tension at the sensor limit suggest that the cover, or at least a portion of it, may briefly become saturated in response to spring snowmelt and large rainfall events. This observation indicates the potential for decreased stability of the cover materials during these times. However, large-scale geotechnical instabilities have not been observed in the cover material (Section 4.1).

Maximum soil-water tensions during non-winter months have rarely reached the permanent wilting point; only briefly reaching this point at a limited number of sensors in certain years. The soil-moisture conditions indicate that the cover materials are retaining water that is available for plant uptake.

These soil-moisture data have also been used in numerical hydrological models to simulate water balance partitioning and estimate net percolation rates through the cover (Harrington et al. 2022), and in ecohydrological models to predict future ecosystem occurrence (e.g. Baker et al. 2020). Results of the hydrological models are not discussed herein.

5 Summary and outlook

The goal of the test cover program at Detour Lake Mine (DLM) was to evaluate the performance of different cover system characteristics to support the initiation of progressive reclamation of mine rock stockpiles (MRS). The objectives established as part of the design basis (Section 2.2) have broadly been achieved.

All the test cover slopes maintained the cover in place as there were no large-scale geotechnical instabilities within the cover. This result indicates that, for the range of slope angles constructed, slope angle does not limit the use of the drift/till cover material. Observations and data were collected to evaluate the performance of cover and vegetation prescriptions, and the findings from the analysis of these data are listed below. While the test cover considered a range of cover material prescriptions within the design basis, the prescriptions were limited to mono-layer covers, given the design objective of establishing a conifer forest. Therefore, the performance of more complex layered cover systems was not assessed by the test cover. Lastly, the partitioning of the cover water balance was evaluated by Harrington et al. (2022).

Based on five years of monitoring results, the geotechnical performance of the test cover has exceeded initial expectations for the silt-rich cover material, and apparent rates of erosion and deposition have slowed over time. In terms of revegetation performance, average densities of conifers on planted areas of the test cover are within the range required to produce the end land-use goal of closed-canopy forest, but are nearing the lower end of that range, with some ongoing mortality.

The test cover monitoring program has provided observations and data to establish design guidance for planning of future MRS reclamation at DLM under the current design basis. These recommendations, summarised below, are intended to support the long-term reclamation goal of providing caribou habitat:

- Organics and peat: include a minimum of 15 to 30% peat (by volume) mixed in reclamation covers to improve vegetation survival and vigour, and to reduce erosion.
- Vegetation planting: plant conifers at a density of 3,000 sph (2,000 sph jack pine, 1,000 sph spruce) to account for mortality due to animal removal and to reach dense coniferous forest targets. Co-plant alders with conifers at a density of 2,500 sph for a total planting density of 5,500 sph. Planting should be completed as quickly as possible following cover placement to minimise erosion.
- Vegetation seeding: promote the rapid establishment of vegetation on slopes where erosion is a concern, with co-seeding of oats or cereal rye at rates of up to 125 kg/ha with a native seed mix. Seeding should also be completed as soon as practical after cover placement to minimise erosion.
- Surface water run-on: establish berms near the top of crests or backslope benches and develop a network of ditches and downslope channels to convey surface water off the landform. This water management will limit the downslope flow of water and its resulting erosion.
- Surface grading: implement microtopography or ‘rough-and-loose’ surface grading (Polster 2009), with hummocks and hollows laterally offset in the downslope direction to reduce erosion.

Hummock and hollow features should be small, with amplitudes on the order of tens of centimetres and lateral dimensions of approximately 1 to 3 m.

- Cover thickness: a cover thickness of 0.7 m, with suitable peat content and bulk density, provides sufficient water storage for vegetation, achieving the design objectives of the test cover.
- Slope length: limit slope lengths to a single regraded bench face for 15 m benches to limit erosion.
- Slope angle: regrade inter-bench slope angles to within a range of 2.5H:1.0V to 3.0H:1.0V to provide a good compromise between operational and functional constraints.
- Slope aspect: consider how slope aspect affects snow redistribution and cover water balance when designing landforms and reclamation covers, and when selecting plant species for revegetation.

These recommendations are being implemented in ongoing progressive reclamation of MRS at DLM, and continued monitoring of the test cover and other reclamation areas will be used to refine reclamation techniques.

Acknowledgement

The authors would like to acknowledge that the Detour Lake Mine is located on Treaty 9, the traditional territory of the Moose Cree First Nation, Apitipi Anicinapek Nation and Taykwa Tagamou Nation, and lands historically utilised by Métis People.

The authors would also like to acknowledge the support of the multidisciplinary team that has contributed to this program over the past five years, including the Detour Lake Mine Environment and Operations teams, BGC Engineering, Integral Ecology Group, McKenna Geotechnical, the University of Waterloo, the University of Alberta and the University of Guelph.

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