Cold Regions Cover Research – Phase 2

MEND Report 1.61.5b

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and

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Executive Summary

The Mine Environment Neutral Drainage program recently completed a review of soil covers on mine wastes in cold regions (MEND 1.61.5a 2009). Several dozen cold regions processes were identified as potentially important for soil covers. These effects can develop slowly enough that they may not be obvious in current observations of soil covers,, but quickly enough that they could have significant negative effects over a cover's design life.

The current report presents the results of a series of tasks that each represent a small advance in the state of cold regions cover research:

- Cold regions phenomena identified in MEND 1.61.5a are characterized as "observed", "suspected", "expected" or "not expected" to affect the performance of various types of soil covers.
- The role of vegetation on cold regions covers is reviewed and available literature on cold regions evapotranspiration and rooting depth are surveyed.
- The state of the art of computer modeling of cold regions soil covers and related hydrologic processes is reviewed.
- Possible applications of convective cooling in both flat and sloping soil cover designs are examined using a series of bounding calculations.
- The potential for insulating layers to limit freeze-thaw effects on low-permeability barrier layers is examined.
- Ongoing soil cover trials or research programs in locations that might experience cold regions effects are identified and tabulated.

A series of additional studies are recommended for consideration. High priorities for immediate action are:

- Inspections of existing cold regions covers to identify and characterize cold regions effects;
- Continued information exchange to increase the likelihood that cold regions phenomena in existing covers will be properly identified, and to ensure that potentially negative effects are taken into account in the design of new covers; and
- Addition of evapotranspiration, root depth and related vegetation studies to ongoing cold regions cover trials.

Résumé

Le Programme de neutralisation des eaux de drainage dans l'environnement minier (NEDEM) a récemment achevé un examen des couvertures de sols construites sur des résidus miniers en milieu nordique (NEDEM 1.61.5a 2009). Plusieurs douzaines de processus en milieu nordique ont été identifiés comme étant potentiellement importants pour les couvertures de sols. La progression de ces processus est quelquefois si lente que les processus sont imperceptibles lors des observations ordinaires des couvertures de sols, mais elle peut être si rapide que les processus pourraient avoir des effets négatifs importants sur la durée de vie théorique des couvertures.

Le présent rapport expose les résultats d'une série de tâches. Chacune représente un petit progrès dans le domaine de la recherche sur les couvertures de sols en milieu nordique :

- Les phénomènes en milieu nordique décrits (NEDEM 1.61.5a) sont caractérisés pour leurs répercussions sur le rendement des divers types de couvertures de sols : « observé », « présumé », « attendu » ou « non attendu ».
- Le rôle de la végétation dans les couvertures en milieu nordique est examiné; la documentation disponible sur l'évapotranspiration et la profondeur de l'enracinement en milieu nordique sont passée en revue.
- La modélisation informatique à la fine pointe de la technologie des couvertures de sols en milieu nordique et des processus hydrologiques associés sont examinés.
- Les applications potentielles du refroidissement par convection dans la conception des couvertures de sols sur les terrains plats ou en pente sont examinées à l'aide d'une série de calculs de limite.
- On examine le potentiel qu'ont les couches isolantes de limiter les effets du gel-dégel sur les couches étanches de faible perméabilité.
- Les essais continus ou les programmes de recherche portant sur les couvertures de sols dans les lieux pouvant être soumis aux effets des milieux nordiques sont identifiés et présentés sous forme de tableau.

  Une série d'études supplémentaires est recommandée à des fins de considération. Une priorité élevée devrait être accordée aux mesures immédiates suivantes :

- Inspections des couvertures existantes en milieu nordique pour décrire et caractériser les effets en milieu nordique;
- Échange d'information continu pour accroître la probabilité que les phénomènes des milieux nordiques touchant les couvertures existantes soient identifiés correctement et pour veiller à ce que les effets potentiellement négatifs soient pris en compte dans la conception des nouvelles couvertures;
- Ajout des éléments suivants aux essais continus portant sur les couvertures de sols en milieu nordique : évapotranspiration, profondeur de l'enracinement et études connexes sur la végétation.

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1 Introduction

1.1 Background

The Contaminated Sites Program of Indian and Northern Affairs Canada (INAC-CSP) is responsible for the remediation of contaminated sites on Crown land throughout the Canadian north. In dollar terms, approximately 80% of the remediation liabilities faced by INAC-CSP are associated with abandoned mines, and the need to construct soil covers over tailings and waste rock represents at least one-third of the mine-related liabilities. The appropriate design and long-term effectiveness of soil covers is therefore of central importance to INAC-CSP and to most of the local and regional stakeholders.

The Mine Environment Neutral Drainage (MEND) program recently completed a Phase 1 review of soil covers on mine wastes in cold regions (MEND 1.61.5a 2009). Several dozen cold regions processes were identified as potentially significant for soil covers. The most widespread processes are ground freezing and ground ice formation, ground thawing and thaw settlement, and freeze-thaw cycling. Combinations of these processes with specific soil or hydrologic conditions can change soil properties such as compaction and permeability, or lead to the development of macroscopic features such as solifluction, cracking, mounding or hummocks, or mudboils. These effects can develop slowly enough that they may not be obvious in current observations of soil covers, but quickly enough that they might have significant effects over a cover's design life.

The Phase 1 review concluded that designing cold regions soil covers using the current methods, which are largely derived from experience in temperate zones, should not be considered best practice. It also highlighted opportunities to improve the understanding of how cold regions processes affect soil cover performance, and to advance the state of knowledge of cold regions cover design and construction. In late 2008, INAC-CSP and MEND commissioned SRK Consulting (Canada) Inc. to pursue some of the opportunities described in the MEND report. The results are presented herein.

1.2 Report Structure

The report presents the results of a series of tasks that each represent a small advance in the state of cold regions cover research:

- Chapter 2 reviews cold regions phenomena and identifies those that could significantly affect the performance of various types of soil covers.
- Chapter 3 presents the results of supplemental work on some of the questions raised in the MEND report, specifically the role of vegetation on cold regions covers, the state of the art of computer modeling of cold regions covers, the possible application of convective cooling, and the effects of cover designs on the freeze-thaw behaviour of low-permeability layers.

- Chapter 4 provides a list of soil cover trials or research programs that are currently underway in locations that might experience cold regions effects.
- Chapter 5 presents recommendation for further research, as developed through meetings or telephone discussions with consultants and researchers currently practicing in these areas.

1.3 Acknowledgements

SRK's role in this project included compiling input from many other specialists. The authors acknowledge with thanks the contributions from: Mr. Justin Straker (CE Jones & Associates Ltd.), Mr. Michael O'Kane and Mr. Brian Ayres (O'Kane Consultants Ltd.), Dr. Lee Barbour (University of Saskatchewan), Mr. Rick Janowicz (Yukon Department of Environment), Dr. Jean-Marie Konrad (Laval University) and Dr. Ward Wilson (University of British Columbia). The contributions of the project sponsors, Mr. Mike Nahir (INAC) and Mr. Gilles Tremblay (MEND), and the Project Manager Ms. Tracy Ma (INAC) are also gratefully acknowledged.

2 Cold Regions Phenomena

This chapter reviews cold regions phenomena and identifies those that might be expected to affect the performance of various types of soil covers. The Phase 1 report introduced the term "cold regions phenomena" to refer to both cold regions processes and cold regions features. The same report proposed two groups of importance to soil covers, namely "frozen ground phenomena" and "cold regions hydrologic phenomena".

The lists of frozen ground and hydrologic phenomena presented in the Phase 1 report were reviewed by a small group consisting of representatives of INAC, SRK, O'Kane Consultants Inc., and the University of Saskatchewan. The group discussed each phenomena and assessed its potential to impact mine waste covers.

The group considered the following broad categories of covers:

- Water covers make use of a pond to completely cover the underlying waste, typically to prevent oxidation of potentially acid generating materials;
- Wet covers are soil covers that remain saturated at all times, primarily to prevent oxidation of the underlying waste;
- Barrier covers incorporate at least one low permeability soil layer to limit the infiltration of water, and in some cases, the ingress of oxygen;
- Geomembrane covers are a form of barrier cover that incorporate a geosynthetic membrane to limit infiltration and oxygen ingress;
- Store-and-release covers make use of a thick layer of soil to store water until it can evaporate or be transpired by plants;
- Isolation covers are generally thin soil or rock layers intended only to prevent direct contact of animals and vegetation with the underlying waste; and
- Insulation covers limit the amount of heat penetration during summer and allow the waste to freeze or remain frozen.

The following categories were used to evaluate the evidence of each phenomenon occurring within each cover type:

- Observed (Code O) – The phenomenon has been observed to occur on an existing cover.
- Suspected (Code S) – Observed features are suspected to have been caused by the phenomenon.
- Expected (Code E) – The current understanding of the phenomenon suggests that it should occur, but it has not been observed. (This includes many phenomena that are expected to occur at rates that are too slow to be observable as yet, given the relatively short experience with cold regions covers.)
- Not Expected (Code N).

Finally, the likelihood that each phenomena would have significant negative effects on cover performance was assessed as follows:

- Likely (Code 1) to affect performance,
- Unlikely (Code 2) to affect performance, or
- Uncertain (Code 3) of whether it would affect performance.

Table 2.1 shows the results of the assessment. The first noteworthy point is that there are very few cases where cold regions phenomena have been definitively observed in soil covers. Examples include mudboils on the tailings covers at the Discovery and Beaverlodge mines, and peat boils at the Syncrude cover test trials in Fort McMurray (personal communication with L. Barbour).

There are a greater number of cases where there is some evidence of cold regions phenomena. Cryoturbation, *i.e.* the churning of soil by freeze-thaw processes, is suspected to be the cause of features observed in cover test plots on the Rose Creek tailings at Faro Mine. The development of micro-topography features running across the slopes at the Syncrude test facility is suspected to be evidence of incipient solifluction, *i.e.* the down-slope movement of soils caused by periodic freezing and thawing. The movement of boulders in the tailings covers at Discovery mine may be evidence of the processes that ultimately form boulder fields and/or patterned ground in natural soils. Localized surface disturbances related to freeze-thaw cycles are common at many sites, and could be evidence of frost mounding or incipient hummock formation.

Table 2.1 also indicates that some cover types are much less sensitive to cold regions phenomena than others. Water- and wet (saturated) covers are expected to be the least affected by cold region processes. However, ice-formed terrain features such as palsas and pingos have been observed in cold regions tailings deposits, and could also occur in saturated soil covers.

Frozen ground phenomena are expected to have greater effects on barrier covers. The reason is that freeze-thaw processes threaten the integrity of the low permeability layer that forms the core of any barrier cover.

Geomembrane covers are less likely to be affected by cold regions phenomena, because the geosynthetic barrier is generally not affected by freezing. However, in most cases the longevity of the geomembrane is ensured by providing a protective layer, which is expected to be subject to frozen ground phenomena such as solifluction. It is even possible the trapping of moisture above the geomembrane could increase solifluction in a protective layer.

Table 2.1. Cold regions phenomena that could affect mine waste covers

	Cover Types						
	Water Cover	Wet Cover	Barrier Cover	Geomembrane Cover	Store-and-Release Cover	Isolation Cover	Insulation Cover
Frozen Ground Phenomena							
Ground freezing and ground ice formation	N	N	E1	E2	E1	E2	E3
Ground thawing and thaw settlement	N	N	E2	E2	E2	E2	E2
Freeze-thaw cycles	N	N	E1	E2	E1	E2	E3
Cryoturbation	N	N	S2	S2	S2	S2	S2
Mass-wasting (including solifluction/gelifluction)	N	N	S1	S1	S1	S1	S1
Convective cooling	N	N	N	N	N	S2	E1
Ice wedges	N	N	S1	S2	S1	S2	S2
Palsas	S1	S1	N	S2	N	N	N
Pingos	S1	S1	N	S2	N	N	N
Thermokarst	N	S2	E1	E2	E2	E3	E3
Patterned ground	N	N	S1	S1	S1	S2	S1
Boulder fields and pavements	N	N	S1	S2	S2	S2	S2
Mounds and/or hummocks	N	N	S1	S2	S2	S2	S2
Seasonal frost mounds	N	N	S1	S2	S2	S2	S2
Mudboils, circles and diapirs	N	N	O3	O3	S1	S1	S3
Involutions	N	N	E2	E2	E2	E2	S3
Rock glaciers	N	N	N	N	N	S3	S3
Ploughing boulders	N	N	S2	S2	E2	S2	S2
Cold Region Hydrologic Phenomena							
Snow accumulation and ablation	N	N	E2	E2	E1	E2	E1
Snowmelt	N	N	E2	E2	E1	E2	E1
Evapotranspiration	N	N	E2	E2	E1	N	E2
Surface water drainage	E2	E2	E2	E2	E1	E2	E2
Aufeis	N	S2	N	N	S1	S2	S2
Infiltration to frozen soils	N	N	E1	E2	E1	E2	E3

Note: Explanation of Codes:

Strength of evidence:
O – Observed
S – Suspected
E – Expected to occur but not yet observed
N – Not expected to occur

Likelihood of detrimental effects
1 – Likely
2 - Unlikely
3 - Uncertain

Store-and-release covers rely on their ability to retain excess soil moisture in the profile for release via summer evapotranspiration. Cold regions hydrologic phenomena like snow redistribution and rapid snowmelt could lead to the moisture storage capacity being overwhelmed, and the limited energy available for evapotranspiration can impair the release of moisture. On the other hand, store-and-release covers are generally less susceptible to changes in soil structure, and therefore are expected to be less sensitive to frozen ground phenomena.

Isolation covers are considered successful as long as the underlying waste is not exposed. In cases where an isolation cover is constructed of fine-grained material with sufficient moisture content, it would be susceptible to frozen ground phenomena. However, unless waste is exposed, for example by mudboils, the overall effectiveness of the isolation cover would not be impaired.

Insulation covers are likely to be designed through careful consideration of ground freezing processes, and perhaps even to take advantage of phenomena such as thermal convection. They would however be negatively influenced by cold regions hydrologic processes that could significantly increase the local moisture content and thereby change the thermal balance.

3 Supplemental Investigations

This chapter presents the results of supplemental work on some of the questions raised in the Phase 1 report, specifically the effects of vegetation on cold regions covers, the state of the art of computer modeling of cold regions covers, the possible application of convective cooling, and the control of freeze-thaw impacts on low-permeability layers.

3.1 Effects of Vegetation on Cold Regions Soil Covers

3.1.1 Background

The presence of vegetation can have both positive and negative effects on the performance of soil covers. Positive effects include protection of the cover from surface erosion and shallow instability in all cover types, and enhanced evapotranspiration leading to reduced infiltration in both store-and-release and low-permeability covers. Possible negative effects include penetration of barrier layers by roots. Some forms of vegetation also influence the capture, melting and runoff of snow, which can have both positive and negative effects on soil cover performance.

The effects of vegetation on cold regions soil covers were generally outside the scope of the Phase 1 report. To attempt to fill that gap, Mr. Justin Straker, a specialist in the reclamation of northern mine sites, was asked to review and summarize the available literature. The results are presented in the following sections.

3.1.2 Effects of Vegetation on Erosion

A large number of studies attest to the important role of vegetation in reduction of soil erosion, often regardless of whether the type of vegetation is native or established through reclamation (e.g. Vanacker *et al*. 2007). Plant canopies provide protection against the destructive effect of rain droplets on soil aggregates and thus significantly reduce relative soil detachment rate (Williams *et al*. 1995, Ternan *et al*. 1996, Woo *et al.* 1997, Rey *et al*. 2004, Thompson *et al*. 2004, Zuazo and Pleguezuelo 2008). Vegetation can also contribute significantly to stabilisation of sloping terrain by reinforcing the soil (increasing soil shear strength). This reinforcement depends on the morphological characteristics of the root systems (Reubens *et al*. 2007) and the tensile strength of single roots (Ali and Osman 2008).

The results of studies by De Baets *et al*. (2007a) suggest that with increasing root diameter the erosion-reducing effect of roots becomes less pronounced. Consequently, tap roots tend to reduce the erosion rates to a lesser degree than fine-branched roots. Several studies (Gyssels *et al*. 2006, De Baets *et al*. 2006, 2007a, b) suggest a negative exponential relationship between the relative soil detachment rate and root density as well as root length density, independent of the runoff flow shear stresses. Relative soil detachment rates decrease to very low values (e.g. by 90% - Gyssels *et al*. 2006) with an increase in root density from 0 to 4 $kg.m^{-3}$ or root length density from 0 to 400 km.m^{-3}. Accordingly, grass roots are very effective in reducing soil detachment rates (De Baets *et al*. 2006, 2007a, 2007b).

While many studies concentrate on the effects of vegetation canopy or on the effects of roots, in reality soil loss reduction likely results from the combined effects of roots and canopy cover. Studies by Gyssels *et al*. (2005) and De Baets *et al*. (2007a, b) strongly suggest that increasing vegetation cover as well as the increasing root mass, both exhibit exponential effects on decrease in water erosion rates. Nevertheless, despite the similarity in the magnitude of their protective effect, it appears that canopy and root characteristics each have their specific mechanisms of influence. Zhou and Shangguan (2008) demonstrated that canopies contribute more to the runoff reduction than the roots, whereas roots contribute mainly to the decrease in sediment yields. It also appears that canopy cover is the most important vegetation parameter associated with splash and inter-rill erosion, whereas for rill and ephemeral gully erosion plant roots are at least as important as vegetation cover (Gyssels *et al*. 2005).

Deposition of organic matter under vegetation canopies and resultant formation of organic surface soil horizons can also reduce erosion of underlying mineral soil, primarily through storage (absorption) of precipitation and attenuation of runoff.

Experiments in steep ravines conducted by Cammeraat *et al*. (2005) suggest that the root contribution to soil strength is limited there to the relatively shallow upper layer of the soil. However, most slope failures tend to occur at greater depths (>1 m) where soil reinforcement by roots is not effective or absent. Stokes *et al*. (2007) have shown that surficial roots contribute little to slope stability. It also appears that most soil reinforcement by roots occurs close to the tree stem and is negligible at a distance > 1.0 m from the tree (Danjon *et al*. 2008). It is also possible that vegetation can enhance instability in certain circumstances, by promoting water infiltration to the shear plain through macro-pores produced by deep roots.

Obviously, for application to protection of mine-waste covers, the initial (immediately following revegetation) contribution of vegetation to reduction of erosion will be minimal. Depending on vegetation type, it could take up to 5 growing seasons for this effect to be significant. Use of plant species that have rapid establishment and that form continuous ground covers will generally enhance reduction of surface erosion, and provide this benefit in a shorter time (e.g. by the second growing season after revegetation), while use of slower-growing vegetation will provide less initial benefit. Shorter growing seasons associated with higher latitudes and altitudes will lengthen the time required for establishment of a vegetation cover sufficient to contribute to erosion reduction.

3.1.3 Evapotranspiration

Evapotranspiration (ET) is a process of exchange of moisture and heat between the earth surface and the atmosphere, which occurs through evaporation of water from the soil surfaces, and through transpiration of water by vegetation. The intensity of ET depends on solar radiation, air and soil temperature, humidity, and wind velocity. In addition to these factors, evaporation from the soil surface is influenced by soil ability to store and transmit water (e.g. surface roughness, soil structure, texture, organic matter content, presence of non-permeable layer such as rock, ice or clay), while transpiration is regulated by plant morphology and physiology (e.g. plant structure and size, leaf anatomy, rooting depth, water use efficiency, photosynthetic capacity, age). While in a non-vegetated soil only the moisture from upper soil horizons is available for evaporation, vegetation facilitates movement of water from deeper soil horizons through water uptake by plant roots.

Controls on Cold Regions Evapotranspiration

Typical daily ET values in cold regions range from approx. 0.5-6.0 mm (see Table A-1, Appendix A), with observed annual values ranging from approximately 125-475 mm. Petrone *et al*. (2000) reports that, generally, ET accounts for approximately 50% of precipitation across mainland subarctic and arctic North America (with somewhat lower values among the arctic islands, and higher values during summer in subarctic wetland areas). Variation around these typical values is influenced by:

- Month/stage of growing season – ET rates change substantially throughout the year as they are affected by seasonal changes in air and soil temperature, insolation, air humidity, soil moisture and leaf area index (see below). In the spring, even during the sunny days, ET rates are low because frozen soils restrict water uptake by plants (Halldin *et al*. 1980, Teskey *et al*. 1984), and because night frost events can damage young leaves and temporarily reduce plant photosynthetic capacity and thus transpiration (Hallgren *et al*. 1990, 1991). Typically ET increases from May to a seasonal peak in July, and then gradually decreases (Vourlitis and Oechel 1999). At that time most of the variation in evaporation is associated with daily changes in insolation, wind velocity and humidity (Baldocchi *et al*. 2000). From September decreasing air temperature and early frost events are associated with a decline in ET. In the winter time, evaporation is high from snow-covered surfaces, but when vegetation is snow-free evaporation is minimal (Harding and Pomeroy 1996). Of the typical values reported above, lower daily values of approximately 0.5 mm are associated with the beginning and end of the growing season (typically May/June and August/September, respectively, depending on latitude and altitude). Higher values are associated with vigorous communities (e.g. boreal aspen) at the peak of the growing season, in the absence of substantial soil moisture deficits.

- Climatic controls – growing-season precipitation and antecedent soil moisture conditions can strongly influence ET. Amiro *et al*. (2006) reported annual variation of 20% from average ET values, with precipitation levels being a strong control on this variation.

- Leaf area index – leaf area index (LAI) is influenced both by vegetation type (see below) and vegetation community age. ET values are strongly correlated with LAI, and so will be maximized when LAI is highest. Patterns of LAI development over time also vary by vegetation community type. LAI trajectories for forest stands occur over decades, with these stands typically reaching maximum LAI at the time of crown closure, which may be at age 30-50 years after stand initiation, depending on the species and location. LAI trajectories for forb- and/or shrub-dominated communities are generally much shorter, with maximum LAI being achieved within five years of establishment in many forb-dominated communities.

- Vegetation type – see below.

Effect of Cold Regions Vegetation Type on Evapotranspiration

Local terrain (e.g. slope, aspect), soil type (e.g. texture, fertility, solum thickness), moisture regime, ecology, and climate all affect the vegetation that will eventually develop on a site (Gibson *et al*. 1993, Slaughter and Kane 1997). Consequently, site conditions may restrict the species available for revegetation of mine-waste covers. Nevertheless, once established, vegetation type has a significant influence on site microclimate, especially on the exchange of the energy and moisture between soil and atmosphere.

McFadden *et al*. (1998) report daily peak-growing-season ET values ranging from 1.3-2.7 mm for different vegetation communities in arctic Alaska. These communities represent a diversity of vegetation types established on substrates of varying moisture regime, and represent approximately 90% of vegetation in arctic Alaska. ET in these communities was strongly correlated with vegetation species, cover and substrate moisture regime. Lowest daily ET values were associated with the dry heath tundra type, which is characterized by sparse (<70% cover) colonization by short (0.03 m) vegetation, accompanied by crustose lichens (16% cover) and exposed mineral soil and gravel (14% cover). In contrast, highest values were associated with the wet sedge tundra type, which is characterized by dense (>90%) cover of sedges and grasses, growing in areas that have standing water present for a majority of the growing season. Intermediate daily ET values (1.5-2.3 mm) were associated with intermediate vegetation types, characterized by dense (>90%) covers of common shrubs such as dwarf birch and willow, grasses, and *Sphagnum* mosses.

The intermediate daily ET values (1.5-2.3 mm) reported by McFadden *et al*. (1998) (and values for similar vegetation types in Table A-1) are representative of non-forest vegetation developing on mine-waste covers in cold regions, for the peak of the growing season. Reduced values (0.5-1.5 mm) would be expected before vegetation reaches maturity, and for the early and late periods of the growing season. Typical annual ET values for non-forest vegetation types in cold regions would range from approximately 150-300 mm, depending on stand density, vigour, species, and stage of development. Lower values (0-150 mm) would be applicable to juvenile communities developed on newly-reclaimed covers. Even in these lower-biomass, higher-latitude vegetation communities, contribution of ET to the surface hydrological balance is substantial, and has implications for design of mine-waste covers, particularly store-and-release covers, in cold regions.

Differences by vegetation type are also considerable for forested communities below the treeline. For example, boreal conifer stands tend to exhibit higher resistance to ET than broadleaved stands (Teskey *et al*. 1984, Betts *et al*. 1996, Grelle 1997, Jarvis *et al*. 1997, Kimball *et al*. 1997, Kelliher *et al*. 1998, Baldocchi *et al*. 1997, 2000, Amiro *et al*. 2006). Consequently, the ET observed for upland conifer forests typically reaches only 25 to 75% of the levels recorded for aspen stands (Black *et al*. 1996, Nijssen *et al*. 1997, Baldocchi *et al*. 2000). Based on Table A-1, the mean reported growing-season daily ET value for aspen is approximately 2.3 mm, while for jack pine stands it is approximately 1.3 mm.

Another difference between forest vegetation types involves the contribution of their understory to ET. During the leaf-on season, aspen stands have substantially higher LAI than conifer stands (Chen 1996, Black *et al*. 1996, Baldocchi *et al*. 2000); consequently the contribution of understory vegetation to ET is reduced (Black *et al*. 1996, Blanken *et al*. 1997). The opposite is true for the conifer stands – lower LAI and generally more open canopy allow a substantial evaporation input from understories (Lafleur 1992, Baldocchi *et al*. 1997, Grelle *et al*. 1997, Kelliher *et al*. 1997, 1998, Heijmans *et al*. 2004). Heijmans *et al*. (2004) reported that moss contributed considerably to boreal black spruce forest ET balance. Moss evaporation rates depended strongly on the openness of the forest and between June and September averaged 0.3 mm per day in the dense forest (*Hylocomium*), 0.9 mm per day in the open forest (*Hylocomium* and *Sphagnum*), and 1.5 mm per day in the bog (*Sphagnum*).

3.1.4 Root Penetration of Barrier Layers

Plant rooting effects are of particular interest to the design of low-permeability or barrier covers, where the primary objective of the cover is to minimize flow through the barrier layer. Deep roots have the potential to penetrate the barrier layer – thus barrier covers are either designed assuming the absence of vegetation (often requiring active vegetation control), or to incorporate a sufficient depth of protective material to prevent roots reaching the barrier layer. Information on typical and maximum rooting depths is therefore important to the design of mine-waste covers generally, and barrier covers in particular.

In a study of relevance to this issue, Stoltz and Greger (2006) demonstrated that roots were able to penetrate both to depth (1.7 m) in mine-waste soil caps (cover layers), and also into the sealing (barrier) layers. Roots of pine (*Pinus sylvestris*) had a particularly good ability to penetrate through hard layers. The addition of nutrients into the soil cap reduced deep root growth and thereby also penetration through the sealing layer. Low hydraulic conductivity of the sealing layer or a thick cover layer did not inhibit root penetration. Plants will produce deep roots to locate water or nutrients if these factors are limiting in shallower layers. Thus, as suggested for nutrients above, one option for discouraging deep rooting is to ensure that adequate water is present in the upper cover material.

Control of nutrient and water depth could be accomplished as follows:

- Nutrients – through fertilization or through high-nutrient amendments (such as particular forms of organic matter, e.g. mesic peat, biosolids).
- Water – through placement of water-retaining materials (e.g. organic matter) or layers in the soil. Both fine-over-coarse and coarse-over-fine textural discontinuities will slow vertical movement of water through the soil, and make it available for plant uptake. Since low-permeability mine-waste cover layers are frequently composed of compacted fine materials, it is possible that placement of a coarse layer immediately above the barrier would discourage rooting to the barrier layer itself.

Vegetation rooting depth also depends on soil factors such as texture, compaction, underlying bedrock, permafrost, water table, clefts, and other physical and chemical properties of the soil (Feldman 1984). Sites where the water table is close to surface or where impermeable soil layers prevent vertical water flow can inhibit development of deep roots if they result in anoxic conditions.

Macyk and Richens (2002) assessed root depth and distribution in reconstructed (mine-waste covers) and undisturbed soils at the Syncrude oil sands mine in NE Alberta. The results of this includes:

1. Rooting patterns were generally similar in the reconstructed and undisturbed sites.
2. The dominant component of the roots at all sites (undisturbed and reconstructed) occurred in the upper 30 cm of the soil.
3. Maximum rooting depths were similar at the reconstructed and undisturbed sites. The mean maximum rooting depth for four reconstructed forest sites with stand ages ranging from 12 to 20 years was 84 cm, compared to 68 cm for six undisturbed forest sites with stands ranging in age from 50 to 120 years.
4. Authors found no evidence of root inhibition or restriction by any of the different soil reconstruction materials (e.g. between the covers and underlying mine waste).

This review indicates that the majority of roots are found in surface soil horizons, well above potential barrier-layer location, that maximum rooting depth in systems well supplied with nutrients and water can be limited to less that 1 m below ground surface, and that, in general, undisturbed or pre-disturbance conditions can provide valuable information on probable maximum rooting depths in mine waste covers, provided that vegetation species are similar in both settings.

Further information on rooting depths and morphologies for different species and ecosystems is summarized in Tables A-2, A-3 and A-4 in Appendix A, based on results of several studies conducted in temperate ecosystems of Asia, Europe, and North America. In general, maximum root depths of herbs and grasses are generally lower than those of trees (Canadel *et al*. 1996, Tables A-2 and A-3). A comparison of maximum rooting depths for northern ecosystems (summarized by ecosystem type and corresponding species) indicates that in tundra ecosystems, the mean maximum root depth is 0.5 m, with a maximum value of 0.9 m. In contrast, for tree species characteristic of boreal forest ecosystems, the mean maximum reported rooting depth is 2 m, with a maximum value of 3.3 m. Agronomic forbs can achieve rooting depths similar to those of trees, with maximum values typically between 1 and 3 m, and even reportedly exceeding 3 m for brome (grass) and alfalfa (legume).

In general, North American and European spruce species tend to produce shallower root systems than most other boreal species (Canadel *et al*. 1996, Breuer *et al*. 2004, Kalliokoski *et al*. 2008). This generalization, however, cannot be extended to all conifer species (e.g. pine). While the mean maximum rooting depth of coniferous trees is slightly higher than that of deciduous trees (Breuer *et al*. 2003), it is difficult to conclude which group produces deeper roots due to high variability (Tables A-2, A-3, A-4).

Rooting depth is also linked with edaphic association and size of particular species. For example, while the water table usually limits rooting depth of boreal wetland tree species (tamarack [*Larix laricina*] and black spruce [*Picea mariana*]) to 0.3 m, other boreal species (e.g. willows) can extend their roots to a depth of 2 m below the water table (Strong and La Roi 1983). Thus, various plant species tend to develop particular types of root systems, which differ in structure, individual root size, and depth. Tap roots generally grow deeper into the soil compared to plate or heart shaped root systems (Breuer *et al*. 2004). Also older plants tend to have deeper root systems than younger ones (Table A-3).

3.1.5 Other Effects of Cold Regions Vegetation

Vegetation mediates soil temperature predominantly through the influence of leaf interception of sunlight. Although LAI is highest in broadleaved stands, this high LAI is a seasonal phenomenon – during spring and fall, aspen stands transmit more than three times as much light to understory compared to stands of white spruce (Constabel and Lieffers 1996). Further, the forest floor of conifer stands is often dominated by a feathermoss layer, which effectively insulates the soil from solar radiation and warm air. Consequently, in aspen stands soil warms up much faster in the spring compared to conifer-dominated ones. Fenniak (2001) demonstrated that growing-season soil temperatures in boreal conifer stands in Alberta were approximately 3°C lower than deciduous forest stands. Fox and Van Cleve (1983) reported similar results for boreal forest sites in Alaska. Cooler soil temperatures in conifer stands and/or denser stands may affect how long snow stays on the forest floor. Slower snow melt may in turn reduce runoff and soil erosion. However, in regions affected by permafrost, this correlation between cooler soil temperatures and reduced runoff may be reversed – as lower soil temperatures can enhance formation of permafrost.

Permafrost impedes vertical drainage and indirectly regulates water table (Carey and Woo 2001). Presence of permafrost and persistence of frozen ground also negatively affects snowmelt infiltration rates and increases levels of runoff (Carey and Woo 2001). Orradottir *et al.* (2008)

recorded significant differences in infiltration rates between land cover types in Icelandic shallow soils. Infiltration rates were consistently highest in broadleaved (birch) woodlands. The lowest infiltration rates were associated with frozen ground, which formed in spruce woodlands and in those grassland communities where snow depth in winter was shallow.

Vegetation capacity to intercept and store precipitation plays an important role in hydrology and energy budgets. It has been shown that vegetation patches enhance rainfall interception (Woo *et al.* 1997, Puigdefabregas 2005) and provide increased infiltration, and water storage capacity (Ternan *et al.* 1996, Puigdefabregas 2005, Orradottir *et al.* 2008), which in turn reduces runoff from vegetated areas (Woo *et al.* 1997). Furthermore, because snow is a major contributor to soil moisture in cold regions (Carey and Woo 2001), its slow melting and relatively low sublimation rates under conifer overstories appear to provide a considerable and extended storage and source of moisture (Price and Dunne 1976, Eaton and Wendler 1982, Carey and Woo 1998, Giesbrecht and Woo 2000, Woo and Giesbrecht 2000).

Vegetation also contributes to soil organic matter, which increases the soil's ability to hold moisture, and with time creates a surface organic, porous layer, which is instrumental in runoff and soil temperature regulation (Ternan *et al.* 1996). Carey and Woo (1999, 2000) reported that while an organic forest floor layer increases runoff/shallow seepage in sites where the water table approaches the soil surface, the same layer reduces runoff in dryer sites by its high moisture storage capacity (Quinton *et al*. 2000).

3.1.6 Knowledge Gaps

The selection of species for the revegetation of cold regions covers varies based on the primary revegetation objective, but the knowledge base for informed choices is limited in all cases. For example, where the primary objective is re-establishment of communities of native species similar to the pre-disturbance environment, little is known about the conditions needed to establish these species on severely disturbed soils in cold climate conditions. Where the primary revegetation objective is rapid control of erosion or runoff, better known agronomic species are often considered, but there is little information on the limits to successful establishment of agronomic species in cold regions, and even less on their effects on natural succession or potential for escape to the adjacent environment.

One of the important parameters in cover systems that are designed to reduce infiltration to mine wastes is the contribution of evapotranspiration (ET). Although previous research in cold regions does provide some bounding estimates of ET rates:

- The majority of this information is from boreal forest settings south of 60° north latitude, and likely overestimates ET in other regions.
- All of the reviewed information from sites north of 60° is for mature vegetation communities established on undisturbed soil; to our knowledge there are no direct, measured estimates of ET on juvenile (maturing) vegetation or vegetation on reclaimed covers in this region; and

- There is no available information on cold regions ET by vegetation types (e.g. native or agronomic grass or grass/legume mixes, tree/shrub container seedlings) likely to be present immediately following cover revegetation.

Rooting depths of vegetation are of interest primarily due to the potential for deep roots to penetrate low-permeability barrier layers, but also due to rooting effects on drawing soil water from covers. As with evapotranspiration, there is very little information on rooting depths in cold regions in general, and even less on rooting depths in cold regions soil covers.

Other vegetation effects that could be significant for some cold regions covers include rain and snow interception, delay of snowmelt, and construction to soil organic matter. In general these effects are poorly understood in natural cold regions systems and have not ever been investigated in cold region soil covers.

3.2 Modeling of Cold Regions Soil Covers

3.2.1 Background

The mathematical models currently used to simulate infiltration through soil covers are based on soil physics algorithms developed in the agricultural sciences. In general, they do not attempt to simulate cold regions processes. The current state of the art in applying these models to cold regions soil covers was examined though discussions with Canadian consultants and researchers that specialize in this area.

3.2.2 General Soil Cover Models

MEND 2.21.4 (2004) outlines the approach and methodologies for modeling of mine waste cover systems in general. Several soil-atmosphere or surface flux boundary numerical models are available to predict the performance of cover systems over all types of mine wastes. The most popular models used include SVFlux, VADOSE/W and HYDRUS.

SVFlux and VADOSE/W are the most rigorous, and are based on simulating the physics of moisture movement in response to atmospheric and vegetation demands. HYDRUS uses less rigorous algorithms, and does not calculate actual evaporation using surface flux boundary inputs. As a result HYDRUS does not have the same high degree of non-linearity as the other models and therefore simulations can be completed significantly faster, which is the main reason for its popularity. Comparative modeling studies have shown that when used in the right context, results produced using the HYDRUS model yield a reasonable outcome (Rykaart and Noël 2003).

All of these models have some ability to simulate ground freezing and thawing. However, the freezing and thawing routines are generally limited to equations describing rudimentary heat transfer within the soil. There is no attempt to simulate the complex effects of snowmelt, snow redistribution, snow interception, sublimation, infiltration into frozen soils, hill slope water movement over permafrost, actual evaporation and runoff from frozen surfaces, and radiation exchange from complex surfaces. The models also do not attempt to simulate the effects of freezing and thawing on soil properties.

3.2.3 Cold Regions Hydrologic Model

The Phase 1 report (section 3.4.3) lists and briefly describes a number of models that have been developed to simulate cold regions hydrologic processes. In general these models are intended to predict runoff at the catchment or basin scale, and they are not commercially available.

One of these models that has been applied to simulate infiltration and runoff from mine waste is the Cold Regions Hydrological Model (CHRM). CHRM was developed by a large multidisciplinary research group from various institutions in Canada (Pomeroy *et al*. 2007). In a multi-year study at the Anvil Range mine site in the Yukon, CHRM was used to model the surface water balance of an uncovered waste rock pile (Janowicz *et al*. 2006). The model was successful in simulating snow accumulation, redistribution and ablation, snowmelt as affected by surface conditions and aspect, and summer evaporation.

However, because infiltration is a relatively small factor in basin or catchment runoff, CHRM and other models in its class do not have a rigorous treatment of water flux through or below the soil surface. Estimates of net infiltration are derived as the difference between precipitation and all other losses. In the CHRM studies at the Anvil Range mine site, that method worked well for the uncovered waste rock, where infiltration was about 40% of precipitation. One would expect it to be less reliable at estimating the lower rates of infiltration typical of many soil covers.

3.2.4 Current Approaches to Simulating Cold Regions Soil Covers

In the absence of a model that combines rigorous treatments of soil physics and cold regions hydrology, cover designers generally attempt to take the cold regions effects into account by modifying inputs to conventional soil cover models. These “fixes” include:

- Modeling only summer seasons, i.e. assuming that the hydrologic cycle is shut down during the period when the ground is frozen;
- Developing an artificial hydrograph to simulate the available moisture that would contribute to snowmelt infiltration after the ground has thawed; and,
- Conducting sensitivity analyses using ranges of soil properties, to examine the effects of soil structure changes arising from freeze-thaw cycles.

These methods are completely empirical, and are therefore only as accurate as the available data allows. Given the general lack of data on these effects on soil covers, one would expect these methods to introduce a significant uncertainty into any predictions of cold regions cover performance.

3.2.5 Knowledge Gaps

The current generation of soil cover models provides only rudimentary simulation of some cold regions processes, and the current generation of cold regions hydrology models does not simulate infiltration in a manner that is sufficiently rigorous for predicting cover performance. However, given the uncertainty about some of the underlying phenomena, it would be unreasonable to ask for a model that incorporates all possible cold regions processes. A better approach would be to first determine which cold regions processes are most influential. That approach will ultimately require the field investigations and long-term monitoring that are described elsewhere in this report.

In the interim, cover designers will need to continue using empirical "fixes" to simulate cold regions effects in conventional soil cover models. It would be helpful to more thoroughly examine the uncertainties that this approach introduces. The following are examples of work that could be moved forward with only the current generation of models:

- Current cold regions hydrologic models are able to simulate the effects of snow accumulation, redistribution and ablation on end-of-season snowpack and freshet snowmelt. It should be possible to use these models to better define the range of "artificial hydrographs" that need to be used in cover modeling.
- The thermal routines incorporated in soil cover models are generally physically correct, and the greater uncertainty is in the selection of appropriate initial and boundary conditions. Cold regions hydrologic models could also be used to assist in defining the appropriate range of these inputs.
- The effects of freezing and thawing on infiltration rates is poorly understood but likely to be very important in soil covers that are designed to minimize infiltration. Again, sensitivity analyses would be helpful to show the range of influence.
- Freeze-thaw effects on soil properties are also a subject of continuing investigation, but sensitivity analyses with the current generation of soil cover models would help to determine what magnitude of such effects is significant for each type of cover.

3.3 Use of Convective Cooling in Soil Covers

3.3.1 Background

As noted in the Phase 1 report (sections 2.2 and 3.2), convective flow of cold winter air through coarse rock materials can cause significant cooling. The convection is driven by the difference in temperature between the air and the rock, which retains some of the heat it gains during summer. Air within the rock pore space is slightly warmed by contact with the rock, which causes it to rise. The rising air pulls colder air into the rock. The resulting convective cycle continues until either the rock is cooled to the same temperature as the surrounding air, or summer conditions cause the air temperature to rise above that of the rock.

The process has been studied as a means to prevent permafrost degradation. Convection within embankments of coarse rockfill has been proposed in designs of road and railways to control settlement caused by thawing of permafrost. Field tests have confirmed (e.g. Goering and Kumar 1996) that convective flow through a porous embankment results in cooling in winter, and that convection stopped during the summer months, limiting heat gain to the much slower process of conduction. The combined effects result in preservation of basal permafrost layers.

The possibility of using convective cooling to enhance freezing below particular examples of mine waste covers has also been considered (e.g. Arenson and Sego, undated). The following sections provide a more general assessment.

3.3.2 Rayleigh-Darcy Criterion for Flat Layers

In general, heat transport in porous media is either by convection or conduction. Convection involves the bulk movement of air, and has the capacity to provide significant cooling. Conduction occurs without any bulk movement of air, primarily by the transfer of heat from one soil or rock particle to another, and produces only relatively slow cooling.

The simplest approach to assess the potential for convective cooling is to calculate the ratio of convective factors to conductive factors. This is most commonly done through reference to a dimensionless number known as the Rayleigh-Darcy number. The Rayleigh-Darcy number (*Ra*) for a compressible gaseous phase is expressed as follows:

$$Ra = \frac{g \cdot \left(\frac{1}{T_o}\right) \cdot H^3 \cdot (\Delta T - \rho_{a,o} \cdot g \cdot \frac{H}{C_{t,a}})}{(\mu_{a,o}/\rho_{a,o})^2} \cdot \frac{\mu_{a,o}/\rho_{a,o}}{k_{t,a}/C_{t,a}} \cdot \frac{K}{H^2} \cdot \frac{k_{t,a}}{k_t}$$

where g is the gravitational acceleration constant, T_o is the reference absolute temperature (mean reference temperature), H is the thickness of the porous layer, ΔT is the difference in temperature between the top and bottom of the cover, $\rho_{a,o}$ is the reference density of air, $C_{t,a}$ is the volumetric heat capacity of air, $\mu_{a,o}$ is the reference dynamic viscosity of air, K is the intrinsic permeability of the porous layer, k_t is the soil thermal conductivity, and $k_{t,a}$ is the thermal conductivity of air. (Lebeau and Konrad 2007).

In the equation above, the first fraction on the left hand side is the dimensionless Grashof number, which is an approximation of the ratio of the buoyancy forces that create convection, to the viscous forces that constrain convection and therefore favour conduction. The remaining terms constitute a dimensionless Prandtl number, which is an approximation of the ratio of the material parameters favouring convection (momentum diffusivity) to the material properties favouring conduction (or thermal diffusivity).

Another explanation for the above equation is that it expresses the ratio of the Rayleigh number to the Darcy number. Rayleigh numbers have a basis in a classical physics experiment, where a layer of oil is sandwiched between two metal plates and the bottom plate is heated while the upper plate is cooled. Once a critical temperature difference is reached, the oil starts to rise from base, creating a series of circulation cells. The Rayleigh number expresses the combinations of temperature differences, layer thicknesses, and fluid properties that determine when the circulation, or convection, begins. Darcy numbers represent the permeability of a porous material or, in other words, the resistance to fluid flow. So the Rayleigh-Darcy number shown above compares the tendency for convection, expressed in the Rayleigh number, against the resistance to convection expressed in the Darcy number.

The importance of the Rayleigh-Darcy number is that many studies have shown that natural convection will occur only when the Rayleigh-Darcy number is above a critical threshold. In the case of a flat-lying layer with an open top surface, the minimum critical Rayleigh-Darcy number is equal to 27.10 (Nield and Bejan 1999). Any combination of geometry, temperature differences, material properties and gas properties can be expressed as a Rayleigh-Darcy number and compared to that value to determine whether convective cooling is possible.

3.3.3 Application to Flat-Lying Soil Covers

For soil flat-lying covers, the major parameters that affect the Rayleigh-Darcy number are:

- Intrinsic permeability: Greater permeability allows air to circulate more readily, and therefore favours convection.
- Temperature difference: Both convection and conduction are driven by temperature differences between the soil and the air, but larger temperature differences tend to favour convection.
- Cover thickness: Cover thickness has a number of compounding effects, but in general, thinner covers can release all of their heat by conduction, so convection is more likely in thicker covers.

A general relationship was developed to identify combinations of the above parameters that would lead to convective cooling. Figure 3.1 plots the relationship between intrinsic permeability and the minimum temperature difference needed to produce convective cooling, for various thicknesses of cover material. For example, the second square on the red line indicates that a 2 m cover with an intrinsic permeability of $1x10^{-7}$ m^2 will exhibit convective cooling when the air temperature is 15 ºC less than the temperature at the base of the cover. The parameters used in the calculations are summarized in the Table 3.1.

The results show that for intrinsic permeabilities greater than $1x10^{-6}$ m^2, natural convection is likely to occur at small temperature differences, regardless of the cover thicknesses. For intrinsic permeabilities between $1x10^{-6}$ and $1x10^{-7}$ m^2, the cover thickness becomes a key factor, with thicker covers experiencing convection at lower temperature differences. For intrinsic permeabilities lower than $1x10^{-7}$ m^2, the temperature differences necessary to promote convection are too large except for very thick covers.

Intrinsic permeability is not a commonly used parameter. Most engineers are more familiar with saturated hydraulic conductivity. The top axis of the figure therefore shows the equivalent values of saturated hydraulic conductivity. This is potentially confusing, as saturated covers would allow no air convection. But it helps relate the intrinsic permeabilities to more common units.

Looking at the hydraulic conductivity scale, the figure shows that convective cooling is only likely to occur in cover material that have hydraulic conductivities in the range of 1 m/s or higher. Among natural materials, only clean gravels exhibit such high hydraulic conductivities. However, some mine or quarry rock with a low fines content is likely to have hydraulic conductivities in that range.

This analysis therefore indicates that convective cooling could be an important effect in cases where the cover material consists of natural clean gravels or, more likely, of uniform mine or quarry rock with a low fines content.

Table 3.1. Material properties used in Rayleigh-Darcy calculations

Property	Value
Reference absolute temperature, T_o	298 K
Density of air, $\rho_{a,o}$	1.21 kg/m^3
Dynamic viscosity of air, $\mu_{a,o}$	1.82x10^{-5} kg/(m·s)
Soil thermal conductivity, k_t	0.3 W/(m·K)
Air thermal conductivity, $k_{a,t}$	2.57x10^{-3} W/(m·K)
Air volumetric hear capacity, $C_{t,a}$	1211 J/(m^3·K)

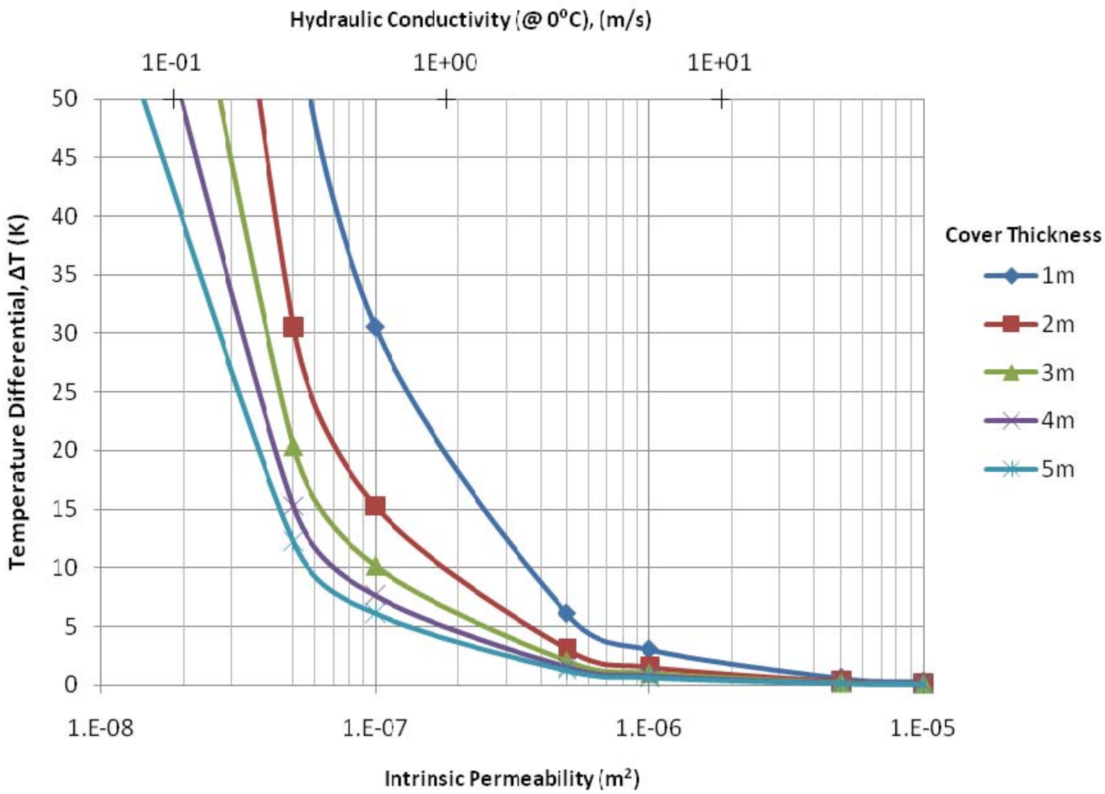

Figure 3.1 Permeability and temperature difference needed for convective cooling of flat-lying soil covers of various thickness. Convective cooling is possible for combinations to the right of the curves.

3.3.4 Application to Sloped Covers

Figure 3.2 illustrates a scenario where convection in a sloping cover system could lead to significant cooling of the underlying materials. The figure shows a strip of cover system consisting of a coarse rock layer of thickness, overlain by a cover soil material of unit thickness. The coarse rock layer is exposed at both the base and the top of the slope and acts as a convection pathway, drawing cold air into the base of the slope and releasing heated air out the top of the slope.

A sensitivity analysis was completed to determine the range of parameters for which convective cooling through the rock layer could be significant. The analysis assessed the importance of convection through the rock layer in comparison to conduction through the cover soil. Conduction would occur in any cover system, but the enhanced cooling available from convection could allow underlying material to become and/or stay frozen.

Heat removed through convection through the rock layer can be estimated from:

$$W_{convection} = A_1 \left(\frac{K}{\mu}\right) \frac{\Delta\psi}{\Delta z} \Delta T \; C_a$$

where W is the heat removed by convection (J/s), A_1 is the cross-sectional area of the coarse rock layer per unit width, K is the intrinsic permeability, μ is the dynamic viscosity of the air, $\Delta\psi / \Delta z$ is the potential gradient between the top and bottom of the slope, ΔT is the difference in temperature between the external atmosphere and the air in the internal rock layer pores, and C_a is the volumetric heat capacity of air.

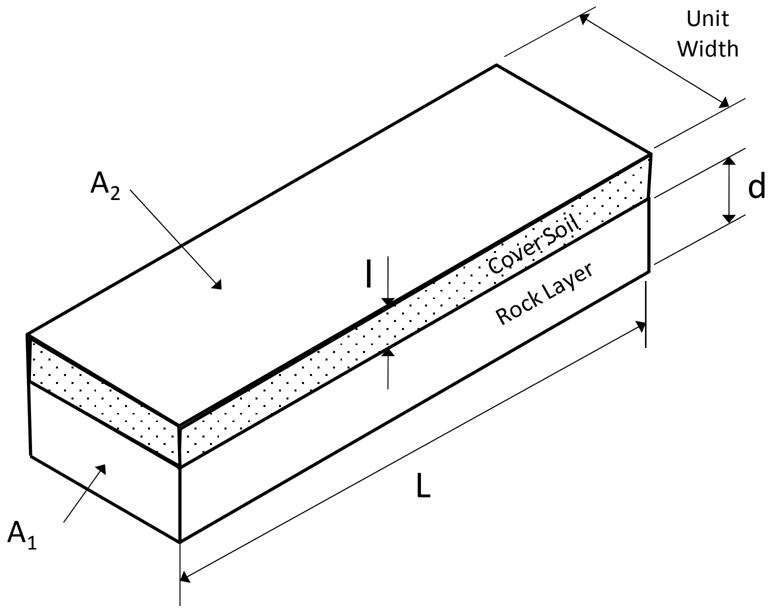

Figure 3.2 Schematic of sloped cover with coarse rock convection layer.

The potential gradient $\Delta\psi / \Delta z$ depends on the difference in density between the gas within the rock pore space and the outside air. It can be shown that the potential gradient can be predicted from the relatively simple expression:

$$\frac{\Delta\psi}{\Delta z} = \Delta T \; g \; \beta \; \rho_{int} \; \frac{\Delta z}{\Delta L}$$

where β is the coefficient of thermal expansion of air, ρ_{int} is the air density within the rock layer, Δz is the elevation difference of the slope, and ΔL is the slope length.

Heat removed by conduction through the cover soil layer is estimated by the formula:

$$W_{conduction} = A_2 \; k \; \frac{\Delta T}{l}$$

where W is the heat removed (J/s) by conduction, A_2 is the planar area of the cover soil layer per unit width, k is the thermal conductivity of the soil, and $\Delta T/l$ is the thermal gradient across the cover soil layer.

The ratio, R, of heat removal by convection to heat removal by conduction is then:

$$R = \left(\frac{d\ l}{L}\right)\left(\frac{K}{\mu\ k}\right)(C_a\ g\ \rho\ \beta)\left(\frac{\Delta z}{\Delta L}\right)$$

As in the preceding section, a range of the cover parameters were modeled to determine combinations where convection is the dominant process. The cover design parameters investigated were the slope angle, coarse rock and cover soil layer thicknesses, and the slope length. Each parameter was varied to estimate the temperature difference required to produce a convective to conductive cooling ratio R of 10. At that ratio, convection is likely to be a significant source of cooling.

Figure 3.3 presents typical results. Each curve in the figure shows the temperature difference ΔT, between the atmosphere and the underlying waste, needed for convection to be dominant over a range of rock layer permeabilities. The bottom axis shows the rock layer permeabilities as intrinsic permeability, and the top axis uses the more common units of hydraulic conductivity. The five curves show the relationship between critical temperature and permeability for soil cover thicknesses ranging from 0.3 to 2.0 m, for a 50 m long 3H:1V slope, with a 1 m thick coarse rock layer. Other material parameters were the same as in the preceding section.

The results show that convection is the dominant process even at low temperature differences when the intrinsic permeability of the rock layer is greater than about $1\text{x}10^{-7}\ m^2$. The soil cover thickness becomes a key factor when the rock has lower permeabilities.

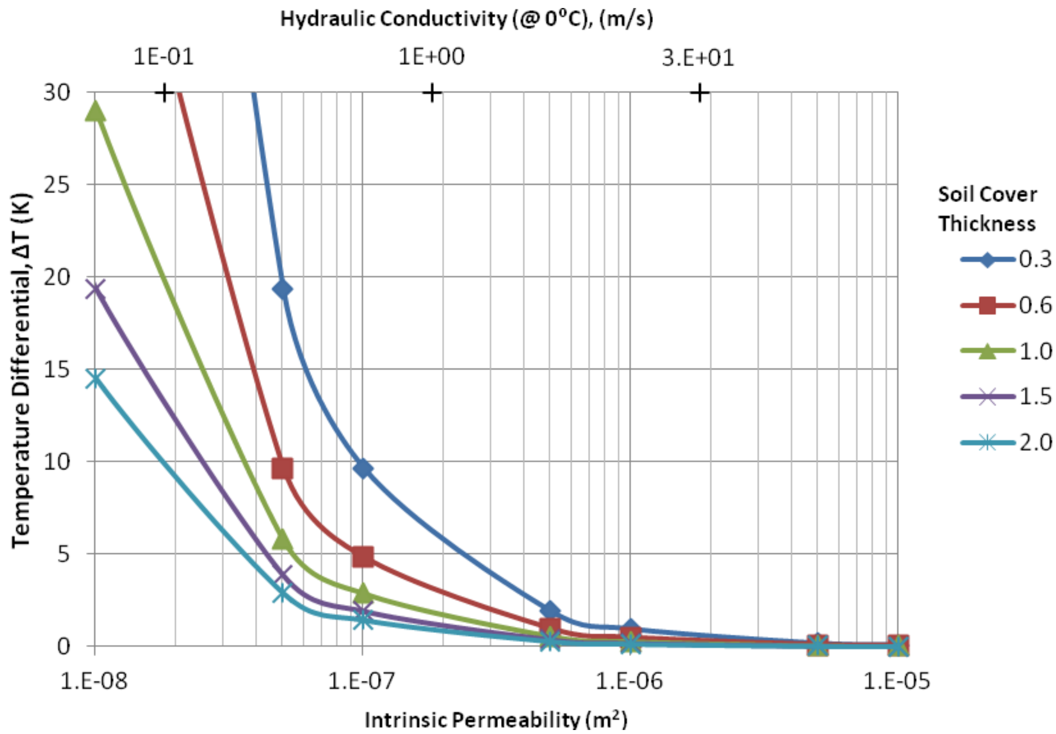

Figure 3.3 Permeability and temperature difference needed for convective cooling in sloping covers of various thickness. Convective cooling is possible for combinations to the right of the curves.

These patterns are the same as noted for flat-lying covers. However, comparison of Figure 3.1 to Figure 3.3 shows that convection occurs more readily in sloping covers. For example, in a sloping cover with a 1 m thick upper layer and a rock layer permeability of 1 x 10^{-7} m^2, convection dominates at temperature differences of about 2.5°C. In contrast, a temperature difference of 30°C is needed for a convection to occur in an analogous flat-lying cover.

Sensitivity analysis of slope angles ranging from 1H:1V to 5H:1V produces similar results. Again, intrinsic permeabilities greater than $1x10^{-7}$ m^2 require small temperature differences for convection to dominate. Between intrinsic permeabilities $1x10^{-7}$ m^2 and $1x10^{-8}$ m^2, the slope angle becomes a key factor, with steeper covers required to promote convection. For intrinsic permeabilities less than $1x10^{-8}$ m^2, the temperature differences required to generate convection are so large that conduction is likely to be the dominant process.

The sensitivity to slope length was assessed for a cover with 1 m coarse rock and cover soil layers, and a slope angle of 3H:1V. Figure 3.4 shows the results. For intrinsic permeabilities greater that $1x10^{-8}$ m^2, convection is dominant at small temperature differences. For instinsic permeabilities less than $1x10^{-8}$ m^2, the slope lengths become a key factor, with slopes of 100 m or more requiring signficantly greater temperature differences before convection becomes dominant.

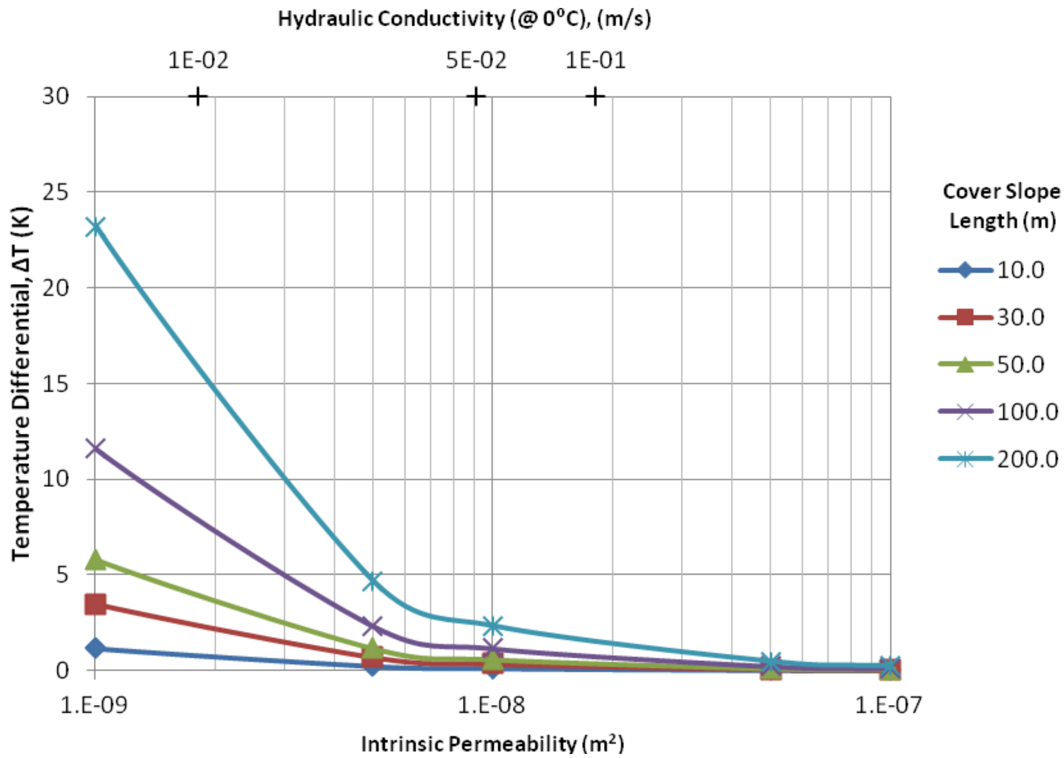

Figure 3.4 Permeability and temperature difference needed for convective cooling in sloping covers of various length. Convective cooling is possible for combinations to the right of the curves.

3.3.5 Knowledge Gaps

As indicated by references in the Phase 1 report, convective cooling in cold regions has been the subject of active research for at least ten years. Practical applications that have been examined include the protection of permafrost under highway and railroad embankments, and the freezing of drain layers in rockfill dams.

The calculations presented herein indicate that convective cooling could also be of interest to designers of cold regions soil covers. Where high permeability rock is available for cover construction, which is often the case at mine sites, the resulting heat removal could be sufficient to cause the underlying waste material to freeze.

Although the calculations are based on well understood physical processes, there is a need for a "proof of concept" test at field scale before the method can be recommended for further consideration. Such a test should be straightforward, requiring little more than a pile of rock and the appropriate instrumentation.

Another useful step would be to examine the likely cost of covers with convective layers, and compare them to costs of other classes of soil cover. Such an analysis would help to indicate conditions where designing convection into the covers method might prove cost effective. For example, it is very unlikely that the construction of convective layers would prove cost effective for benign wastes, but it might be very competitive with other methods being proposed for high strength wastes.

3.4 Effect of Cover Design on Freezing of Barrier Layers

3.4.1 Background

Several studies have shown a significant increase in the permeability of barrier layers subjected to freezing and thawing. Those studies are often quoted as evidence that barrier type covers are not suited to cold regions. As noted in the Phase 1 report however, most of the studies have used laboratory freezing or field tests where the barrier layer is completely exposed. In practice, cover designs almost always include a significant depth of soil above the barrier layer, as a rooting zone or simply as protection. Those layers will also act to insulate barrier layers from some of the effects of freezing.

3.4.2 Soil Freezing and Thawing Calculations

To further examine the insulation effect, a series of calculations were completed. A simplified method of calculating the rate of freezing of a soil estimates the heat flux, Q (W/m^2) through the following formula:

$$Q(t) = \frac{-k \cdot T_s}{Z_f}$$

where k is the average thermal conductivity of the frozen zone (W/(m·°C)), T_s is the average surface temperature during the freezing period (°C), and Z_f is the depth (m) to the freezing front at time t. The rate of advance of the freezing front is given by:

$$\frac{dZ_f}{dt} = \frac{Q(t)}{L(z)}$$

where $Q(t)$ is the heat flux (W/m^2), $L(z)$ is the latent heat of freezing of the soil (J/m^3) at the freezing front. The latent heat of freezing is estimated from the volumetric moisture content in the soil by:

$$L(z) = \theta(z) \cdot 333.7 \frac{kJ}{kg} \cdot 1000 \frac{kg}{m^3}$$

where $\theta(z)$ is the volumetric moisture content of the soil and 333.7 kJ/kg is the latent heat of freezing of water.

Calculations of thawing depths both follow the same procedure. For clarity, only the freezing calculations are shown. The corresponding parameters used in the thawing calculations are provided where appropriate.

Estimation of the average surface temperature (T_s) during the freezing period is obtained from climate normals:

$$T_s = \frac{n_f \cdot I_{at}}{FP}$$

where n_f is the freezing surface n-factor, I_{at} is the air freezing index (degree-days), and *FP* is the freezing period in days. The air freezing index for a site is the sum of the average daily temperatures that are below 0°C. Both the freezing index and freezing period data are commonly reported climate parameters in cold regions. The surface *n*-factor is used to convert the temperature to a surface temperature. The *n*-factors vary by the surface type.

The above set of equations is known to mathematicians as a "moving boundary" or "Stefan" problem. Analytical solutions to such problems are available only for very simple cases, such as when moisture contents $\theta(z)$ are constant throughout the profile. For more realistic situations, the equations must be solved numerically. A numerical solution was therefore developed and implemented in an MS-Excel spreadsheet.

3.4.3 Freeze-Thaw Depths in Typical Mine Waste Covers

A series of calculations were completed to show the depth of freezing and thawing that would be expected in typical mine waste covers, located at various cold regions sites in western and northern Canada.

Table 3.2 shows the cover types, layer thicknesses and moisture conditions that were considered. Table 3.3 shows the locations and the climate properties. The freeze/thaw indices and periods were obtained from Environment Canada's Canadian Climate Normals (1971-2000) website, with the exception of the Tundra mine site, for which 12 years of data were available from an onsite weather station. Table 3.4 shows the assumed material thermal properties. A 'sand and gravel' type surface was assumed, which corresponds to an n_f of 0.9.

Table 3.5 shows the range of freeze penetration depths for two of the cover variants. It is clear from the table that a site's location has the greatest influence on freezing and thawing depths. However, it is also clear that cover designers have some ability to protect deeper layers from freeze-thaw cycles by providing a more saturated or thicker insulation layers.

The results in Table 3.5 can also be used for a preliminary assessment of whether permafrost will develop in the underlying mine waste. This is likely to occur in cases where the estimated freeze depth is greater than the estimated thaw depth, which is the case for the sites located in the territories, as well as in La Ronge, SK and Flin Flon, MB, depending on the cover type. However, slight differences between estimated freezing and thawing depths are very sensitive to the assumed surface conditions, which are likely to vary from the assumed n-values. More detailed calculations would be required to fully assess the likelihood of permafrost aggradation in any particular case.

Table 3.2. Typical covers assumed for freeze thaw analyses

Cover Type	Tailings Variants	Waste Rock Variants
Isolation	0.5 m – 1.5 m dry cover Water table at cover-tailings interface	0.5 m – 1.5 m Moisture content variable
Wet	0.5 m – 1.5 m Saturated cover	
Barrier		0.5 m – 2.5 m uncompacted overlying 0.5 m compacted Moisture content variable in upper layer but always near saturation in barrier layer
Store and Release		1.0 m – 3.0 m uncompacted Moisture content variable

Table 3.3. Cover locations and climate data for freeze-thaw analyses

Location	Freezing Index (deg-days)	Freezing Period (days)	Freezing T_{avg} (^{0}C)	Thawing Index (deg-days)	Thawing Period (days)	Thawing T_{avg} (^{0}C)
Vancouver, BC	39	5	-8.6	3731	360	10.4
Prince George, BC	920	69	-13.4	2385	297	8.0
Edmonton, AB	1473	92	-16.0	2368	273	8.7
La Ronge, SK	2268	129	-17.6	2234	237	9.4
Flin Flon, MB	2345	139	-16.9	2302	227	10.2
Winnipeg, MB	1821	117	-15.6	2804	248	11.3
Sudbury, ON	1353	104	-13.0	2722	261	10.4
Dawson, YT	3395	201	-16.9	1818	164	11.1
Mayo, YT	2967	188	-15.8	1904	177	10.8
Whitehorse, YT	1998	172	-11.6	1769	193	9.2
Norman Wells, NWT	3844	208	-18.5	1860	157	11.8
Tundra Mine, NWT	4192	245	-17.1	1122	121	9.3
Yellowknife, NWT	3475	198	-17.6	1836	167	11.0
Baker Lake, NU	5196	249	-20.9	913	116	7.9
Cambridge Bay, NU	5837	267	-21.9	600	98	6.1
Lupin, NU	4931	240	-20.5	929	125	7.4

Table 3.4. Material parameters for freeze-thaw calculations

Parameter	Freezing Parameter	Thawing Parameter
Freezing surface n-factor	0.9	2
Thermal conductivity, k [W /(m°C)]	1.88	2.50
Cover thickness, [m]	0.5	
Cover volumetric moisture content, θ_c	0.05	
Tailings volumetric moisture content, θ_t	0.5	

Table 3.5. Range of estimated freeze and thaw depths for typical covers

	Cover Variant 1: 0.5 m Wet Till Cover on Tailings		**Cover Variant 2: 3.0 m Dry, Uncompacted Store-and-Release Cover on Waste Rock**	
Location	Freeze Depth (m)	Thaw Depth (m)	Freeze Depth (m)	Thaw Depth (m)
Vancouver, BC	0.3	2.9	0.6	4
Prince George, BC	1.4	2.3	3	3.5
Edmonton, AB	1.8	2.3	3.2	3.5
La Ronge, SK	2.3	2.2	3.5	3.5
Flin Flon, MB	2.3	2.4	3.5	3.5
Winnipeg, MB	2	2.5	3.3	3.7
Sudbury, ON	1.7	2.5	3.1	3.6
Dawson, YT	2.8	2	3.9	3.3
Mayo, YT	2.7	2.1	3.7	3.4
Whitehorse, YT	2.1	2	3.4	3.3
Norman Wells, NWT	2.9	2	4	3.3
Tundra Mine, NWT	3.1	1.6	4.1	3.1
Yellowknife, NWT	2.8	2	3.9	3.3
Baker Lake, NU	3.4	1.4	4.4	2.9
Cambridge Bay, NU	3.6	1.2	4.6	2.4
Lupin, NU	3.3	1.4	4.3	3

3.4.4 Freezing Rates in Insulated Barrier Layers

A simplified form of the above equations can be used to estimate the rate of freezing in a covered barrier layer:

$$\frac{dZ_f}{dt} = \frac{Q(t)}{L(z)}$$

The simplified form shows that the rate of freezing in a covered barrier layer depends only on the surface temperature, the thickness of the covering layer, and the moisture content of the barrier layer.

Figure 3.5 shows rates of barrier layer freezing for various depths of cover, at selected northern and western Canadian locations. The figure shows that freezing rates are strongly dependent on location when the cover layer is less than about 1.0 m. Freezing rates with covers less than 0.5 m are also relatively fast, several millimetres or more per day. Those rates are within the ranges that resulted in significant increases in barrier layer permeability in laboratory and field experiments.

Figure 3.5 also shows that, as the thickness of cover above the barrier increases to 1.0 m or more, barrier layer freezing rates reduce markedly. These results indicate that, even when the total depth of freezing extends into a barrier layer, the rates of freezing may be well below the rates that led to permeability increases in laboratory tests. However, it cannot be concluded that the low rates of freezing are harmless. To date, there has not been testing at sufficiently low rates of freezing.

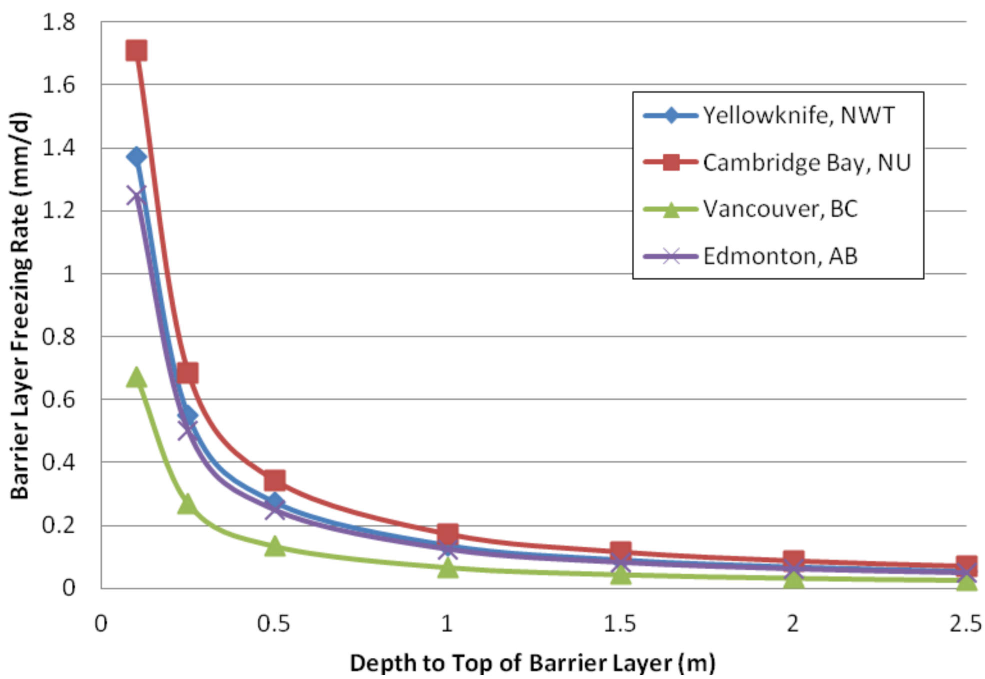

Figure 3.5 Effect of depth of cover soil on rates of freezing in barrier layers at various locations.

3.4.5 Knowledge Gaps

The Phase 1 report (section 3.3.1) summarized the results of studies examining the effects of freezing on low permeability layers. A number of those studies noted significant increases in permeability, but other studies showed that permeability increases are much less significant when mitigating factors are present. The mitigating factors identified in the literature include:

- The presence of certain kinds of clay (e.g. montmorillonite) that tend to swell and heal any freezing induced cracks;

- Combinations of clayey soils near their plastic limit and sufficient overburden stress, which causes deformations that seal freezing-induced cracks; and,
- The presence of low plasticity fine-grained clays (e.g. illite) that can plug freezing-induced cracks.

The current analysis also shows that the use of insulating protective layers can limit both the depth and rate of freezing within the barrier layers of soil covers. As noted above, the question of how low a freezing rate needs to be before it does no damage has not been answered, and would require laboratory testing.

More generally, the combination of literature and the current work provides only spotty coverage of an important topic. A better understanding of the long-term effectiveness of barrier layers in cold regions soil covers and opportunities to include mitigation measures in future design or construction practices are needed. This will require the currently available work to be supplemented by additional studies of more soil types subjected to a wider range of laboratory and field conditions.

4 Survey of Ongoing Cover Trials

This chapter presents a table of well-documented soil cover trials that might be affected by cold regions phenomena.

The Phase 1 report included a table and map showing over 85 cold regions sites with soil covers on mine wastes. It also listed a number of sites that were known to the authors as having instrumented cover tests.

To facilitate future efforts to observe or investigate cold regions effects, two Canadian consulting companies, SRK and O'Kane Consultants Ltd., reviewed their files and developed a combined summary of cover trials being carried out in cold regions. Table 4.1 below provides the results, including descriptions of:

- Cover type and materials;
- Waste material;
- Monitoring sites, parameters and years of data;
- Site conditions; and
- Other comments.

Table 4.1. Summary of current active cold region cover monitoring trials

Site Name / Location / Lat.	TP or FS	Cover Type / Materials	Waste Material	Monitoring Site Details: Name	Monitoring Site Details: Parameters Measured	Monitoring Site Details: Yrs. of Data	Monitoring Site Conditions: Slope	Monitoring Site Conditions: Vegetation	Monitoring Site Conditions: Snowpack	Comments
Aitik Mine N. Sweden 67° N	FS	Barrier / 1.0 m comp. till, 0.5 m loose till, overlain by 0.2 m sewage sludge	Waste rock	Plateau, E. slope, W. slope	Climate (NR, RF) Soil (ST, SU, W/C) Hydrology (SS)	0.5	2% on flat 33% on slope	Good grass cover	50-100 cm	Started monitoring Aug-08; OKC responsible for data QC and interpretation Proposed monitoring of AT, RH & WS starting 2009
				S-01 to S-22	Soil (W/C)					
Albian Sands Fort Mac, AB 57° N	TP	Store & release / 0.5 m tailing sand overlain by 0.5 m peat/mineral soil	Lean oil sands	Upslope, down-slope	Climate (AT, RH, WS, WD, NR, RF) Soil (ST, SU, W/C) Hydrology (IF, RO, SS)	5	25%	Poor grass cover	40-60 cm	High data capture rates and QC over 5-yr period Runoff data corrected for high sediment loading in weir box
Brewery Creek Yukon 64° N	FS	Isolation 0.5 m compacted argillite/sedimentary overlain by 0.5 m uncompacted argillite/sedimentary	Waste rock	Blue Dump	Infiltration	5	30%	Poor grass cover improving to good cover	N/A	Reports available on initial lysimeter installation Total infiltration measured each year and provided in Water License Annual Reports
Cluff Lake Northern SK 58° N	TP	Enhanced S&R / 0.2 m compacted WR overlain by 1.0 m sandy till	Waste rock	TP-1 TP-2	Climate (AT, RF) Soil (ST, SU, W/C) Hydrology (NP, SS)	7	2% @ TP-1 25% @ TP-2	Fair G&L cover	40-60 cm	High data capture rates and QC over 7-yr period
	FS	Enhanced S&R / 0.2 m compacted WR overlain by 1.0 m sandy till	Waste rock	Plateau, Upslope, & Down-slope	Climate (AT, NR, RF) Soil (ST, SU, W/C) Hydrology (SS)	2	2% on flat 25% on slope	Fair G&L cover	40-60 cm	High data capture rates and QC over 2-yr period
				Weir	Hydrology (RO)	2	N/A	N/A	N/A	
	FS	Store & release / 1.0 m sandy till	Tailings	Site A Site B	Climate (AT, RH, WS, WD, NR, RF) Soil (ST, SU, W/C, WTE) Hydrology (SS)	2	2-3%	Fair G&L cover	40-60 cm	High data capture rates and QC over 2-yr period
Faro Mining Complex Faro, YT 62 °N	TP	S &R and Barrier/ CT1: 1.8 m loose till CT2A: 1.1 m loose till CT2B: 0.75 m loose till CT3A: 1 m loose till overlain by 0.45 m sand & gravel CT3B: 0.6 m loose till overlain by 0.5 m sand & gravel CT4: 0.5 m compacted till overlain by 1.8 m loose till L#1: 0.5 m compacted till overlain by 0.5 m loose till L#2: 1 m compacted till	Waste rock	CT1, CT2A, CT2B	Climate (AT, RH, WS, WD, NR, BP, RF) Soil (ST, SU, W/C) Hydrology (RO)	4	40% @ CT1 2% @ CT2A and CT2B	None	0-60 cm (high drifting)	High data capture rates and QC over 4-yr period Annual snow survey Independent weather station 2 km from site
				CT3A, CT3B, CT4	Climate (AT, RH, WS, WD, NR, BP, RF) Soil (ST, SU, W/C) Hydrology (RO, IF)	4	40 %	None	0-60 cm (high drifting)	
				L#1, L#2	Climate (AT, RH, WS, WD, NR, BP, RF) Soil (ST, SU, W/C) Hydrology (RO, NP)	0.5	2%	Saplings on L#1	0-60 cm (high drifting)	Lysimeters constructed in 2007, instrumentation installed in 2008 Saplings planted in 2007
	TP	Traffic layer/ 0.8 m loose WR	Tailings	East Pad West pad	Consolidation and settling	5	Flat	None	0-60 cm	Elevation surveys every 2 weeks during summer season West Pad underlain by geotextile

Site Name / Location / Lat.	TP or FS	Cover Type / Materials	Waste Material	Monitoring Site Details			Monitoring Site Conditions			Comments
				Name	Parameters Measured	Yrs. of Data	Slope	Vegetation	Snowpack	
Giant Mine Yellowknife, NWT 62 °N	TP	S&R / 0.5 m rock overlain by 0.3 m to 0.7 mm clayey silt	Tailings	Slime A Slime B Beach A Beach B	Soil (ST, W/C) Consolidation and settlings	0.5	Flat	None	N/A	Elevation surveys every 2 weeks during summer season High data capture rates and QC since construction Slime A underlain by geotextile Flooded over winter of 2008/2009
Greens Creek Juneau, AK 58° N	TP	Barrier / 0.2 m gravel, 0.6 m comp. till, 0.2 m gravel, 0.6 m loose till	Waste rock	Site 23	Climate (AT, RH, WS, WD, NR, PPT) Soil (ST, SU, W/C) Hydrology (NP)	8	33%	Good grass cover	40-60 cm	High data capture rates and QC over 8-yr period
HBM&S Flin Flon, MB 55° N	TP	Standard and enhanced S&R / Prototype geosynthetic capillary break overlain by 0.3 m and 1.0 m of silty-sand till	Tailings	TP-A TP-B TP-C TP-D TO-E	Climate (AT, RH, WS, NR, PPT) Soil (ST, SU, W/C, PG, WTE) Hydrology (SS)	2	0-2%	?	40-60 cm	4 alternate test covers and 1 control plot (bare tailings) U ofS M.Sc. graduate research program (Meier / Fleming) Current status of data collection & QC unknown
Myra Falls Vancouver Island, BC 49° N	TP	Barrier / TP2: 0.5 m comp. till-fly ash TP3: 0.5 m comp. till TP4: 0.2 m comp. till-bentonite plus 0.3 m comp. till	Waste rock	TP1 TP2 TP3 TP4	Climate (AT, RH, WS, WD, NR, RF) Soil (ST, SU, W/C) Hydrology (NP)	6	10%	Poor to fair grass cover	10-50 cm (melts shortly after forming)	TP1 is bare waste rock surface (control plot) Barriers in TP2, TP3 & TP4 overlain by 0.3 m loose till Minimal 'good' data collected since 2006 Test plots to be decommissioned in 2009
Red Dog Mine NW Alaska 69° N	TP	S&R and Barrier / TP-2: 1.0 m OB TP-3: 1.0 m OB over comp. WR TP-4: 1.0 m OB over GCL	Waste rock	Little Bear Cells (TP-1 to TP-4)	Climate (AT, RH, NR) Soil (ST, SU, W/C) Hydrology (SD, NP)	1.5	Flat	None	0-20 cm (high drifting)	TP-1 is bare waste rock surface (control plot) High data capture rates and QC over 1.5-yr period
	FS	Enhanced S&R / Comp. WR, 0.5 m comp. OB, 0.5 m loose till	Waste rock	Oxide S-pile (plateau, slope)	Climate (AT, NR, RF) Soil (ST, SU, W/C) Hydrology (SD, RO, NP)	0.5	4% on flat 33% on slope	None	0-20 cm (high drifting)	Flume to be installed in 2009 for runoff monitoring system
Suncor Coke Reclaimed Watershed Fort Mac, AB 57° N	FS	Store & release / 0.4 to 0.8 m sand overlain by 0.3 m muskeg mix	Coke	Plateau 5:1 slope 3:1 slope	Climate (AT, RH, WS, WD, NR, RF) Soil (ST, SU, W/C) Hydrology (NP, SS)	3	Flat 20% 33%	Varies from poor G&L cover to good grass cover	20-40 cm (high drifting)	Large-scale prototype High data capture rates and QC over 3-yr period
Syncrude South Bison Hill Reclaimed Watershed Fort Mac, AB 57° N	TP	Store & release / ~0.8 m silty-clay till overlain by ~0.2 m peat	Saline-sodic shale	D1 D2 D3	Climate (AT, RH, WS, WD, NR, RF) Soil (ST, SU, W/C) Hydrology (AET, IF, RO, SS)	9	20%	Good G&L cover, w/ some trees	40-60 cm	High data capture rates and QC over 9-yr period Field permeability testing of upper cover profile conducted for first 5 years
	FS			Plateau	Climate (AT, RH, WS, WD, NR, RF) Soil (ST, SU, W/C) Hydrology (SS)	7	Flat	Good G&L cover	40-60 cm	High data capture rates and QC over 7-yr period
	FS			Peat Pond	Hydrology (RO)	5	N/A	N/A	N/A	High data capture rates and QC over 5-yr period

Site Name / Location / Lat.	TP or FS	Cover Type / Materials	Waste Material	Monitoring Site Details			Monitoring Site Conditions			Comments
				Name	Parameters Measured	Yrs. of Data	Slope	Vegetation	Snowpack	
	FS			Golden Pond	Hydrology (RO)	4	N/A	N/A	N/A	High data capture rates and QC over 4-yr period
Whistle Mine Sudbury, ON 46° N	FS	Barrier / 0.5 m CCL overlain by 1.3 m sand & gravel	Waste rock	P-01 P-02	Climate (AT, RH, WS, WD, NR, BP, RF) Soil (ST, SU, W/C, PG) Hydrology (NP)	3	7% @ P-01 23% @ P-02	P-01: good G&L cover P-02: riprap	50-75 cm	High data capture rates and QC over 3-yr period Annual snow survey conducted 10 km from site P-02 lysimeter not functioning properly
				S-01 to S-13	Soil (W/C, PG)	3	Varies	Varies	50-75 cm	
				W-02	Hydrology (RO)	3	N/A	N/A	N/A	
N/A	TP	N/A / Up to 2.0 m WR or coarse coal reject	N/A	Cell 1 to Cell 6	Soil (ST, W/C, PG) Hydrology (NP)	0	N/A	None	N/A	Test cells constructed in 2008; instrumentation to be installed in 2009

Legend:

Miscellaneous:

CCL = compacted clay layer
FS = full-scale
G&L = grass & legume
GCL = geosynthetic clay liner
N/A = not applicable
OB = overburden
QC = quality control
S&R = store and release
TP = test plot
WR = waste rock

Climatic Parameters:

AT = air temperature
BP = barometric pressure
NR = net radiation
PE = pan evaporation
PPT = rainfall and snowfall
RF = rainfall
RH = relative humidity
SR = incoming solar radiation
WD = wind direction
WS = wind speed

Hydrologic Parameters:

AET = actual evapotranspiration
IF = interflow
NP = net percolation
RO = runoff
SD = snowpack depth
SS = snow survey

Soil Parameters:

PG = *in situ* pore-gas concentrations
ST = soil temperature
SU = soil suction
W/C = soil water content
WTE = water table elevation

5 Recommendations

The Phase 1 report identified the following priorities for further research:

- Further investigation of fundamental cold regions phenomena relevant to soil covers;
- Establishment of a database of cold regions covers;
- Development of models with surface flux terms that include cold regions effects;
- Tracking long-term performance of full scale cold regions covers;
- Development of best practice guidelines; and
- Coordination of existing cover trails and monitored full-scale covers.

The following sections reflect the above themes but focus on immediate opportunities to advance the state of the art. An additional section has been included to address recommendations coming out of the review of cold regions cover vegetation.

5.1 Recommendation 1: Information Transfer

The Phase 1 report reviewed cold regions phenomena in general, and Section 2 of this report examines their significance with respect to soil cover performance. A key finding is that many of the cold regions phenomena are expected to have significant effects on covers. However, making a commitment to further study those processes is complicated by a second finding, that very few of the expected effects have actually been observed.

The long time frame of some cold regions processes and the relatively short experience with cold regions soil covers are probably the main reasons for the disconnect between expectations and observations. But another reason might be that, prior to this work, the field of cover design and peri-glacial science have not crossed over. In other words, cover specialists may have not observed cold regions phenomena because they haven't known what to look for.

5.1.1 Scope 1a – Broader Distribution of Current Information

The latter problem can be resolved relatively easily. The Phase 1 report and this report are published as MEND documents, and are accessible to a wide audience. Opportunities to present the work at conferences should continue to be acted upon.

A further recommendation is to produce a short booklet that would expand upon the table presented in Section 2 of this report, adding illustrations and short explanations of each cold regions process and discussions of how they might affect cover performance. The booklet could be produced in a fashion that is easily transferable to web pages. Distribution of such a booklet to cover practitioners, regulators and operators would serve to increase the likelihood of cold regions effects being properly noted and understood. Over time, the general improvement in observation skills would help the soil cover community to identify which of the cold regions processes are most worthy of further fundamental research.

Estimated Cost

Publication of the reports by MEND and participation in seminars is covered by other budgets. The only additional cost item in this recommendation is the preparation and production of the booklet/web pages. Most of the raw material is available in either the Phase 1 report or Section 2 of this report. There would be a need for several additional illustrations, and review by both cover and peri-glacial specialists would help to ensure that the vocabulary is clear to all parties. Total costs would be in the range of $40,000.

5.1.2 Scope 1b – Development of Best Practice Guidelines

Development of “Best Practice Guidelines” for the design and construction of cold regions soil covers would be an effective way to distribute information. Given the current state of knowledge it may be premature to issue a complete guideline. However, a draft guideline would allow the considerable body of current knowledge to be distributed, while still reflecting the uncertainties. The use of web-based methods such as “wiki” would allow for collaborative development of draft guidelines, and future updating as additional knowledge is gained.

Estimated Cost

The cost of producing a web-based draft guideline incorporating material from the Phase 1 and Phase 2 reports would be in the order of $40,000. There would be a need for review by a range of people in industry and consulting.

The costs of Scope 1a and 1b could be reduced if the two were done in combination.

5.2 Recommendation 2: Coordinate Current Efforts

The Phase 1 report listed several ongoing cover trials in cold regions, and Section 4 of this report provides a more comprehensive listing along with basic information about each test. The number of tests that are underway or soon to be started suggests opportunities for coordinating efforts. Three levels of coordination are discussed here:

a. Compiling a repository of information on the existing tests;

b. Convening a technical working group to facilitate exchange of experience and results; and

c. Development of a comprehensive database.

5.2.1 Scope 2a – Library Compilation

Although cover design is site specific, cover practitioners do give considerable weight to precedents. As shown in Section 4 of this report, there is a large and growing number of cold region cover tests and full scale implementations from which to draw information. However, data from these case studies are difficult to obtain. It would greatly simplify future reviews if the relevant reports from each project could be compiled in one electronic collection. The type of relevant documents will differ from site to site, but could include design reports, as-built reports and monitoring data reviews.

Estimated Cost

Costs for collecting a complete set of documents from the cover tests and full scale covers listed in Section 4 would be low. Approximately $15,000 would cover the cost of collection, scanning and setting up an indexed SharePoint site.

5.2.2 Scope 2b – Technical Coordination Meetings

Periodic meetings amongst the relatively small number of soil cover experts workings in cold regions would provide a highly cost effective means to transfer knowledge, and could also be a focal point for decisions about coordinating field test plans and/or cooperating on more fundamental research.

Estimated Cost

Costs for periodic meetings of interested specialists could be low where the meetings can be combined with other functions. Allowing for approximately 10 people to travel to one meeting per year, with production and circulation of meeting notes, would increase the costs to around $30,000 per year.

5.2.3 Scope 2c – Comprehensive Database

A universally accessible database that stores relevant data from past cover construction and current performance monitoring projects would benefit practitioners looking to apply the lessons learned from previous projects in cold regions. Such a database would not only provide access to critical 'typical' data required for design but would promote more consistency in the design process (e.g. selection of climate, climate variability, evolution of material properties, etc.), and would allow accumulated site performance data to be interpreted in an integrated manner.

Two phases would be required. The general approach in similar projects has been to establish the detailed scope and design specifications for the required system in the first phase, and to perform the system development and implementation activities as part of the second phase. In the first phase of the project a relational database structure would be designed and all pertinent data collected and inventoried. At this stage, representative users would be engaged to determine specific needs in terms of data archiving, reporting, and functionality. Following the first phase, a revised detailed cost estimate would be developed. In the second phase, implementation of the existing software would commence, followed by populating the database. Population of the database would take advantage of quality assurance and control checks inherent in the system to ensure the integrity of the data that is being migrated to the new platform.

Estimated Cost

Costs involved with the implementation of a web-based database would depend on the structure and quality of the data to be migrated into the new system. Depending on previous data collection methods, the data to be included in the new system may require configuration. As well, the database system would require a certain degree of customization, depending on the requirements and requests of the stakeholders. Based on past experience, a basic web-based system that employs existing software and provides useful functionality that serves a primary purpose as a secure data repository should cost on the order of $75,000 to $100,000. Depending on user requirements, an annual hosting fee of $5,000 to $10,000 would be required, as well as ongoing technical data management for an estimated annual cost of $15,000 to $20,000.

5.3 Recommendation 3: Inspection of Long-Term Covers

The slow rate of many cold regions processes means that they may only be observable after many years. However, typical monitoring plans for closed mines assume that a “stable” condition is reached once vegetation is well-established, and therefore focus monitoring efforts on the first few years after cover construction. This has been the case for many of the soil covers constructed in the Canadian north over the last ten years. Furthermore, most of the monitoring plans do not specifically look for evidence of cold regions phenomena.

From a research perspective, northern sites where soil covers were constructed over the last ten years represent a significant opportunity. They effectively provide a five to ten year “head-start” for investigating cold regions processes. A return to some of those sites, with the specific intention of looking for evidence of cold regions processes, might allow the “suspected” and “expected” phenomena listed in Table 2.1 to be confirmed. In cases where incipient effects are observed, inspections would also establish a baseline for subsequent monitoring.

5.3.1 Scope 3 – Inspection of Yukon Covers

The following cold regions sites are known to have reasonably well-documented soil covers that have been in place for five or more years:

- Beaverlodge tailings (northern Saskatchewan),
- Key Lake heap leach (northern Saskatchewan),
- Arctic Gold and Silver tailings (Yukon),
- Venus tailings (Yukon),
- Brewery Creek waste rock and heap leach (Yukon),
- Vangorda waste rock (Yukon),
- Colomac tailings (NWT),
- Discovery tailings (NWT),
- Rayrock tailings (NWT), and
- Lupin tailings (Nunavut).

The Yukon sites, which are all road accessible, are a good choice for testing the field inspection methods. A suggested process would be as follows:

- A small team would be established to carry out the inspections. It is expected that an inspection team of 2-3 people would allow for safety and efficiency.
- A general inspection protocol would be established. This would focus on methods to identify cold regions phenomena.
- The documentation on each candidate site would be reviewed in order to produce a succinct summary of the cover history. For each site, the general protocol would be modified to develop specific inspection plans. These would include surface observations and hand test pits. For the road-accessible sites, machine dug test pits would also be possible.
- The inspections would be scheduled and travel and support arrangements finalized. For the Yukon sites, one day on each site and an additional half-day of travel would be needed.
- Results of the inspections would be documented in a report that would include recommendations for follow-up inspections of the Yukon covers, where warranted, and as the value of further inspections at the more remote Saskatchewan, NWT and Nunavut sites.

Estimated Cost

Cost for review and inspection of the Yukon sites would be approximately $60,000. That estimate includes $10,000 for preparation, $30,000 for the inspections, and $15,000 for reporting.

5.4 Recommendation 4: Model Development

As noted in Section 3.2, development of soil cover models with complete cold regions capabilities will require a long term effort that starts with some of the basic research described elsewhere in this report. However, there is a more immediate need to better understand the uncertainties and possible errors associated with using the current generation of models to simulate cold regions covers.

5.4.1 Scope 4 – Sensitivity Analyses using Available Models

Section 3.2.5 lists information gaps associated with the current approaches to modelling cold regions soil covers and suggests that they could be better characterized by a series of sensitivity analyses. The sensitivity analyses would use combinations of currently available soil cover and cold regions hydrology models:

- To examine the sensitivity of cover moisture balances and net infiltration to snow accumulation, redistribution, ablation and melting processes, use a cold regions hydrology model to develop a range of snowpack and snowmelt patterns, and then apply those patterns as inputs to soil cover models of a range of cover designs.

- To examine the sensitivity of soil cover thermal behaviour to surface inputs, use a cold regions hydrology model or snow heat balance model to develop a range of heat inputs to the soil surface, then apply those inputs to soil cover models.
- To examine the effects of soil freezing on infiltration patterns, combine the above two analyses within a soil cover model that has at least a rudimentary freezing routine (e.g. SVFlux).
- To examine the effects of soil property changes (induced by freeze-thaw cycles) carry out soil cover model runs using the range of permeability increases and fracture healing effects documented in the currently available literature. Include consideration of the limited depth of freezing and thawing in cases where insulating layers are present.

Estimated Cost

The above scope could be undertaken at many levels of detail. To test the overall utility of the approach, a modest initial attempt would be sensible. Limiting efforts to possibly three typical cover profiles in three different climates, would allow all of the above steps to be completed for approximately $50,000. That figure could be reduced if sites are chosen to include those where the cold regions hydrology effects have already been characterized (e.g. Faro).

5.5 Recommendation 5: Improved Monitoring Methods

Soil cover monitoring, like other elements of soil cover design and construction, is dominated by concerns associated with temperate regions. For example, monitoring of trial covers generally focuses on the cover moisture balance and infiltration, and monitoring of full-scale covers generally focuses on revegetation and erosion. There is a need to develop soil cover monitoring protocols, and possibly new monitoring methods, that are more appropriate for cold regions.

5.5.1 Scope 5a: Recommend Monitoring Parameters and Methods

This scope involves only currently available monitoring methods, and would consist of the following:

- Review of case histories highlighting lessons learned from performance monitoring of mine waste cover systems in cold regions;
- Recommending of a set of parameters that should be monitored in cold regions covers;
- Recommended methods for measuring each parameter;
- Development of an overall monitoring strategy that considers the minimum and 'ideal' spatial and temporal monitoring requirements for different waste storage facilities.

Results would be presented in a report or, preferably, web-based wiki or SharePoint system that would allow updating as further information becomes available.

Estimated Cost

The estimated cost for this scope is $30,000. Costs could be reduced if this effort were combined with Scope 1b.

5.5.2 Scope 5b: Develop Distributed Fibre Optic Temperature Sensing

This scope involves development of a new monitoring method. Distributed Fibre Optic Temperature Sensing (DTS) is a relatively new technology that provides real-time measurements of temperature at 1 m intervals over a horizontal scale of kilometres when the fibre is laid out as a linear cable, or at vertical intervals of centimetres when it is wrapped as a tight vertical coil.

There are potential uses of DTS systems in monitoring thermal regimes, snow pack distributions, and snowmelt infiltration dynamics for soil covers systems in cold regions. The following stages of research are recommended:

- Desk Study: A detailed literature survey on the background technology and applications of DTS would allow the potential limitations associated with monitoring soil covers and mine wastes to be identified.
- Laboratory Study: Controlled laboratory experiments would evaluate the functionality of DTS for measuring temperature and water contents under thermal and soil regimes typical of waste rock, tailings, and cover materials. These studies would require controlled column or desktop experiments under cold room conditions.
- Field Study: Field testing would require installation of a DTS system as part of the cover monitoring at an existing cold regions site. Capture, data quality, and data interpretation would need to be evaluated over the course of two years of monitoring.

Estimated Cost

The desktop study could be undertaken using university research personnel over a period of 2-3 months, but may require some specialized expertise from electronics specialists. The cost estimate for this study is approximately $30,000.

The laboratory study would require the acquisition of a state-of-the-art DTS system (~$100,000). In addition, research staff and laboratory facilities would be required for approximately six (6) months. This element of the study would likely cost out in the range of $200,000 to $250,000 (including purchase of the DTS).

The field monitoring could utilize the same DTS and the logistical support of an existing site. The additional costs would likely be those for research staff support on a part-time basis over two years and would likely be in the range of $150,000 to $200,000.

5.6 Recommendations Related to Cover Vegetation

Section 3.1 above identifies several knowledge gaps related to vegetation of soil covers in cold regions. The following scopes address those gaps in combinations suitable for efficient study.

5.6.1 Scope 6a: Evapotranspiration from Cold Regions Soil Covers

The contribution of evapotranspiration (ET) in cold regions is one of the primary uncertainties relevant to covers that are designed to reduce infiltration to mine wastes.

The only method for acquiring a direct measure of ET is through eddy covariance (EC) techniques. Installation of one or more EC-instrumented meteorological towers on reclaimed mine-waste covers in northern Canada would address this identified knowledge gap, and would make a substantial contribution to the field of soil-vegetation micrometeorology. The following discussion presents constraints/site requirements, required equipment, suggested approaches, and rough cost estimates for such an installation.

Constraints and Site Requirements

Sites for installation of EC equipment should ideally provide a minimum of 100 m of relatively homogeneous cover/soil material and vegetation in all directions surrounding the potential tower location. Ideally sites will be level or have gentle slopes, as steeper slopes can interfere with accurate estimation of ET.

Required Equipment

There are two viable approaches to using EC to estimate/measure ET, as below.

EC Measures all Energy Consumption Except ET

In this approach, instrumentation is used to measure energy inputs and all energy consumption except ET. The shortfall, or difference, is ET. A minimum equipment list for this approach is as follows:

- Sonic anemometer
- Data logger
- Net radiometer
- Ground heat flux plate and soil temp
- Temperature/RH sensor
- Tower
- Power system (solar)

EC Measures ET Directly

In this approach, instrumentation is used to measure water (and CO_2) flux directly. A minimum equipment list for this approach is as follows:

- Sonic anemometer
- H_2O/CO_2 gas analyzer
- Data logger
- All-wave radiometer
- Ground heat flux plate and soil temp
- Temperature/RH sensor
- Tower
- Power system (solar)

An EC system would ideally be installed on a mine-waste cover immediately following revegetation, so that changes in ET over the initial years following vegetation could be documented. Because of the value of multi-year data, and because of substantial inter-annual climatic variation, EC towers should be maintained on individual sites for a minimum of three years. After that time, systems could be retained to collect longer-term data, or moved to other sites.

Estimated Cost

Cost estimates presented here are rough estimates for equipment and labour for installation and maintenance of EC instrumentation. A more complete estimate for an integrated program is discussed below. Note that these estimates are very approximate, as site location and access constraints can alter costs substantially.

Costs for equipment for the indirect and direct EC methods as discussed above would be approximately $25,000 and $50,000, respectively, per installation. Note that these are essentially one-time costs, as once purchased, installations can serve sites for multiple years.

Annual costs for installation and maintenance would of course vary depending on site locations and personnel available for periodic checks and maintenance of the systems, and on the EC method selected. Although installation requirements are similar with the two methods described above, requirement for regular maintenance of the direct-measurement methods are higher. Instrumentation for the indirect method can be left unattended for extended periods (2 weeks-4 months, depending on confidence in power supply, security, etc.), while the direct-measure methods require regular presence with respect to the gas analyzer (and thus, in reality are only applicable where permanent on-site expertise or trained personnel are available, or for use in collaborative programs with academic researchers).

Annual costs for installation and maintenance of a system would likely be approximately $35,000-$80,000, with the lower end associated with maintenance of an already-installed indirect-estimation EC system, and the higher end associated with installation and maintenance of the direct-estimation EC system.

5.6.2 Scope 6b: Rooting Depths in Existing Cold Regions Covers

Rooting depth is determined through destructive sampling – excavation into covers to determine average and maximum rooting depths, and, where applicable, to observe root behaviour at the various cover and waste interfaces. Information on rooting depths could be gathered through a sampling program including as many revegetated cold-region mine sites as practicable, with a range of vegetation types, cover materials, and climate settings.

Estimated Cost

Collecting information on mean and maximum rooting depths on revegetated mine-waste covers is a relatively inexpensive endeavour. The costs are labour and travel only.

The most cost effective approach would be to integrate a rooting depth study with the programs described and costed in Scope 3 above. The cost of more expansive efforts would vary with the number of sites and access constraints.

5.6.3 Scope 6c: Selection and Establishment of Appropriate Species

Mine-site revegetation is often conducted as a single-site effort, with minimum transfer of knowledge between sites, and even less summary of overall patterns of results and learning. In order to address these limitations in knowledge, two potential approaches are suggested.

Establishment Requirements

Trial work on methods of vegetation establishment (including direct seeding and seedling propagation methods) could be conducted on available sites, based on site-specific revegetation objectives. If multiple sites were available for such work, research could be conducted as a concerted program to yield more broadly applicable results. For instance, it would be valuable to gather information on establishment/propagation techniques and successes for primary candidate northern reclamation species such as birches (e.g., *Betula nana, B. Glandulosa*), dwarf willows and species with cultural value such as crowberry (*Empetrum nigrum*) and blueberries (*Vaccinium spp.*). Research methods would be replicated to allow statistical inference, and could be compared across the variety of available sites.

Retrospective Survey

Vegetation assessments could be conducted on available revegetated mine sites to characterize species present and relative success (ground cover) of these species. Such an effort could be conducted in conjunction with a corresponding investigation of rooting depth, with results compiled, summarized and interpreted across surveyed mine sites. Such a survey could be conducted relatively quickly and cost-effectively, and would yield valuable information for future revegetation efforts.

Estimated Cost

The most useful approach to addressing the vegetation-related information gaps, as well as other issues related to cold-region cover performance, would be integrated instrumentation of covers during and post construction. Monitoring of soil/cover parameters needed to understand cover performance (e.g., soil water content, temperature) could be coupled with EC-based estimation of evapotranspiration, to provide a full range of data on the performance of maturing reclaimed systems.

As part of such a program, vegetation species selection, establishment techniques, and rooting depth could be documented, both on different sites and over time (where applicable) on the same site. This approach would yield a comprehensive understanding of the controls on success of cold-region covers, from engineering parameters and design to post-management vegetation effects.

A rough cost estimate for the vegetation components (including EC) of such a program would be $100,000 for a small mine site with a single EC installation to $200,000 or more for a program with two or more EC installations on larger mine sites.

5.7 Summary of Recommended Investigations

Table 5.1 on the following page summarizes the recommended studies and cost estimates. It also identifies the recommendations that in the opinion of the authors represent the highest priority.

The basis for selection of the high priority items was as follows:

- As shown in Table 2.1, the effects of many cold regions processes are “expected” or “suspected” rather than “observed”, and studies that would confirm or bound the range of possible effects (Scopes 3 and 4) should therefore be given priority.
- As noted in several sections, a lack of understanding of cold regions phenomena decreases the likelihood that they will be properly identified when existing covers are inspected and increases the likelihood that potentially negative effects will be overlooked when new covers are being designed. Information exchange efforts continue to be needed. The most cost-effective information exchange recommendations (Scopes 1a and 2b) should be adopted first.
- As noted in Section 3.1, the effects of vegetation on cold regions cover systems are certainly significant and the understanding of these effects is clearly inadequate. Making use of opportunities to add vegetation studies (6a, 6b, 6c) to existing cover trials would both benefit those trials and be a cost-effective way to advance the general understanding.

Table 5.1. Summary of recommended investigations

Scope Number and Title		Estimated Cost	Priority[1]
1a	Broader distribution of currently available information	$40,000	Yes
1b	Development of best practice guidelines	$40,000	No
2a	Library compilation	$15,000	No
2b	Technical coordination meetings (per year)	$30,000	Yes
2c	Comprehensive database		No
	Setup and data entry	$100,000	
	Annual hosting fee (per site)	$5,000-$10,000	
	Annual database management	$15,000 - $20,000	
3	Inspection of Yukon covers	$60,000	Yes
4	Sensitivity analyses using available models	$50,000	Yes
5a	Recommend monitoring parameters and methods	$30,000	No
5b	Develop DTS system		No
	Initial desk study $30,000	$30,000	
	Laboratory testing	$200,000-$250,000	
	Field testing	$150,000 - $200,000	
6a	Evapotranspiration from cold regions soil covers		Yes[2]
	Equipment and installation (per site)	$25,000 - $50,000	
	Annual monitoring and maintenance	$35,000 - $80,000	
6b	Rooting depth in existing cold regions covers	Part of Scope 3	Yes[2]
6c	Selection and establishment of vegetation species		Yes[2]
	Vegetation component of integrated study	$100,000 - $200,000	

Notes to Table 5.1:

1. See text for reasons.
2. Only in combination with existing cover trials.

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Appendix A - Vegetation Summary Tables

Table A-1: Examples of Average Daily Evapotranspiration Measured in Various Northern Ecosystems in North America and Europe

Ecosystem Type	Region	Season	ET (mm/day)	Reference
aspen stand	Prince Albert, SK	May	1.0	Amiro *et al*. 2006
aspen stand	Prince Albert, SK	June	2.0	Amiro *et al*. 2006
aspen stand	Prince Albert, SK	July	3.0	Amiro *et al*. 2006
aspen stand	Prince Albert, SK	August	2.0	Amiro *et al*. 2006
aspen stand	Prince Albert, SK	September	1.0	Amiro *et al*. 2006
aspen stand	NW Territories	May	1.5	Blanken *et al*. 2001
aspen stand	NW Territories	June	3.0	Blanken *et al*. 2001
aspen stand	NW Territories	July	3.0	Blanken *et al*. 2001
aspen stand	NW Territories	August	3.0	Blanken *et al*. 2001
aspen stand	NW Territories	September	2.0	Blanken *et al*. 2001
aspen stand 13 y old	Grand Prairie, AB	May-September	3.2	Swanson and Rothwell 2001
aspen stand 3 y old	Grand Prairie, AB	May-September	2.2	Swanson and Rothwell 2001
aspen stand 5 y old	Grand Prairie, AB	May-September	2.0	Swanson and Rothwell 2001
aspen stand 8 y old	Grand Prairie, AB	May-September	2.8	Swanson and Rothwell 2001
aspen stand mature	Grand Prairie, AB	May-September	2.9	Swanson and Rothwell 2001
S-slope, dense aspen stand	Yukon	May-September	2.6	Carey and Woo 2001
aspen-w. spruce mixedwood	Prince Albert, SK	May-September	2.2 -2.4	Pomeroy *et al* 1998
mixed S. pine- N. spruce stand	Sweden	May	1.5	Cienciala *et al*. 1998
mixed S. pine- N. spruce stand	Sweden	June	2.0	Cienciala *et al*. 1998
mixed S. pine- N. spruce stand	Sweden	July	2.5	Cienciala *et al*. 1998
mixed S. pine- N. spruce stand	Sweden	August	1.0	Cienciala *et al*. 1998
mixed S. pine- N. spruce stand	Sweden	September	0.5	Cienciala *et al*. 1998
mixed S. pine- N. spruce stand	Sweden	May	2.0	Grelle *et al*. 1997
mixed S. pine- N. spruce stand	Sweden	June	2.5	Grelle *et al*. 1998
mixed S. pine- N. spruce stand	Sweden	July	3.0	Grelle *et al*. 1999
mixed S. pine- N. spruce stand	Sweden	August	2.0	Grelle *et al*. 2000
mixed S. pine- N. spruce stand	Sweden	September	1.0	Grelle *et al*. 2001
30 y old jack pine stand	Manitoba	June-September	1.4	McCaughey *et al*. 1997
jack pine on sand	boreal	May-September	1.1	Moore *et al*.2000
jack pine stand	Prince Albert, SK	May	0.5	Amiro *et al*. 2006
jack pine stand	Prince Albert, SK	June	1.0	Amiro *et al*. 2006

jack pine stand	Prince Albert, SK	July	2.0	Amiro *et al*. 2006
jack pine stand	Prince Albert, SK	August	1.0	Amiro *et al*. 2006
jack pine stand	Prince Albert, SK	September	0.5	Amiro *et al*. 2006
jack pine stand	Prince Albert, SK	May	1.0	Baldocchi *et al*.1997
jack pine stand	Prince Albert, SK	June	1.5	Baldocchi *et al*.1997
jack pine stand	Prince Albert, SK	July	2.0	Baldocchi *et al*.1997
jack pine stand	Prince Albert, SK	August	1.5	Baldocchi *et al*.1997
jack pine stand	Prince Albert, SK	September	1.0	Baldocchi *et al*.1997
jack pine stand	southern boreal	May-October	1.6	Amiro and Wuschke 1987
jack pine stand	southern boreal	May-September	1.8	Nijssen *et al*. 1997
jack pine stand	Prince Albert, SK	May-September	2.5 - 2.7	Pomeroy *et al* 1997
tundra	Alaska	June-August	1.5	Beringer *et al*. 2005
low shrub	Alaska	June-August	1.5	Beringer *et al*. 2005
low shrub dry tundra	NW Territories	May-August	2.2	Rouse 2000
moist tussock tundra	Alaska	June-August	1.5	Vourlitis and Oechel 1999
shrub	Alaska	June-August	1.6	Beringer *et al*. 2005
valley – org. veneer on silty sand	NW Territories	May 2000 - May 2001	1.8	Spence and Woo 2003
forest	Alaska	June-August	1.8	Beringer *et al*. 2005
woodland	Alaska	June-August	1.8	Beringer *et al*. 2005
N-slope, spruce and shrubs	Yukon	May-September	2.5	Carey and Woo 2001
W-slope, sparse spruce, shrubs	Yukon	May-September	1.8	Carey and Woo 2001
E-slope, sparse spruce, shrubs	Yukon	May-September	2.2	Carey and Woo 2001
bog	Minnesota	n.d.	3.0 - 3.6	Bridgham *et al*. 1999
fen	Minnesota	n.d.	2.7 - 2.9	Bridgham *et al*. 1999
hummocky sedge fen	Churchill, MA	May-August	2.5	Petrone and Rouse 2000
hummocky Sphagnum peatland	NW Territories	May-August	2.7	Petrone and Rouse 2000
harvested peatland (drained)	E-Quebec	May-September	2.5	Petrone *et al*.2004
restored peatland (mulched)	E-Quebec	May-September	2.2	Petrone *et al*.2004
lake (avg. depth 41m)	NW Territories	June-December	~1.0 - 4.0	Blanken *et al*. 2000
small lake (avg. depth 2 m)	NW Territories	1991-1996 open water season	2.7	Gibson *et al*. 1998
tailings pond (avg. depth 3 m)	NW Territories	1993-2004 continuous	0.8	Reid *et al*. 2004
sandstone overburden pile	N- Saskatchewan	June-August	1.7 - 1.9	Carey *et al*. 2005

Table A-2: Examples of maximum rooting depth of tundra, boreal and crop species. The table is adapted (abbreviated to show most relevant species) from Canadell *et al*. 1996, Oecologia (1996) 108:583-595

Species Name	Max. Rooting Depth (m)	Soil Type	Country	Reference
TUNDRA				
Carex aquatilis	0.3		Alaska, USA	Dennis *et al.* 1978
Dryas punctata	0.5	permafrost at 40-55 cm	N-Russia	Khodachek 1971
Dupontia fischeri	0.3	organic matter on sediments	Alaska, USA	Dennis 1977
Eriophorum vaginatum	0.6	silty soil on permafrost	Alaska, USA	Wein and Bliss 1974
Betula nana	0.5	permafrost at 50 cm	Alaska, USA	S. Hobbie, unpublished work
Luzula confusa	0.3	loams	N-Canada	Bliss and Svoboda 1984
Salix glauca	0.5	permafrost at 45-60 cm	W-Russia	Ignatenko and Khakimzy 1971
Salix planifolia	0.9	coarse textured/bottom pit	Colorado, USA	Webber and May 1977
BOREAL FOREST				
Larix laricina	1.2	medium-coarse sand/podzol	S-Canada	Bannan 1940
Larix sibirica	1.8	medium-loamy	Russia	Verzunov 1980
Picea glauca	1.8	medium-loamy	Russia	Verzunov 1980
Pinus banksia	1.2	medium-coarse sand/podzol	S-Canada	Bannan 1940
Pinus banksiana	2.0	aeolian sands/Eutric brunisol	S-Canada	Strong and La Roi 1983
Pinus contorta	3.3		S-Canada	Horton 1958
Populus tremuloides	2.0	sandy substrate	S-Canada	Strong and La Roi 1983
AGRONOMICS				
Avena sativa	1.8		Kansas, USA	Weaver 1926
Bromus inermis	1.1	silty-clay to clay-loam alluvial	Canada	Leyshon 1991
Elymus angustus	3.5		S-Canada	Lawrence 1975
Elymus junceus	1.8		S-Canada	Lawrence 1975
Hordeum vulgare	1.3	Lowland silt loam	Nebraska, USA	Weaver 1926
Hordeum sp.	2.2	loamy sand/Xeric	W-Australia	Hamblin and Tennant 1987
Lupinus angustifolius	2.5	loamy sand/Xeric	W-Australia	Hamblin and Tennant 1987
Medicago sativa	3.7		Nebraska, USA	Weaver 1926

Table A-3. Comparison of published data on maximum rooting depth of vegetation typical of temperate regions. The table was adapted (abbreviated to show most relevant species) from Breuer L., Eckhardt K. and Frede H.G., 2003. Plant parameter values for models in temperate climates. Ecological Modelling 169 (2-3): 237-293.

Depth (m)	Species Name	Site Type	Age	Country	Reference
Herbs, forbs, grasses					
0.42	*Arabidopsis thaliana*			AT	Kutschera (1960)
0.75	*Arrhenatheretum* spp.			DE	Ellenberg (1996)
0.75	*Arrhenatherum elatius*			n.d.	Ellenberg (1996)
1.95	*Avena sativa*	Tall-grass prairie		USA, NE	Weaver (1926) in Kutschera (1960)
0.70	*Cirsium oleracum-*			DE	Ellenberg (1996)
0.80	*Equisetum arvense*			n.d.	Ellenberg (1996)
0.80	*Festuca rubra*			n.d.	Ellenberg (1996)
0.70	*Knautia arvensis*			n.d.	Ellenberg (1996)
1.35	*Lolium multiflorum*			AT	Kutschera (1960)
1.45	*Lolium multiflorum*			CH	Kauter (1933) in Kutschera (1960)
1.80	*Phragmitis communis*			AT	Kutschera (1960)
0.14	*Plantago lanceolata*			UK	Anderson (1927) in Kutschera (1960)
0.59	*Plantago lanceolata*			AT	Kutschera (1960)
0.60	*Plantago lanceolata*			DE	Wehsarg (1935) in Kutschera (1960)
0.85	*Plantago lanceolata*			n.d.	Ellenberg (1996)
0.70	*Poa pratensis*	Valley bog		DE	Kamprath (1933) in Kutschera (1960)
0.72	*Poa pratensis*	Loamy brown soil over shingle		AT	Kutschera (1960)
0.83	*Poa pratensis*	Clay		DE	Kamprath (1933) in Kutschera (1960)
0.89	*Poa pratensis*	Loam		DE	Kamprath (1933) in Kutschera (1960)
0.94	*Poa pratensis*	Sand		DE	Kamprath (1933) in Kutschera (1960)
1.22	*Poa pratensis*			USA, KS	Kutschera (1960)
1.44	*Poa pratensis*	Stony sandy brown soil		AT	Kutschera (1960)
1.52	*Poa pratensis*	Silty loam		USA, NE	Weaver (1926) in Kutschera (1960)
1.83	*Poa pratensis*	Clay loam		USA, NE	Weaver (1926) in Kutschera (1960)
2.13	*Poa pratensis*	Sandy soil		USA, NE	Weaver (1926) in Kutschera (1960)
0.25	*Polygonum aviculare*			DE	Meisel (1955) in Kutschera (1960)
0.72	*Polygonum aviculare*			AT	Kutschera (1960)
0.80	*Trifolium pratense*			n.d.	Ellenberg (1996)

0.81	*Trifolium pratense*	Sandy brown soil		AT	Kutschera (1960)
1.32	*Trifolium pratense*			n.d.	Könnecke (1967)
1.35	*Trifolium pratense*	Black earth over loess		DE	Könnicke (1951) in Kutschera (1960)
3.04	*Trifolium pratense*			USA, NE	Weaver (1926) in Kutschera (1960)
0.15	*Trifolium repens*			n.d.	Fraas in Kutschera (1960)
0.18	*Trifolium repens*			n.d.	Pistohlkors (1898) in Kutschera (1960)
0.40	*Trifolium repens*	Loamy sand		DE	Kraus (1914) in Kutschera (1960)
0.61	*Trifolium repens*			USA, NY	Beckwith (1886) in Kutschera (1960)
0.70	*Trifolium repens*	Stoney sandy loam		AT	Kutschera (1960)
0.76	*Trifolium repens*	Silty loam		USA, NE	Weaver (1926) in Kutschera (1960)
1.00	*Trifolium* spp.			AU	Hamblin and Hamblin (1985) in Gregory (1988)
0.68	*Trisetum* spp.			DE	Ellenberg (1996)
0.70	*Trollius europaeus-*			DE	Ellenberg (1996)
Trees					
2.50	*Populus tremuloides*	Sand	10	n.d.	Köstler *et al*. (1968)
1.80	*Populus tremuloides*			n.d.	Brown and Tompson (1965) in Rutter (1968)
1.20	*Populus tremula*	Clay, moist	40	DE	Schoch (1964) in Köstler *et al*. (1968)
1.40	*Populus tremula*	Pseudogleyig loam	50	DE	Köstler *et al*. (1968)
1.50	*Populus tremula*	Clay			
0.40	*Abies alba*		10	n.d.	Köstler *et al*. (1968)
1.50	*Abies alba*	Heavy clay	100	DE	Köstler *et al*. (1968)
1.60	*Abies alba*		40	n.d.	Köstler *et al*. (1968)
1.30	*Larix decidua*	Pseudogley		DE	Köstler *et al*. (1968)
2.50	*Larix decidua*	Deep loamy sand		n.d.	Köstler *et al*. (1968)
0.80	*Larix leptolepis*	Clay, alternate moist	60	DE	Schoch (1964) in Köstler *et al*. (1968)
1.20	*Larix leptolepis*		60	DE	Schoch (1964) in Köstler *et al*. (1968)
1.20	*Larix leptolepis*	Pseudogley	60	DE	Köstler *et al*. (1968)
1.70	*Larix leptolepis*	Pseudogley	60	DE	Köstler *et al*. (1968)
2.80	*Larix leptolepis*	Sand over loam		DE	Yao-Ming (1962) in Köstler *et al*. (1968)
1.00	*Picea abies*			DE	Köstler (1956) in Schmidt-Vogt (1987)
1.10	*Picea abies*		80	DE	Rastin and Mintenig (1992)
1.50	*Picea abies*			DE	Graser (1935) in Köstler *et al*. (1968)

1.70	*Picea abies*			DE	Schoch (1964) in Köstler *et al*. (1968)
2.00	*Picea abies*			DE	Raspe *et al*. (1998)
2.00	*Picea abies*			n.d.	Büsgen-Münch (1927) in Köstler *et al*. (1968)
2.00	*Picea abies*		30	n.d.	Köstler *et al*. (1968)
2.10	*Picea abies*			DE	Vater (1927) in Köstler *et al*. (1968)
2.35	*Picea abies*			DE	Wagenknecht and Belitz (1959) in Schmidt-
3.25	*Picea abies*			n.d.	von Kruedener (1943) in Schmidt-Vogt (1987)
4.40	*Picea abies*			n.d.	Römper (1954) in Schmidt-Vogt (1987)
4.50	*Picea abies*			n.d.	Wagenknecht (1955) in Köstler *et al*. (1968)
6.00	*Picea abies*			n.d.	Jüttner (1954) in Schmidt-Vogt (1987)
2.52	*Pinus* spp.	Mixed stand with *Betula verrucosa*		RU	Rachtejenko (1952) in Köstler *et al*. (1968)
1.40	*Pinus sylvestris*	Rendzina on shingle		DE	Köstler *et al*. (1968)
1.50	*Pinus sylvestris*		20	DE	Engler (1903) in Köstler *et al*. (1968)
1.50	*Pinus sylvestris*		55	UK	Ovington (1957)
1.80	*Pinus sylvestris*			n.d.	Rutter (1968)
2.50	*Pinus sylvestris*		40	n.d.	Köstler *et al*. (1968)
6.00	*Pinus sylvestris*				

Table A-4. Spatial dimensions of excavated root systems of Betula pendula, Picea abies and Pinus sylvestris in different developmental stages and site types. Mean radial extension was calculated as the average of observed maximum radial extensions of completely exposed roots in each species and site. Table adapted from published study done in Finland by Kalliokoski, T., Nygren, P. & Sievänen, R. 2008. Coarse root architecture of three boreal tree species growing in mixed stands. Silva Fennica 42(2): 189–210.

Species and	Boreal forest type	Radial extension (m)			Depth (m)		
Developmental Stage		max	mean	SD	max	mean	SD
Betula pendula							
Sapling	mesic	5.7	3.2	1.8	0.76	0.25	0.17
Pole	mesic	8.1	5.2	2.1	1.08	0.43	0.21
Mature	mesic	20.5	11.6	6.7	2.65	0.74	0.47
Pole	richer	10.2	6.6	3.9	1.57	0.47	0.2
Pole	poorer	10.6	8.1	1.9	1.7	0.55	0.16
Picea abies							
Sapling	mesic	5.4	3.8	1.4	0.64	0.16	0.18
Pole	mesic	4.4	3.2	0.8	0.83	0.21	0.14
Mature	mesic	10.1	8.7	1.4	1.61	0.56	0.37
Pole	richer	5.6	3.9	1.1	0.8	0.37	0.12
Pole	poorer	10.1	6.7	2.3	1.62	0.36	0.2
Pinus sylvestris							
Sapling	mesic	4.7	2.5	1.1	0.8	0.26	0.24
Pole	mesic	7.6	4.5	2.0	1.05	0.43	0.17
Mature	mesic	9.5	6.0	2.3	2.91	0.81	0.43
Pole	richer	8.3	4.9	2.2	1.05	0.42	0.18
Pole	poorer	6.9	5.3	1.8	0.86	0.33	0.17