

Enhancing the Understanding for the Influence of Vegetation on Cover System Performance in a Canadian Mining Context

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Abstract

Models developed to predict vegetative cover system performance for reactive mine waste currently require users to specify vegetation parameters. As such, they tend to remain ‘static’ throughout numerical simulations and are not representative of their dynamic nature in natural systems. Evapotranspiration, leaf area index, rooting characteristics, and abundance are all parameters that respond to site-specific biotic and abiotic factors, which affect overall cover system performance on a site-specific basis. Here the objective is to gain an understanding for the manner in which different plant functional groups respond physiologically to interacting biotic and abiotic factors in the biogeoclimatic regions of Canada. Emphasis is placed on plant responses to water availability with reference to the effect of nutrient availability. The goal is to establish a set of guidelines for plant model parameters and the most appropriate approach to incorporating them into numerical models. These guiding principles could subsequently form the basis for determining site-specific performance for a particular cover systems, locations, and plant functional groupings.

Introduction

Currently, predictions of vegetative cover system performance for reactive mine waste requires users to specify rooting depths, rooting patterns, and empirical relationships that control transpiration rates. Within models, these parameters tend to remain constant throughout the numerical simulation and thus, are not representative of their dynamic nature in natural systems. Rather, parameters such as rooting characteristics, leaf area index (LAI), and evapotranspiration (ET) respond to site-specific biotic and abiotic interactions that affect overall cover system performance on a site-specific basis.

The objectives of this review are

- To gain an understanding of how different plant functional groups respond physiologically to interacting biotic and abiotic factors on cover systems;
- To establish a set of guidelines for plant-model parameters, and to determine the most appropriate approach to incorporating them into numerical models;
- To differentiate vegetation performance on the basis of the different biogeoclimatic regions within Canada; and
- To determine the methodology to appropriately determine the thickness required for a growth medium of a particular site, such that the proper balance between performance and cost can be achieved.

A review of the ‘typical’ reactive mine waste covers in Canada found that general objectives include dust and erosion control, control of oxygen and/or water ingress, improved quality of runoff water, control of infiltration, and the use of a growth layer for the establishment of vegetation to meet end land use objectives. Performance criteria for dry covers are developed on a case-by-case basis due to the heterogeneous landscape and diverse climatic conditions found in Canada. Vegetation is included during the design process and as a criterion for mine closure. The establishment of vegetation increases overall cover performance mainly through erosion control and increased evapotranspiration to limit percolation. These benefits are the result of

specific vegetation performance parameters such as the LAI and ET of varying plant functional groups. Performance parameters are affected by varying biotic and abiotic factors such as the available water holding capacity of soil, climate, physiological differences, competition, spatial variability between cover locations, and more. Thus, an emphasis must be placed on plant performance parameter response to abiotic and biotic factors present in the biogeoclimatic regions of Canada to better understand how vegetation improves the performance of cover systems. Emphasis is placed on plant responses to water availability, with some reference to the effect of nutrient availability.

Typical Performance Parameters for Plant Functional Groups on Cover Systems

Rooting

Information pertaining to rooting depths for different plant functional groups within the biogeoclimatic regions of Canada is important to the design of mine waste covers. Covers are often designed with the intent of limiting net percolation (NP) through mine waste; hence, rooting effects in response to moisture at different depths is of interest. Given an insufficiently thick growth medium layer, deep roots have the potential to penetrate barrier layers at the expense of cover system performance.

Trees

The soil profile is a relatively transient system as root depths vary with the development of a mature community. For a young community, the critical zone for soil moisture to support young trees is the top 15-20 cm, where moisture is in the immediate vicinity of their roots (Barbour et al. 2010). Although numerous studies have attempted to quantify rooting depths, values vary across the heterogeneous landscape and are largely influenced by the amount of plant available water at a particular location. Jackson et al. (1996) found that 83% of roots in boreal forests occurred in the top 30 cm of the soil profile. Systems with shallow roots tended to occur at high latitudes due to permafrost or high moisture. Moreover, Canadel et al. (1996), summarized that tree species of the boreal forests had a mean maximum rooting depth of 2 m with a maximum of 3.3 m. Considering Canada's boreal forest zone occupies 552 million ha and is home to some 20 tree species (Natural Resources Canada 2010), these findings are very general and can only be improved upon by in situ experimentation.

Although tree rooting characteristics are dependent on a multitude of factors, broad conclusions may be drawn to create general guidelines for rooting depths on covers. Through the course of plant succession, tree root biomass increases due to extirpation and reduction of early successional species, which allows root development of later successional species to occur. Interestingly, as stands reach a certain age, it appears that root length of trees may decrease due to changes in species composition or moisture enhancement. Trees appear to have physiological differences driving differential rooting depths. Aspen tends to have the deepest roots with depths > 3 m, most likely to a maximum of 3.3 m as presented by Canadel et al. (1996). An average maximum rooting depth of 2 m appears applicable to the majority of trees in Canada as the majority of roots are found in the top soil layers. Physical restrictions such as the water table have a deterministic role in driving root depth, most often limiting depth when the water table is shallow in the soil profile. In most instances, soil compaction does not appear to hinder root development especially in pine tree roots as they display a remarkable ability to penetrate compacted soils and reach normal depth (Stoltz and Greger 2006).

Shrubs and Grasses

Shrubs are often used to vegetate dry cover systems due to shallower rooting systems and higher development rates, which inhibit them from reaching barrier layers and allows them to begin transpiring water sooner (INAP 2003; MEND 2007). The global mean maximum rooting depth of shrubs is 5.1 ± 0.8 m (Canadel et al. 1996), which most likely represents the extreme upper limit of shrub roots in Canada. More realistically, shrub roots in Canada could be confined to the upper 2.5 m of the soil profile depending on various environmental drivers and root system differences among shrub species. Environmental factors such as depth of water table (Murphy and Moore 2010) and the compaction level of soil layers or bedrock appear to significantly influence shrub root system development (Kummerow et al. 1977). Root system adaptations

such as differential rooting depths and larger volumes of occupied soil appear to promote shrub establishment on the landscape (Lee and Lauenroth 1994).

Grass roots are generally considered to be the shallowest of the three functional groups. They typically have herringbone root systems, optimal branching patterns, and uniform diameters with the largest root densities occurring in upper soils, although some may reach depths > 2 m (Weaver 1919). In Canada, grasses are abundant making up the majority of biomass in temperate grasslands of the prairies and the tundra. Differences in water availability, length of growing season, and permafrost give rise to differential rooting patterns of grasses between biogeoclimatic regions (Jackson *et al.* 1996). On a broad scale, Jackson *et al.* (1996) demonstrated that 93% of roots occurred in the top 0.3 m of soil in the tundra and 83% in the temperate grasslands. In another global-scale study, Canadel *et al.* (1996) determined that mean maximum rooting depths were 2.6 ± 0.2 m for temperate grasslands and 0.5 ± 0.1 m for tundra. The global mean maximum rooting depth of grasses is 2.4 ± 0.1 m (Canadel *et al.* 1996), which appears to be a plausible maximum root depth for grasses in Canada. This value may represent the upper maximum as the majority of studies have occurred in the prairies of the United States where ground freezing likely occurs to a lesser extent allowing roots to penetrate deeper. Tundras are grass dominated; they often represent the largest standing biomass within the biome. The global average maximum estimate of rooting depths for grasses in the tundra biogeoclimatic region of 0.5 ± 0.1 is likely.

Linking Soil Moisture and Leaf Area Index

Some research has attempted to find the link between soil moisture and LAI by exclusively observing their interactions. As a general trend, LAI appears to increase with increasing soil moisture. Deviation from this trend is generally attributed to site- and species-specific differences; some species may have a tolerance threshold for soil moisture and will not persist if the threshold is surpassed. This may facilitate species change resulting in varying LAI values for a particular site, due to differences in vegetation morphology, physiology, and development rate (Jose and Gillespie 1997; Li 2010). Shifts in the dominant vegetation through site evolution may also impact LAI as different vegetation have varying growing season lengths, which may influence the timing and extent of maximum LAI (Carey 2008). Seasonal and annual temperature / soil moisture variation may also impact LAI values on covers (Carey 2008).

Determining the link between soil moisture and LAI from studies that have endeavoured to quantify these parameters individually remains difficult. In most cases, it appears that layering / soil types have an influence on available soil water thus impacting the type of vegetation present at a particular site. Interestingly, once vegetation is established it may impose constraints on the amount of available water present at a particular site, which also varies between plant species (Elliott *et al.* 1997). When evaluating LAI individually, temporal, climatic, edaphic, and species-specific factors must be considered to have an accurate measurement of LAI for a particular location (Buermann *et al.* 2002). To evaluate the interaction between soil moisture and LAI using individual studies, future work should attempt to create a geographic base map of available soil moisture overlain by LAI. This work could be used to better predict LAI values according to available soil moisture for specific locations and be subsequently included into modelling operations to generate more accurate outputs.

Linking Leaf Area Index and Evapotranspiration

Each combination of plant community or functional group within different biogeoclimatic regions theoretically possess their own maximum potential LAI, partly constrained by soil moisture conditions. LAI development also varies over time for each plant community within different regions. By using LAI as a metric for plant growth, the relationship between soil moisture and its effect on LAI can be considered.

Evapotranspiration (ET) is the process by which moisture is exchanged between the earth's surface and the atmosphere. The process occurs through evaporation of water from the soil and by transpiration of water by vegetation. Transpiration is mediated by plant physiological and morphological traits such as leaf anatomy / size, water use efficiency, rooting depth, age, photosynthetic capacity, and plant structure. In general, as the number of transpiring leaves increases (increasing LAI), evapotranspiration (ET) also increases, which varies

according to vegetation type / species and vegetation community age. Therefore, the link between the vegetation response parameter (LAI) and the vegetation performance parameter (ET) was evaluated. Plant functional groups were divided into dominant forest types for the biogeoclimatic regions in Canada and typical LAI-ET ranges were determined for each.

Coniferous Forests

Separated by land cover class, LAI (Figure 1) can be compared with Liu et al.'s (2003) ET results (Figure 2) and land cover (Figure 3) maps to draw links between estimated LAI and ET values. The mean estimated ET for coniferous forests in Canada is $276 \text{ mm/yr} \pm 71 \text{ SD}$ (Liu et al. 2003). Similarly, in a global estimate of ET rates separated by land cover type, Zhang et al. (2010) found evergreen needle leaf forests had an average ET rate of $294 \pm 81 \text{ mm/yr}$. Using forest type land maps; it is possible to infer the spatial extent of the ET value for coniferous forests (Figure 3). Evapotranspiration (Figure 1) and forest distribution (Figure 3) agree remarkably well with the coniferous forest cover ET value ($276 \text{ mm/yr} \pm 71 \text{ SD}$) (Liu et al. 2003; Natural Resources Canada 2007). Corresponding maximum LAI growing season values range from approximately 3.5 – 5.5 (Figure 2). Although broad-scale trends are useful, in situ measurement is still necessary. A study from the boreal forest of Saskatchewan found that LAI values averaged 4.5 although variable (Chen et al. 1997) with a total ET of $711 \text{ mm/yr} \pm 70 \text{ SD}$ over a two-year monitoring period (Arain et al. 2003). Separated into single monitoring years, the ET value agrees closely with the large-scale inference. The average ET value presented by Liu et al. (2003) also falls between the observed annual values of 125 – 475 mm for cold regions (MEND 2010). In the case of jack pine stands, if a five-month growing season is assumed, and the mean reported growing season daily ET value of 1.3 mm from MEND (2010) is used, the mean annual growing season ET value for jack pine would be approximately 195 mm. The lower value may be attributed to the understory's contribution to ET, as many in situ experiments only measure stand ET rates. In the case of coniferous forests, this is vital as their lower LAI form a more open canopy leading to a higher ET contribution from the understory (Baldocchi et al. 1997). Although minimal, winter ET contributions may have also slightly increased average annual ET. Nonetheless, the broad-scale value for coniferous forests in Canada presented by Liu et al. (2003) seems to agree well with the LAI and forest type maps, in addition to in situ experimental findings.

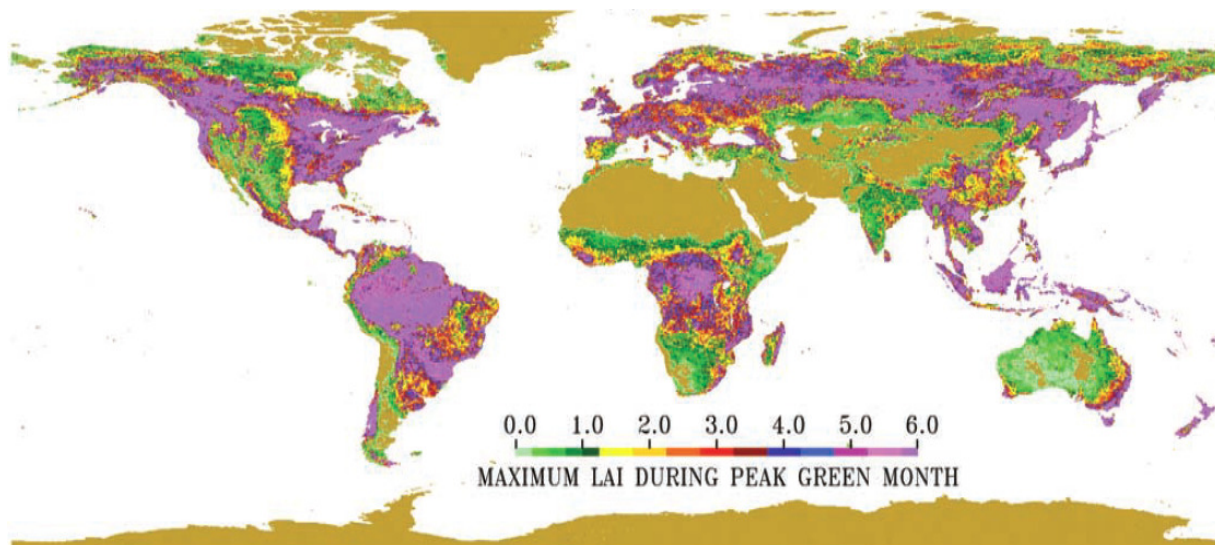


Figure 2 The maximum geographical distribution of LAI over the 1981 – 1991 during the month of peak greenness (Buermann et al. 2002).

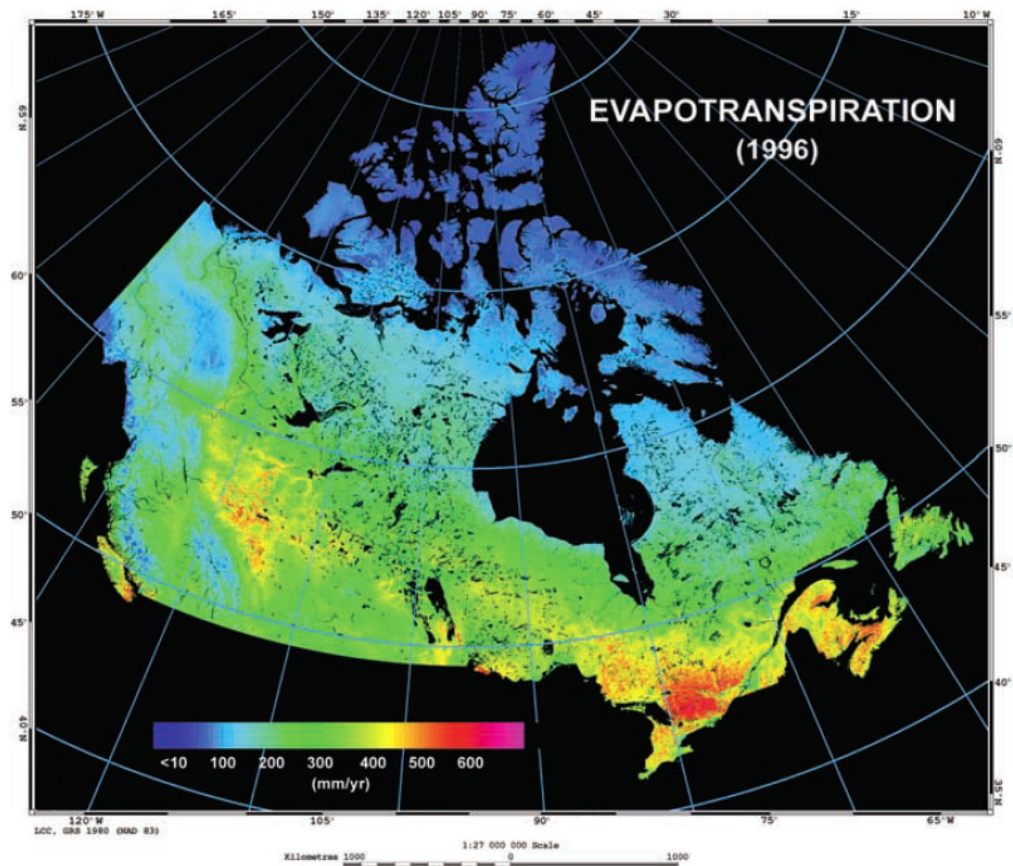


Figure 1 Simulated ET distribution for Canada (Liu et al. 2003).

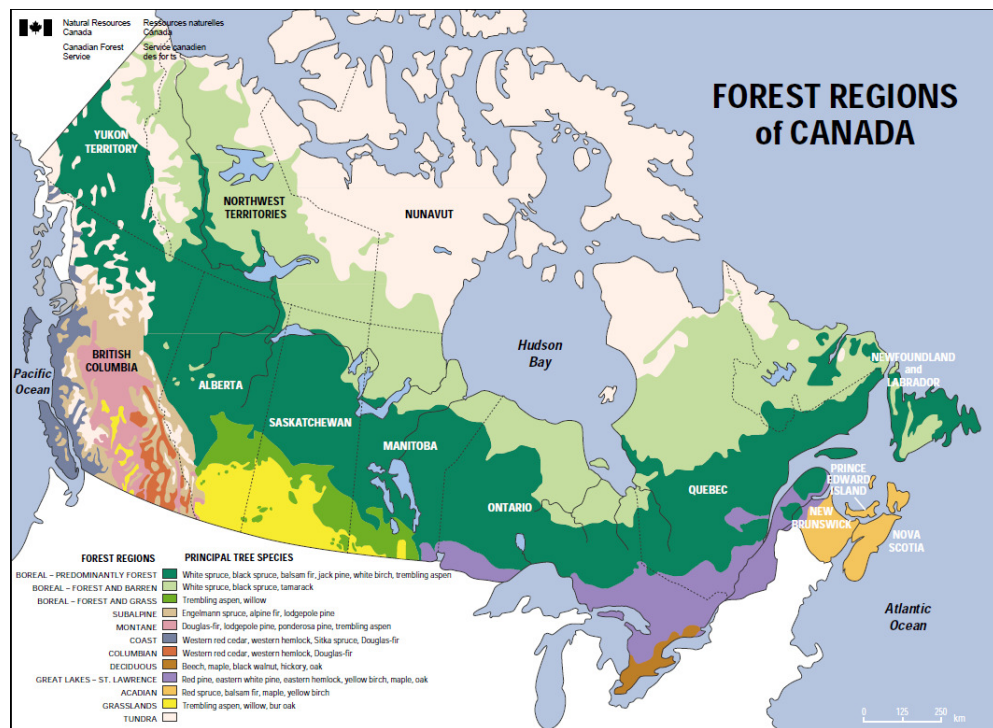


Figure 3 Forest regions of Canada (Natural Resources Canada 2007).

Mixed Forests

Mixed forests in Canada are characterized by conifers and broadleaf species. In a global estimate of ET rates, mixed forests had an average rate of 361 ± 124 mm/yr (Zhang et al. 2010). According to Liu et al. (2003) the average annual ET rate for mixed forests in Canada is $405 \text{ mm/yr} \pm 78$ SD. On a forest distribution map (Figure 3) the mixed-wood forest corresponds to the boreal forest and grass area (also known as the aspen parkland) extending from central Alberta, south-east to the Manitoba US border (Figure 3). It also encompasses the Great Lake – St. Lawrence area (Figure 3). The Acadian region of New Brunswick and Nova Scotia form the last portion (Figure 3). The forest distribution map (Figure 3) agrees well with the ET distribution map (Figure 1). Evapotranspiration rates range from approximately 350 – 550 mm/yr following a similar distribution to the forest cover map. Maximum growing season LAI values appear more variable for this forest class with values ranging from approximately 1.5 – 3 in the boreal forest and grass area (aspen parkland) and staying relatively consistent at approximately 5, with slight variability in the other areas. Variability may be due to the aspen parkland's slightly patchier mosaic, which allows grasses to grow and results in lower LAI values. Mixed forests in eastern Canada have a comparatively less patchy mosaic, resulting in greater LAI values. Thus, evapotranspiration rates may be higher in less patchy land covers. For instance, Pejam et al. (2006) determined that the ET rate for a mixed forest in Ontario, Canada was 480 ± 30 mm. Variability may still exist within the aspen parkland as one study found LAI values of 5.8 for an aspen dominated stand in Saskatchewan (Amiro et al. 2006). The high LAI values corresponded to ET rates of 441 and 323 mm/yr in 2001 and 2002, respectively (Amiro et al. 2006). In general, large-scale patterns between LAI, ET, and forest distribution maps tend to agree. However, as larger spatial scales are observed more closely, the resolution between LAI and ET at smaller scales becomes more variable. Thus, it is important to understand factors driving variability so that more accurate assessments of LAI and its influence on ET may be made at smaller spatial scales.

Deciduous Forests

Canada's smallest forest cover type, the deciduous forest, is limited to the southernmost tip of Ontario (Figure 3). Canadian ET estimates for this land cover class are $492 \text{ mm/yr} \pm 86$ SD (Liu et al. 2003). Comparatively, deciduous forest ET rates are high; however, due to their low abundance (2.1%; Natural Resources Canada 2009) they only contribute to approximately 1% of Canada's total ET (Liu et al. 2003). From the ET distribution map of Canada (Figure 1), deciduous forest ET rates vary from approximately 350 to 550 mm/yr with corresponding LAI values ranging from 5 to 6 (Figure 2). Global estimates of deciduous broadleaf forests are slightly higher at 635 ± 200 mm/yr (Zhang et al. 2010) with much larger variation, which may be due to climatic and site-specific differences between the deciduous forests of the world. A mixed deciduous stand in Massachusetts, USA, dominated by an oak, maple, and hickory canopy, had an average annual LAI of 5.75 and a corresponding average annual ET rate of 567 mm over a three-year monitoring period (Wilson and Baldocchi 2000). While LAI and ET values are roughly in agreement with broad-scale findings, other studies have found varying results. In the Harvard Forest dominated by northern red oak (*Quercus rubra*) in Petersham, MA, USA, LAI was approximately 3.4 (Sakai 1995) with a corresponding one year ET rate of 244 mm (Moore et al. 1996). Comparing *in situ* experiments to broad-scale findings is beneficial as it should improve the resolution of known LAI and ET values for deciduous forests.

Grasslands

Like other land cover classes, it is generally thought that grass transpiration increases linearly with LAI. Zhang et al. (2010) found the global average ET rate for grasslands to be 311 ± 193 mm/yr. Similarly, at the Canadian scale, Liu et al. (2003) determined that the average annual ET rate for grasslands was $275 \text{ mm/yr} \pm 42$ SD. Canadian grasslands occur particularly in southern regions of the Prairie Provinces (Figure 3) but can also occur in boreal, subalpine, montane, and maritime regions among others. When compared to the ET distributions map (Figure 1) these areas appear to range from 250 mm/yr to 450 mm/yr depending on the region, thus making it difficult to see correlation between maps. With this coarse resolution, the Prairie Provinces appear to agree best ranging from 250 mm/yr to 350 mm/yr (Figure 1) with corresponding maximum growing season LAI values ranging from approximately 0.5 – 1.5 (Figure 2). To gain a better

understanding of actual grassland ET rates, in situ experimentation is necessary. On an oil sands overburden reclamation soil cover from Alberta, Canada, Carey (2008) found that, one year after seeding, foxtail barley (*Hordeum jubatum*) was the dominant grass species. That year LAI increased from 0.3 in early June and reached its peak of 1.2 by late June (Carey 2008). Over a four-month monitoring period, its corresponding total ET was 246 mm (Carey 2008). Evapotranspiration values in this instance agree well with ET and LAI map comparisons but are slightly lower than broad-scale findings from Liu et al. (2003) and Zhang et al. (2010).

Shrublands

Data concerning shrub ET rates is relatively sparse in; however, global estimates have revealed that shrublands have an average annual ET of 202 ± 83 mm/yr (Zhang et al. 2010). Like other cover types, shrubland ET rates are subject to biological and physical factors influencing them from site to site. The Canadian ET estimate for shrublands is $195 \text{ mm/yr} \pm 51 \text{ SD}$ (Liu et al. 2003), which agrees remarkably well with global estimates. In Canada, shrubs tend to dominate alpine environments, upper elevations near tree lines, some prairie areas, the boreal-tundra ecotone and shrubed bogs or fens (Natural Resources Canada 2009). Because shrubs are present over a large range of ecosystems, LAI and ET values tend to vary depending on location. Using aforementioned location information and the LAI distribution map, minor generalities can be made for shrub LAI values, which appear to range from 0.5 – 1.5 (Figure 2). However, when applied to the ET distribution map of Canada, it is even more difficult to see a trend as ET values appear to range from 100 – 400 mm (Figure 1) depending on location. In northern cold regions, shrubs are associated with intermediate ET values ranging from approximately 150 – 300 mm depending on factors such as species, development stage, density, and heartiness (MEND 2010). Although broad-scale ET estimates for this land cover class are very similar, it is apparent that site-specific factors may influence actual ET rates. Additionally, when calculating ET rates for a specific land cover type it may be beneficial to include all species within the desired sample area for a more accurate assessment of actual ET rates.

Factors Influencing Plant Performance Expectations on Soil Covers

Soil Cover Thickness

Generally, thicker growth mediums (storage layers) have higher moisture storage capacity than thinner growth mediums (O’Kane and Wels 2003; Barbour et al. 2011). Enhanced storage capacity provided by thick growth layers allows water to be held within the cover for longer periods permitting more water to be transpired by vegetation rather than registering as net percolation (O’Kane and Wels 2003). Kelln et al. (2009) determined that 50 and 100 cm covers were better able to meet the moisture demands of plant communities compared to a 35 cm cover on an overburden oil sands pile. Lower available water holding capacity (AWHC) of the 35 cm cover was associated with lower boundary transpiration rates for trembling aspen and white spruce saplings present on the site, which could translate into decreased cover performance (Elshorbagy and Barbour 2007; Kelln et al. 2009). Moreover, at Cluff Lake in Northern Saskatchewan, a 1.2 m cover was placed on a waste rock pile, which resulted in overall moisture enhancement within the growth medium (OKC 2011). Available water was such that vegetation establishment continued to improve over time resulting in an increase in cover performance (OKC 2011). Thicker covers also have the ability to buffer extreme weather events. During extensive dry periods thicker covers are better able to retain water for longer periods meaning that the probability of thick covers reaching wilting point (WP) is lower than that of thinner covers (Kelln et al. 2009). Enhancement of water retention means that vegetation is less likely to experience cessation of ET during dry periods (Barbour et al. 2010). Elshorbagy and Barbour (2005) demonstrated that covers with 50 – 100 cm growth layers achieved the appropriate AWHC during wet / dry periods to attain the desired plant community. Many studies indicate that thicker, layered covers reduce the risk of soil moisture stress and result in increased performance (Barbour et al. 2010). Some have even suggested minimum cover thicknesses to provide sufficient soil moisture for vegetation during dry climate conditions in Canada, notably; > 0.6 m (Shurniak 2003), > 0.5 (Barbour et al. 2010), and 1.2 m in southwest Virginia, USA (Burger and Zipper 2002). Required soil cover thickness is highly site-specific and will vary with biological, physical, and

chemical processes from site to site (INAP 2003). Maintaining an adequate supply of soil moisture through appropriately thick soil covers remains key to the overall performance of cover systems.

Layering and Soil Properties

Many studies have shown that layering of coarse / fine soil material and varying soil properties can have profound effects on plant available water within cover systems (Barbour et al. 2010). Depending on soil profile texture (layering) and its composition, studies have demonstrated that plant available water can either increase or decrease. The idea of enhancing moisture storage by creating layers of different texture was explored by Zettl et al. (In Press 2011) in which a texturally heterogeneous site at field capacity (FC) was between 110 to 330 mm higher than a homogeneous profile. Other studies have reported moisture holding capacity enhancements of 30 to 100 mm (Barbour et al. 2010), 30 to 110 mm for a 1 m cover (Burgers 2005), and 32 to 47 mm for a 0.5 m cover (Moskal 1999) all comprised of varying soil mixtures. It is thought that by enhancing the amount of moisture available to plants through layering, site productivity might increase and improve cover system performance (Zettl et al. In Press 2011). Soil properties may also influence the amount of water available to vegetation as different soil mixtures have varying moisture retaining capabilities. For instance, some have shown that covers using mixtures of peat with local till materials improve moisture infiltration rates and AWHC, improving the cover's ability to store and release moisture for vegetation (Kelln et al. 2009; Barbour et al. 2011). Others have used ameliorating agents such as bentonite and flyash to increase the absorptive potential of covers but with mixed results (Ayres et al. 2003).

Slope Aspect and Position

Moisture availability to vegetation can be profoundly influenced by the slope of a landform, its aspect, and position within a system (Burger and Zipper 2002). In Canada, and colder regions alike, these effects are strongest over the course of the growing season (Burger and Zipper 2002). Depending on the slope, aspect, and position, water availability may be enhanced or diminished leading to vegetation responses according to water availability. Productivity on a reclaimed mine site in Virginia, USA, was found to be greatest on north and east aspects with a position towards the toe of the slope (Burger and Zipper 2002). Differences in productivity at these positions are due to several factors. Northern and eastern aspects tend to have more shade and are cooler during all seasons allowing for increased moisture leading to higher plant growth. During this time, the majority of sunlight is concentrated on southern aspects resulting in dryer conditions and less vegetative growth. This phenomenon was observed during the monitoring of two enhanced store and release test covers in Ronneburg, Germany (O'Kane et al. 2010). Two identical test covers were constructed: one had a northern aspect while the other had a south-western aspect. The authors observed superior performance from the cover with a northern aspect due to greater moisture availability for vegetation leading to higher establishment rates and higher overall ET rates (O'Kane et al. 2010). Additionally, as northern and eastern aspects generally have more shade and lower temperatures, the snow pack tends to remain longer ensuring an adequate supply of water over a longer period for vegetation.

Additionally, due to surface water drainage and interflow through the soil, a position at the toe of the slope will have greater plant available moisture allowing for greater establishment of vegetation (Burger and Zipper 2002). The down-slope translocation of moisture tends to leave upper-slope regions drier and thus slightly less productive (Burger and Zipper 2002; Kelln et al. 2009). The preferential flow of water down slope may act to facilitate sediment / soil accumulation at lower positions. Should soils move from upper to lower positions, its accumulation may raise moisture retention at down-slope positions due to increased thickness (INAP 2003). The upper slope however, may experience a reduction of moisture retention due to its decreasing thickness (INAP 2003). Given lower moisture conditions, vegetation establishment may be hindered on upper slopes leading to decreased cover performance. It is clear that slope, aspect, and position all have a large influence on plant available moisture. Designing soil covers which incorporate these factors will undoubtedly improve the establishment of vegetation resulting in effective cover system performance.

Designing Covers to Increase the Probability of Meeting Plant Performance Expectations

Characteristics that improve water availability to vegetation on covers can be tailored for specific biogeoclimatic regions and plant species. Once an understanding for plant requirements is obtained, covers may be designed to optimize these requirements and, hence, overall cover system performance. This may be accomplished through improved modelling efforts or tailoring cover design to plant demands, species, and biogeoclimatic regions. The following section uses information pertaining to plant physiological and morphological characteristics reviewed in previous sections in an attempt to improve the design of covers by increasing the probability of establishment and persistence. Expected LAI and corresponding ET values are also presented for functional groups over a range of biogeoclimatic regions. These may be incorporated into cover system performance modelling in an attempt to improve the predictive power of soil cover performance in Canada. We caution that the information is approximate and its applicability is subject to site-specific conditions. Much of the literature pertains to broad-scale findings and would benefit from *in situ* experimentation to verify results.

Plant Parameters

Grass and Shrublands

Generally considered shallow rooting, these functional groups often do not pose a considerable threat to cover system integrity, although some studies have found certain species attain depths of concern. For the majority of Canada, the upper limit for maximum grass root depths is approximately 2.4 m with the tundra having shallower rooting depths at approximately 0.5 m. Root depth in the tundra is likely limited by permafrost and shorter growing seasons. Similarly, shrub roots in Canada appear confined to the upper 2.5 m of soil. To accommodate grass and shrub roots, a cover thickness of 2.5 m or greater would most likely be sufficient assuming moisture and nutrients are not limiting (Table 1).

For grasses, the cover would also have to be sufficiently thick to have a plant extractable water capacity of approximately 12 – 17 cm water/cm soil. These soil moisture values may correspond to an approximate growing season LAI range of 0.5 -1.5 with corresponding ET rates of 250 mm/yr to 450 mm/yr for grasslands in Canada (Table 1). Liu et al. (2003) estimated that the average annual ET rate for grasslands in Canada was 275 mm/yr $\pm$ 42 SD. Shrubs tend to display high plasticity as they are able to grow over a wide range of soil moisture values. As shrubs grow in varying habitats their LAI values also vary from approximately 0.5 – 1.5 with equally broad ET values of 100 – 400 mm/yr (Table 1). Although shrubs are present on a range of sites Liu et al. (2003) estimated a mean annual ET rate of 195 mm/yr $\pm$ 51 SD for shrublands in Canada.

Table 1

Summary of estimated / recommended growth layer thickness, approximate LAI ranges, and approximate ET ranges for forest classes in Canada.

Functional Group	Conservative Estimate of Growth Layer Thicknesses (m)	Approximate LAI Range	Approximate ET Range (mm/yr)
Grasslands	2.5	0.5 - 1.5	250 - 450
Shrublands	2.5	0.5 - 1.5	100 - 400
Coniferous Forests	3	3.5 - 5.5	175 - 450
Mixed Forests	3	1.5 – 3* and 5	350 - 550
Deciduous Forests	3	5.0 - 6.0	350 - 550

Note: * indicates potential LAI values in the aspen parkland

Trees

Tree rooting depths in Canada appear less variable than other functional groups. Aside from species-specific physiological factors, rooting depths are dependent on soil factors such as depth of water table, soil type, permafrost, compaction, and texture, among others (Feldman 1984). Through succession, it appears that tree root biomass increases due to extirpation and reduction of early successional species. As climax communities establish, root length of trees may decrease due to changes in species composition or moisture enhancement due to crown closure. Though broad-scale dynamics tend to govern tree rooting patterns, species differences play a large role in rooting depths. For the majority of tree species in Canada an average maximum rooting

depth of 2 m is applicable. The deepest rooting species appears to be aspen with depths reaching > 3 m to a possible maximum of 3.3 m as presented by Canadel et al. (1996). A conservative cover thickness estimate of 3 m is thus recommended in order to satisfy the spatial requirements of all tree species in Canada assuming water and nutrients are not limiting (Table 1). This value however is subject to site-specific factors that may cause variation in rooting depths.

Given that covers may be located in coniferous, mixed, and broadleaf forest regions, modelling efforts may be improved if typical LAI and ET values were available for those regions. According to the reviewed literature and an LAI distribution map (Figure 3) the range of maximum growing season LAI values for coniferous forests in Canada is 3.5 – 5.5 with a corresponding ET range of 175 mm/yr to 450mm/yr (Table 1). The mean annual ET rate found by Liu et al. (2003) was 276 mm/yr $\pm$ 71 SD estimated at a Canadian scale and 294 $\pm$ 81 mm/yr (Zhang et al. 2010) estimated at a global scale. An important consideration for coniferous forests is the influence of understory vegetation on ET rates. The understory of coniferous forests can significantly contribute to overall ET as conifers have characteristically lower LAI values compared to broadleaved trees creating more open canopies (Baldocchi et al. 1997; Heijmans et al. 2004). Mixed forests have more variable LAI values across Canada as those in the aspen park land have a range of 1.5 – 3 where as the rest of the distribution is fairly consistent at approximately 5 (Table 1). From an ET distribution map (Figure 1) and reviewed literature, ET rates range from approximately 350 to 550 mm/yr (Table 1). Global estimates have given average annual ET rates of 361 $\pm$ 124 mm/yr (Zhang et al. 2010) whereas estimates at a Canadian scale are slightly higher at 405 mm/yr $\pm$ 78 SD (Liu et al. 2003). Variability in LAI, and subsequently ET in mixed wood forests may be dependent on location and species composition. As deciduous, coniferous, shrub, and grass species compose mixed forests, their proportions within the forest may influence LAI and hence ET. Lastly the smallest of all forest classes in Canada is the deciduous forest class. LAI values are the largest from approximately 5 to 6 during the growing season (Table 1). Evapotranspiration rates vary from 350 to 550 mm/yr from an ET distribution map (Figure 2; Table 1) while the Canadian estimate is approximately 492 mm/yr $\pm$ 86 SD (Liu et al. 2003).

Site Evolution

Cover system modelling efforts that incorporate vegetation performance parameters tend to remain constant throughout numerical simulations and thus are not representative of plant dynamics. Rather, the establishment of vegetation on soil covers will most likely undergo a series of community shifts until a climax community is reached. Using static LAI and ET values for an expected climax forest community or functional group does not yield the most accurate representation of cover system performance over the course of site evolution. Site evolution (i.e. succession) on soil covers often commences with the establishment of pioneer weedy / grass species followed by forbs / shrubs then an early forest community and lastly a climax forest community. Each successional shift is thought to modify site conditions such that the next successional community may establish. True climax forest communities are, however, seldom reached as the rate of natural disturbance (i.e. fire, disease) is high, causing non-equilibrium. The natural process of succession may take centuries, however, through modern silviculture practices the process may only take decades to reach a community capable of harvest (Burger and Zipper 2002).

As each successional shift occurs, morphological and physiological differences between species will most likely influence LAI and ET values occurring on covers. Varying leaf morphologies between functional groups will influence LAI trajectories over time. For instance, during the establishment of early successional grasses, occurring from approximately year 0 to 3, LAI values may reflect those of grasslands (approx. 0.5 – 1.5) with corresponding ET ranges (approx. 250 mm/yr to 450 mm/yr). However, as the site evolves, LAI and ET values may shift to those more representative of a mixed forest during years 3 to 9 and subsequently those of the climax forest community during years 9 to disturbance. Incorporating the state of vegetation throughout site evolution using respective performance parameters according to the site's successional status would most likely improve the accuracy of long-term cover performance modelling.

Summary

The development of the technical guidance document upon which this paper was based is intended to be a resource of baseline plant information to potentially guide cover system modellers and designers. The typical LAI-ET ranges for plant functional groups within the biogeoclimatic regions of Canada presented in this paper offer advancements in engineering practice related to partitioning surface energy and surface water between plant canopy and soil. These advances may allow users to input vegetative performance parameters that are more representative of what will be present on cover systems. Using these findings, the overall ‘predictive power’ of soil-plant-atmosphere numerical models may be improved when applied in a Canadian mining context. Results may also offer corrections for deficiencies in engineering practice by improving the understanding of root growth to specific plant species and soil moisture availability. Furthermore, suggestions on improving the design of cover systems from a vegetation standpoint may increase the probability of meeting vegetation performance expectations. The influence of site evolution on cover system performance is rarely accounted for in soil-plant-atmosphere numerical models. Preliminary suggestions for the implementation of successional processes into models may increase the probability that vegetative components are maintained within the specified design parameters and objectives over longer periods. Application of plant characteristics and improvements to cover design for vegetation must be incorporated on a site-specific basis.

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