Modelling the Critical Interactions between Cover Systems and Vegetation

MEND Report 2.21.6

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MODELLING THE CRITICAL INTERACTIONS BETWEEN COVER SYSTEMS AND VEGETATION

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EXECUTIVE SUMMARY

Introduction

Establishing a productive vegetation community is critical to ensuring the long term success of a cover system. A plant community will enhance cover system performance by increasing resistance to soil erosion, increasing organic matter content and structure, transpiring stored water, providing habitat for wildlife, and improving aesthetics, among many other benefits. While a productive vegetation community is an important contributor to cover system performance, the physical presence of a plant community will alter its environment, both above and below the cover system surface. The changes to the cover system as a result of vegetation establishment are non-linear and will have myriad effects on the transfer of mass and energy between the atmosphere, plants, and soil. Plants exist as a critical component in a plant-soil-atmosphere continuum, and consequently will drastically alter expected performance.

Numerical modelling investigations are often conducted in order to understand the effects that vegetation will have on cover system performance. However, many current modelling codes used in the cover system industry over-simplify the contribution of vegetation to cover system performance. A productive plant canopy serves many more functions than simply as a means of removing water stored in the cover system. Many modelling codes simplify the analyses by simulating soil water uptake by roots as a user-defined function, and ignoring the effect of the plant canopy on the water and surface energy balances altogether. Ignoring the physical mechanisms and physiological processes at work in plant transpiration over-simplifies the analysis, and the cover system designer risks misinterpreting modelling results that could have a critical effect on the overall performance of the system.

Objectives

Numerical modelling approaches that ignore the effect of a plant canopy and root dynamics do not fully capture the processes and mechanisms contributing to the performance of a cover system. Numerical model codes that do not account for plant physical and physiological processes and mechanisms are no longer appropriate for understanding how a cover system will behave. The objective of this report is to determine the preferred approach for numerical simulation of vegetation in cover system design. This objective was met by summarizing physical, physiological, and ecological properties of vegetation that are relevant to cover system design. A summary of current modelling codes and their deficiencies is then compiled, followed by examples of how models that accurately capture plant processes are formulated. Finally, a set of recommendations and conclusions is provided.

Summary of Plant Properties

Plant communities will evolve over time as the cover system develops. Cover system modelling efforts that incorporate vegetation performance parameters tend to remain constant throughout numerical simulations and thus are not representative of their dynamic nature in natural systems. Rather, the establishment of vegetation on soil covers undergo a series of community shifts until a mature community

is reached many years after establishment has occurred. A recognition of plant community structure shifts should be incorporated into long-range modelling analyses.

Plants seek to maintain an internal water balance, and will extract water from the soil to replace water lost through transpiration. Root uptake of soil water is a function of the negative pressure gradient between roots and the soil. Plant roots continuously grow towards sources of water, and optimal use of available soil water requires continuous root growth. Root systems will grow in accordance with species specific morphology and in response to site specific conditions. Tree root patterns will depend on the species, and are generally categorized as heart (aspen), flat (spruce) and tap (pine). For example, over 80% of root biomass in the boreal forest root is concentrated in the upper 30 cm of soil, although fine roots will commonly penetrate to 2 m. Shrubs are characterized by shallower rooting systems with greater than 70% of root biomass being concentrated in the top 0.2 m of soil. Grass roots are concentrated near the surface, with more than 80% of root biomass concentrated in the top 0.3 m of soil.

Leaf area index (LAI) is an important variable in determining plant productivity, but is one that is frequently improperly used. Leaves and needles act as collectors of solar radiation for converting CO_2 into carbohydrates. As the surface area of leaves increases, so too will plant productivity, until the point at which self-shading of leaves decreases marginal productivity. Typical modelling analyses take LAI to be the primary determinant of transpiration. While transpiration and LAI are correlated, LAI is a genetic factor that will determine productivity, and not simply water withdrawal from the soil as is implied in modelling analyses. Plants that have access to an unrestricted water supply will increase LAI up to the maximum for that species and leaf morphology. Using LAI as the main determinant of transpiration oversimplifies the parameter and ignores important physiological processes.

Transpiration as a physical process is governed by the total potential in the soil-plant-atmosphere continuum. Restrictions in the plant are analogous to electrical resistances, and the entire transpiration process can be conceptualized using Ohm's law. Conceptualizing resistances in the roots, stems, and leaves will allow for an intuitive formulation when deriving mathematical equations describing transpiration. The primary resistance of interest when discussing transpiration is stomatal resistance, which is used by the plant to control transpiration rates. Transpiration rates will vary throughout the day and over a growing season in response to climatic, biotic, and abiotic controls.

Plant Root Models

Modelling the contribution of vegetation to cover system performance requires consideration of processes and mechanisms both above and below the soil surface. Modelling extraction of water by plant roots generally uses either a microscopic formulation that models the uptake of individual roots, or a macroscopic approach where a diffuse root mass is modelled for an individual soil layer. Microscopic approaches are often too detailed for a water balance model, while macroscopic models tend to oversimplify root geometry. The cover design modeller should be aware of the advantages and disadvantages of each approach and select the appropriate one based on the specific cover objectives.

Plant roots grow in order to exploit water and nutrient resources. Modelling root growth is desirable, especially in water balance models, where plant roots may grow deeper as the surface of the cover system desiccates. Root growth consists of a set of concurrent and sequential processes that include proliferation, extension, senescence, and death. Root growth in natural systems requires a partitioning of biomass from the areas of the plant that are actively photosynthesizing. Modelling of root growth would require estimates of photosynthetically active radiation, leaf area index, leaf-water content, stomatal opening, and atmospheric CO_2, and biomass partitioning. The ROOTSIMU model combines root uptake and growth, and has been used to account for photosynthesis, respiration, transpiration, and soil hydraulic processes. Despite the availability of models, the estimation of carbon production in plants for biomass accumulation in roots has likely restricted the widespread adoption of root growth models for water balance monitoring.

Summary of Current Modelling Codes

Many numerical model codes exist for simulation of water balances and near-surface soil microclimates. The complexity and focus of each individual model varies depending on the intended application. Ecophysiological models, such as those developed for the forestry industry, focus primarily on the plant canopy. Models such as FOREST BGC and MAESTRO provide very detailed estimates of carbon and nitrogen budgets for vegetation. Soil water balances are computed as a model input for estimation of carbon balances.

Many current numerical codes that are used in the cover design industry treat vegetation as a simple sink term for soil water, and do not simulate turbulent transfer of mass and energy in the plant canopy. Common model codes such as UNSAT H and VADOSE/W oversimplify vegetation and in so doing, ignore the important effects that vegetation has within the soil-plant-atmosphere continuum. The HYDRUS model code incorporates a rigorous model of solute concentrations and uptake by plants as well as the effect of osmotic stress on plant water uptake responses. Nevertheless, plant water uptake is still modelled as a sink term in HYDRUS, and is not driven by atmospheric conditions.

The ideal approach to simulating vegetation in cover systems is to have the simulated plant canopy respond in a physically appropriate manner with respect to plant physiology. A plant canopy is also important in modifying the near surface atmosphere, and an appropriate model must account for changes in mass, energy, and momentum transfer caused by plants. The Fast All-Season Soil Strength (FASST) model is capable of estimating a rigorous coupled water and energy balance, and calculates the transfer of mass and energy at the air-canopy-snow-soil interface. The model specifically models radiation transfer through the plant canopy and into the underlying soil. Turbulent transfer induced by the plant canopy is explicitly captured by incorporating vegetation height and roughness length. Most importantly, transpiration is simulated as a component of the soil-plant-atmosphere continuum, and is governed by stomatal resistance in response to the vapor pressure deficit. Transpiration is linked to soil water content through a resistance term between soil and plant roots. The Simultaneous Heat and Water (SHAW)

model is a detailed one-dimensional process model that simulates the transfer of heat and water through a plant-snow-residue-soil system to simulate a coupled water and energy balance. The SHAW model is unique in that transpiration is mechanistically linked to soil water by calculating a flow through roots and leaves within the soil-plant-atmosphere continuum, while satisfying a leaf energy balance. In contrast to VADOSE/W, SHAW calculates a rigorous fully coupled energy balance, and computes soil evaporation separately from transpiration. The SHAW and FASST models stand as excellent examples of how a numerical model should incorporate plants into an analysis, due to their physical treatment of transfer of mass and energy within the plant canopy. However, there is no single modelling code that accurately captures the detailed physics and physiology of the transfer of mass, energy, and momentum within the soil-plant-atmosphere continuum, and the cover system designer should account for this when selecting their model of choice. Nevertheless, modelling vegetation as a sink term is no longer appropriate, and it is recommended that future modelling analyses account for the physical and physiological drivers of transpiration.

RÉSUMÉ

Introduction

Pour garantir la performance à long terme d'un système de couverture, il est essentiel d'implanter une communauté végétale productive, car celle-ci augmente la résistance du sol à l'érosion, améliore la structure du sol et sa teneur en matière organique, évacue par transpiration l'eau stockée dans le sol, procure un habitat à des espèces sauvages, améliore l'aspect esthétique des lieux et offre de nombreux autres avantages. Cette communauté contribue ainsi de manière importante à la performance du système de couverture, mais la présence physique d'une communauté végétale modifie également l'environnement du système, dans le sol et au-dessus. Or, les changements survenant dans le système de couverture avec l'établissement de la végétation ne sont pas de nature linéaire et ont une multitude d'effets sur les transferts de masse et d'énergie entre l'atmosphère, les plantes et le sol. À titre de composante critique du continuum sol-plantes-atmosphère, la végétation peut énormément altérer la performance du système par rapport à celle qui était attendue.

Pour prédire les effets de la végétation sur la performance d'un système de couverture, on a souvent recours à des modélisations numériques. Cependant, de nombreux codes de modélisation actuellement utilisés par l'industrie des systèmes de couverture ont tendance à trop simplifier la contribution complexe de la végétation à la performance du système. Une végétation productive peut avoir de nombreuses fonctions, en plus d'évacuer l'eau stockée dans le système. Or, pour simplifier l'analyse, de nombreux codes de modélisation emploient une fonction définie par l'utilisateur pour simuler le prélèvement d'eau par les racines et omettent entièrement l'effet de la végétation sur le bilan hydrique et le bilan énergétique de surface. En ignorant ainsi les mécanismes physiques et physiologiques intervenant dans la transpiration végétale, ces codes simplifient l'analyse de manière excessive, et le concepteur de

systèmes de couverture risque de mal interpréter certains aspects du modèle qui pourraient avoir un effet critique sur la performance globale du système.

Objectifs

Les approches de modélisation numérique qui ignorent les effets de la présence de végétation et de la dynamique des racines ne prennent pas en compte tous les processus et mécanismes contribuant à la performance du système de couverture. Donc, les codes de modélisation numérique qui omettent les mécanismes physiques et physiologiques de la plante ne peuvent plus convenir pour prédire le comportement d'un système de couverture. Le présent rapport vise à déterminer quelle approche numérique permet le mieux de simuler la végétation dans le cadre de la conception d'un système de couverture. Nous commençons par passer en revue les propriétés physiques, physiologiques et écologiques pertinentes de la végétation, puis nous présentons un sommaire des codes de modélisation actuellement utilisés et des lacunes de chacun. Nous proposons ensuite quelques exemples de modèles dont la formulation permet de prendre en compte de manière exacte les processus végétaux. Nous présentons enfin un ensemble de conclusions et de recommandations.

Sommaire des propriétés de la végétation

À mesure que le système de couverture se développe, les communautés végétales évoluent. Or, les travaux de modélisation numérique fondés sur des paramètres de performance de la végétation ont tendance à produire des simulations qui n'évoluent pas dans le temps, ce qui n'est pas représentatif de la nature dynamique de ces paramètres dans les systèmes naturels. En effet, dès que la végétation s'établit sur une couverture de terre, diverses communautés végétales s'y succèdent jusqu'à ce qu'une communauté à structure stable ait pu occuper les lieux, au bout de nombreuses années. Les analyses de modélisation à long terme devraient donc prendre en compte cette succession.

Par ailleurs, les végétaux cherchent à maintenir un équilibre hydrique interne, en prélevant de l'eau du sol pour remplacer celle qui est évacuée par la transpiration. La quantité d'eau ainsi prélevée par les racines est fonction du gradient négatif de tension existant entre les racines et le sol. Les racines poussent continuellement vers les sources d'eau, et l'utilisation optimale de l'eau disponible dans le sol exige une telle croissance continue. Le système racinaire se développe selon la morphologie particulière de chaque espèce et en fonction des conditions propres à chaque terrain. La configuration des racines d'un arbre dépend donc de l'espèce, ce qui permet de classer les arbres selon que leur système racinaire est cordiforme (tremble), aplati (épinette) ou pivotant (pin). Par exemple, dans la forêt boréale, plus de 80 % de la biomasse racinaire se trouve dans les 30 cm supérieurs du sol, même si les racines les plus fines pénètrent souvent jusqu'à une profondeur de 2 m. Les arbustes se caractérisent par un système racinaire moins profond, avec plus de 70 % de la biomasse racinaire se trouvant à moins de 20 cm. Les racines des graminées se concentrent également près de la surface, plus de 80 % de leur biomasse se trouvant à moins de 30 cm.

L'indice foliaire, ou indice de superficie foliaire, est un paramètre important pour le calcul de la productivité de la plante, mais il est souvent mal utilisé. Les feuilles (ou les aiguilles) servent à recevoir le rayonnement solaire permettant de convertir le CO_2 en glucides. Plus la superficie foliaire de la plante augmente, plus sa productivité augmente également, jusqu'au point où la plante fait de l'ombre sur ses propres feuilles, ce qui réduit les gains de productivité. Les analyses de modélisation classiques utilisent l'indice foliaire comme principal déterminant de la transpiration. Il existe effectivement une corrélation entre la transpiration et l'indice foliaire, mais cet indice correspond à un facteur génétique qui détermine avant tout la productivité, et non seulement le prélèvement d'eau comme le supposent ces analyses de modélisation. La plante ayant un accès illimité à de l'eau accroîtra son indice foliaire jusqu'à un maximum dépendant de l'espèce et de la morphologie des feuilles. L'utilisation de l'indice foliaire comme principal déterminant de la transpiration est donc une interprétation simpliste, car elle fait négliger des processus physiologiques importants.

Enfin, la transpiration est un processus physique régi par le gradient hydraulique global du continuum sol-plantes-atmosphère. Les restrictions imposées par la plante sont analogues à une résistance électrique, ce qui permet d'utiliser la loi d'Ohm pour obtenir une bonne représentation théorique de l'ensemble du processus de transpiration. En imaginant ainsi des résistances qui seraient exercées par les racines, les tiges et les feuilles, on peut formuler intuitivement des équations mathématiques décrivant la transpiration. La résistance qui présente le plus d'intérêt du point de vue de la transpiration est la résistance stomatique, qui permet à la plante de contrôler son taux de transpiration. Ce taux varie au cours de la journée et au cours de la saison de végétation, en réaction à certains facteurs climatiques, biotiques et abiotiques.

Modèles du système racinaire

Pour modéliser la contribution de la végétation à la performance du système de couverture, il faut tenir compte des processus et mécanismes agissant au-dessus et en dessous de la surface du sol. La modélisation du prélèvement d'eau par les racines est généralement fondée sur un schéma microscopique décrivant le prélèvement individuel par chaque racine, ou sur un schéma macroscopique décrivant le prélèvement d'eau par l'ensemble diffus de racines occupant une couche donnée du sol. L'approche microscopique est souvent trop détaillée pour les besoins d'un modèle de bilan hydrique, tandis que l'approche macroscopique a tendance à trop simplifier la géométrie des racines. Le concepteur de systèmes de couverture doit donc être conscient des avantages et inconvénients de chaque approche et choisir celle qui convient le mieux aux objectifs précis de chaque système.

Les racines doivent pousser pour que la plante puisse exploiter l'eau et les éléments nutritifs du sol. Il est souhaitable de modéliser cette croissance, particulièrement pour les modèles de bilan hydrique, car les racines peuvent pousser plus profondément à mesure que la surface du système de couverture se dessèche. Or, la croissance des racines est constituée d'un ensemble de processus concurrents et séquentiels comprenant la prolifération, l'extension, la sénescence et la mort. Dans les systèmes

naturels, la croissance des racines exige un transfert de biomasse à partir des parties de la plante où se déroule la photosynthèse. Pour modéliser la croissance des racines, il faudrait estimer le rayonnement photosynthétiquement actif, l'indice foliaire, la teneur en eau des feuilles, l'ouverture des stomates, la teneur de l'atmosphère en CO_2 et le transfert de biomasse. Le modèle ROOTSIMU, qui vise à la fois le prélèvement par les racines et la croissance des racines, a été utilisé pour prendre en compte la photosynthèse, la respiration, la transpiration et les processus hydrauliques du sol. Malgré l'existence de modèles de croissance des racines, la nécessité d'estimer la production de carbone de la plante pour pouvoir simuler l'accumulation de biomasse dans les racines a probablement limité l'adoption de ces modèles pour le suivi du bilan hydrique.

Sommaire des codes de modélisation actuels

De nombreux codes numériques permettent une simulation du bilan hydrique et du microclimat du sol superficiel. Le degré de complexité et la cible principale de chaque modèle dépendent de l'usage auquel il est destiné. Les modèles écophysiologiques tels que ceux élaborés pour l'industrie forestière ont pour cible principale le couvert végétal. Les modèles FOREST BGC et MAESTRO, par exemple, fournissent une estimation très détaillée des bilans carboné et azoté de la végétation. Le bilan hydrique du sol doit être calculé puis servir d'intrant pour l'estimation du bilan carboné.

Dans de nombreux codes numériques employés pour la conception de systèmes de couverture, la végétation est considérée comme un simple puits pour l'eau du sol, et ces codes omettent le transfert turbulent de masse et d'énergie se produisant dans le couvert végétal. Certains codes de modélisation fréquemment utilisés, comme les codes UNSAT H et VADOSE/W, reposent sur une interprétation simpliste de la végétation, ce qui leur fait négliger les effets importants de la végétation dans l'ensemble du continuum sol-plantes-atmosphère. Le code HYDRUS intègre un modèle rigoureux de la concentration des solutés et de leur prélèvement par la plante et prend en compte l'effet du stress osmotique sur le prélèvement d'eau par la plante. Cependant, dans le code HYDRUS, ce prélèvement est toujours considéré comme un puits et non comme un processus régi par les conditions atmosphériques.

La manière idéale de simuler la végétation dans les systèmes de couverture consisterait à faire en sorte que le couvert végétal simulé réagisse de manière conforme aux contraintes physiques imposées par la physiologie des plantes. De plus, comme le couvert végétal modifie de manière importante les conditions atmosphériques existant à proximité de la surface, le modèle doit prendre en compte les changements de masse, d'énergie et de quantité de mouvement causés par les plantes. Le modèle FASST (*Fast All-Season Soil Strength*) permet une estimation rigoureuse du bilan couplé de l'eau et de l'énergie et un calcul des transferts de masse et d'énergie survenant à l'interface air-végétation-neige-sol. Ce modèle simule spécifiquement le transfert d'énergie radiative s'opérant à travers le couvert végétal jusqu'à l'intérieur du sol. Il prend en compte de manière explicite le transfert turbulent induit par le couvert végétal, en intégrant comme paramètres la hauteur et le coefficient de rugosité de la végétation.

Cependant, l'aspect le plus important du modèle est que la transpiration est simulée sous forme de composante du continuum sol-plantes-atmosphère, régie par la résistance stomatique et donc par le déficit de pression de vapeur. La transpiration est reliée à la teneur en eau du sol par un terme décrivant la résistance s'exerçant entre le sol et les racines. Le modèle SHAW (*Simultaneous Heat and Water*) est quant à lui un modèle de processus unidimensionnel détaillé qui permet de simuler le transfert de chaleur et d'eau dans un système plantes-neige-résidus-sol pour estimer le bilan couplé de l'eau et de l'énergie. Le modèle SHAW a l'avantage particulier d'établir un lien mécanique entre la transpiration et la teneur en eau du sol en calculant le flux traversant les racines et les feuilles dans le continuum sol-plantes-atmosphère tout en respectant l'équilibre énergétique de la feuille. Contrairement au modèle VADOSE/W, le modèle SHAW établit un bilan d'énergie rigoureux et entièrement couplé et calcule séparément l'évaporation du sol et la transpiration. Les modèles SHAW et FASST sont d'excellents exemples d'intégration des processus végétaux à un modèle numérique, car les transferts de masse et d'énergie s'opérant au sein du couvert végétal y sont simulés de manière explicite. Cependant, aucun code de modélisation ne permet à lui seul de prendre en compte de manière exacte et détaillée tous les déterminants physiques et physiologiques du transfert de masse, d'énergie et de quantité de mouvement au sein du continuum sol-plantes-atmosphère. Le concepteur de systèmes de couverture doit donc en tenir compte au moment de déterminer quel modèle convient le mieux. Quoi qu'il en soit, dans le cadre de la modélisation, il n'est plus justifié de considérer la végétation comme un simple puits. Nous recommandons plutôt que les analyses de modélisation futures prennent en compte les divers déterminants physiques et physiologiques de la transpiration.

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1   INTRODUCTION

A productive vegetation community is an essential component of a properly functioning soil cover system. Vegetation serves myriad purposes in cover system functionality including erosion control, development of soil structure, transpiration of stored soil water, wildlife habitat, as well as enhancing aesthetics. Plants affect cover system performance by modifying near surface boundary layers and affecting turbulent transfer of mass and energy. Thus, a plant community will be a strong determinant of cover system evaporation and soil temperatures. Given the strong influences vegetation has on a cover system, success or failure of a cover system, or rather whether a cover system is meeting performance expectations, is often dependent on whether or not a vegetative cover can be successfully established. Successful vegetation establishment will depend on the ability of the cover system to supply sufficient volumes of water for plant use, appropriate nutrients in sufficient concentrations, and a suitable physical structure for root establishment. Plant communities will in turn begin to alter the structure, nutrient status, and water content of the soil, as well as vadose zone and atmospheric boundary layer dynamics of the cover system. The interactions between plants and cover systems are complex and can exert a dominant control on the long term performance of the system, depending on estimated trajectories of plant development. Therefore, understanding how vegetation will develop and function as part of a cover system represents a key step in cover system design and long-term performance.

Modelling analyses are useful exercises in enhancing our understanding of how vegetation development will be expected to affect cover system performance. When using a numerical model in the design process, the cover system engineer has the flexibility to examine the interactions of certain plant and soil variables in isolation or in combination. However, in order to be useful the model must accurately reflect the physical mechanisms that characterize plant-soil interactions. Current hydrological and water balance models typically used in the cover design industry generally require users to specify rooting depths, rooting patterns, and empirical relationships related to soil water content that control transpiration rates. These parameters tend to remain constant throughout the numerical simulation and thus are not representative of their dynamic nature in natural systems. Plant transpiration and root growth respond to stressors and signals at work both above and below the soil surface. The fundamental argument is that plants function as part of the soil-plant-atmosphere continuum and conceptualizing plants as a simple sink term for water uptake oversimplifies their contribution to the long term performance of a cover system. Simplistic representations of vegetation are no longer sufficient in developing an accurate model of cover system function.

1.1   Objectives of the Report

The objective of this report is to determine the preferred approach for numerical simulation of vegetation in cover system design. In order to meet the objective, a review of relevant plant physiology with a focus

on the physical controls on transpiration has been conducted. Current approaches to modelling vegetation are then summarized, followed by an examination of the preferred approach. Finally, advantages and deficiencies to the approaches are discussed.

1.2   Report Structure

The following is an overview of the structure of this report:

- Chapter 2 presents a review of the design, function, and purpose of typical mine waste cover systems in Canada.

- Chapter 3 discusses failure modes relating to how vegetation and cover systems can fail, and presents a discussion of how sites would be expected to evolve over the long term.

- Chapter 4 provides a background in the appropriate plant physiology pertinent to cover system design, and explores the interaction of vegetation and cover system soils.

- Chapter 5 discusses the modelling of plant roots and currently available methods for simulating the soil-plant-atmosphere continuum.

- Chapter 6 provides recommendations for future research.

- Chapter 7 presents a general conclusion.

- Chapter 8 contains a glossary of terms used in this manual.

- Chapter 9 has a comprehensive list of sources used in the document.

2   TYPICAL MINE WASTE COVER SYSTEMS IN CANADA

Cover systems can broadly be described as a layer or layers of earthen or synthetic material placed over mine wastes to reduce or control acid rock drainage (ARD) and metal leaching (ML) of certain constituents that may have a deleterious effect on downstream receptors (MEND 5.4.2d, 2001). Performance of mine waste cover systems in Canada is largely controlled by soil and climatic factors. Performance criteria for cover systems are developed in consideration of the heterogeneous landscape and diverse climate conditions found in Canada. Short- and long-term effects on the receiving environment at particular sites are also considered when implementing a cover system. Soil cover objectives vary from site to site but may include one or a combination of dust and erosion control, control of oxygen and/or water ingress, improved quality of runoff water, control of infiltration, and establishment of vegetation to meet end land-use objectives (MEND 2.21.4, 2004). A detailed review of various cover system types applicable to closure of mine waste storage facilities in Canada can be found in MEND 1.61.5c (2012). The following sections are a synopsis of information contained in MEND 1.61.5c (2012).

2.1   Reclamation / Erosion-Protection Cover Systems

Reclamation cover systems were the first soil covers implemented to mitigate ML/ARD in North America. These cover systems usually consist of 20-30 cm of non-compacted, finer textured soils such as topsoil, clays, and glacial tills (MEND 2.35.2b, 1997). The primary purpose of a reclamation cover system is to provide a medium for the establishment of sustainable vegetation communities. Reclamation cover systems were intended to be effective by simply acting as a barrier between the mine waste and meteoric water, thereby improving the quality of surface runoff water and groundwater quality. However, these single layer soil covers were not effective at reducing ML/ARD because they did not prevent oxygen diffusion and water infiltration into mine waste to the extent required (MEND 2.35.2b, 1997; INAP, 2009).

The key closure objectives at some sites may also solely be dust control and erosion protection. In these cases, the waste material itself is typically not reactive and the primary goal is to develop a stable landform. Erosion-protection cover systems may comprise a thinner soil layer with vegetation or a surface layer of coarse gravel or riprap. Erosion protection is typically enhanced by the rapid establishment of a vegetation cover over the waste in order to stabilize the soil matrix and minimize erosion.

2.2   Store-and-Release Cover Systems

The suitability of cover systems that rely on the concept of storing water in the cover matrix and subsequently releasing through evapotranspiration as a means of controlling net percolation (NP) will depend on site-specific climate conditions, material availability, and the required performance criteria. Store-and-release cover systems must be designed and monitored to evaluate the design against a longer term, site-specific climatic record encompassing realistic climate variation rather than an average

design year.   Furthermore, performance must be monitored over the long term to develop a realistic picture of how the system is performing (O'Kane and Barbour, 2006; MEND 2.21.4, 2004).

2.3   Enhanced Store-and-Release Cover Systems

Enhanced store-and-release (ESR) covers have recently been implemented in arid and semi-arid environments. The term "enhanced store-and-release" is used to describe a cover system that employs the store-and-release concept to meet most of the cover objectives, but includes additional layers designed to limit net percolation during relatively short-duration seasonal events in which the storage capacity of a store-and-release cover system might be exceeded. Short-term enhanced performance differentiates ESR cover systems from barrier-type cover systems in that the permeability of these layers only needs to be lower than the average flux rate during these short-duration seasonal events, rather than functioning as a barrier to water flow throughout the year. If the low-permeability barrier used in an enhanced store-and-release cover is susceptible to processes such as freeze-thaw cycling, root penetration, etc., then sufficient cover soil must be provided to protect the barrier layer from these effects. Two types of ESR covers are described below:

First, an ESR cover system may include an additional low hydraulic conductivity layer below a non-compacted layer.   The purpose of this lower hydraulic conductivity layer is to 'delay' downward percolation, as well as enhance the probability of surface runoff occurring sooner than would otherwise occur without the lower layer. Second, an ESR cover system may also include a capillary break layer. A capillary barrier results when a finer textured material overlays a coarser textured material. The reader is referred to MEND 1.61.5c (2012) for a more complete description of the physical mechanisms at work in ESR cover systems.

2.4   Barrier-Type Cover Systems

Barrier-type cover systems incorporate a low hydraulic conductivity layer to control the ingress of atmospheric water and in some cases, atmospheric oxygen. Low hydraulic conductivity layers might include a compacted clay layer, compacted soil-bentonite, a permanently frozen layer, or a geosynthetic product such as a geosynthetic clay liner, polyethylene geomembrane, or bituminous geomembrane. Protective soil layers must overlay the low hydraulic conductivity layer to protect it from desiccation, erosion, animal burrowing, frost action, and plant rooting to minimize deterioration and maintain cover performance (Caldwell and Reith, 1993). If the low hydraulic conductivity layer is to limit both percolation and oxygen ingress, performance will generally increase with augmented growth layer thickness and tension saturation of the low permeability layer (O'Kane and Wels, 2003; Morris and Stormont, 1997).

3 DESIGNING SOIL COVER SYSTEMS TO INCREASE THE PROBABILITY OF MEETING VEGETATIVE PERFORMANCE EXPECTATIONS

3.1 Failure Modes

Understanding the effects of drought stress on vegetation is central to end land-use and performance expectations of particular sites. It is important to consider consequences that may arise due to cover system failure. The term "failure" however, is not used in the sense of a catastrophic cover system failure, but rather, in this context, defined as one of two possibilities:

1) The desired vegetation does not establish, which leads to a failure to achieve end land-use or other stakeholder-driven closure objectives, but does not compromise hydrologic aspects of cover performance, such as maximum net percolation objectives; or

2) Vegetation performance with respect to water removal is less than that required for the specific cover system design, which leads to failure in achieving hydrologic aspects of cover system performance such that net percolation exceeds the cover system design criteria for reducing ML/ARD.

Performance of cover systems should not be viewed as being a failure if it is not able to supply an adequate amount of water for the desired vegetation. Rather, lower volumes of available water may likely shift the site capability to a drier system over time where another community could occupy the site over another operative edatopic range of leaf area index (LAI) and evapotranspiration (ET) (Barbour et al., 2010). Varying water regimes would then correspond to shifting ecosites that support different plant communities (Figure 3.1). As a broad example, a 35 cm cover may support a community of jack pine with a lichen ground cover, a 50 cm cover may support an aspen and jack pine, a white spruce, or a white birch community, while a 100 cm cover may support an aspen and spruce community with low bush cranberry understory (Barbour et al., 2010). Thus, it becomes important to understand the manner in which maximum potential ET rates of vegetation communities / functional groups are modified and at what soil water contents they are no longer able to persist on a particular site. Identifying the effect of vegetation shifts and reductions on cover system performance in terms of net percolation is a priority. Recognizing the manner in which cover system performance is affected by shifts in vegetation will help with the design of cover systems that increase the probability of maintaining vegetative components within specified design parameters and objectives.
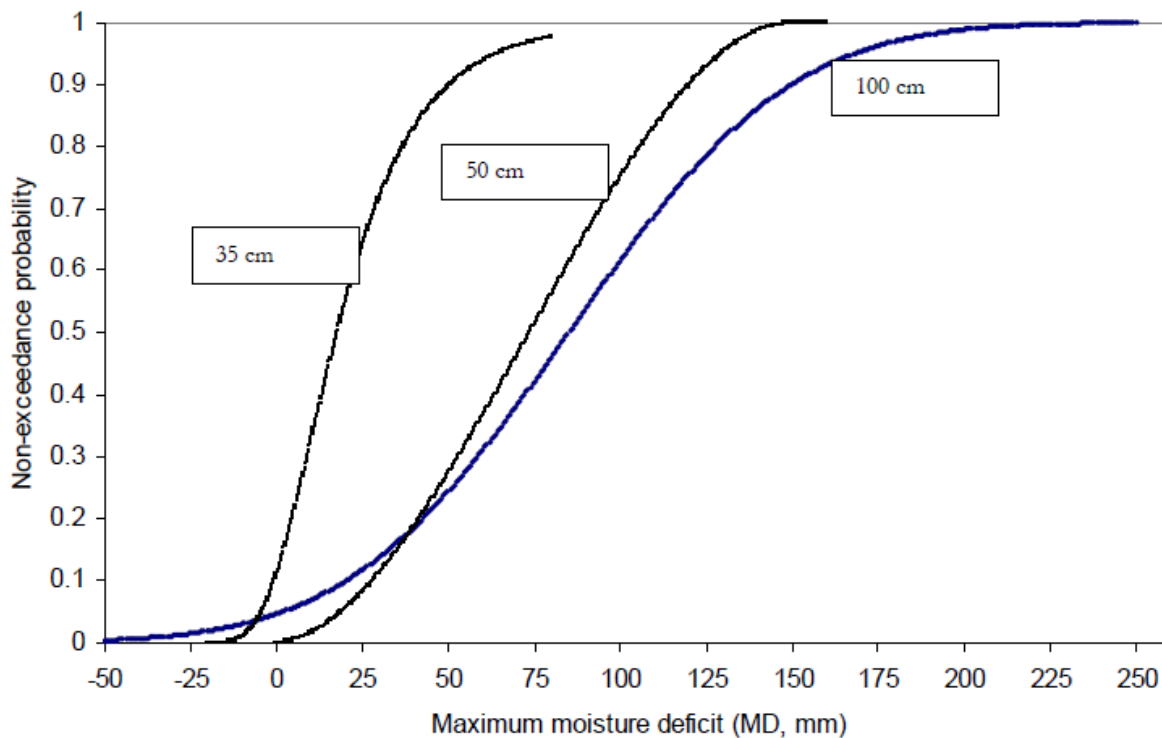
Figure 3.1   Relative probabilities of soil caps being able to supply moisture requirements through various climate cycles (Elshorbagy and Barbour 2007).

3.2   Site Evolution

Cover system modelling efforts that incorporate vegetation performance parameters tend to remain constant throughout numerical simulations and thus are not representative of their dynamic nature in natural systems. Rather, the establishment of vegetation on soil covers undergo a series of community shifts until a mature community is reached many years after establishment has occurred. Using static input values for an expected mature forest community or functional group does not yield the most accurate representation of cover system performance over the course of site evolution.

Site evolution on cover systems often commences with the establishment of pioneer weed and grass species followed by forbs and shrubs, then an early forest community, followed finally by a mature forest community. It is important to note that true climax forest communities are seldom reached. The frequency of natural disturbances due to fire and disease is high in forest communities causing non-equilibrium states. Nonetheless, the establishment of early colonizers is vital as they often facilitate autogenic modification of the site and improve conditions for later colonizers. Modification may occur through the accumulation of organic matter, the release of nutrients, and changes in pH among other benefits.

Once secondary colonizers begin to establish they may begin to shade and outcompete pioneer species leading to their reduction or extirpation. Only shade tolerant species will persist until a gap in the canopy is formed where shade tolerant species may grow and eventually shade and outcompete early forest species. Natural vegetation development may take centuries; however, through modern silviculture practices, the process may be sped up only taking decades to reach a community capable of harvest (Burger and Zipper, 2002; Figure 3.2). It is also important to recognize that particular sites or regions have different mature communities, meaning a mature community for a particular site may be a grass or shrubland.

Figure 3.2   Successional timeline for reforestation silviculture (Burger and Zipper, 2002).
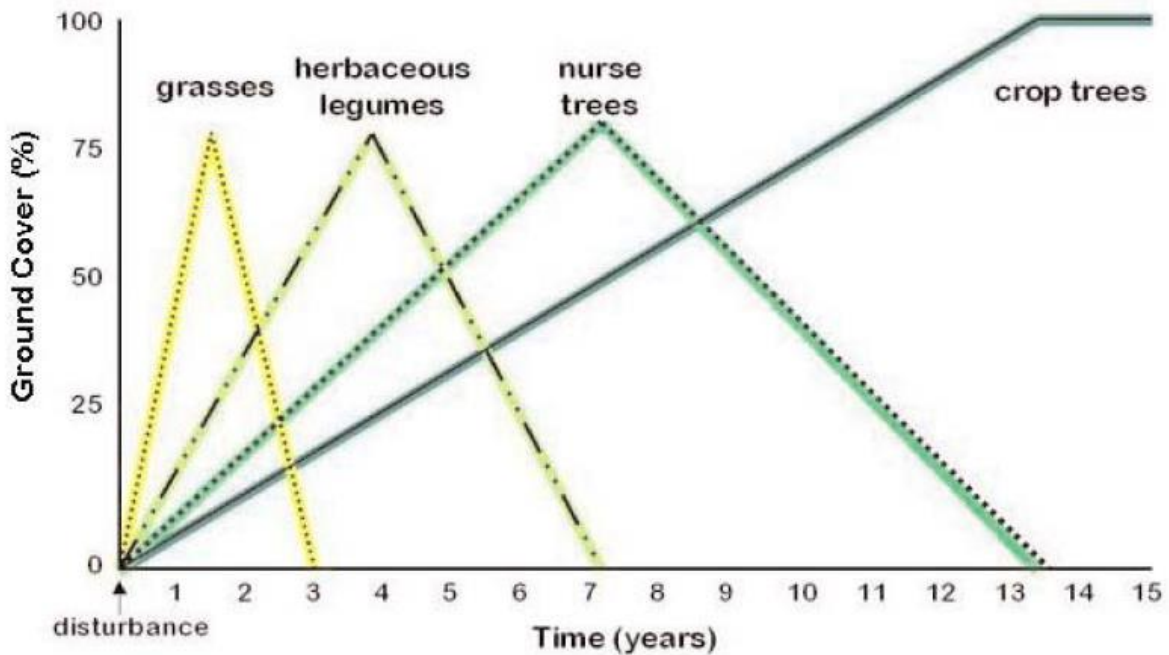
4   VEGETATION AND COVER SYSTEMS

Vegetation is key to the effective performance of cover systems. Successful establishment of a productive vegetation community enhances cover system performance through erosion control, limiting percolation through increased transpiration, as well as enhancing the overall aesthetics of the system (MEND 2.21.4, 2004; MEND 2.21.5, 2007; INAP, 2009). In many cases, regulations specifically require that a certain vegetation community be established so that a productive land use such as commercial forestry, can be resumed. Vegetation establishment is of sufficient importance that it is frequently included during the cover system design process and as a criterion for mine closure (INAP, 2009).

The structure and function of vegetation on cover systems depends on complex interactions of climate, species, rooting depth, the volume of water available in the soil, among many others (INAP, 2009; MEND 1.61.5a, 2009). Given the importance of vegetation on the overall success of a reclamation program, it is essential for the cover system designer to have a general understanding of vegetation performance through conducting a numerical modelling program. Moreover, in order to realistically model vegetation to an acceptable level, the model must account for the physical processes and interactions that govern plant growth. The following section provides an overview of the physiological processes involved in plant transpiration, and the general interactions between plants and cover systems.

4.1   Plant-Water Relations

Water losses incurred by the plant must be replaced by water taken from the soil. The vapour pressure deficit of the air is the primary driver of transpiration, while soil water governs water supply to the plant (Larcher, 1995). Water uptake by vascular plants is through the roots, which are the primary absorption organs for water and nutrients. There are three primary mechanisms that enable water and nutrient uptake by plant roots (Casper and Jackson, 1997). The first is the mass flow of water and nutrients, which is driven by transpiration, and is a function of dissolved nutrients in the soil solution and the rate of water movement to the root (Casper and Jackson, 1997). The second occurs via root interception, which accounts for less than 10% of resource uptake by roots (Marschner, 1995; Casper and Jackson, 1997). Root interception occurs as roots grow through the soil, physically displacing soil particles and capturing water and nutrients in the process (Casper and Jackson, 1997). The third mechanism is through diffusion where a local concentration gradient is created between the root and soil matrix facilitating the uptake of water and nutrients (Casper and Jackson, 1997).

4.1.1   Root Water Uptake

Water uptake from soil into plant tissue is a function of the negative pressure gradient between roots and the soil. A plant will continue to take water from the soil so long as the water potential of its fine roots is more negative than the soil matrix immediately surrounding the roots (Larcher, 1995). Plant roots are capable of routinely developing negative potentials of a few hundred kPa, which is sufficient to withdraw a

large proportion of the pore water held in most soils. Plants are capable of actively lowering root water potential for limited periods to reach potentials of -1,000 to -2,000 kPa for standard agricultural crops and -2000 to -4000 kPa for forest trees; beyond this limit the plant reaches a water status from which it cannot recover, known as the permanent wilting point.

4.1.2   Plant Roots

Plant roots continuously grow towards sources of water, and optimal use of available soil water requires continuous root growth. Root systems will grow in accordance with species specific morphology and in response to site specific conditions.

4.1.2.1   Tree Roots

The volume of soil explored by tree roots will depend on the species, stand age, water availability, and soil physical properties. For a young plant community, the critical zone for soil moisture to support young trees is the top 15 to 20 cm where water is in the immediate vicinity of their roots (Barbour et al., 2010). At the same time, early successional species explore a larger portion of the root zone because they establish their root systems faster (Barbour et al., 2010). As the community matures, early successional species are replaced by trees and other later successional species resulting in fuller exploitation of the root zone. Root biomass will be expected to decrease with a concomitant root length increase as a stand ages from early to late successional stages (Finér et al.,1997; Børja et al., 2008).

Tree root patterns depend on the particular species. For the Canadian context, the most common tree rooting patterns and the species most associated with the type are flat (spruce) (Figure 4.1), heart (aspen) (Figure 4.2) and tap (pine). While 83% of boreal forest root biomass is concentrated in the upper 30 cm of the soil profile, fine roots can penetrate to much greater depths (Jackson et al., 1996). Van Rees and Jackson (1994) discovered fine roots at depths of 1.2 m for three common boreal forest soils. In a similar region, Strong and La Roi (1983) found white spruce roots extending to a depth of 0.5 to 0.75 m and aspen roots descended to a maximum depth of 2 m. Values commonly reported in the literature range from 1.4 to 3 m and 1.5 to 3 m for white spruce and aspen stands, respectively (Stone and Kalisz, 1991).

Figure 4.1   The vertical and partial horizontal root system of white spruce taken from sandy soil (from Strong and La Roi, 1983).

Aside from species-specific physiological factors, tree rooting depths are also dependent on soil factors such as depth of water table, soil type, permafrost, compaction, and texture, among others (Feldman, 1984). Lieffers and Rothwell (1987) determined that black spruce and tamarack roots extended to 0.6 m on dry sites but were confined to elevated microtopography on wet sites.

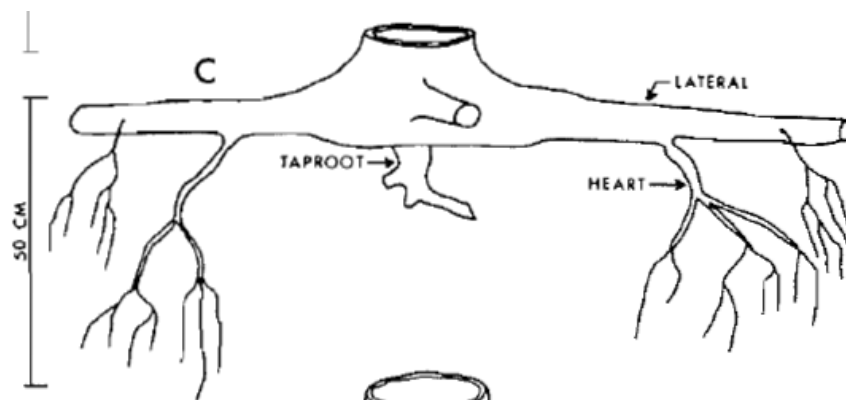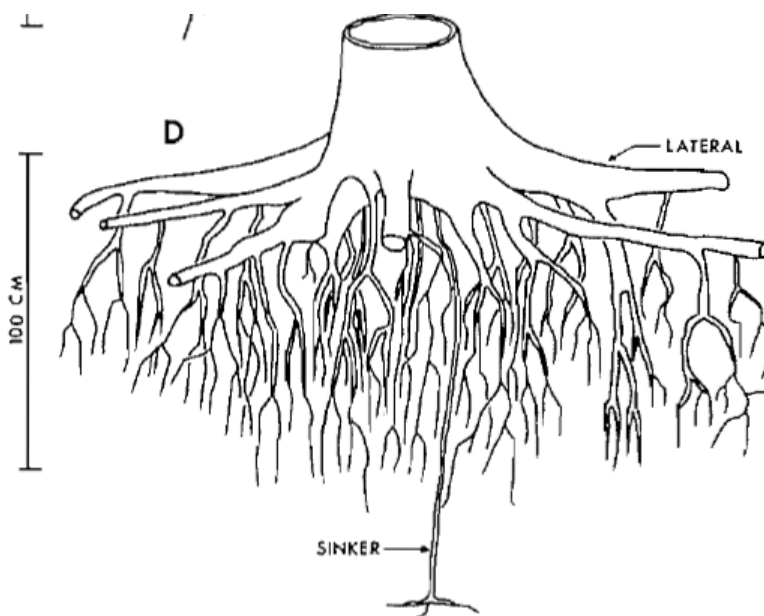**Figure 4.2**   The vertical and partial horizontal root system of aspen taken from sandy soil (from Strong and La Roi, 1983).

Soil density is also a major determinant of a tree root's ability to establish in the soil (Figure 4.3). Several studies have demonstrated the ability of roots from pine trees to penetrate through compacted soils

(Stoltz and Greger, 2006; Van Rees and Jackson, 1994). Pine tree roots were able to penetrate through thick soil and a barrier layer to a depth of 1.7 m in search of water and nutrients according to Stoltz and Greger (2006). Similar results were observed by Van Rees and Jackson (1994) where jack pine was found to a depth of 1.2 m. Moreover, root depth on mine waste covers and undisturbed soils at the Syncrude oil sands mine were found to have the majority of roots occurring in the first 0.3 m of soil (Macyk and Richens, 2002).
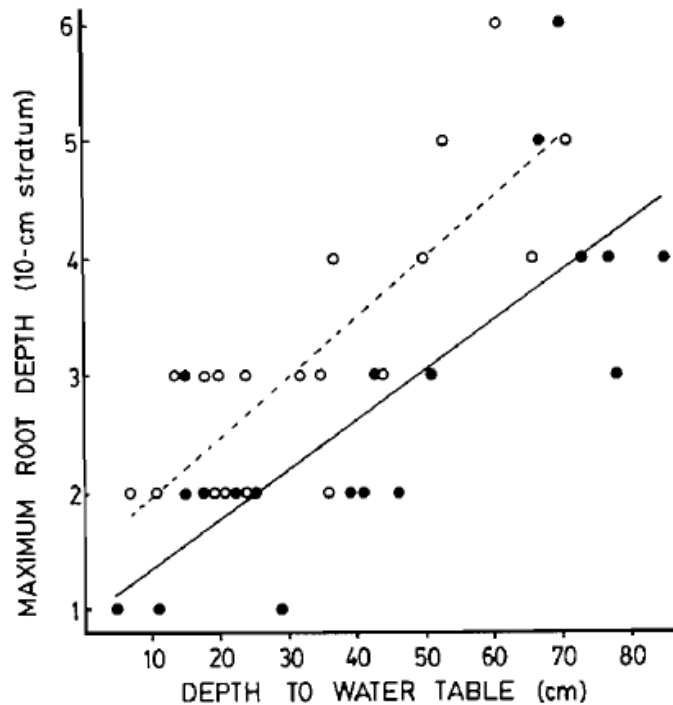
Figure 4.3   Maximum root depth of black spruce (●) and tamarack (○) in relation to depth of water table (from Lieffers and Rothwell, 1987).

4.1.2.2   *Shrub Roots*

Shrubs are often used to vegetate mine waste cover systems due to shallower rooting systems, higher development rates, and non-competitive interactions with grasses. These characteristics inhibit shrubs from reaching barrier layers, while allowing for earlier onset of transpiration (INAP, 2003; MEND 2.21.5, 2007). Shrubs have been shown to coexist effectively with grasses by concentrating biomass deeper in the soil profile, while allowing grasses to concentrate in shallower depths (Weaver 1958; Fernandez and Caldwell, 1975; Lee and Lauenroth, 1994).   In the absence of competition, shrub roots tend to concentrate in upper portions of the soil profile, with some reporting that 72% of roots are concentrated in the upper 0.2 m (Murphy and Moore, 2010). Maximal rooting depth will be strongly influenced by depth to the water table.   Murphy and Moore (2010) reported that maximum shrub rooting depth, total root production, and root production at depth were all greater in areas with deeper water tables, which is

driven by the greater volume of aerated soil within areas with lower water. In cases where water tables were close to the surface, roots were only observed to a depth of 0.6 m.

4.1.2.3 *Grass Roots*

Grasses generally have the shallowest rooting patterns when compared to trees and shrubs. Grass roots typically have herringbone root patterns, optimal branching, and uniform diameters with the largest root densities occurring in upper soils, although some may reach depths greater than 2 m (Weaver, 1919). Grasses cover a wide range of biogeoclimatic regions in Canada giving rise to differential rooting patterns between the regions (Jackson et al., 1996). On a broad scale, Jackson et al. (1996) demonstrated that in the tundra, 93% of roots occurred in the top 0.3 m of soil and 83% in the temperate grasslands. In the prairies of central North America, Weaver (1958) found that most grass roots occupied approximately the first 1.2 to 2.1 m of soil.   Lee and Lauenroth (1994) determined that the maximum root depth for *Bouteloua gracilis*, was 0.9 m on silty clay loam and 1 m on sandy loam, while Swan (2004) reported rooting depths of 1.2 m for *Pseudoroegneria spicata*. Similarly, Frank et al. (2010) observed grasses extending to depths slightly greater than 0.9 m on mesic sites, but only to 0.4 m in dry sites. Rooting depth will ultimately be based on a combination of biotic and abiotic factors.

4.1.3   *Leaf Area Index*

The process of photosynthesis requires solar radiation as the energy input for converting CO_2 into carbohydrates.   Plant leaves can be thought of as the primary energy collectors for absorbing photosynthetically active radiation in the 380 to 710 nm wavelength range. As the surface area of leaves increases, so too will plant productivity, until the point at which self-shading of leaves decreases marginal productivity. Attenuation of radiation in a plant canopy will depend on the density and arrangement of the leaves. The arrangement of leaves can be expressed quantitatively as the leaf area index (LAI), which is the ratio of total one-sided leaf area, to total ground area (dimensionless). For example, an LAI of 2 would have a leaf area double that of a given ground area.

Leaf area index is variable over the course of a day, over a growing season, and in response to soil water content (Jonckheere et al., 2004). However, LAI is primarily a genetic factor of the species in question and is limited by the species' morphology. Nevertheless, LAI is a widely used variable that provides information on ecosystem processes, and canopy composition, biomass, density, and heterogeneity.

Common LAI values for various stand types and functional groups are provided in Table 4.1. Leaf area indices for three common boreal tree species is provided in Table 4.2.

Table 4.1

Statistical distribution of leaf area index by biome after removal of outliers following Inter-Quartile Range statistical analysis.

Biome	Mean	Standard deviation	Min.	Max
Tundra, circumpolar and alpine	1.9	1.5	0.2	5.3
Wetlands	6.3	2.3	2.5	8.4
Grasslands	1.7	1.2	0.3	5.0
Crops	3.6	2.1	0.2	8.7
Forest, boreal deciduous broadleaf	2.6	0.7	0.6	4.0
Forest, boreal, evergreen needleleaf	2.7	1.3	0.5	6.2
Forest, boreal/temperate deciduous needleleaf	4.6	2.4	0.5	8.5
Forest, temperate deciduous broadleaf	5.1	1.6	1.1	8.8
Forest, temperate evergreen broadleaf	5.7	2.4	0.8	11.6
Forest, temperate evergreen needleleaf	5.5	3.4	0.0	15

Note: Table adapted from Scurlock et al. (2001).

Table 4.2

Leaf area index of individual species.

Species	Leaf Area Index
Aspen	3.3
Jack Pine	2.2
Black Spruce	5.6

Leaf area index is correlated to the volume of water in the soil that is available for plant growth (Jose and Gillespie, 1997; Li, 2010). A positive correlation between LAI and soil water content was found by Li (2010) on a 600 m mixed prairie grassland transect; as water content increased, so too did LAI. However, it should be noted that LAI for an individual species is not a limitless quantity to be confused with plant production. Given a limitless supply of water, a plant will not increase its LAI *ad infinitum*. An unrestricted supply of water will simply allow the plant to fulfill its genetic potential. This point was underscored by Wever et al. (2002) who found that after 42 mm of rain, soil water content reached a seasonal maximum of 0.34 m^3/m^3 followed by an LAI recovery to 65% of that year's maximum due to a second pulse of plant growth. Variability of LAI at a particular site may also be the result of temporal variation in precipitation and temperature. On an oilsands overburden reclamation cover system, Carey (2008) found that LAI was temporally variable and was attributable to variability in precipitation timing. Although LAI was variable over the course of the study conducted by Carey (2008), summer maximum LAI were essentially the same across three study years, and reflected the general species composition at the site.

The general dryness of a site will lead to a certain species composition, as generally reflected by LAI. Significant correlations (R^2 = 0.92; Figure 4.4) have been reported between soil water holding capacity and LAI on sites with varying available soil moisture (Jose and Gillespie, 1997). It was concluded that changes to LAI were the result of changes to community composition caused by environmental factors with water availability as the main driver (Jose and Gillespie, 1997). Soil available water has also been found to be the dominant factor influencing conifer seedling establishment (Hogg and Schwarz, 1997) and maximum LAI in mixed deciduous forests (Le Dantec et al., 2000), resulting in LAI variability across landscapes.
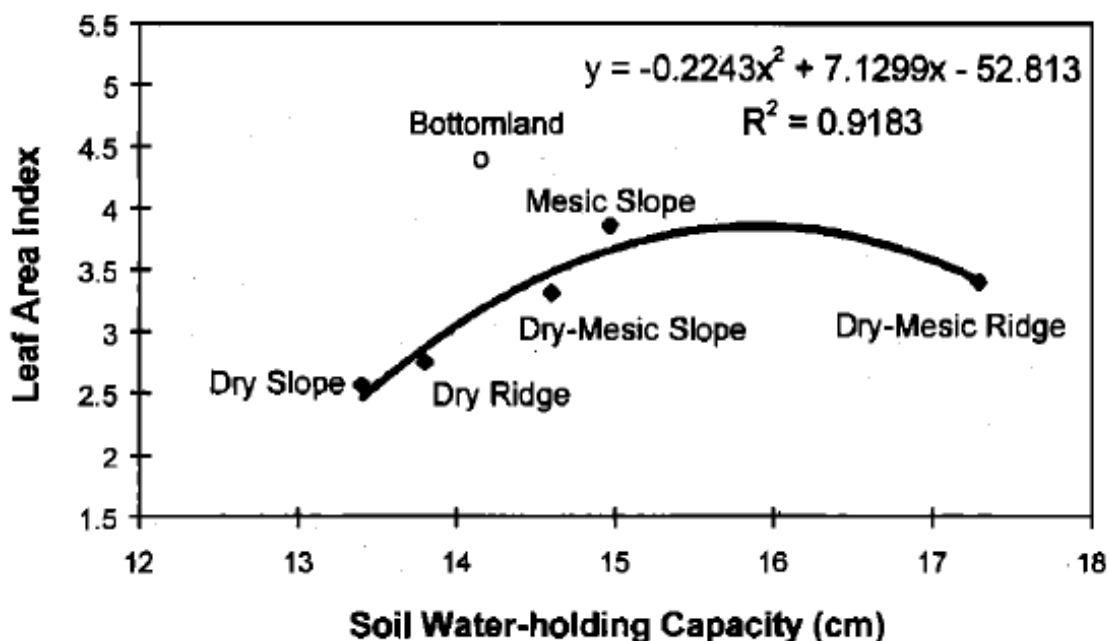
Figure 4.4   Leaf area index as related to soil water holding capacity (cm) (from Jose and Gillespie, 1997).

4.1.4   Biotic Factors

Wilson and Baldocchi (2000) observed a similar phenomenon during growing season leaf expansion when stomata resistance decreased, consequently increasing transpiration with leaf area. As such, shrub maximum LAI trajectories may peak in five years as opposed to a forest stand that may reach a higher maximum over 30 – 50 years during crown closure (MEND 1.61.5b, 2010). As dense canopies develop, exponential declines in soil evaporation due to radiation attenuation by canopies may occur and result in a net ET decrease (Obrist et al., 2003).

4.1.5   Abiotic Factors

Wever et al. (2002) found that LAI and ET declined as soil water was depleted and remained higher during periods of high soil moisture for mixed grasslands in Lethbridge, Alberta. Similarly, Wilson and Baldocchi (2000) observed that transpiration was a function of leaf area when soil moisture was abundant but as soils dried, soil water content began driving transpiration.

Many studies have also attributed atmospheric vapour pressure deficits as a contributor to decreased ET rates by reductions in leaf level transpiration via partial stomatal closure (Baldocchi et al., 1997; Wilson and Baldocchi, 2000; Wever et al., 2002). The vapour gradient diminishes as the air around vegetation becomes saturated with water vapour, resulting in ET decreases.

Evapotranspiration variation between species may also be due to site-specific factors that impose limitations on ET. Baldocchi et al. (1997) found that long-term growth may be limited by low rates of decomposition and nutrient cycling in boreal regions that consequently limit LAI, transpiration, photosynthetic capacity, and hydraulic conductivity. In regions such as the boreal forest, the harsh climate may also lead to mechanical damage on plant structures such as damage to the photosynthetic portion of pines caused by low winter temperatures (Grelle et al., 1999). Harsh winter conditions may also limit root growth, reducing the amount of active root surface available to supply the demand for water resulting in decreased ET rates (Grelle et al., 1999).

4.1.6   Transpiration as a Physical Process

Movement of water through the plant is governed by rules that are analogous to Ohm's law (Larcher, 1995). The principal driver of transpiration is the total potential gradient in the soil-plant-atmosphere continuum, with the vapour pressure deficit providing the source of atmospheric tension. Restrictions to flow in the plant are conceptualized as resistances, while the negative potentials developed within the plant provide the negative pressures necessary to develop a gradient. Resistances to evaporation of plant cellular water are high and remain high in order to avoid desiccation; hence the presence of a waxy cuticle along the surface of many plants' outer cells. However, in order to maintain plant functions, the plant must transpire water through pores in the leaves known as stomata (singular: stoma). Stomata are protected by kidney-shaped guard cells. During periods of high water availability the guard cells become turgid and open fully to maximize the stomatal opening, leading to minimal resistances and maximal transpiration rates. During periods of lower water availability, the guard cells become flaccid and close the opening, thus increasing resistance to evaporation and preventing unnecessary water loss. Therefore, when discussing transpiration as a physical process, it is the quantity known as stomatal resistance that governs plant transpiration rates (Larcher, 1995).

Transpiration occurs due to a difference in potential between the atmosphere, plant, and soil. As long as potential gradients exist between the atmosphere and the plant, and the plant and soil, the total flux of water will continue from the soil to the plant, and finally out to the atmosphere (Hillel, 1998).

4.1.7   Physiological Control of Transpiration

Plant transpiration is only proportional to the evaporative power of the air when stomata are either fully open, or fully closed (Larcher, 1995). Unrestricted plant transpiration will occur in a plant that is well supplied with water, and closely mirrors evaporation (Figure 4.5). In all other cases, there is a degree of stomatal regulation, which changes the stomatal resistance to transpiration over the course of a day. Temporary reductions in stomatal opening can be caused by decreases in light intensity, dry winds, water deficit, and extreme temperatures (Larcher, 1995). In some cases a water deficit will trigger a hormonal response, where abscisic acid will be released from the roots to the leaves, causing the stomata to close (Gollan et al., 1986).
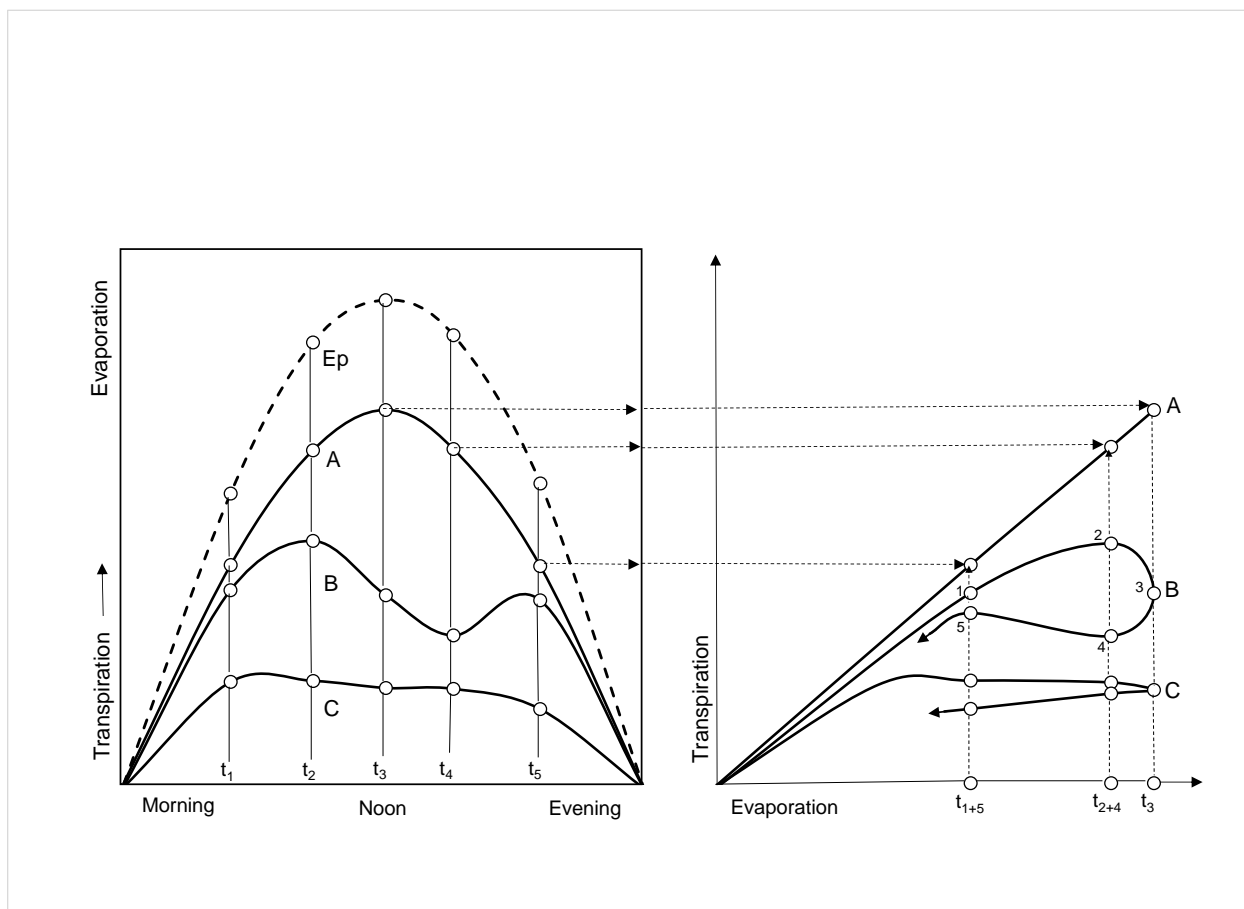
Figure 4.5   **Left:** Schematic diagram of potential evaporation (Ep) and daily variation in transpiration by A a plant undergoing unrestricted transpiration, B a plant that is water limited during the middle of the day, and C a plant continuously regulating stomatal opening. **Right:** The transpiration to evaporation ratio corresponding to the figure on the Left. A one-to-one line is given for unrestricted evaporation (A), and any departure from the line is an indication of a reduction in transpiration (After Larcher, 1995).

4.1.8   Plant Water Uptake

The driving force for transpiration is the potential gradient between the leaves and the atmosphere (Hillel, 1998). However, a gradient in potential must be maintained at all points in the soil-plant-atmosphere continuum in order to maintain transpiration (Hopmans and Bristow, 2002). A typical example (given in Hillel, 1998) of the distribution of water potentials is given below in Figure 4.6. During periods of high soil water content (Curve 1), the potential between the soil and roots (AB) is low. Inside the plant (CD) the potential is still below that which would cause cells to lose turgor pressure, and the plant is able to transport water without wilting. Curve 2 represents a situation where soil water is still sufficient to supply plant demands, but atmospheric demands are increased (E), leading to elevated leaf potentials close to

critical wilting values. Curve 3 represents a situation where soil water potential values are more negative, but atmospheric demands are low. Curve 4 represents a similar case to Curve 3, except that atmospheric demands are sufficiently high so as to lead to wilting conditions in the plant.
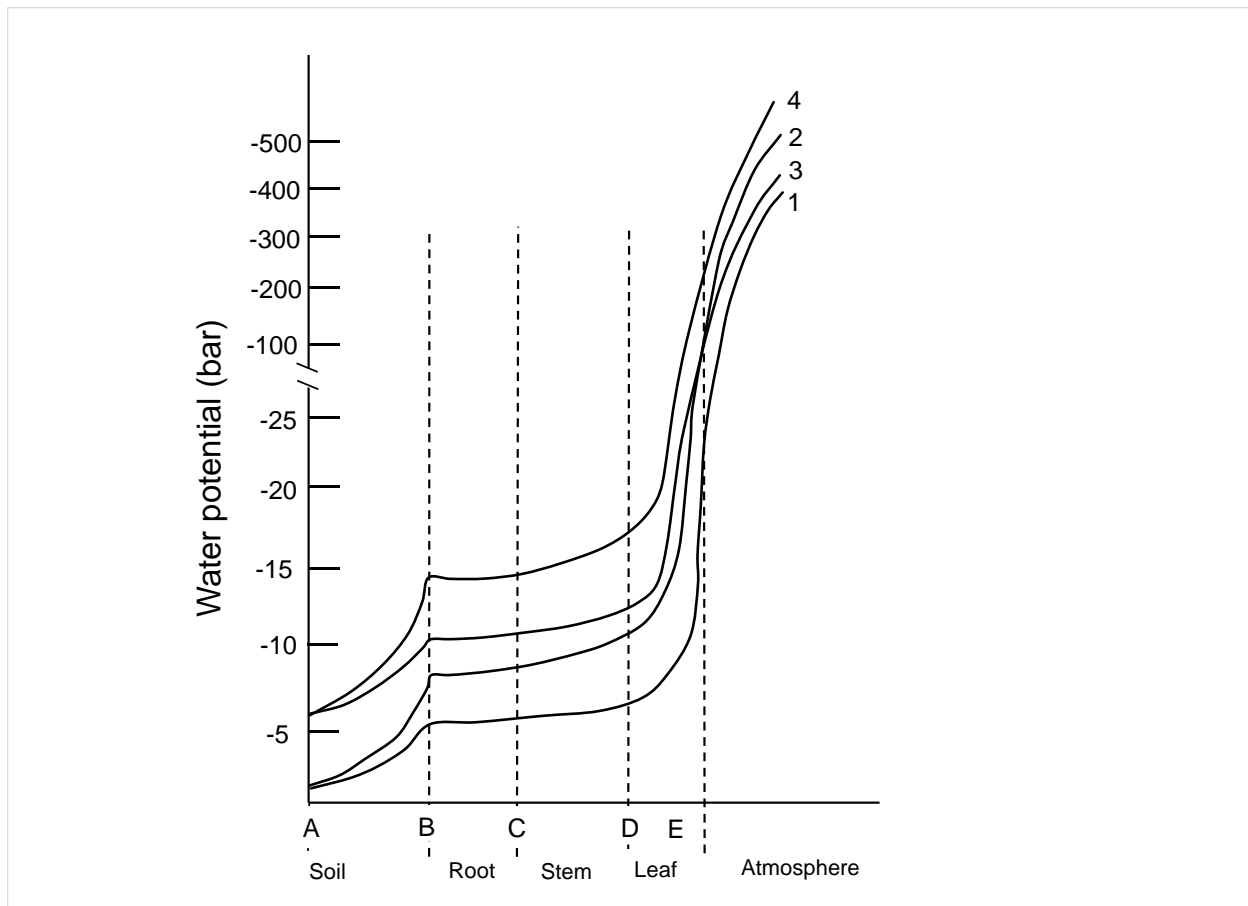
Figure 4.6   Distribution of potentials in the soil-plant-atmosphere continuum in response to different levels of soil water content and atmospheric evaporative demand (After Hillel, 1998).

The rate of plant water uptake will depend on rooting density, soil hydraulic conductivity, and the potential gradient between soil and roots (Hillel, 1998). Rapid uptake of soil water in the area of greatest root density results in a rapid decrease of water in the immediate vicinity of the roots. In mature plant stands the root volume will remain essentially constant, and water uptake will depend on the size of the volume, soil physical properties, water content, and atmospheric demands. In the case of a young, actively growing plant stand, roots will often explore larger soil volumes to satisfy high demands for water and nutrients (Campbell, 1991). In some cases, the suction gradients that develop as a result of drainage from roots will be sufficient to induce water movement within the soil profile from lower wetter areas, to shallower drier areas (Hillel, 1998).

4.1.9   Internal Water Balance

Plants seek to achieve equilibrium in their internal water balance (Figure 4.7). Any decrease in water through transpiration must be balanced by increase through soil water uptake. A temporary departure from equilibrium due to a negative water balance (plant desiccation) is countered with partial stomatal closure and a return to equilibrium following a temporary partial overshoot (Larcher, 1995). Initial reductions in transpiration due to, for example, excessively high temperatures are met with partial stomatal closure during the hottest part of the day, followed by reopening in the late afternoon and early evening. As water deficits increase, stomata will only open during the morning and will remain shut in the afternoon. Finally, as the severity of water deficit reaches critical levels, leaf stomata will remain closed to conserve water, and any transpiration that does occur will be substantially diminished.

Figure 4.7   Daily changes in transpiration in response to declining soil water content. Curves represent: 1 unrestricted transpiration; 2 mid-day transpiration limitation; 3 full mid-day stomatal closure; 4 full transpiration regulation, and; 5 maximally reduced transpiration (After Larcher, 1995).
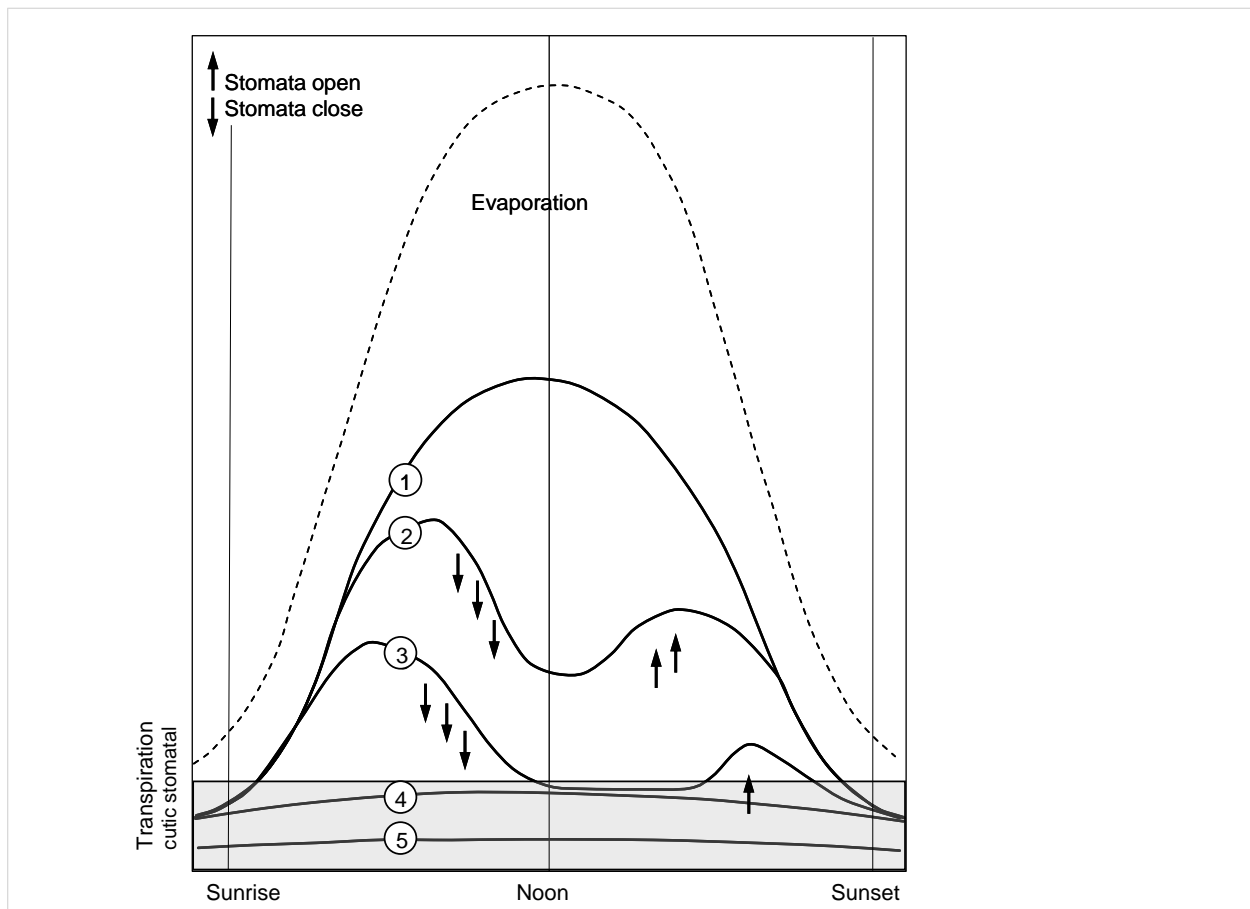
4.2   Plant-Cover Interactions

The interactions of plants and cover systems is a non-linear process that changes over time. Plant communities change over time, while total productivity is related to the amount of water and nutrients that the cover system is able to supply. Examining how plants affect cover system performance, and vice versa, will provide an insight into how the system should be modelled for future designs.

4.2.1   Plant Roots

A primary benefit of plant establishment in cover systems is erosion prevention by plant roots. Plant roots provide erosion resistance through reinforcement by increasing the soil shear strength. Shear strength is a function of the tensile strength of single roots (Ali and Osman, 2008) and the specific morphological characteristics of root systems (Reubens et al., 2007). However, as root diameter increases the erosion reducing effect of roots becomes less pronounced (De Baets et al., 2007). Fine roots are beneficial to plants by increasing the uptake of resources while being less resource intensive to produce compared to coarse roots; however, coarse roots have greater longevity (Fitter, 1994; Swan, 2004). Consideration of root diameter variation among plant functional groups, their varying responses to resource availability, and how different plant species respond to varying environmental factors are important to the longevity and performance of cover systems.

4.2.2   Soil Cover Thickness

The volume of water available to plants depends on the physical characteristics of the soil, such as texture, organic matter content, structure, and layer heterogeneity, among others (Hillel, 1998). The volume of plant available water in the soil is generally considered to be the amount held between field capacity and permanent wilting point. Field capacity is often described as the amount of water retained in the soil after a period of draindown following saturation (Larcher, 1995; Hillel, 1998). Permanent wilting point is taken as the water content at which plants can no longer access the tightly held water in the smallest macropores (Larcher, 1995). Although the actual values for field capacity and permanent wilting point are arbitrary, they do provide a necessary starting point for quantifying the amount of water available for plant use.

For a given texture of soil it is possible to increase or decrease the water storage capacity by increasing or decreasing thickness of the layer. In some cases in the mining context, increasing layer thickness is the only way in which to increase storage capacity, as thicker growth media have higher water storage capacity compared to a thinner layer of the same media (O'Kane and Wels, 2003; Barbour et al., 2010). The 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 reporting as NP (O'Kane and Wels, 2003). Increased storage capacity of thicker cover layers reduces the likelihood that vegetation production will be limited by water deficits.

The effect of cover thickness on water storage has been previously investigated in the mining industry. Kelln et al. (2009) determined that covers 50 and 100 cm thick were better able to meet the water demands of plant communities, compared to a 35 cm cover on an overburden oil sands pile. Lower available water holding capacity 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). Tree growth may benefit from thicker covers as was demonstrated by Kelln et al. (2009), when aspen growth was lower on a 35 cm cover compared to 50 and 100 cm covers. Lower plant available water was the source of growth reduction, potentially affecting cover performance and its vegetation community objectives (Kelln et al., 2009).

Cover systems with higher water holding capacities provide plants with sufficient water reserves to survive during periods of drought. During extensive dry periods, thicker covers are better able to retain water for longer periods decreasing the probability of a thicker cover reaching permanent wilting point (Kelln et al., 2009) and evapotranspiration is less likely to decrease and affect cover performance (Barbour et al., 2010). Elshorbagy and Barbour (2007) demonstrated that covers with a 50 to 100 cm growth layer achieved the appropriate water holding capacity during wet and dry periods to attain the desired end plant community with respect to covers employed in the oil sands industry. Additionally, Lowry and Loheide (2010) concluded that thicker covers are better able to buffer groundwater subsidy caused by varying water table regimes due to their higher retention capacity. Many lines of evidence indicate that thicker layered covers reduce the risk of drought stress resulting 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, notably; > 0.6 m (Shurniak, 2003) and > 0.5 m (Barbour et al., 2010) in Canada, and 1.2 m in southwest Virginia, USA (Burger and Zipper, 2002). It should be noted, however, soil cover thickness is highly site specific and will vary with biological, physical, and chemical processes from site to site (INAP, 2003). Developing field-based measurement of these processes and hydraulic properties is key to effectively designing a soil cover (INAP, 2003). Additionally, periods of water deficit will not likely result in complete vegetation failure on soil covers but rather result in a shift to vegetation that is better adapted to dry sites. As such, the actual vegetation community that develops may not coincide with that specified by end land-use or performance objectives. Therefore, a lack of plant available water at a site may shift the vegetation rather than result in complete failure of vegetation growth (Barbour et al., 2010). Nonetheless, maintaining an adequate supply of water through appropriately thick soil covers remains key to the overall performance of cover systems.

4.2.3   Layering / Soil Properties

Many studies have shown that layering of soil materials with textural differences can have profound effects on plant available water within cover systems (Barbour et al., 2010). Water storage enhanced by layers of different texture was shown by Zettl et al. (2011) to have higher available water than a homogeneous profile. Other studies have reported water storage enhancements of 30 to 110 mm for

covers ranging in thickness from 0.5 to 1.0 m for varying soil textures (Barbour et al., 2010; Burgers, 2005; Moskal, 1999). Enhancing the amount of water available to plants through layering may increase productivity and result in improved cover system performance (Zettl et al., 2011).

4.2.4   Seasonal Climate Variation

Climate conditions play a key role in determining cover system objectives for a particular site. Sites are usually characterized as "dry" or "wet" using average annual criteria. Natural drought and surplus cycles have been shown to have profound effects on the establishment, growth, and sustainability of vegetation on soil covers. Though precipitation is beneficial for vegetation, extreme rainfall events may be detrimental in some instances (INAP, 2003). Soil covers may become saturated and no longer able to retain moisture; rainfall subsequently registers as NP and/or runoff resulting in decreased performance (INAP, 2003). Saturation of the growth medium layer with continued rainfall may mean vegetation is not able to transpire adequate amounts of soil moisture to achieve lower NP rates. Additionally, large amounts of runoff may reduce the establishment and sustainability of vegetation by washing away topsoil and fines, leaving coarser, rockier soil on which vegetation is less likely to establish (INAP, 2003).

Below average precipitation or drought conditions may also be detrimental to vegetation. Less soil water storage may threaten vegetation and potentially lead to desiccation and increased percolation during precipitation (INAP, 2003). Regeneration of white spruce seedling was found to be significantly reduced due to dryer than normal climatic conditions in the aspen parkland and grasslands of Saskatchewan, Canada (Hogg and Schwarz, 1997). It is, however, recognized that mature plant communities can endure drought due to greater root proliferation through the soil profile (Barbour et al., 2010).

Natural climate variability will affect the amount of water available to vegetation on soil covers. Therefore, when designing soil covers, it is important to recognize that above or below average climate years can have an effect on cover system performance through its interaction with vegetation. In short, cover system design must not be conducted using average climate conditions; rather, the variability and influence of year-to-year climate conditions on cover system water storage must be evaluated. Further analysis of weather events during monitoring periods and projected changes associated with climate change will aid in understanding how climate affects water availability to vegetation.

4.2.5   Slope, Aspect, and Position

The volume of water available to vegetation is affected by the slope, aspect, and position of a slope within a landform (Burger and Zipper, 2002). 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). In the northern hemisphere, northern and eastern aspects tend to have more shade and be cooler during all seasons. The majority of sunlight is concentrated on southern aspects resulting in drier conditions and less vegetative growth on those aspects. This phenomenon was observed during the

monitoring of two ESR test covers in Ronneburg, Germany (O'Kane et al. 2011). Two identical test cover systems were constructed; one had a northern aspect while the other had a south-western aspect (O'Kane et al., 2011). The authors observed superior performance from the cover system with a northern aspect due to greater moisture availability for vegetation leading to higher establishment rates thus higher overall ET rates (O'Kane et al., 2011). 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.

The toe of a slope will generally have greater plant available moisture due to surface water drainage and interflow through the soil, allowing for greater establishment of vegetation (Burger and Zipper, 2002). Upper-slope positions tend to be drier and thus slightly less productive due to the preferential flow of water from upper to lower positions (Burger and Zipper, 2002; Kelln et al., 2009). Designing cover systems that incorporate slope aspect and position will improve the establishment of vegetation resulting in overall improved cover performance.

5   MODELLING VEGETATION

5.1   Modelling Plants

5.1.1   Climate Change

The effects of climate change on plants and plant communities is considered to be outside the scope of this document. While considerations of climate change are important and will certainly have an effect on plant productivity, forecasting what those effects will be is not the goal of the cover system designer. Modelling of shifts in the relative abundance of C_3 and C_4 plants occurs on geologic timescales and are not accounted for by the models listed in this section. The timescales of interest to the cover system designer are on the order of years to decades, and models should focus on plant responses to small timescale variations in climate. Climate change is implicitly incorporated into soil-plant-atmosphere modelling programs through variations in climate input data. Atmospheric conditions are a primary driver of vegetation models, and thus a vegetation model that adequately accounts for vegetation responses to atmospheric drivers will by default be responding to changes in climate. Therefore, climate change should be accounted for via the climate input dataset.

5.1.2   Leaf Area Index

Leaf area index is often chosen as the primary control on transpiration in water balance models. The emphasis placed on LAI in determining model transpiration is mostly due to the fact that LAI is an easily estimated and understood parameter, and integrates a wide range of processes associated with transpiration. While LAI is positively correlated with transpiration (Santiago et al., 2000) it does not govern the process. Leaves exist to produce carbon for the plant and do so by collecting solar radiation in photosynthetically active wavelengths.   However, it is how the specific arrangement, angle of incidence, and morphology of the leaves combine to affect radiation absorption, energy transfer, and turbulent processes within the canopy that will determine transpiration, and not the area of ground coverage by leaves, *per se* (Perrier, 1975). Leaf area index will continue to be an important input into water balance models. However, the transfer of mass and energy is far too important and complex to simply parameterize as one single value of LAI.

5.2   Modelling Plant Roots

Roots play a critical role in plant development, and in turn, have a direct effect on modifying the soil environment. The primary function of roots is to serve the plant as a physical foundation, extract water, uptake nutrients, and produce hormones and other growth regulators (Hoogenboom, 1999). As a result, the soil environment will experience changes in water content, chemistry, organic matter content, and

aeration among others. Therefore an accurate representation of plant root functions and processes is critical for a complete understanding of the soil water dynamics in the cover system.

5.2.1   Water Extraction

Numerous models have been developed to simulate the extraction of water from the soil by plant roots. Models vary in complexity, focus, and approach. Two approaches have become dominant in the methods used to model root water extraction. The microscopic, or single root model, approximates convergent radial flow of water towards an individual cylindrical root sink (Hillel, 1998). The approach can be solved either numerically or analytically by posing the flow equation in cylindrical coordinates (Hillel, 1998). Examples of the single root model are given in Philip (1975) and Hillel (1975).

The second approach, known as the macroscopic scale, or root system model, is more commonly used in water balance models. The approach is to conceptualize the root system as a diffuse sink that occupies each soil layer to a given density. The approach simplifies the model geometry, yet suffers from the gross spatial averaging of matric and osmotic potentials, which does not account for an increase in suction and salts in the areas immediately surrounding roots (Hillel, 1998).

5.2.1.1   Single Root Model

A formulation of the single root model was given by Hillel (1998). The transient flow of water unsaturated soil is given as:

$$c\frac{\partial \emptyset_m}{\partial t} = K\frac{\partial^2 \emptyset_m}{\partial r^2} + \frac{K}{r}\frac{\partial \emptyset_m}{\partial r} + \frac{\partial K}{\partial r}\left(\frac{\partial \emptyset_m}{\partial r}\right)^2 \qquad\qquad 5.1$$

where $\emptyset_m$ is the matric potential of soil moisture c is specific soil-moisture content (the slope of the soil-moisture characteristic, $d\theta/d\emptyset_m$ where θ is volumetric wetness), K the unsaturated soil's hydraulic conductivity (a function of matric potential, or of wetness), r is the cylindrical root radius, and t time.

$$\frac{\partial \emptyset}{\partial t} = D\frac{\partial^2 \emptyset}{\partial r^2} + \frac{D}{r}\frac{\partial \emptyset}{\partial r} \qquad\qquad 5.2$$

where $\emptyset$ is the tissue water potential and D the tissue's hydraulic diffusivity.

5.2.1.2   Root System Model

The root system model does not account for flow to individual roots, but simulates roots as a diffuse sink in each soil layer. The model is summarized by Hillel (1998) and given as:

$$\frac{\partial \emptyset}{\partial z} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial(\emptyset_m - z)}{\partial z}\right] - S_w \qquad\qquad 5.3$$

where θ is volume wetness, z is depth, $K(\theta)$ hydraulic conductivity (a function of wetness), and S_w is a sink term representing the presence of plant roots. The term ($\emptyset_m$-z) is the overall hydraulic head. The rate of extraction of water from a unit volume of soil can be represented in the following way:

$$S_w = (\emptyset_{soil} - \emptyset_{plant})/(R_{soil} + R_{roots})$$

5.4

where R_{soil} and R_{roots} are the hydraulic resistance of the soil and roots, respectively.

Here, $\emptyset_{soil}$ is the total potential of soil water, which is the sum of the matric $\emptyset_m$, gravitational ($\emptyset_g = z$), and osmotic $\emptyset_o$ potentials, all of which are expressible in head units:

$$\emptyset_{soil} = \emptyset_m + \emptyset_g + \emptyset_o$$

5.5

The hydraulic resistance to flow in the soil toward the roots was expressed inversely proportional to the hydraulic conductivity K and to the total length of active roots L in the unit volume of soil (Gardner, 1964) as:

$$R_{soil} = 1/BKL$$

5.6

Where B is an empirical constant taken to represent a specific root-activity factor.

The term $\emptyset_{plant}$ is the plant-water potential at the base of the stem the plant converges to a single water potential called the crown potential ($\emptyset_c$).

The flow rate from any soil layer to the roots is taken as the ratio of potential difference to the total hydraulic resistance:

$$(q_r)_i = [(\emptyset_s)_i - \emptyset_c]/[(R_r)_i + (R_s)_i]$$

5.7

where $(\emptyset_s)_i$ is the soil moisture potential, $(R_r)_i$ the resistance of the roots, and $(R_s)_i$ the hydraulic resistance of the soil in the ith layer.

Finally, the total extraction, Q, from all layers of soil, equal to the transpiration rate, is a sum of the contributions of all volume elements within the root zone:

$$Q = \sum_{i=1}^{n} \frac{(\phi_s)_i - \phi_c}{(R_r)_i + (R_s)_i}$$

5.8

and,

$$\phi_c = \sum_{i=1}^{n} \frac{(\phi_s)_i}{(R_r)_i + (R_s)_i} - Q \bigg/ \sum_{i=1}^{n} \frac{1}{(R_r)_i + (R_s)_i}$$

5.9

The reader is directed to Hopmans and Bristow (2002) for a comprehensive review of root water and nutrient uptake models.

5.2.2   Root Growth

A major deficiency of many water balance models is the omission of root growth as a process that affects the patterns and movement of water in the cover system profile (Hillel, 1998). Plant roots will grow in order to explore areas of greater water and nutrient concentrations, rather than depending entirely on the available resources in a given layer, as is implied by current model formulations. Root growth consists of a set of concurrent and sequential processes that include proliferation, extension, senescence, and death (Hillel, 1998). The most difficult aspect to model is accounting for spatial root distribution in relation to growth (Hoogenboom, 1999). The simplest option is to restrict root growth to one-dimensional vertical growth, under the assumption that roots will grow uniformly in a given soil layer. Two dimensional root growth models allow for both horizontal and vertical growth using a grid system. The most complex treatment of root growth is a three-dimensional representation. In order to have simulated roots interact with soil media, a full three dimensional treatment must therefore be given to the transport of water, nutrients, and energy (Hoogenboom, 1999). It is clear that a rigorous treatment of root growth will require much more information than simply the volume of water held in a given layer.

Root growth requires an input of biomass to be partitioned from other actively growing areas of the plant. Modelling biomass partitioning to roots begins with estimates of photosynthesis, which requires estimates of photosynthetically active radiation, leaf area index, leaf-water content, stomatal opening, and atmospheric CO_2 (Lommen et al., 1971). Although not all root growth models specifically account for biomass partitioning or transport of assimilates to roots, a rigorous treatment must account for the process (Somma et al., 1998; Wang and Smith, 2004). Modelling of carbon production in plants for biomass accumulation in roots has likely restricted the widespread adoption of root growth models for water balance monitoring.

5.2.3   Combined Root Uptake and Growth Models

Root growth cannot be examined in isolation from other processes taking place in the soil. Roots will grow not only in response to soil water content and nutrient concentration, but also in response to physical and chemical factors such as bulk density, temperature, salinity, and oxygen concentration (Hoogenboom, 1999). The ROOTSIMU model was originally developed by Huck and Hillel (1983) to account for photosynthesis, respiration, transpiration, and soil hydraulic processes. The model was refined by Hoogenboom et al. (1988) to simulate partitioning of biomass as a function of drought stress using daily time steps. Drought stress in ROOTSIMU leads to a decrease in transpiration until equal to actual water uptake, as well as a greater partitioning of biomass to roots in comparison to non-stressed periods (Hoogenboom, 1999).

Root growth model development has been led primarily by crop researchers interested in maximizing the efficient crop use of water and nutrients. The Decision Support System for Agrotechnology Transfer (DSSAT) is a one-dimensional crop growth model that incorporates a water and nitrogen balance (Jones et al., 1998; Hoogenboom, 1999). While the DSSAT Model is popular in the agronomy sector, the treatment of a soil water balance may be too simplistic for use with cover systems. Root geometry models such as ROOTMAP (Tsegaye et al., 1995) and SimRoot (Nielsen et al., 1999), have been shown to be accurate for simulating root growth, although in the case of ROOTMAP, the model does not include root biomass (Hoogenboom, 1999).

The focus and complexity of available root simulation models reflect the requirements and interests of the developers. Plant root simulation models developed by engineers, agrologists, soil physicists, plant physiologists and other disciplines will all have data requirements, assumptions, complexities, and simplifications that will likely be unsuitable for application in another discipline. This is evidenced by the dearth of models that simultaneously simulate both above ground canopies and below ground root development with the same level of detail. The models discussed previously do not adequately simulate environmental stresses due to the lack of a canopy component (Hoogenboom, 1999). Without a canopy component, an accurate surface energy and mass balance cannot be determined. In turn, soil temperature profiles, a major factor in root growth, cannot be estimated without a coupled surface energy and water balance model with a rigorous treatment of energy exchanges at the soil surface and in the plant canopy.

5.3   Soil-Plant-Atmosphere Models

Many numerical model codes exist for the simulation of water balances and near-surface soil microclimates. The complexity and focus of each individual model varies depending on the intended application. Some models are meant to be simple to use with a minimum of input data to give a general indication of water and plant dynamics over a growing season. Others are meant to be very accurate in simulating transfers of mass, energy, and momentum at the soil-plant-atmosphere interface, and are consequently input data intensive and operate at small time steps. Still other models, such as those used in the forestry sector, can require very detailed plant physiology inputs for estimating carbon balances, and merely calculate a soil-plant water balance as an input requirement. Compromises between model complexity and physical veracity will always be required, regardless of the chosen modelling tool.

The following section will detail a selection of models commonly used in situations where vegetation may need to be simulated. Examples from industries such as the forestry sector are given in the first section as an example of models that primarily focus on the physiological aspects of vegetation and plant ecology. The second section will detail how models commonly used in cover system design simulate, with a detail of how vegetation is simulated and their associated deficiencies. The final section will examine other modelling codes that have been found to be accurate in simulating mass and energy

transfer in the soil-plant-atmosphere continuum. Lessons from other industries and how they can be applied to cover system design will be discussed.

5.3.1   Examples from Other Industries

Examples of numerical models used in other industries such as the forestry and ecological modelling sector are provided in the section below. Forestry and ecophysiology models demonstrate how vegetation is modelled in sectors where the primary focus is on the plant canopy, and any consideration of a soil water balance is a secondary input used for carbon and nutrient dynamic modelling.

5.3.1.1   FOREST BGC

FOREST-BGC is an ecosystem model that is specifically designed to provide estimates of carbon, nitrogen, and water cycling across forested landscapes. The model uses stand water and nitrogen limitation values to alter the leaf/root/stem/carbon allocation fraction dynamically at each annual iteration. This model calculates a complete water balance that includes canopy interception, evaporation, transpiration and drainage. It emphasizes LAI as a key structural attribute for the simulation of water balance. However, the model requires no information about canopy properties such as stand density or canopy architecture (Running and Gower, 1991). The canopy is treated as a homogeneous mass and thus, soil layers are not considered in this model. This model requires input data including daily maximum and minimum temperature, relative humidity, precipitation and shortwave radiation. This model has been used successfully for regional scale ecological research for the simulation of carbon balance of forests (Running and Coughlan, 1988).

5.3.1.2   MAESTRO

The MAESTRO / MAESTRA / MAESPA suite of models were developed in Australia as an ecophysiology model. The model is a highly detailed canopy model that uses an array of trees in a stand to calculate physiological processes. The strength of the MAESTRO suite of models lies in the ability to simulate photosynthesis and transpiration within the forest canopy. The positions of all individual trees in the stand are specified by their x, y and z co-ordinates. The model is developed specifically to deal with the heterogeneous distribution of leaves and the complex age structure of leaves within the tree crown which is essential for estimating the radiation absorption, photosynthesis, and transpiration of a tree crown. This model requires input data including soil parameters (surface temperature, near infrared and thermal radiation of the soil surface), vegetation parameters (leaf area density distributions of leaves in the different age and position classes, co-ordinates of trees, crown radius and total area of leaves within the tree crowns) and meteorological data (temperature, water vapour saturation deficits, wind speed and CO_2 concentration of ambient air at a reference height above the stand) (Wang et al., 1990). Due to the detailed nature of the model, MAESTRO is best suited to analyses focused on the above ground canopy over short periods and small time scales.

5.3.1.3 *BIOMASS*

BIOMASS is a process based stand-level model consisting of a number of sub-models that calculate the carbon balance of the canopy. This model is similar to MAESTRO, having a simpler canopy structure than the former and is suited to running simulations for periods ranging from days to decades. The model requires input data including the parameters of foliage photosynthetic response relationships, rooting depth, soil moisture retention characteristics, rainfall interception model parameters, leaf reflectance, air density, daily precipitation, and maximum and minimum air temperatures. This model has been successfully tested for a range of pine species growing in Wisconsin, Sweden, Florida, Australia and New Zealand (McMurtrie et al., 1994).

5.3.2   Current Approaches Used in Cover System Design

Models that account for a plant canopy by necessity require more detailed inputs than those that simply model vegetation as a sink term for water. When trading complexity for veracity, models that do not account for plant physiology and effects on turbulent transfer ignore a very important component in a surface energy balance. Ignoring a major component of the surface energy balance increases the uncertainty of the estimation, and affects the overall estimation of the water balance, as well as providing poor estimates of soil temperatures, evaporation, transpiration, and sensible heat exchange.

5.3.2.1 *Hydrological Evaluation of Landfill Performance (HELP) Model*

The Hydrological Evaluation of Landfill Performance (HELP) is a quasi-two-dimensional hydrologic model for analysis of water movement in and out of landfills (Schroeder et al., 1994). This model was developed to be used as a tool for landfill designers and regulators to evaluate the hydrologic performance and economic benefits of landfill designs to allow comparison of design alternatives for both the landfill itself or any associated leachate collection and treatment systems. Data requirements include climate, soil, and design geometry data to estimate the amount of water that is received and is leaving the landfill accomplished by the computation of a daily water balance.

A vegetative growth model in HELP was developed for crops and perennial grasses which assumes the vegetative growth and decay can be characterized by assuming the vegetation transpires water, shades the surface, intercepts rainfall and reduces runoff in similar quantities as grasses or as an adjusted equivalence of LAI. A value for LAI can be manually entered or chosen with guidance available from the location database within the model. Valid vegetation cover entries are 1 through 5 according to:

     1 = Bare ground

     2 = Poor stand of grass

     3 = Fair stand of grass

     4 = Good stand of grass

     5 = Excellent stand of grass or dense stands of trees or shrubbery

To determine the amount of water loss through evapotranspiration in the water balance, the model requires a location, evaporative zone depth, and LAI to be designated. HELP includes a database of climate characteristics of U.S cities for the user to select from based on similarities to their project location, or the user may manually enter required parameters. Program limits for the evaporative zone depth are set such that the depth must be greater than zero, but less than the depth to the top of the upmost liner. Where surface vegetation is present, this zone should at minimum be at least equal to the average expected root depth penetration. The specified evaporative root zone depth will be important since the depth must be representative of the maximum depth where moisture changes from evapotranspiration are most apparent, typically that seen when peak quantity of vegetation is present. If the depth of this zone is too shallow, model results would tend to underestimate water removal through evapotranspiration and overestimate drainage.

The growing season in the program is based on mean daily temperature and plant species. The growing season is typically designated when the normal mean daily temperature rises above 10° to 13°C and ends when mean daily temperatures are below this, although there is some variance based on a warmer or cooler climate. The default growing season can be generated by selecting the city location, or entered manually based on actual data.

The influences of vegetation in other areas of the model that use LAI for calculation include an adjustment to the saturated hydraulic conductivity of the soil for the effects of root channels, computation of a runoff curve number, and interception which adds to the amount of water available for potential evaporation, with any amount exceeding this added to infiltration.

5.3.2.2   UNSAT-H

The UNSAT-H is a one-dimensional finite difference model developed by the Hydrology Group at the Pacific Northwest National Laboratory (PNNL) to assess the water dynamics of arid sites, particularly estimate recharge fluxes from waste disposal facilities (Fayer, 2000). Flux recharge rate calculation is accomplished by simulating soil water infiltration, redistribution, evaporation, plant transpiration, deep drainage and soil heat flow to help inform decisions regarding land use, waste disposal, and climate change. The model uses Richards' equation to simulate deep water flow, Fick's law to simulate water vapor diffusion and the Fourier equation to simulate sensible heat flow.

Water removal through vegetation transpiration is simulated as a sink term calculated using empirical algorithms based on potential evapotranspiration, which is either input or calculated by the model based on climate inputs. Plant information (such as LAI, maximum rooting depth, root density variations with depth, and the suction head limits that impact the withdrawal efficiency of plants) is supplied to the model which then partitions PET into potential evaporation and potential transpiration.   The potential transpiration portion is then applied to the root zone, in proportion to the relative root density defined at each depth establishing a potential sink term, for nodes with roots assigned to them. Removal of water from a particular node is then dependent on the suction head at the node. The user defines how the

potential transpiration rate is reduced based on suction head values. Below the minimum value (wilting point) transpiration is reduced to zero.

Some advantages for water removal through vegetation using UNSAT-H include:

- Offers flexibility in terms of varying the maximum rooting depth during simulations; and

- Has a thorough understanding of transpiration from crop species using a biomass to transpiration ratio.

Shortcomings for the vegetation simulation in UNSAT-H include that this model:

- Does not deal well with changes in plant phenology in response to significant changes in climate patterns (Bensen et al., 2004);

- Is unable to vary the distribution of roots in the profile during a simulation;

- Biomass to transpiration ratio is based on a local crop species. Can use for simulation of other vegetation types, but likely would use the alternative method which relies on LAI;

- Does not well represent responses of mixed plant communities containing annual and perennial species, with varying life cycles and rooting characteristics; and

- There is no provision to simulate the effect of the plant canopy on water and heat flow.

5.3.2.3 *VADOSE/W*

VADOSE/W developed by Geo-Slope International Ltd is a finite element software that analyzes flow from the environment, across the ground surface, through the unsaturated zone and into the local groundwater regime linking processes occurring in the soil, vegetation, and the atmosphere (Geo-Slope, 2012). This model can be used for both one and two-dimensional analyses as chosen by the user based on project needs. One-dimensional analyses may be employed to better understand the physical processes and sensitivity of the surface conditions to the potential of lateral flow in the system, while two-dimensional analyses can analyze if this lateral flow results in water removal or introduction into the system. VADOSE/W model set up is accomplished by creating regions using a finite element mesh to fit the geometry of the area and interactively applying boundary conditions and specifying material properties for each region.

VADOSE/W does recognize that vegetation is an important piece in establishing a water balance for any system that does or will support vegetative growth. Vegetation response to soil and atmospheric processes are based on growth properties of grasses and cereal crops. The effect of vegetation on water distribution within the model domain is represented as a nodal uptake term accomplished by using any combination of three related functions including a moisture limiting function, plant root depth function, and LAI. The moisture limiting function determines the percentage decrease in the plants ability to draw water as negative potential increases in the unsaturated ground. This representation follows the common

principle of available water holding capacity (AWHC) found in agriculture, environmental engineering, and hydrological sciences. The AWHC exists as a range of matric potentials between field capacity and permanent wilting point where water is not available for plant uptake. This moisture limiting function is defined by the user based on knowledge of the plant requirements and site characteristics. To determine the depth of soil from which plants will be extracting water, the anticipated root depth profile for the duration of the growing season is required. In addition to the rooting depth, Vadose/W allows the user to choose the shape profile for the root distribution to follow, either a rectangular or triangular pattern. The LAI parameter in the model is used to develop a ratio that determines the amount of energy that reaches the soil surface for direct evaporation, and the amount that is available to plants for use in transpiration. This parameter can be cycled during a multi-year analysis by selecting a cycle function option. VADOSE/W ensures that the conservation of energy principal is followed by ensuring that the sum of evaporation and any actual transpiration can never be greater than the potential evapotranspiration at the surface node.

Users of this software have found that they are satisfied with VADOSE/W's incorporation of vegetative processes in that:

- Vegetation effects can be toggled on or off using a check box to allow a comparison of the results from a bare surface or with vegetation without forcing a change in the overall boundary conditions; and

- The software is flexible in that the user can control plant responses by controlling the root depth, the basic root shape, the ratio of evaporative energy allotted to transpiration, and the actual evaporation to potential evaporation ratios at all pore water pressures via the plant limiting moisture function.

Compared to the other modules within VADOSE/W, the vegetation module has several shortcomings. Required improvements that have been noted include:

- The user controls the root depth; it is not developed based on response to nutrient and water stress;

- The plant water uptake rate is defined by the plant-moisture limiting function that is defined by the user, not the material properties of the system (Bensen et al., 2004);

- VADOSE/W does not account for any canopy interception of precipitation;

- The LAI is used to determine the ratio of energy used for evaporation or transpiration. The software includes a limit where any LAI greater than 2.7 denotes that all energy is being utilized for transpiration (i.e. ground surface is entirely shaded);

- The root distribution pattern is limited to the two shapes, triangular or rectangular; and

- VADOSE/W vegetation model was developed based on responses from grasses and cereal crops, and is not directly applicable to other vegetation types commonly used in cover systems, such as shrubs and/or trees.

In light of the deficiencies outlined for VADOSE/W, the modeller is urged to use caution when interpreting the results of cover systems with vegetation that are simulated with this model.

5.3.2.4   *HYDRUS 2D/3D*

HYDRUS 2D/3D is used to simulate the movement of water, heat and solutes in variably saturated media. The Richards equation is solved for variably saturated water flow and advection-dispersion equations are used for both heat and solute transport (Simunek et al., 2011). This model includes all the hydrological balance components (infiltration, soil moisture storage, evaporation, plant water uptake, groundwater recharge, runoff and erosion) with the additional features including nutrient uptake by plant roots, a range of soil hydraulic functions, hysteresis model, provision for non-linear and non-equilibrium reactions, physical non-equilibrium type solute transport, the transport of viruses, colloids and bacteria, the transport of CO_2, a constructed wetland module (in 2D), flowing particles in 2D applications and calculation of fluxes across internal mesh lines (Simunek et al., 1999).

Vegetation water uptake is accounted for by transpiration treated as a sink term in the flow equation. HYDRUS considers the root zone to consist of all nodes where the potential water uptake distribution is greater than zero. This sink term is a function of root-water uptake stress response function and the potential water uptake rate. The root water uptake stress response function is a function of the soil water pressure head, which follows the same principle of soil available water holding capacity, where maximum water available water for plant uptake lies between a 'wet' (in this case saturated) and 'dry' (wilting point) soil pressure conditions. HYDRUS differs in the traditional application of this principle in that plant water uptake is considered to be zero at both the wilting point pressure head as well as at the point near saturation, or wetter than an assigned "anaerobiosis point" (Simunek et al., 2011). This sink term can be further expanded to include osmotic stress based on the concentration of solutes present. HYDRUS incorporates a rigorous solute uptake model described in Simunek et al. (2011) that can be considered or ignored as part of the analysis. Potential water uptake rate, the second parameter governing the sink term representing plant response, is a function of root distribution. Root distribution can be implemented in a spherical sense in two or three dimensions. Calculation of this function requires input of the maximum rooting depth, the depth of maximum root density and the maximum rooting radius and radius of maximum intensity must be specified. For three-dimensional analysis, the maximum radius and radius of maximum density is required in the third dimension. HYDRUS allows a user to define any shape of the water uptake distribution function, provided that this function is constant during through the simulation. For annual vegetation, a growth model is required to simulate the change in rooting depth with time. HYDRUS assumes that the actual root depth is the product of the maximum rooting depth, and a root

growth coefficient. The growth rate is calculated either from the assumption that 50% of the rooting depth will be reached after 50% of the growing season has elapsed, or measured field data.

Some benefits of the vegetation model in HYDRUS include:

- The model can be used to analyze water and solute movement in unsaturated, partially saturated, or fully saturated porous media;

- It includes inbuilt models of root distribution database;

- Plant water uptake is considered to be zero at the wilting point and point near saturation. This likely simulates plant response to climate processes more accurately than other models, as noted in Bensen et al. (2004);

- HYDRUS incorporates rigorous model of solute concentrations and uptake by plants and the impact of osmotic stress on plant water uptake responses and includes both active and passive uptake; and

- It includes an interception model.

Some required improvements that have been noted include:

- Does not allow for more than one plant to be simulated which does not accurately capture dynamic systems containing more than one plant species;

- A lack of data that supports species from sites located all over the world;

- Cannot simulate plant growth: improved accuracy could be gained by coupling HYDRUS with a separate plant-growth model; and

- Assumption that plant water uptake shuts down near saturation has not been found to occur at a consistent rate for all plant species.

Although HYDRUS 1D is able to compute a coupled energy balance for a bare soil, the same capability does not exist for a plant canopy. Furthermore, vegetation does not respond to atmospheric potentials, which is the principle driver of transpiration.

5.3.3 *Physically Based Approaches*

The ideal approach to simulating vegetation in cover systems is to have the simulated plant canopy respond in a physically appropriate manner with respect to plant physiology. A plant canopy is also important in modifying the near surface atmosphere, and an appropriate model must account for changes in mass, energy, and momentum transfer caused by plants. The following section summarizes models that take a more physically based approach to simulating vegetation.

5.3.3.1 *FASST*

The Fast All-Season Soil Strength (FASST) model was developed by the United States Army Corps of Engineers as a one dimensional dynamic state of ground model (Frankenstein and Koenig, 2004). The model is capable of estimating a rigorous coupled water and energy balance, and calculates the transfer of mass and energy at the air-canopy-snow-soil interface. The model specifically models radiation transfer through the plant canopy and into the underlying soil. Turbulent transfer induced by the plant canopy is explicitly captured by incorporating vegetation height and roughness length. Most importantly, transpiration is simulated as a component of the soil-plant-atmosphere continuum, and is governed by stomatal resistance in response to the vapor pressure deficit. Transpiration is linked to soil water content through a resistance term between soil and plant roots. The method iteratively solves a simultaneous estimate of ground and foliage temperature (Frankenstein and Koenig, 2004).

The FASST model was initially developed to provide information regarding mobility and sensor performance algorithms for military purposes but has found wide acceptance in non-military applications due to the rigorous treatment of the surface energy balance (Frankenstein et al., 2008). The model was designed specifically for applications in cold regions, and would be a useful tool for cover system design in Canadian applications. A deficiency of the model with respect to cover system design is the lack of a root growth calculation. Roots are distributed through soil layers with water uptake occurring at soil layer nodes (Frankenstein and Koenig, 2004). Nevertheless, the model has been found to model water balances in vegetated systems with an acceptable level of accuracy (Frankenstein et al., 2008).

5.3.3.2 *SHAW*

The Simultaneous Heat and Water (SHAW) model is a detailed one-dimensional process model that simulates the transfer of heat and water through a plant-snow-residue-soil system to simulate a coupled water and energy balance (Flerchinger and Saxton 1989). The SHAW model is unique in that transpiration is mechanistically linked to soil water by calculating a flow through roots and leaves within the soil-plant-atmosphere continuum, while satisfying a leaf energy balance (Flerchinger et al., 1996). In contrast to VADOSE/W, SHAW calculates a rigorous fully coupled energy balance, and computes soil evaporation separately from transpiration. The model has the added benefit of being tested in a wide range of climates and soil conditions (Wang et al., 2010).

The physical system modelled by SHAW consists of a vertical profile of a plant canopy, snow pack and plant residue through to the soil (Figure 5.1). Heat, water, and solute balances are computed simultaneously at every level. A plant canopy affects all aspects of an energy and water balance in the model. Net radiation is affected by the transmissivity of each canopy layer and the albedo. Sensible heat flux is modified by the plant through a resistance term that incorporates friction velocity and surface roughness from the plant. Most importantly, SHAW determines plant transpiration by assuming a continuum exists between the soil, plants, and the atmosphere. Water flow through the plants maintains

continuity with the soil and is simulated through a series of potentials and resistances (Figure 5.2.). Water flow within the plant is primarily controlled by stomatal resistance.
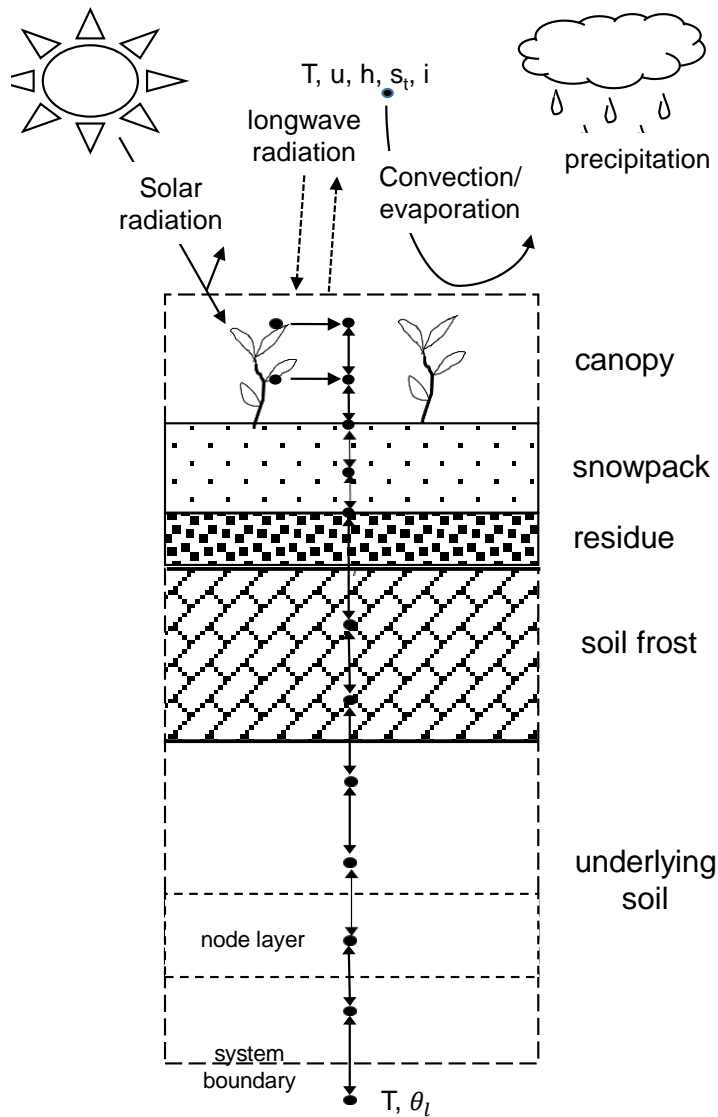

Figure 5.1   Schematic of the physical representation of the SHAW model. T is temperature, u is wind speed, h is relative humidity, St is solar radiation, i is precipitation, and θv is water content (After Flerchinger et al., 1996).
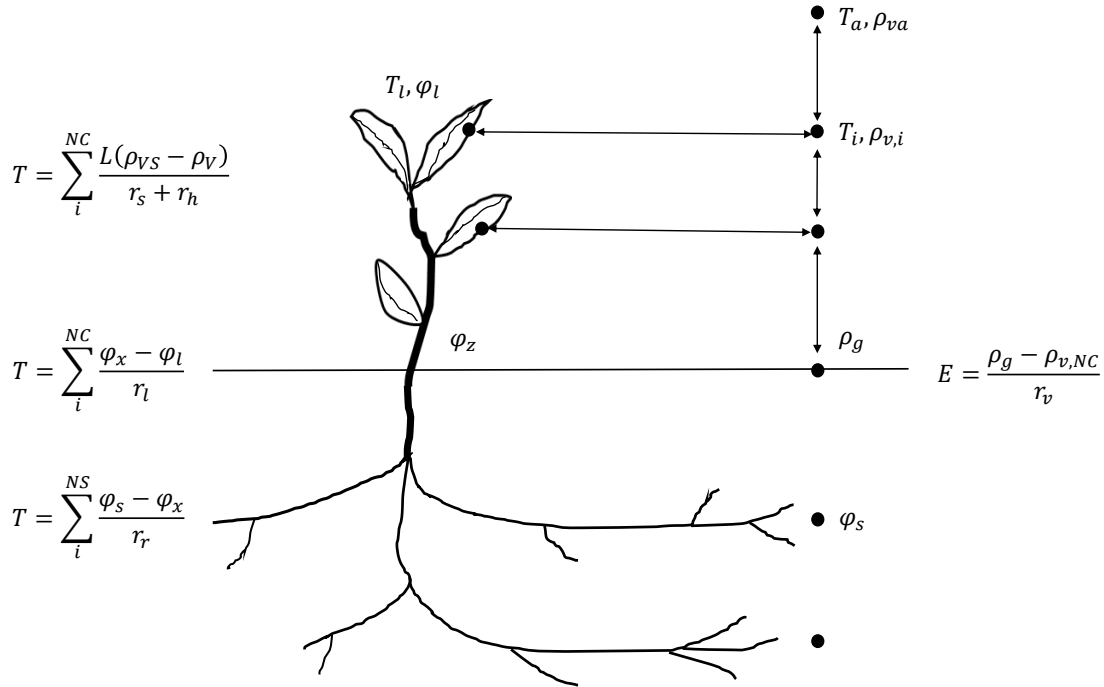
The following equations appear alongside the schematic:

$$T = \sum_{i}^{NC} \frac{L(\rho_{VS} - \rho_V)}{r_s + r_h}$$

$$T = \sum_{i}^{NC} \frac{\varphi_x - \varphi_l}{r_l}$$

$$T = \sum_{i}^{NS} \frac{\varphi_s - \varphi_x}{r_r}$$

$$E = \frac{\rho_g - \rho_{v,NC}}{r_v}$$

Labels in the figure: T_a, ρ_{va}; T_l, φ_l; $T_i, \rho_{v,i}$; φ_z; ρ_g; φ_s

Figure 5.2   Schematic of the SHAW model physical representation of water flow through a plant in response to plant transpiration, where: L is the leaf area index, E is the transfer of water vapor, NC is the number of canopy nodes, T is the temperature of the exchange surface, Ti is the temperature within the canopy layer, Ta is the temperature of the air at reference height z, Tl is leaf temperature, ρg is vapor density at ground level surface, ρv is vapor density, ρva is the vapor density at the reference height, ρv,i is the vapor density of the air within the canopy layer, and ρvs is the vapour density within the soil, rr is root resistance, rl is total leaf resistance, rv is resistance to vapor transfer within the canopy and equal to 1/ke, rh is the resistance to convective heat transfer, φs, φx, φl, φ z, is the water potential in the soil, in the plant xylem, leaves, and plant crown, respectively.

A deficiency of the SHAW model is the inability to simulate plant and root growth. Fortunately, given the flexibility of the model code, other researchers have coupled SHAW with other models that do simulate plant growth. Jamieson et al. (1998) simulated root growth and depth using a series of parameters that included potential root water uptake, root restriction factor, assimilation, carbon allocation and root biomass. Plant growth was simulated by Wang et al. (2009) for a continuous wheat crop using DSSAT-CSM (Cropping System Model). It was found that when this model was coupled with SHAW, plant growth was adequately simulated, although soil water uptake was often overestimated. The SHAW model has been rigorously tested in a wide range of climates, soil conditions, and plant canopies. Given the integration capabilities with plant growth models of SHAW, the code remains the preferred option for simulating vegetation in cover systems.

5.4   Summary

There is no single modelling code that accurately captures the detailed physics and physiology of the transfer of mass, energy, and momentum within the soil-plant-atmosphere continuum. By definition a model is only a representation of physical reality, and the cover system designer must accept that compromises, simplifications, and assumptions are part of the process. The model user should be aware of the strengths and weaknesses of the particular code they are using, and account for any deficiencies through the model interpretation (Table 5.1). Nevertheless, there are modelling codes that exist that more accurately capture the physical mechanisms governing the interaction of vegetation and cover systems. Depending on the level of detail required in the analysis, model codes that account for the actual physical mechanisms governing plant transpiration should be favoured over those that simply model vegetation as a sink term. As shown above, not only are vegetation sink terms a poor representation of reality, the effects of vegetation near-surface turbulent transfer will be ignored. Neglecting turbulent transfer and radiation transfer through the plant canopy will result in erroneous estimations of soil temperatures, air temperatures, and most importantly, evaporation from soil. The fundamental point is that plants are an integral part of the soil-plant-atmosphere continuum and neglecting their effects on the cover system will lead to spurious water balance estimations.

Table 5.1
Summary of soil-plant-atmosphere model strengths and weaknesses.

Model Code	Strengths	Weaknesses
FOREST-BGC	Detailed forest nutrient and carbon dynamics	Basic soil water balance
MAESTRO	Detailed forest canopy processes	Basic soil water balance
BIOMASS	Process based carbon model	High parameter requirements
HELP	Fast processing, easy implementation	Plants modelled as sink term
UNSAT-H	Accurate soil physics	Plants modelled as sink term
VADOSE/W	Coupled water and vapour flow	Plants modelled as sink term
HYDRUS 2D/3D	Rigorous surface energy balance	Plants modelled as sink term
FASST	Rigorous physics, accurate plant physiology	One dimensional, not user-friendly
SHAW	Rigorous physics, accurate plant physiology	One dimensional, not user-friendly

6   RECOMMENDATIONS

The deficiency of current model codes to accurately simulate a realistic representation of the soil-plant-atmosphere continuum needs to be addressed. As computing power increases, model codes that once would have taken prohibitive lengths of time to solve are now solved in a matter of minutes or hours. The most rigorous codes are generally one-dimensional models, and efforts should be taken to expand these models at least to two-dimensional.

It is no longer appropriate to model vegetation as a sink term for soil water. The atmospheric and physiological drivers of transpiration have been simulated in currently available numerical models. However, the models are often not user friendly. Integration of plant physiology and its effects on turbulent transfer and mass and energy balances is required. Root growth models that require internal biomass partitioning and estimation of carbon production are likely too detailed for the purposes of the cover system designer. A simpler formulation of root growth that responds to water and nutrients would still be beneficial.

The physiological interactions of plants and soil covers has not been extensively explored. Validation of vegetation models will require focused research for use in the mining context, rather than an assumption of direct applicability from agriculture and forestry. Field trials should aim to determine the required soil properties to effectively support a given plant community. Furthermore, understanding root growth and cover system interactions will help determine appropriate growth layer depths to support sustainable and effectively transpiring vegetation.

Climate change and its effects on the natural ecology of our landscapes continues to remains poorly defined. Modeling efforts to account for climate change effects on cover system vegetation and natural analogues should be conducted. The integration of the plant and soil parameters affected by climate change should improve the predictive ability of models over time and translate into better performance. Continued research regarding plant requirements, and their response to biotic and abiotic factors on cover systems will undoubtedly improve the predictive ability of numerical models leading to improvements in long-term cover system performance.

7   CONCLUSION

Plants are an integral component of the soil-plant-atmosphere continuum. A plant canopy modifies its environment; thus, by neglecting the effects of vegetation on heat and mass transfer processes both above and below the soil, the modeller is ignoring a major determinant of cover system dynamics. Simulating plants as a sink term that remove soil water at the user's input is not appropriate if the goal of the analysis is to determine how vegetation will affect cover system performance. Rather, vegetation must be modelled as part of the continuum and must respond to atmospheric forcing in a physically appropriate manner. Accounting for plant physiology and the physical mechanisms controlling plant transpiration will lead to a better understanding of how the system would actually be expected to perform. A cover system that has been designed with a good understanding of all the processes involved will lead to a more sustainable system and that achieves mine closure objectives.

8   ACKNOWLEDGEMENTS

9   GLOSSARY OF TERMS

Abiotic Factor - A factor created by a nonliving physical and/or chemical attribute of a system.

Abscisic Acid (ABA) - A lipid hormone that inhibits cell growth in plants; partly responsible for leaf abscission and responsible for promoting dormancy in buds and seeds.

Abscission - The normal shedding from a plant of an organ that is mature or aged.

Available Water Holding Capacity (AWHC) - The amount of soil water available to plants.

Biogeoclimatic Regions - A geographical area with a relatively uniform macroclimate, characterized by a mosaic of vegetation, soils, and to a lesser extent, animal life reflecting that climate.

Biome - A major ecological community of organisms adapted to a particular climatic or environmental condition in a large geographic area where they occur.

Biotic - A factor created by a living thing or any living component within an environment in which the action of the organism affects the life of another.

Ecotone - A region of transition between two biological communities.

Edaphic - Related to or caused by particular soil conditions such as texture or drainage rather than by physiographic or climate factors.

Edatopic Niche - Typically a range of factors (soil nutrient regime vs. soil moisture regime or typical LAI vs ET) in which vegetation may be found in, or operate under.

Forbs - A broad-leaved herb other than a grass, especially on growing in a field, prairie, or meadow.

Functional Groups - In ecology; a collection of organisms based on morphological, physiological, behavioral, biochemical, environmental responses or, on trophic criteria.

Herbivory - An animal that feeds on plants.

Leaf Area Index (LAI) - The ratio of total upper leaf surface of vegetation divided by the surface area of the land on which the vegetation grows. LAI is a dimensionless value, typically ranging from 0 for bare ground to 6 for a dense forest.

Mesic Site - A site in which growing conditions consist of a medium water supply.

Morphology - The form and structure of an organism or one of its parts.

Niche - The function or position of an organism or population within an ecological community and/or the particular area within a habitat occupied by an organism.

Phenology - The relationship between a periodic biological phenomenon (flowering, breeding, and migration) and climatic conditions.

Physiology - The basic processes underlying the functioning of a species or class of organism, or any of its parts or processes.

Plasticity - The adaptability of an organism to change in its environment or differences between its various habitats.

Senescence - The growth phase in a plant or plant part (leaf) from full maturity to death.

Vapour Pressure Deficits - The difference (deficit) between the actual water vapour pressure and the saturation water vapour pressure at a particular temperature.

Xeric Site - A site in which growing conditions contain little moisture and is very dry.

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