Performance of Interior Spruce Seedlings
Planted Under Dry Soil and Climatic Regimes

By

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to the required standard

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August 12, 1997
Abstract

A soil water balance model was used in a retrospective study of the survival and performance of short-day treated interior spruce seedlings, operationally planted in the Prince George region under dry soil and climatic regimes in July and August, 1994.

The soil water balance model has potential to be used in operational forestry as a tool in managing plantation sites that are susceptible to drought. Comparison of modelled and measured soil water content indicated that the model is able to predict soil moisture accurately if applied to sites where model assumptions are met. The model should be a good predictor of soil water content between early May and mid-August for the Prince George region.

A linear regression model was developed predicting seedling performance by soil moisture. The relationship between a seedling performance index and mean $\Psi_m$ (soil matric potential) for 30 days following planting is strong, $r^2 = 0.75$. The best predictor of a root variable from above ground morphological measurements was found to involve a volume surrogate (caliper$^2$ x height) as the independent variable and dry root mass as the dependent variable, $r^2 = 0.50$. Site characteristics were found to be a good predictor of seedling survival, $r^2 = 0.64$.

An additional seedling study showed that percent survival has a strong relationship with the modelled mean $\Psi_m$ for 30 days following planting. Survival decreases substantially below a mean $\Psi_m$ of $-0.2$ MPa.
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<tr>
<td>$\alpha$</td>
<td>Priestley-Taylor alpha</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>psychrometric constant</td>
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<tr>
<td>$\Theta$</td>
<td>volumetric soil water content</td>
</tr>
<tr>
<td>$\rho_w$</td>
<td>density of water</td>
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<tr>
<td>$\Psi$</td>
<td>water potential</td>
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<td>$\Psi_\pi$</td>
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<td>$\Psi_g$</td>
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<td>turgor potential</td>
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<td>$E_{\text{max}}$</td>
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<td>soil surface evaporation</td>
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<tr>
<td>$E_{\text{as}}$</td>
<td>soil limited surface evaporation rate</td>
</tr>
<tr>
<td>$E_{\text{psr}}$</td>
<td>soil limited extraction of water by roots for a layer</td>
</tr>
<tr>
<td>I</td>
<td>interception</td>
</tr>
<tr>
<td>k</td>
<td>hydraulic conductivity</td>
</tr>
<tr>
<td>$L$</td>
<td>rooting density</td>
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<tr>
<td>$L$</td>
<td>latent heat of the vaporisation of water</td>
</tr>
<tr>
<td>LAI</td>
<td>leaf area index ($m^2$ leaf per $m^2$ ground)</td>
</tr>
<tr>
<td>P</td>
<td>rainfall</td>
</tr>
<tr>
<td>Symbol</td>
<td>Definition</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
</tr>
<tr>
<td>Q</td>
<td>uptake of water by vegetation</td>
</tr>
<tr>
<td>R</td>
<td>runoff</td>
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<td>$R_n$</td>
<td>calculated 24 hour net radiation</td>
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<tr>
<td>Rp</td>
<td>plant resistance to water flow</td>
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<tr>
<td>$R_s$</td>
<td>soil resistance to water flow</td>
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<tr>
<td>$s$</td>
<td>slope of the saturated pressure curve</td>
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<td>SPAC</td>
<td>soil - plant - atmosphere continuum</td>
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<td>SDT</td>
<td>Short Day Treated</td>
</tr>
<tr>
<td>TDR</td>
<td>Time Domain Reflectometry</td>
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1. Introduction

Summer planting of conifers in the central interior of British Columbia is effective on some sites. However, during periods of limited precipitation, drought stress resulting from certain combinations of soil type, topographic position, and competing vegetation, may be sufficient to impair growth and even kill summer planted seedlings. Tree seedlings require one month of sufficient soil moisture following planting to allow root growth for establishment and survival (Spittlehouse and Childs 1990).

Many forest companies are skeptical about summer planting programs. For example, in the summer of 1994, with the abnormally low precipitation rates and high temperatures, most planting operations were either cut short or completely cancelled. Although this may have been justifiable to a certain extent, the end result is an increased hesitancy of forest companies to initiate and/or maintain extensive summer planting programs.

Logistically, it is desirable to increase the size of summer planting programs. From a management perspective, it is much simpler to plant the proposed number of seedlings, for a given season, over a longer time frame. Northwood Pulp & Paper Ltd. and Rustad Brothers Ltd., in Prince George, have adopted a seedling planting system in which short-day treated (SDT) interior spruce seedlings are planted during June and July. The focus of this research is to investigate the performance of these SDT interior spruce seedlings planted under dry soil and climatic conditions. "Short-day" treated refers to the nursery
Introduction

regime prior to seedlings being lifted and sent for out-planting in the field. Nurseries generally have developed their own sequence of conditioning seedlings for direct out-planting, usually scheduled to occur within a few days of lifting. This conditioning involves a light and watering regime. A progressive shortening of day length is simulated by a blackout process, which is intended to initiate bud set and dormancy in seedlings. Also a decrease in watering is considered to stress the seedlings in an attempt to prepare them for the field.

The performance of interior spruce seedlings on various sites is directly linked to the seedlings’ physiological response to environmental conditions of the site. There are a number of environmental factors that may lead to seedling stress, poor performance, or even mortality, such as temperature, light, soil moisture and nutrient content, and humidity. However, the focus of this research will be soil moisture as a limiting environmental variable and its effect on performance of interior spruce seedlings. A brief look at the physiological and environmental principles applied in this study will help rationalise and justify this research.

Seedling water supply is discussed in terms of $\Psi$ (water potential). $\Psi$, referred to in terms of energy, is the difference between the free energy state of water in various states and that of “free” pure water at standard pressure and temperature. Seedling $\Psi$ is primarily made up of turgor potential ($\Psi_p$) and osmotic potential ($\Psi_o$). Effects of gravitational potential ($\Psi_g$) may be neglected because of short seedling height and the magnitude of $\Psi_p$ and $\Psi_o$. Soil water potential is discussed as having the following
components, gravitational potential ($\Psi_g$), osmotic potential ($\Psi_o$) and matric potential ($\Psi_m$).

A number of studies suggest that osmotic potential changes seasonally in white spruce (Grossnickle 1988b & 1989, Colombo and Teny 1992). One may assume that the ability of some conifer seedlings to tolerate drought is partially due to seasonal changes in $\Psi_o$. These $\Psi_o$ changes are primarily due to shoot phenology; $\Psi_o$ increases considerably during shoot elongation (Grossnickle 1996). As a result, newly planted interior spruce seedlings undergoing shoot elongation are less drought-tolerant (Grossnickle 1988b). Thus, one may argue from a physiological perspective that planting SDT interior spruce seedlings is advantageous during June and July due to this increased tolerance to drought.

Seedling ability to take up water is determined by available soil water, root system size and distribution, root-soil contact, and root hydraulic conductivity (Grossnickle 1996). Leaf water potential, the degree of stomatal opening, needle area and the atmospheric demand for water are variables influencing transpiration rates. Seedling water stress is a result of transpirational demands exceeding the ability of the seedling to take up water (Grossnickle 1996). Water moves through the soil-plant-atmosphere continuum (SPAC) from higher $\Psi$ to lower $\Psi$ under the combined influence of these variables.

Seedlings that are short-day treated and whose buds have set, utilise carbohydrate reserves for root growth rather than foliage growth, avoiding the problem of having a root system that is unable to support the seedling's leaf area. Water stress in planted seedlings may result from conditions that limit water flow along the SPAC. Often, newly planted seedlings have a number of problems that increase resistances along the SPAC, such as
Introduction

poor root-soil contact, low root system permeability and a lack of root system development into the soil (Kozlowski and Davis 1975, Burdett 1990, Grossnickle 1988a, Grossnickle 1996). New root growth is crucial to seedling water availability. It decreases root resistance (Grossnickle and Blake 1985, Grossnickle 1988a, Colombo and Asseltine 1989) and increases seedling $\Psi$ (Grossnickle 1996).

Summer planting may often lead to adverse environmental conditions for seedling growth and establishment, including high temperatures and resulting high atmospheric evaporative demands, and limited soil moisture. If high evaporative demand conditions persist, prolonged stomatal closure can reduce growth, and induce leaf and ultimately seedling senescence (Blake and Tschaplinski 1992). As evaporative demand in the air increases, seedlings have reduced stomatal conductance and lower $\Psi$, indicating water stress (Grossnickle 1996). Limited soil moisture exacerbates the problem by providing high soil and root resistances along the SPAC as well as low $\Psi$. Under these conditions newly planted seedlings are unable to generate new root development to acquire sufficient soil moisture to reduce water stress and resume growth (Grossnickle 1996).

To increase the size of summer planting programs and decrease the risks to such programs effectively, silviculturalists must be able to identify and plan for sites that are most susceptible to soil moisture levels and other environmental conditions conducive to seedling water stress. D.L. Spittlehouse, M.J. Goldstein, and R.J. Stathers have developed a soil water balance model, which assists foresters in evaluating soil moisture conditions (Spittlehouse and Goldstein 1989). It is a physically based model of seasonal soil moisture. The model uses site characteristics, climatic data and a hydrological budget to predict soil
moisture in the root zone. Using the model, along with a physiological assessment of planting stock, it is possible to determine the feasibility of planting proposed sites given climatic and soil conditions.

Another tool that may be useful in the quick assessment of plantation sites, for susceptibility to limiting soil moisture, is a multiple regression model with a number of independent variables based on site characteristics and a dependent variable being a relative drought index or seedling performance index. The advantages of such a model are that a limited amount of data is required and quick risk assessments are possible using available site characteristics.

For this research project, the soil water balance model was used in a retrospective study of the survival and performance of short-day treated interior spruce seedlings, operationally planted in the Prince George region under dry soil and climatic regimes in July and August, 1994. The model was used to reconstruct the soil moisture for the 1994 field season and seedlings were sampled for morphological parameters at the end of the 1995 growing season. Analysis attempted to correlate survival and performance with modelled soil moisture at the time of planting and during the following month. The model is based on physical relationships and initial model development included some field-testing. Extensive field testing of the model was undertaken for the 1995 field season to verify model performance for soils and climate in the Prince George region and to assess model sensitivity and limitations. Also, a multiple regression model, using site characteristics, was built to predict seedling performance.
The objectives of this research project were twofold. The first section’s objectives were to:

1. validate the soil water balance model for a range of conditions in the Prince George region.

2. determine and understand assumptions and limitations of the model.

3. investigate the sensitivity of the model to inputs.

The second sections objectives were to:

1. determine relationships between the survival and performance of short-day treated interior spruce seedlings, and the soil moisture regime for the first month following planting.

2. construct a multiple regression model to predict seedling performance from site characteristics.
2. The Soil Water Balance Model

2.1 Introduction

The objective here is to outline the model, discuss the assumptions that the model makes and its limitations, and investigate the sensitivity of the model to some key inputs. The model is described briefly and the reader is directed to Spittlehouse and Goldstein (1989) for a detailed discussion of the model.

2.2 History and Development of the Model

The model was originally developed and tested on mature Douglas-fir stands in the interior of British Columbia (Spittlehouse and Black 1981). The original model treated vegetation as a single layer over a single slab of soil. This version of the model has been successfully used to determine evapotranspiration of forested (Spittlehouse 1985, Giles et al. 1985) and grassland communities (Wallis et al. 1983, 1985) in British Columbia. The model was further developed and tested for application to a backlog clear-cut in the Interior of British Columbia (Spittlehouse and Goldstein 1989). This version of the model treats the soil profile as multilayered and the vegetation as single-layered. It is similar to the model described by Childs et al. (1987). The model has been used, along with long-term weather records, to assess the probability of the occurrence of various moisture regimes (Spittlehouse and Childs 1990). A spreadsheet version of the model was
suggested to be used as an educational tool (Spittlehouse and Stathers 1989). MacMillan
Bloedel adopted a version of the model as a tool for silvicultural management and
determination of planting windows.

M. J. Goldstein programmed the version of the model being used in this study in
1990 with contributions from R.J. Stathers. It is a DOS-based program written in Turbo
Pascal 6.0.

2.3 How the Model Works

2.3.1 Model Inputs

Many models for simulating root zone water budget have been documented in the
literature; however, few are appropriate for the limited information available in operational
forestry (Spittlehouse and Black 1984, Spittlehouse and Childs 1990). The soil water
budget model described by Spittlehouse and Goldstein (1989) requires a limited amount of
data.

The model requires climate data, site characteristics, and soil profile
characteristics. The following climate data are required on a daily basis for the period to
be modelled: solar radiation (measured or calculated using clear sky and sunshine hours),
air temperature (maximum, minimum, and average), and rainfall. The site characteristics
needed include latitude, elevation, slope, aspect, vegetation cover, vegetation class, alpha
(Priestley and Taylor 1972), and albedo. Soil water retention characteristics and physical
properties may be input as measured values or calculated values may be inferred from soil
texture, stone content, and soil organic matter content. Rooting density and depth are also
required. Initial conditions for soil moisture may be input as measured values of soil water
content or soil water potential, or the soil may be assumed to be initially at field capacity. Layer thickness and modelling depth also need to be chosen.

2.3.2 Model Components

The components of the model may be grouped into three main areas. There are two aboveground sections. The first deals with the calculation of evaporative demand ($E_{\text{max}}$), and the interception ($I$) and runoff ($R$) of rainfall ($P$). The second deals with the evaporation of intercepted rainfall and soil surface evaporation ($E_{\text{soil}}$). The belowground section calculates the redistribution of water within and the drainage ($D$) of water from the root zone and the uptake of water by vegetation ($Q$). The model considers the aboveground component of the site as a single layer and the belowground is considered to be multilayered.

2.3.2.1 Evaporative Demand, Interception, and Runoff

Evaporative demand, interception, and runoff are calculated on a 24-hour interval. The evaporative demand of the atmosphere or the energy-limited evapotranspiration is calculated following Priestley and Taylor (1972):

$$E_{\text{max}} = \alpha \left( \frac{s}{(s + \gamma) L \rho_w} \right) R_n$$

where $\alpha$ is an empirically determined constant, $s$, $\gamma$, and $L$ are the slope of the saturated pressure curve, the psychrometric constant, and the latent heat of the vaporisation of water, respectively, calculated based on the mean daily temperature, $\rho_w$ is the density of water, and $R_n$ is the calculated 24 hour net radiation. $R_n$ is calculated using solar
irradiance, surface reflectance, and the air temperature (Spittlehouse and Black 1981b, Spittlehouse 1985).

Rainfall interception is calculated using (Spittlehouse and Black, 1984)

\[ I = 0.08 \text{ LAI} \ P^{0.6} \]  

(2)

where LAI is the leaf area index (m² leaf per m² ground) and P is daily rainfall (mm d⁻¹).

Runoff is defined as any rainfall that at the end of the 24-hr interval has not been intercepted or added to the top soil layer (this includes evaporation).

2.3.2.2 Evaporation of intercepted rainfall and soil surface evaporation

Intercepted rainfall is assumed to evaporate at the energy-limited rate (Calder 1979, Wallis et al. 1983, McNaughton and Jarvis 1983). The value of \( E_{\text{max}} \) is reduced by I prior to any other calculations taking place. Evapotranspiration is considered to be the lesser of energy- and soil-limited rates (Spittlehouse and Black 1981b, 1984, Spittlehouse 1985).

Water is extracted from the surface layer by roots and surface evaporation. The soil limited surface evaporation rate \( E_{\text{s_l}} \) is calculated using (Rowse and Stone, 1978)

\[ E_{\text{s_l}} = k \ (\Psi_s - \Psi_a)/(0.5Z) \]  

(3)

where k is the hydraulic conductivity (mm d⁻¹) dependent on the water potential of the first layer (\( \Psi_s \), mm water), \( \Psi_a \) is the soil's air dry water potential, and Z is the thickness (mm) of the layer (Spittlehouse and Goldstein, 1989). The movement of water as vapour flow is accounted for by not further decreasing k once the water potential reaches -0.6 MPa. Surface mulching is assumed to occur over the depth of the whole layer and thus water
flow is estimated at a depth of 0.5 $Z$ rather than at the surface. The actual surface evaporation rate is the lesser of the energy-limited or soil-limited rates. For the energy limited surface evaporation rate, $R_n$ is calculated using Beers Law and is dependent on the LAI.

### 2.3.2.3 The Below-ground Component

The below-ground component of the soil water balance model deals with each layer individually. The water balance equation for the surface layer is

$$W_{1,i} = W_{1,i-1} + (P-I)_i - E_{\text{soil},i} - D_{1,i} - Q_{1,i} - R_i$$  \hspace{1cm} (4)

and for the other layers is

$$W_{z,i} = W_{z,i-1} - Q_{z,i} + D_{z-1,i} - D_{z,i}$$  \hspace{1cm} (5)

$W_{z,i}$ is the water content (mm) of layer $z$ at the end of the time interval $i$, $P$ is rainfall in mm, $I$ is intercepted rainfall, $E_{\text{soil}}$ is evaporation from the soil surface, $D_{z,i}$ is drainage out of the bottom of layer $z$ during time interval $i$, $Q$ is the uptake of water from a layer by the vegetation (mm), and $R$ is surface runoff (mm). The actual surface evaporation rate ($E_{\text{soil}}$) is the lesser of $E_{\text{max}}$ and $E_{\text{soil}}$. Equations 4 and 5 are solved simultaneously for each layer at each time step. Layer thickness and length of intervals are chosen input variables.

The soil limited extraction of water by roots for a layer ($E_{pS_z}$ mm d$^{-1}$) depends on the soil water potential of the layer, the soil hydraulic properties, and the amount of roots present (Taylor and Klepper 1975, Rowse et al. 1978, Federer 1979, Spittlehouse and Goldstein 1989) and is calculated as:

$$E_{pS_z} = Z \cdot L \cdot (\Psi_{S_z} - \Psi_p)/(R_{S_z} + R_p)$$  \hspace{1cm} (6)
where $L$ is the rooting density (mm mm$^{-3}$), $\Psi_p$ is plant water potential (mm water), $R_S$ and $R_p$ are soil and plant resistances to water flow (mm d$^{-1}$). The calculation of soil resistance is based on Gardner’s model (1960):

$$R_S = \frac{\ln(1/r_r^2 \pi L_r)}{4\pi k_z} \tag{7}$$

where $k$ is the hydraulic conductivity of the soil at the soil water potential of the layer and $r_r$ is the root radius. $R_p$ is considered to be dependent on root resistance and hydraulic conductivity. Xylem resistance is not considered and is thought to be negligible.

The actual amount of water extracted from a layer ($Q_z$) is the lesser of $[(E_{maxV}/E_{pS, total}) - E_{pS, z}]$ and $E_{pS, z}$. $E_{maxV}$ is calculated by the same equation as $E_{max}$, but $R_m$ is reduced by the amount reaching the soil surface (Spittlehouse and Goldstein 1989). $E_{pS, total}$ is the value of $E_{pS}$ for each layer summed over the root zone.

Drainage in between layers is calculated according to Darcian flow:

$$D_z = -k_z(\Psi_{sz} - \Psi_{sz+1} + 1)/Z \tag{8}$$

where $k$ is the hydraulic conductivity of the soil at the average soil water potential of both layers and $Z$ is the distance along the axis of flow. Hydraulic conductivity and soil water retention follow Campbell (1974, 1985). Campbell’s equation for hydraulic conductivity for unsaturated soils is sufficient when used with a reliable value for saturated hydraulic conductivity ($k_{sat}$):

$$k = k_{sat} (\Theta/\Theta_{sat})^{2b+2+p} \tag{9}$$

where $\Theta$ is volumetric soil water content, $p$ is sometimes assumed to equal 1 and $b$ is given by
The Soil Water Balance Model

\[ b = -\ln\left(\frac{\Psi_m}{\Psi_{AEV}}\right)/\ln \left(\Theta/\Theta_{sat}\right) \]  

(10)

\( \Psi_m \) and \( \Theta \) correspond to \( k \); \( \Psi_{AEV} \) is the air entry value of \( \Psi \); \( \Theta_{sat} \) is \( \Theta \) at saturation. Soil water retention characteristics are based on Campbell’s relationship:

\[ \Psi = \Psi_{AEV} \left(\frac{\Theta}{\Theta_{sat}}\right)^b \]  

(11)

where \( b \) is the same as above.

2.3.3 Model Outputs

The output section provides records of the water balance for each day including drainage, precipitation, evapotranspiration, deficit, runoff, and storage. The soil water potential, soil water content and maximum and minimum temperatures are outputted for the surface, as well as the 10-, 20-, and 50-cm soil depths. The output is given in an ASCII file that is importable into a spreadsheet. The output also includes the following indexes which influence plant growth: air temperature, soil temperature, soil moisture and solar radiation.

2.4 Limitations of the model.

Any model has limitations and certain assumptions that must be understood by the user. There are a number of sources that lead to errors in the model output. Inaccuracies with model input variables for the particular site may lead to errors. The proximity of the site to climate stations, and how well these measured conditions, especially rainfall, are reflected at the site, also determine the accuracy of the model performance.
A fundamental assumption of the model is that site and soil characteristics are homogenous. However, in reality this is not the case. Tremendous variability in site surface characteristics and soil properties may exist from microsite to microsite. Also, the model does not recharge the soil profile from a water table. Thus, one is limited to sites that do not have a water table within a metre or two of the soil surface.

Algorithms in the model are based on a number of soil-plant-atmosphere relationships, which are not all clearly understood. To a certain extent, inaccuracies caused by the model itself are difficult to quantify.

2.5 Model Sensitivity to Input Variables

To fully understand model limitations, an understanding of the models sensitivity to some key input variables is necessary. The following input variables were considered: LAI, rooting density, albedo, Priestley - Taylor alpha and soil physical properties.

LAI becomes an increasingly significant player as it increases above 0.5 m²/m². In day-to-day real-life events, it is especially a key player if rainfall events are small and short in duration. Rainfall is intercepted by the leaf area and (in small, brief events) is evaporated from the leaf surface with minimal rainfall reaching the soil surface. The model, however, considers rainfall on a daily basis and not on an event basis; it subtracts the amount of water evaporated from the leaf area that particular day from the total input of precipitation into the system. Thus, if LAI is large enough and/or precipitation is small enough the impact LAI may have on modelled values is significant.

Sensitivity analyses were conducted using climate data and soil profile characteristics for one of the sites in the validation study. The site chosen was a clearcut
located approximately 50 km southwest of Prince George along the Gregg Creek Forest Service Rd. The site has an elevation of 850 m, a slope of 20% and a south-southeast aspect. The soil is a Humo-Ferric Podzol with a loamy sand texture having a 30% coarse fragment content by volume. The vegetation cover is moderate, having a LAI (one-sided) of 0.76 m² leaf area per m² ground. The methods for running the model are the same as the ones described in section 3.3.2. The soil profile and physical properties characteristics used to run the model are described in Tables 3.1 and 3.2 (site 8). Climate data are summarised in Figures 3.4 to 3.6. Sensitivity analysis were run for the following inputs: root density, water retention characteristics, Priestley-Taylor alpha and albedo.

The sensitivity of the model to rooting density is much greater than that of LAI. Although LAI and rooting density are interrelated in real life, they are considered separately in the model. Rooting density is treated analogous to a piping system with a number of parallel resistances from the various soil layers and thus the greater the rooting density the greater the amount of water evapotranspired, given sufficient solar radiation to drive it. At the Gregg Creek site, with a moderate baseline rooting density, a 50% increase in rooting density decreased soil water content at the dry end by approximately 20% (Figure 2.1).

The effects of a 20% decrease in bulk density, air entry value, albedo and the Priestley-Taylor alpha were minimal. Significant decreases in soil water content were observed with a 20% decrease in porosity and the Campbell “b” (figure 2.2 & 2.3).
Figure 2.1 Trend of seasonal soil water content for the top 20 cm of the soil at site 8, comparing between the actual rooting density and a 50% increase in rooting density.

Figure 2.2. Trend of seasonal soil water content for the top 20 cm of the soil at site 8, comparing between the calculated Campbell b and a 20% decrease in Campbell b.
Figure 2.3. Trend of seasonal soil water content for the top 20 cm of the soil at site 8, comparing between the calculated porosity and a 20% decrease in porosity.

2.6 Conclusions

The model described has potential to be used in operational forestry as a tool in managing plantation sites, which are susceptible to drought. One of the advantages of the model is that limited data are required. However, to effectively use the model it is necessary to understand assumptions and limitations of the model. Further model testing is necessary as the model was developed based on only a few sites.
3. Validation of the Soil Water Balance Model

3.1 Introduction

This chapter describes a validation of the soil water balance model in the Prince George region. The validation consisted of a comparison of modelled values of soil moisture against measured ones across a range of sites. Validation of the model will assist in determining how accurately the model performs under a range of climatic conditions (SBSmk1 and SBSdw3 subzones), soil textures, leaf area indexes, and radiation loading indexes. The purpose here was not to comprehensively test all the combinations of the mentioned parameters, but to test the model extensively enough to determine its reliability in a broad range of site characteristics and conditions.

3.2 Materials and methods

Validation of the model was accomplished by tracking soil moisture with the model, at ten sites, for the 1995 growing season and comparing these simulated values against actual field measurements of soil moisture. Bi-weekly measurements of soil moisture were taken using Time Domain Reflectometry (TDR). The TDR instrument used was the Environmental Sensors Moisture Point Model MP-917. There were 6 TDR probes per site located approximately 20 m apart along a line transect. In addition to the TDR measurements, soil water content was determined gravimetrically twice during the season.
3.2.1 Sites

3.2.1.1 Site Locations

Two geographical areas were chosen to locate the validation sites. In an attempt to get varying climatic conditions, two distinct biogeoclimatic subzones were chosen: the SBSmk1 subzone (Mossvale Moist Cool Sub-Boreal Spruce) and the SBSdw3 subzone (Stuart Dry Warm Sub-Boreal Spruce Variant) (DeLong et al. 1993). The sites in the SBSmk1 subzone were located along the Caine Creek Forest Service Road approximately 60 km north of Prince George. The sites in the SBSdw3 were located along the Gregg Creek Forest Service Road approximately 50 km southwest of Prince George. The sites were chosen so as to represent a broad spectrum of soil textures, vegetation cover, and slope and aspect. Another criterion in determining site location was proximity to existing climate stations.

3.2.1.2 Site descriptions

Site and soil profile descriptions are documented in Table 3.1 and Table 3.2. Sites 1 through 3 were chosen to reflect varying leaf area indexes. The sites are located at Caine Creek at an elevation of 900 m with a 10% slope to the northwest. They are being used as part of a herbicide timing and rate trial, and thus had varying levels of vegetation cover as a result of different intensities of herbicide sprayed the year before. The soil is a Humo-Ferric Podzol with a loamy texture containing approximately 20% coarse fragments by volume. Faint mottling at depth covering approximately 20% of the area suggested the presence of a water table on occasion.
Sites 4 and 5 give a comparison of the effect of slope and aspect. They are located on an east-west running drumlin on the same cutblock as sites 1-3. Site 4 is located on the north - northwest facing slope and site 5 is located on the south - southeast facing slope. Both sites have a slope of 45 %. LAI is considerably greater on the north-facing slope. The TDR probes were placed along transects running mid-slope. The soil is a Humo-Ferric Podzol with a loamy texture and approximately 25% coarse fragments by volume.

Sites 6 and 7 are located in the Gregg Creek area at an elevation of 800 m. This location was chosen due its fine textured lacustrine soil. The soil is a Gray Luvisol with a silty clay loam texture containing no coarse fragments. The sites having been recently logged, had very little vegetation. Both sites are located in a flat area of the clearcut. The forest floor was scraped away in 4 m² patches surrounding each TDR probe for site 7. The forest floor was left intact for site 6.

Site 8, also located in the Gregg Creek area, has an elevation of 850 m, a slope of 20%, and has a south-southeast aspect. This location was chosen due its glacio-fluvial coarse textured soil. The soil is a Humo-Ferric Podzol with a loamy sand texture having a 30% coarse fragment content by volume. The vegetation cover is moderate. Site 8 was disc trenched so the forest floor was disturbed. However, TDR probes were located in spots where the forest floor was intact.

Sites 9 and 10 are located on the same cutblock in the Gregg Creek area at an elevation of 950 m. The parent material is a glacial till. Site 9 is flat. The soil is a Humo-Ferric Podzol, having a depth of only 30 cm on top of the compact glacial till. The texture is loam and the soil has a 30 % coarse fragment content by volume. Site 10 is northwest
facing having a slope of 55%. The soil is a Regosol with a clay loam texture having a coarse fragment content of 45%. At both sites, the forest floor was disturbed during site preparation. Site 9 was disc trenched and site 10 was bladed in spots. However, at both sites the TDR probes were located in sites with the forest floor intact.

Table 3-1: Site Characteristics

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Table 3-2: Soil Description and Physical Properties

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<td>6.1</td>
<td>0.19</td>
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### 3.2.1.3 Determining Leaf Area Index

The leaf area index (m² leaf area/ m² ground) was estimated during the last two weeks in July using the Li-Cor LAI-2000 Plant Canopy Analyzer (Welles and Norman...
Measurements at each TDR probe location were made. The average LAI of the six readings per site was used in the above site description and soil moisture simulation. The reliability of using the LAI-2000 for LAI measurements in such a manner was found to be adequate using the Delta T imaging system. A sensitivity analysis, for each site, using the soil water balance model and the range of variation in LAI given by the LAI-2000 measurements had little effect on soil moisture.

3.2.1.4 Soil Descriptions and Physical Properties Analysis

The soils for each site were classified and described following Luttmerding et al. (1990). Core samples for soil physical properties analysis were taken at each pit site at the following depths: 5 cm, 15 cm, and 50-60 cm. The following properties were determined: soil particle size and texture, saturated hydraulic conductivity, bulk density, particle density, volumetric water retention characteristics during dewatering, total porosity, aeration porosity at 5 J/Kg, Campbell b, and air entry value. The analysis of the above mentioned properties was conducted by Soilcon Laboratories, Richmond, B.C.

3.2.2 Climate Data

Weather data for 1995 used in the model, are illustrated in Figures 3.1 to 3.6. Temperature and Solar radiation at Caine Creek and Gregg Creek were collected by spot reading the sensors every 10 s using a Campbell Scientific 21X datalogger. The sensors used were the Campbell Scientific 107 air temperature probe (thermistor) and the Li-Cor LI200s pyranometer. Precipitation data and any missing temperature data were provided by adjacent fire weather stations (Northwood Pulp and Timber Inc. and Rustad Brothers Ltd.). At these fire weather stations, daily precipitation was measured using a tipping rain
gauge bucket and temperature readings were spot read hourly. Missing solar radiation
data was taken from Prince George Airport. Overall, the 1995 growing season was quite
wet, with the driest periods occurring in early June and mid September.
Figure 3.1. Daily maximum and minimum temperatures at Caine Creek, 1995.

Figure 3.2. Daily rainfall at Caine Creek, 1995.

Figure 3.3. Daily solar radiation at Caine Creek, 1995.
Validation of the Soil Water Balance Model

Gregg Creek Climate

![Graph showing daily temperature variation at Gregg Creek, 1995.]

Figure 3.4. Daily maximum and minimum temperature at Gregg Creek, 1995.

![Graph showing daily precipitation at Gregg Creek, 1995.]

Figure 3.5. Daily precipitation at Gregg Creek, 1995.

![Graph showing daily solar radiation at Gregg Creek, 1995.]

Figure 3.6 Daily solar radiation at Gregg Creek, 1995.
3.2.3 Measuring Soil Moisture

3.2.3.1 Time Domain Reflectometry

Mean soil volumetric water content for the top 20 cm of mineral soil was measured using TDR. Three prong, single diode probes, 20 cm in length, were constructed following Hook et al. (1992). A random sample of 12 out of a total of 80 probes showed little variation in readings during laboratory testing using dry and wet sands. For each of the sites, calibrations were conducted on oven-dried samples of the soils (Hook et al. 1992).

Six probes were placed along a transect approximately 15 to 20 m apart at each site, and left in place for the duration of the field season. They were oriented vertically with the complete 20 cm of the stainless steel rods in mineral soil. The number of replications at each site was limited to six, due to cost and time involved in probe construction. Measurements were initially planned to be taken once a week; however, approximately bi-weekly measurements were made because changes in soil moisture were slow. The first TDR measurements were taken on June 6th and the last ones were taken on September 19th.

3.2.3.2 Gravimetric Measurements

Gravimetric soil moisture measurements were taken at each probe location for all of the sites. Two samples were taken on both June 25-27 and September 11-12. One of the samples included all coarse fragments from a sample 20 cm in depth with vertical walls. The second sample also spanned the 20 cm depth but did not include all coarse
fragments. The samples were weighed, oven dried, and passed through a 2 mm sieve. Coarse fragment content (for sample a) and soil gravimetric water content were determined for the samples. These values were then converted to volumetric values. Prior to doing these calculations the bulk density at each site was adjusted for the coarse fragment content at each probe. The mean value of coarse fragment content from the two sampling dates was used. Mean coarse fragment particle density was determined to be 2512 kg/m³ for the study sites. This was based on 12 random samples.

3.3 Results and Discussion

3.3.1 Comparing TDR and Gravimetric soil water content measurements.

The mean values of soil volumetric water content calculated from gravimetric measurements are for the most part within 0.05 m³/m³ of the mean values obtained using TDR. This is not unreasonable considering the heterogeneity of soil moisture within a clearcut and errors introduced by both methods. With exception of the June 28-29 measurement at site 9, the values obtained gravimetrically do not appear to be significantly different (i.e. standard error bars overlap). The significant difference between the two values at site 9, may in part be explained by increased coarse fragment content. There is a consistent pattern that at all sites, both gravimetric means are either above or below the values obtained using TDR. At sites 6 and 7, gravimetric values are less than TDR values.

Gravimetric determination of soil water content may have the following errors associated with it: weighing errors, sampling depth inconsistencies, and the calculation to a volumetric water content uses assumed bulk densities and particle densities. Careful monitoring of weighing processes should have eliminated weighing errors. However, bulk
densities and particle densities were based on one core sample for the site and thus the calculated volumetric water content is not accurate. Bulk densities for the bulk gravimetric sample were adjusted according to coarse fragment content, which should have alleviated the problem to a certain extent.

Errors introduced by TDR may include the following: site disruption when inserting the rods, limited contact between the rod and soil (pore spaces), and large coarse fragments adjacent to the rod. The intercept for the dry end TDR-theta calibration line determined for each of the soils is inaccurate due to change in soil structure by excavation and oven drying.

3.3.2 Modeling Soil Moisture

The seasonal trend in soil moisture at each site was modelled using the soil water balance model. Model inputs include climate data (daily precipitation, solar radiation, and maximum and minimum temperatures), site characteristics (slope, aspect, elevation, latitude, albedo, Priestley-Taylor alpha and LAI, which are summarised in Tables 3.1 and 3.2), and soil profile characteristics (soil texture, coarse fragment content by volume, rooting density, saturated hydraulic conductivity, bulk density, porosity, Campbell b, and the air entry value which are summarised in Table 3.2).

The model was run for all sites for the duration of the period between May 1 and September 18. Initial conditions were set at –0.03 MPa (inferred to be approximately field capacity) for sites 4, 5, 8, 9 and 10. Initial conditions for the remaining sites were assumed to be at 0 MPa as they were noted as being saturated often during the growing season.
Measured values of bulk density and subsequently porosity, air entry value and the Campbell b, were corrected for the coarse fragment content of the bulk soil. The core samples do not provide an accurate bulk density because it is taken in between the large coarse fragments. Gravimetric coarse fragment contents were compared for the core sample and a bulk sample of the soil, and where necessary bulk densities were corrected. Bulk density was recalculated using the coarse fragment content determined gravimetrically. An average particle density was determined for twelve samples using a water displacement method. It was assumed that a change in bulk density would also affect other physical properties. Porosity was recalculated using the new bulk density. The Campbell b was increased or decreased inverse to and by the proportion the porosity increased or decreased. The air entry value was adjusted accordingly: either decreased or increased by the same proportion as porosity. The physical property values presented in Table 3.2 are the corrected values and were used for modelling purposes. The model requires physical properties to be input for the forest floor. These values were provided by M.J. Goldstein of Soilcon Laboratories, Richmond, B.C., and are based on analysis of samples from the Prince George region. The physical properties values used for the forest floor for all sites are the same. They are included for site 1 in Table 3.2.

Rooting abundance for fine and very fine roots was determined by standard soil description methodology (Luttmerding et al. 1990). Rooting abundance was evaluated at the height of vegetation cover and in an area that had as close to 100 % cover as possible. An assumption was made that only the fine and very fine roots are able to draw water out of the soil. Based on Nnyamah et al. (1978) the following root densities were attributed to
the rooting abundance categories: abundant = 0.8 cm/cm³, plentiful = 0.5 cm/cm³, and few = 0.1 cm/cm³. These values were then multiplied by the average percent cover of vegetation for each particular site to come up with the effective rooting density. It was assumed that percent cover of vegetation would reflect rooting density.

Effective rooting density values and measured LAI values are assumed to be maximum seasonal values. Modelling was done in steps, simulating the seasonal trend of LAI and associated rooting density. Values for pre-maximum LAI were determined using observations for early season values and the relationship determined by DeLong (1991). DeLong made observations of light interception development over the growing season by early seral vegetation in clearcuts in the Prince George Forest Region. Since there is a direct correlation between light interception and LAI, these trends were used. From these data the following generalisations of seasonal LAI and rooting density were made by a percentage of the maximum at the following dates: May 1 = 10%, May 26 = 30%, June 14 = 50%, July 3 = 75%, and July 22 = 100%.

The Priestley-Taylor alpha was kept at 1.26 following Spittlehouse (1989), as determined for agricultural crops. Vegetation in recent clearcuts resembles agricultural crops to a certain extent. (The literature does not give any better values that could be used.) Albedo was kept at 0.2. A comparison of modelled net radiation (Rn) and measured net radiation at the Gregg Creek climate station suggests that this generalisation for albedo is good for most of the season (Figure 3.7). However, mid August and onwards the modelled net radiation drops off significantly compared to the measured. This is most likely due to a decreasing actual albedo as a result of surface roughness effect with
decreasing azimuth angle of the sun. The model, keeping albedo constant has the resulting lower $R_n$. This is not conclusive as the net radiometer was most likely affected by heavy dewfalls, common during the late summer.

Figure 3.7. Daily measured and modelled net radiation at Gregg Creek, 1995.

3.3.3 Trends of Measured and Modeled Seasonal Soil Moisture

Comparisons of measured and modelled values of soil moisture are based on soil water content rather than soil water potential. The model outputs both; however, TDR measures soil moisture on a volumetric basis. Converting measured values to soil water potentials may introduce additional errors. The two lowest soil water contents at all the sites occurred in early June and mid September, reflecting the low amounts of precipitation for approximately a month prior. Site numbers 1, 4, 5, 8, and 10 had lowest soil water contents in early June (Figures 3.8 to 3.17) the remaining sites had lowest soil
water contents in mid September. Note that all error bars on the following figures are standard errors of the mean. Differences between measured and modelled values were evaluated visually. Overlap, between modelled and measured values, by twice the range of the error bars was considered not to be significantly different.

Sites 1 to 3

Sites 1 through 3 had increasing LAI's of 0.29, 1.06, and 3.04 m²/m² respectively. It was anticipated that site 1 would be the wettest and site 3 would be the driest due to the influence of LAI. However, this was not the case. Site 2 is considerably wetter than the other two. Site 3 is only slightly drier than site 1 for most of the season. The site does not meet the model's assumption of no water table near the surface. The predominant problem may be a perched water table, which would mean that the use of the model for this site would be inappropriate. The sites being adjacent, it was assumed that soil profile characteristics and drainage would be the same. However, due to the direction of the slope and its slightly concave nature, the results are distorted. The discrepancy was most likely exacerbated by the wet summer. The high amounts of precipitation may have negated the expected difference in soil moisture conditions due to leaf area. Thus, there is limited value in the comparison of modelled to measured values for sites 1, 2 & 3. Figures 3.8 to 3.10 illustrate the modelled and measured trends.
Validation of the Soil Water Balance Model

Figure 3.8. Trend of seasonal soil water content at site 1.

Figure 3.9. Trend of seasonal soil moisture at site 2.
Validation of the Soil Water Balance Model

Figure 3.10. Trend of seasonal soil moisture at site 3.
Sites 4 and 5

Seasonal trends of soil moisture at sites 4 and 5 are similar (Figures 3.11 and 3.12). Site 5, the south-facing slope, is on average 0.03 to 0.05 m$^3$/m$^3$ drier. Measured means for the two sites appear not to be significantly different. It was expected that the difference between the two sites would be greater than this. Vegetation cover can best explain the lack of a significant difference between the two sites. Site 4 has a considerably greater LAI at 2.69 than site 5 at 1.74. This greater LAI results in an increase in evapotranspiration and canopy interception, resulting in water loss in almost the same proportions as the south-facing slope.

Modelled values for both sites follow the trend of the measured values quite well, and do not appear significantly different from the measured for most of the season. The only significantly different values are the ones at the end of the season in September. At site 4 the modelled is greater than the measured and at site 5 the modelled is less than the measured. The model responding to the changing angle of the sun and consequent difference of $R_n$ driving the evapotranspiration may explain this difference.
Validation of the Soil Water Balance Model

Figure 3.11. Trend of seasonal soil moisture at site 4.

Figure 3.12. Trend of seasonal soil moisture at site 5.
Sites 6 and 7

Sites 6 and 7 have the greatest soil water contents through the season due to the fine textured soil (SiCL). Measured values of soil water content are significantly different between site 6 and site 7 at the dry end, with site 7 having lower values (Figure 3.13 and 3.14). At the wet end or near saturation, the values do not appear to be significantly different. Site 7 has lower values of soil water content in general. This difference is most likely due to the mulching effect of the intact forest floor in site 6, which presumably decreased surface evaporation. The measured values for site 7 have greater within-site variability, indicated by the broader range of their standard errors.

Modelled and measured values of soil water content for site 6 and site 7 are significantly different for most of the season. The difference between modelled and measured is greater for site 6. Modelled trends in soil water content follow the measured. The higher modelled water content at site 6 at saturation is due to the forest floors assumed high porosity. For the first 10 cm layer, the model averages the physical properties of the forest floor and the mineral soil. Thus, the mean soil water content over the 20 cm is much greater at saturation for site 6 than it is for site 7.

The discrepancy between measured and modelled values is thought to be primarily due to a limitation of the model. The model does not recharge soil layers from a water table below. The summer of 1995, being as wet as it was, resulted in a perched water table and subsequent higher soil water contents than what the model predicted for both of these sites.
Validation of the Soil Water Balance Model

Figure 3.13. Trend of seasonal soil moisture at site 6.

Figure 3.14. Trend of seasonal soil moisture at site 7.
Site 8

Site 8, on average, has the lowest soil water content out of all the sites (Figure 3.15). This was expected due to the coarse texture (loamy sand) and high coarse fragment content of the soil and the slightly south-facing slope. The fit between the modelled and the measured seasonal trend of soil moisture is very good. The greatest difference between modelled and measured occurs at the end of the season. However, this difference does not appear to be significant. The difference is partly explained by the fact that the LAI and rooting densities were assumed to be the maximum from July 22 onward. In reality, the

![Trend of seasonal soil water content at site 8.](image)

Figure 3.15. Trend of seasonal soil water content at site 8.
LAI and subsequent evapotranspiration declined from the end of August and onwards. A slightly better fit for the end of the season could be attained by running the model with lower LAI and rooting density September 1 and onwards.

Site 9 and 10

Measured and modelled values for site 10, a north-facing slope, are surprisingly close to those for site 9 with no slope (Figures 3.16 and 3.17). The north-facing slope was expected to have higher soil moisture due to lower evaporative demand. This apparent anomaly might be partly explained by the higher coarse fragment content of the soil at site 10.

At both sites there is a relatively good fit between the modelled and the measured seasonal trend of soil water content. However, there is at least one instance at both sites, where the modelled appears to be significantly different from the measured. At site 9, the August 13th and 24th, and September 10th values appear to be significantly different. At site 10, the August 24th value appears to be significantly different. Most of these discrepancies occur at the wet end of the soil water content, and do not pose problems in regards to the model predicting moisture stress for seedlings.
Validation of the Soil Water Balance Model

Figure 3.16. Trend of seasonal soil moisture at site 9.

Figure 3.17. Trend of seasonal soil moisture at site 10.
3.4 Conclusions

Overall, the model is able to predict soil moisture quite well as long as it is applied to sites where model assumptions are met. The model did not perform well on sites that had a perched water table. This was the case with sites 1, 2, 3, 6 and 7. These sites, under the wet climatic conditions that occurred during the summer of 1995, were not suitable sites for the validation study. Initially they seemed like good sites given the purpose of the study and their proximity to climate stations. The understanding gained of model assumptions and limitations through the process of the model validation would allow for selection of more appropriate sites.

For the remainder of the sites, the modelled trends of seasonal soil moisture appear not to be significantly different from the measured. The model performed the best at the dry end of soil water content occurring in early to mid June. It generally overestimated soil water content at the wet end (mid July to mid August).

September 1 and onwards, the model would overestimate soil water content on north-facing slopes and flat sites and underestimate soil water content on south-facing slopes. For north-facing slopes and flat sites this discrepancy can partially be explained by the drop in modelled $R_n$. Lower modelled than actual $R_n$ at the end of August and onwards would result in prediction of lower rates of evapotranspiration and subsequently greater soil water content.

For south-facing slopes, the angle of the sun is much closer to the incident angle and this problem does not occur. However, the underestimation of soil water content may partially be explained by the overestimation of LAI and effective rooting density for this
time of the season. For modelling purposes, LAI and rooting density were assumed to be at their maximum value from July 22 and onwards. However, in reality LAI and very likely effective rooting density decreased considerably at the end of August and onwards.

The model should be a good predictor of soil water content between early May and mid August. It performed exceptionally well at low soil water contents, however it is not known to what extent the model would diverge under extended droughts. Significant rain events may have acted as correcting factors in the 1995 season.
4. Seedling Performance Study

4.1 Introduction

The objective of the seedling performance study was to determine relationships between the survival and performance of short-day treated interior spruce seedlings, and the soil moisture regime for the first month following planting. This was accomplished by a retrospective study of sites planted in 1994 by Rustad Brothers and Company Ltd. in the Prince George region. The soil water balance model was used to reconstruct the soil moisture conditions using recorded climate data, field investigation of site characteristics, and known planting dates. Seedling survival and performance data were collected for each site. Analysis attempted to determine the relationship between seedling survival and performance and the soil water potential at the time of planting and the first four weeks following planting. A second objective was to construct a regression model to predict seedling performance by site characteristics.

4.2 Methods

4.2.1 Seedling and Site Selection

4.2.1.1 Seedling Stocktype and Age Selection (study #1, study #2)

Reconnaissance of sites planted by Rustad Brothers Ltd. in the summer of 1994 indicated that the seedling stocktype and age planted on the most diverse sites and over a broad time sequence was the Sx 415d 2+0, seedlot number 29160. Thus, this stocktype
was chosen for the main study (study 1). Sx 415b 1+0 , seedlot number 29160 as well, copper treated, were chosen for a sub-study (study 2) because of the range in survival.

4.2.1.2 Site Selection and Descriptions

Appropriate study sites were chosen from all sites planted with the above seedlings. Sites were chosen in an attempt to represent a range of soil parent material and textural characteristics, slope and aspect, vegetation cover and planting date. Study sites were limited to areas within blocks that were homogenous in slope and aspect. Fifteen sites were selected for study 1 and five for study 2. The sites were located in three main geographical areas: Weedon Lake, Summit Lake (Caine Creek) and Mt. Mackenzie. The Weedon Lake area is approximately 130 km north of Prince George in the SBSmk1 biogeoclimatic unit (DeLong et al. 1993). The Summit Lake area is approximately 40 km north of Prince George, also in the SBS mk1 biogeoclimatic unit (DeLong et al. 1993). The Mt. Mackenzie area is approximately 40 km southwest of Prince George in the SBS dw3 biogeoclimatic unit (DeLong et al. 1993).

The soils for each site were classified and described using an abbreviated form of standard methodology (Luttmerding et al. 1990). LAI was measured at each seedling as described in section 3.2.1.3 and a mean value of LAI was then used for modelling purposes. Soil physical properties were analysed (as described in section 3.2.1.4) for only a portion of the sites due to budget constraints. However, between the validation study and this seedling performance study, data were collected enabling physical properties to be attributed to soils from all the study sites. For sites where there was no physical properties analysis, the soils were matched to the closest texture of a soil where physical properties
were evaluated, and these physical properties were then used for modelling purposes.

Physical properties were adjusted according to coarse fragment content, as described in section 3.3.2. Coarse fragment content was determined for the soils by gravimetric bulk samples of the soils. Textures for the soils for the validation study were determined by particle size analysis (described in section 3.2.1.4) and these textures were then used for calibration of hand texturing for all other soils. Tables 4.1 and 4.2 contain all site descriptions and physical properties for all the sites used in the seedling performance study.

Table 4-1: Site Characteristics

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¹Planting date is approximate date of when planting began on the site.
### Table 4-2: Soil Description and Physical Properties

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1. n refers to the number of seedlings sampled for that site. 2. m refers to maximum rooting depth in cm.
Seedling Performance Study

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4.2.2 Seedling Sampling

4.2.2.1 Sampling Method

Seedlings were chosen along a line transect on an appropriate compass bearing, in 10 m intervals. Seedlings that fell on microsites that were extreme, such as depressions, mounds and burned windrows, were rejected. Seedlings that were dead were accepted, as determining percent survival was part of the study. Each seedling was staked and flagged so that it could be relocated later in the summer. Target number of seedlings was 30 to 60; however, there were a few sites where it was not possible to attain this target. The number of seedlings sampled within each site is indicated in Table 4.2.

4.2.2.2 Measuring Performance Variables

Seedlings within each site were evaluated according to survival and performance. Percent survival was determined by the mortality rate within each site. Seedling performance was evaluated at the end of the 1995 growing season by taking measurements of the following: calliper (mm), leader growth (cm), seedling height (cm), and vigour. Stem diameter was assessed slightly above the root collar using a standard
mechanical micrometer. Seedling vigour was assessed subjectively as ranging from 0 to 4: 
0 = dead, 1 = moribund, 2 = poor, 3 = moderate, and 4 = good.

4.2.3 Root Growth Study

Root growth may be the best indicator of seedling performance. It was not possible, due to time and budget constraints, to assess root growth in all of the seedlings to be sampled. A subset of the seedlings was sampled for root growth and then an attempt was made to determine a relationship between root growth and seedling morphological measurements, which could be applied to the rest of the seedlings. The root study was limited to study 1. Six seedlings from each site in study 1 were selected randomly for a total of 90 seedlings. The roots were excavated within a cube of soil with dimensions of 30cm x 30cm x 30cm with the seedling in the centre. Any roots that were protruding beyond this point were not included. This approach was used as it considerably decreased excavation time in comparison to whole root excavation. The roots were carefully washed and root count, dry mass of the plug (with all the soil washed off) and the dry mass of the roots extruding from the plug were determined.

4.2.4 Climate Data

Climate data for modelling purposes were attained from fire weather stations located within each of the three main geographical areas. The only solar radiation data available was from AES at the Prince George airport. The climate data from the Prince George airport was also used to fill holes for any missing data from the three fire weather stations. This was especially a problem early in the season, as the fire weather stations
were not activated until later in the spring. The climate data from the Prince George airport are summarised in Figures 4.1 to 4.3.

Figure 4.1. Daily maximum and minimum air temperatures at the Prince George Airport, 1994.

Figure 4.2. Daily rainfall at the Prince George Airport, 1994.

Figure 4.3. Daily solar radiation at the Prince George Airport, 1994.
4.2.5 Running the Model

The model was run for the entire season (May 1 to September 15) for each of the sites. The same approach as described in section 3.3.2 was used. The 1994 climate data was used and the site and physical properties characteristics summarised in Tables 4.1 and 4.2 were used for modelling purposes. For the purposes of the seedling performance study, it was not necessary to adjust for LAI and rooting density, as the time of interest is early July onwards. LAI and rooting should have reached its maximum for the season. Even if the model had diverged from reality in the spring, any significant drying or wetting period would have restored the model to reality. Furthermore, if the model were to be used on an operational basis, time would not have been taken to adjust these values.

4.3 Results and Discussion

4.3.1 Study #1- Sx415d 2+0

4.3.1.1 Seedling Root Growth

The best predictor of a root variable based on above ground measurements (in terms of the strength of the relationship and its applicability in determining overall seedling performance) was found to involve a volume surrogate (caliper^2 x height) as the independent variable and dry root mass as the dependent variable, r^2 = 0.50 (see Figure 4.4). The root mass used was that of the roots protruding from the plug. A number of other relationships were tried, following are some of the stronger relationships: total root mass and calliper, r^2 = 0.36; plug mass and calliper, r^2 = 0.37; and root count and calliper, r^2 = 0.21. A number of multiple regression were also tried, the strongest relationship was
found where the independent variable was total root mass and the dependent variables being calliper and root count, $r^2 = 0.54$.

Figure 4.4. Relationship of root biomass to seedling calliper and height.

4.3.1.2 Seedling Performance and Modelled Soil Water Potential

Several methods were considered in the analysis of seedling performance in respect to soil moisture during the first four weeks following planting. The strategy was to build a simple linear regression model between soil moisture as the independent variable and seedling performance as the dependent variable.

To quantify soil moisture, the modelled daily values of soil water potential were used. The mean of modelled $\Psi_m$ (MPa) for 30 days following planting was calculated for each site. Choosing a seedling performance variable was somewhat more complicated. The
most successful relationship, in regards to \( r^2 \) value, was a seedling performance index (PI) calculated as follows:

\[
\text{PI} = \frac{\text{HCVS}}{100}
\]

where \( H \) is the site mean seedling height (cm), \( C \) is the site mean seedling root collar diameter (mm), \( V \) is the site mean seedling vigour (1-4), and \( S \) is the percent of seedling survival at that site. The relationship between this seedling performance index and mean \( \Psi_m \) for 30 days following planting is quite strong. Excluding the values of three sites which were determined to be outliers, the \( r^2 = 0.75 \) (Figure 4.5).

![Figure 4.5. Relationship of seedling performance to soil moisture.](image)

The outliers include sites 5, 15, and 18. Performance was very high at sites 5 and 18, PI = 9 and 10.5 respectively, even though mean \( \Psi_m \) was very low, - 0.95 and - 0.98 M.
Pa. This is most likely a result of a combination of the following. Both sites are on south facing slopes with relatively high LAI's - nearing 2 m²/m². The model may be overestimating evapotranspiration on these sites. A second factor may be the advantageous effect of the high leaf area of competing vegetation on seedling microclimate. A higher LAI would lead to higher humidity and decreased atmospheric demand on the seedlings. Interior spruce is shade tolerant and thus light levels under competing vegetation would not necessarily be limiting. Site 15 is a slightly north facing slope with a LAI of 1.26 m²/m². Reasons for such high performance, PI = 15, could involve confounding issues such as stock condition and a more favourable level of planting stress. Planting stress can result from various factors including the care and transportation of seedlings, on site storage of seedlings prior to out planting, and time elapsed between lifting and planting. When including site 15 in the analysis, the r² value was 0.47, and the equation for the regression line is as follows: y=11.41+8.75x.

In the seedling performance index described above, vigour plays a significant role. Vigour, as a performance variable on its own has a r² value of 0.65. The use of this variable in building a performance index is justified because it reflects an overall condition of the seedlings at all the sites.

Other performance indexes developed include:

1. the product of root collar diameter, vigour, height increment, and percent survival, r² = 0.49.

2. the product of vigour, volume (height x root collar diameter) and percent survival, r² = 0.65.
Initially it was hoped that a morphological variable or a combination of variables would provide a strong relationship between seedling performance and soil moisture. The following are results of the best relationships found: mean $\Psi_m$ and height x calliper, $r^2 = 0.44$, mean $\Psi_m$ and height increment, $r^2 = 0.28$, mean $\Psi_m$ and calliper$^2$ x height, $r^2 = 0.24$.

4.3.2 Study # 2 - Sx 415b 1+0, copper treated

This sub-study was included because a range of seedling survival was noted during initial reconnaissance of sites and stocktypes. The objective was to look for trends in seedling survival with soil moisture. Soil moisture was modelled as described in section 3.3.2 and mean $\Psi_m$ was calculated as in section 4.3.1.2. Figure 4.6 illustrates the trend in soil water potential for July and August for the five sites. Figure 4.7 shows the percent survival with the modelled mean of the first 30 days following planting. Percent survival has a strong relationship to mean $\Psi_m$, $r^2 = 0.89$, over the range of observations, but this would not be expected at higher $\Psi_m$. Survival decreases substantially below a mean $\Psi_m$ of $-0.2$ MPa.
Figure 4.6. Trend of soil water potential for July and August 1994, at Study #2 sites.

Figure 4.7. Percent survival in relation to soil moisture.
4.4 Predicting Seedling Performance Using Site Characteristics

The objective here is to construct a multiple regression model to predict seedling performance by site characteristics. A number of dependent variables and combinations of independent variables were attempted. Using the seedling performance index developed in section 4.3.1.2 as the dependent variable did not lead to any significant results nor did the use of seedling morphological parameters. The most successful model uses survival as the dependent variable ($r^2=0.64$). Independent variables are available soil water capacity (AWSC) in the root zone, slope, aspect, and LAI. The coefficients for the model are 104.46, -1.60, 0.01, 0.12, 0.27 for the constant, AWSC, aspect, slope, and LAI respectively. This model did not include the data from sites 5, 15, and 18 which were considered outliers in section 4.3.1.2. The same model using the data from the sites had an $r^2=0.53$. Using vigour as the dependent variable resulted in a model which is much weaker ($r^2=0.14$). The independent variables used are AWSC for the top 50-cm of the soil, slope, aspect and percent cover of competing vegetation.

Available water storage capacity was calculated for the root zone and for the top 50 cm of the soil for each site. AWSC is dependent on the soil texture and coarse fragment content for each horizon in question. AWSC is calculated based on methodologies used by T.M. Ballard (unpublished report, 1974). AWSC values by texture are based on data from British Columbia Irrigation Committee (no date), and Zottl and Ballard (1966).
4.5 Conclusions

The relationship developed using a seedling performance index and mean $\Psi_m$ for 30 days following planting is quite strong. Excluding the values of three sites which were determined to be outliers, the $r^2 = 0.75$. It was determined that sites that have a high LAI are not appropriate ones to be used in this regression model. There may be factors that are advantageous to seedling performance that the soil water balance model does not account for. On sites that have a LAI, the soil water balance model may be underestimating soil moisture. This may be due to topography of these individual sites or that model error is occurring on such sites. Most likely this discrepancy is a result of a combination of the above factors along with the fact that interactions of high LAI and associated microclimate on seedling physiology is not understood very well. Study two indicated that percent survival decreases substantially below $\Psi_m$ of -0.2 MPa. The best correlation between roots and morphological measurements was found to be a volume surrogate ($\text{caliper}^2 \times \text{height}$) as the independent variable and dry root mass as the dependent variable. No relationships were determined for predicting seedling performance using site characteristics. However, site characteristics were a good predictor of percent survival, $r^2 = 0.64$. 
5. Conclusions

The soil water balance model was used in a retrospective study of the survival and performance of short-day treated interior spruce seedlings, operationally planted in the Prince George region under dry soil and climatic regimes in July and August 1994. Extensive field testing of the model was undertaken for the 1995 field season to verify model performance for soils and climate in the Prince George region and to assess model sensitivity and limitations. The model was used to reconstruct soil moisture for the 1994 field season and seedlings were sampled for morphological parameters at the end of the 1995 growing season. Analysis attempted to correlate survival and performance with modelled soil moisture at the time of planting and the first month following. An attempt was made to build a multiple regression model to predict seedling performance using site characteristics.

Further development of the soil water balance model would be beneficial. Currently the model does not work on sites that have a water table close to the soil surface. Some of the algorithms in the model would need to be reprogrammed. It would also be interesting to test the model’s performance under prolonged periods of drought. This study was unsuccessful in determining significant relationships for predicting seedling performance using site characteristics. Further work is necessary using a broader range of sites to develop such a regression model. This may be possible using a database such as the one compiled by the Northern Interior Vegetation Management Association.
The water balance model described has potential to be used in operational forestry as a tool in managing plantation sites that are susceptible to drought. However, to use the model effectively, it is necessary to understand assumptions and limitations of the model. Field-testing indicated that the model is able to predict soil moisture quite well as long as it is applied to sites where model assumptions are met. The model should be a good predictor of soil water content between early May and mid August. It performed exceptionally well for dry points for 1995; however, it is not known how far off track the model would go during more extended droughts. Significant rain events may have acted as correcting factors in the 1995 season.

The relationship between a seedling performance index and mean $\Psi_m$ for 30 days following planting is strong, $r^2 = 0.75$. It was determined that sites that have a high LAI are not appropriate ones to be used in this regression model. This raises questions regarding the performance of the soil water balance model on such sites. It would be interesting to study seedling physiological response in conjunction with soil moisture conditions in clearcuts having competing vegetation with high LAIs ($> 2.0 \text{ m}^2/\text{m}^2$). Study two indicated that percent survival decreases significantly below mean $\Psi_m$ of -0.2 MPa for copper treated seedlings. The best predictor of a root variable from above ground morphological measurements was found to involve a volume surrogate (caliper$^2 \times$ height) as the independent variable and dry root mass as the dependent variable, $r^2 = 0.50$. Site characteristics were found to be a good predictor of seedling survival, $r^2 = 0.64$. 
References


British Columbia Irrigation Committee (no date). British Columbia irrigation guide. Publ. by authority of Min. of Agric. Victoria, B.C.


