Scale Influences of Surface Parameterization on Modeled Boreal Carbon and Water Budgets

by

Richard Anthony Fernandes

A thesis submitted in conformity with the requirements for the degree of Doctor of Philosophy
Graduate Department of Geography
University of Toronto

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Ph.D. (1999)

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ABSTRACT

Current analyses of Boreal carbon and water budgets suggest that the Boreal ecosystem may be acting as a sink of atmospheric CO₂ by accumulating soil organic matter in mesic conifer landscapes. An empirical study demonstrated that moss and soil moisture content differs significantly between sphagnum and feather moss regions within mesic conifer stands. Moss moisture content was also related to top of moss mid-infrared reflectance to facilitate remote mapping of moss type. Inversion of LANDSAT TM imagery, using a radiative transfer model relating top of moss reflectance to top of canopy reflectance, was used to map moss types within sparse, mesic conifer stands. Uncertainties in canopy cover and the co-variation of canopy cover with surface moisture limited the precision of retrieved moss maps.

A diagnostic, daily time-step, model of energy, water and carbon cycles in Boreal conifer stands, was developed based on the RHESSys model. The model included a distributed hydrologic
parameterization with lateral water redistribution and a spatially variable moss surface layer. Comparison of estimated total evapotranspiration (ET) to eddy flux measurements indicated typical relative bias errors within 5% and precision errors between 13% to 22%. Modelled understory ET ranged from 31% to 50% of total ET with substantially higher average ET rates in sphagnum dominated regions compared to feather moss or lichen covered areas. Substantial bias errors in modelled ET and net ecosystem production were observed over mesic conifer sites when a uniform feather moss cover was specified. A two patch representation based on the proportion of moss cover type was sufficient to provide estimates of total ET and NEP that were not substantially different from model estimates using over 20 patches in a site. Further research should investigate the relative sensitivity of modelled fluxes to uncertainties in the joint spatial distribution of wetness, biomass and nutrients. The validated numerical model could be used to calibrate simpler, analytical, models relating remotely sensed or empirical parameterizations of moss wetness, biomass and leaf area to spatial patterns of Boreal water and carbon dynamics.
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LIST OF SYMBOLS

This section lists the notation used in each chapter of the thesis. Every attempt was made to prevent duplicate use of the same symbol. Dimensionless parameters are indicated by (DIM).

Chapter 2

A - area, m²

\( cd \) - crown diameter, m

\( C \) - canopy cover, %

\( C_h \) - horizontal projected canopy cover, %

\( C_u \) - upper hemispherical projected canopy cover, %

\( D \) - distillation input to live moss surface from below, mm water day\(^{-1}\)

\( dbh \) - diameter at breast height, cm

\( E \) - live moss surface evaporation, mm water day\(^{-1}\)

\( E^* \) - estimated live moss surface evaporation, mm water day\(^{-1}\)

\( ET \) - overstory evapotranspiration, mm water day\(^{-1}\)

\( h \) - stem height, m

\( I \) - canopy interception, mm water day\(^{-1}\)

\( \mathcal{L} \) - leaf area index (DIM)

\( \mathcal{L}_e \) - effective leaf area index (DIM)

\( \mathcal{P} \) - plant area index (DIM)

\( P \) - gross precipitation, mm water day\(^{-1}\)

\( q_{in} \) - live moss lateral recharge, mm water day\(^{-1}\)

\( q_{out} \) - live moss lateral throughflow, mm water day\(^{-1}\)

\( q_{drum} \) - live moss surface drainage, mm water day\(^{-1}\)

\( S \) - turf lysimeter relative saturation (0-1)

\( w_{surf} \) - capillary rise to live moss surface, mm water day\(^{-1}\)

\( \rho_{bou} \) - basal area density, m² ha\(^{-1}\)

\( \rho_{stem} \) - stem density, stems ha\(^{-1}\)

\( \tau \) - throughfall, mm water day\(^{-1}\)
\( \tau \) - stem flow, mm water day \(^{-1} \)

\( \theta \) - turf lysimeter water equivalent depth, mm water

\( \theta_{max} \) - maximum turf lysimeter water equivalent depth, mm water

\( \theta_{over} \) - overstory storage water equivalent depth, mm water

**Chapter 3**

\( \rho \) - nadir reflectance, %

\( \rho_{\text{RED}} \) - nadir reflectance within 630 nm to 690 nm, %

\( \rho_{\text{NIR}} \) - nadir reflectance within 760 nm to 900 nm, %

\( \rho_{\text{IR}} \) - nadir reflectance within 1550 nm to 1750 nm, %

**Chapter 4**

\( C_n \) - overstory canopy cover fraction (DIM)

\( dbh \) - stem diameter at breast height, cm

\( LAD_u \) - understory crown leaf area density, m\(^2\) leaf / m\(^2\) crown

\( LAD_o \) - overstory crown leaf area density, m\(^2\) leaf / m\(^2\) crown

\( LAI_u \) - understory leaf area index, m\(^2\) leaf / m\(^2\) ground

\( LAI_o \) - overstory crown leaf area index, m\(^2\) leaf / m\(^2\) ground

\( \rho_{\text{TOK,RED}} \) - top of canopy red reflectance, %

\( \rho_{\text{TOK,NIR}} \) - top of canopy near infrared reflectance, %

\( \rho_{\text{TOK,MIR}} \) - top of canopy mid infrared reflectance, %

\( \rho_{\text{MOM,RED}} \) - top of moss red reflectance, %

\( \rho_{\text{MOM,NIR}} \) - top of moss near infrared reflectance, %

\( \rho_{\text{MOM,MIR}} \) - top of moss mid infrared reflectance, %

\( \theta \) - moss relative moisture content, g water / g moss

**Chapter 5**

\( APAR \) - absorbed photosynthetically active radiation per unit all sided leaf area, mol photon m\(^2\) leaf area day \(^{-1} \)

\( APAR_o \) - g, vs. \( APAR \) parameter, mol photon m\(^2\) leaf area day \(^{-1} \)
APAR$_i$ - $g_s$ vs. APAR parameter, mol photon m$^{-2}$ leaf area day$^{-1}$

$a_i$ - area of patch $i$, m$^2$

$a_{ute}$ - area of site, m$^2$

$b$ - pore size distribution index (DIM)

$c_1$ - $g_s$ vs. vpd parameter (DIM)

$c_2$ - $g_s$ vs. vpd parameter, Pa$^{-1}$

$c_3$ - $g_s$ vs. vpd parameter (DIM)

$c_d$ - canopy drag coefficient (DIM)

$c_n$ - porosity decay coefficient, m$^{-1}$

$C_{s,ud}$ - surface (soil or moss) volumetric heat capacity, J m$^{-3}$ K$^{-1}$

$C_p$ - specific heat capacity of air, J kg$^{-1}$ K$^{-1}$

$D$ - day index, day of year

$D^*$ - net diffuse stratum shortwave irradiance, J day$^{-1}$ m$^{-2}$

$D_1$ - down welling top of stratum diffuse shortwave irradiance, J day$^{-1}$ m$^{-2}$

$E$ - daily actual evaporation rate, m water/day

$E_{i,overstory}$ - overstory daily evaporation rate from patch $i$, m water/day

$E_{i,sur}$ - soil daily evaporation rate from patch $i$, m water/day

$E_{ij,understory}$ - daily evaporation rate of the $j^{th}$ understory component from patch $i$, m water/day

$E_{dry}$ - dry period actual daily evaporation rate, m water day$^{-1}$

$E_{rainy}$ - rainy period actual daily evaporation rate, m water day$^{-1}$

$E_{surf}$ - daily moss and canopy evaporation not replenished by capillary rise, m water day$^{-1}$

$E_{unsur}$ - moss evaporation replenished by capillary rise plus bare soil evaporation, m water day$^{-1}$

$E_{over}$ - instantaneous potential evaporation rate from an overstory layer, m water s$^{-1}$

$E_{surface}$ - instantaneous potential evaporation rate from a surface layer component, m water s$^{-1}$

$E_{dry}$ - dry period potential instantaneous evaporation rate, m water s$^{-1}$

$E_{rainy}$ - rainy period potential instantaneous evaporation rate, m water s$^{-1}$

$f_{ij}$ - fractional cover of component $j$ in surface layer of patch $i$ (DIM)

$G^*$ - net soil heat flux, J day$^{-1}$ m$^{-2}$

$g_0$ - non-vascular conductance intercept parameter, m water s$^{-1}$

$g_t$ - non-vascular conductance slope parameter, m water s$^{-1}$
\( g_a \) - aerodynamic conductance, \( \text{m water s}^{-1} \text{m}^{-2} \)
\( g_c \) - canopy conductance, \( \text{m water s}^{-1} \)
\( g_{\text{cuticular}} \) - leaf cuticular conductance, \( \text{m water s}^{-1} \text{m}^{-2} \text{leaf area} \)
\( g_{\ell} \) - leaf stomatal conductance, \( \text{m water s}^{-1} \text{m}^{-2} \text{leaf area} \)
\( g_{\ell, \text{max}} \) - maximum leaf stomatal conductance, \( \text{m water s}^{-1} \text{m}^{-2} \text{leaf area} \)
\( I \) - soil surface infiltration rate, \( \text{m water day}^{-1} \)
\( i_o \) - layer rain interception coefficient for events less than \( I_o \) (DIM)
\( i_o' \) - canopy rain interception coefficient for events greater than or equal to \( I_o \) (DIM)
\( I_p \) - canopy potential interception breakpoint, \( \text{m water day}^{-1} \)
\( I' \) - potential stratum interception rate, \( \text{m water day}^{-1} \)
\( I^* \) - incident precipitation rate on vegetation layer, \( \text{m water day}^{-1} \)
\( K(S) \) - vertical unsaturated hydraulic conductivity as a function of relative moisture content, \( \text{m water day}^{-1} \)
\( K_{\text{sat}}(z) \) - lateral and vertical saturated hydraulic conductivity at depth \( z \), \( \text{m water day}^{-1} \)
\( K_{\text{sat,avg}}(z\ell) \) - mean hydraulic conductivity of the unsaturated zone, \( \text{m water day}^{-1} \)
\( \mathcal{L} \) - stratum all sided leaf area index (DIM)
\( L_v \) - latent heat of vaporization, \( \text{J kg}^{-1} \)
\( m \) - lateral saturated hydraulic conductivity decay parameter, \( \text{m water}^{-1} \)
\( m_z \) - vertical saturated hydraulic conductivity decay parameter, \( \text{m}^{-1} \)
\( M \) - soil exfiltration parameter (DIM)
\( n \) - van Genuchten soil column parameter (DIM)
\( N \) - number of patches in a study site (DIM)
\( \mathcal{P} \) - all sided plan area index (DIM)
\( \mathcal{P}_{\text{proj}} \) - projected plant area index (DIM)
\( Q^* \) - layer (or layer component) net shortwave radiation, \( \text{J day}^{-1} \text{m}^{-2} \)
\( q_{\text{diam}} \) - unsaturated zone drainage, \( \text{m water day}^{-1} \)
\( q_{\text{net}} \) - net site lateral runoff, \( \text{m water day}^{-1} \)
\( s_r \) - patch water equivalent depth to water table, \( \text{m water} \)
\( s_{\text{site}} \) - site area weighted water equivalent depth to water table, \( \text{m water} \)
\( S \) - relative moisture content (DIM)

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S* - net direct shortwave irradiance for a vegetation layer, J day⁻¹ m⁻²
S_/ - transmitted direct shortwave irradiance for a vegetation layer, J day⁻¹ m⁻²
T - daily overstory transpiration rate from site, m water/day
Ti.o - overstory daily transpiration rate from patch i, m water/day
T - overstory instantaneous transpiration rate, m water s⁻¹
T_day - daylight average canopy air temperature, °C
T_coef - g, vs. daytime canopy air temperature parameter, °C
T_day - daylight average canopy air temperature, °C
T_min - daily minimum canopy air temperature, °C
T_max - daily maximum canopy air temperature, °C
T_opt - optimal canopy conductance air temperature, °C
tr - rainy daylight period, s
td - daylight period, s
T_sunrise - active soil layer mean temperature at sunrise, °C
T_sunset - active soil layer mean temperature at sunset, °C
u - daytime mean top of canopy wind speed, m s⁻¹
vpd - daylight average atmospheric vapour pressure deficit within canopy, Pa
w - capillary rise rate from saturated to unsaturated zone, m water day⁻¹
w_unsat - capillary rise rate from unsaturated zone to moss canopy layer, m water day⁻¹
z - depth below soil surface, m
z_r - depth to water table, m water
z_d - diurnal damping depth, m
α_D - layer upper hemispherical mean daily diffuse shortwave albedo (DIM)
α_D,PAR - layer upper hemispherical mean daily diffuse PAR albedo (DIM)
α_s - layer upper hemispherical mean daily direct shortwave albedo (DIM)
α_s,PAR - layer upper hemispherical mean daily direct PAR albedo (DIM)
β - component fraction weighted surface direct shortwave albedo (DIM)
Δ - slope of the saturation vapour pressure-temperature curve, Pa °C⁻¹
γ - psychrometric constant, Pa °C⁻¹
\( \eta(z) \) - effective porosity at depth \( z \) (DIM)

\( \eta(z,d) \) - mean porosity of the unsaturated zone respectively (DIM)

\( \lambda_i \) - patch \( i \) soil-topographic index (DIM)

\( \lambda_{site} \) - site average soil-topographic index (DIM)

\( \kappa \) - stratum direct shortwave extinction coefficient assuming random leaf area distribution (DIM)

\( \Omega \) - canopy clumping index (DIM)

\( \rho_{air} \) - density of air, kg m\(^{-3}\)

\( \rho_{water} \) - density of liquid water, kg m\(^{-3}\)

\( \theta_u \) - unsaturated zone soil moisture content, m water

\( \theta_{fc} \) - field capacity of unsaturated zone, m water

\( \theta_x(t) \) - water stored on layer (or layer component) at time \( t \), m water

\( \theta_c \) - layer (or layer component) water capacity, m water

\( \theta_{c-specific} \) - specific layer (or layer component) water capacity, m water per unit plant area

\( \theta_{c-max} \) - maximum layer (or layer component) water capacity, m water

\( \psi_{wp,pre-dawn} \) - pre-dawn leaf water potential, Pa

\( \psi_{max} \) - maximum pre-dawn leaf water potential, Pa

\( \psi_{min} \) - minimum pre-dawn leaf water potential, Pa

\( \psi_{ne} \) - air entry pressure head, m water

\( \psi_c \) - soil water potential, m water

**Chapter 6**

\( E \) - evaporation for a specified water budget component, mm water day\(^{-1}\)

\( T \) - overstory transpiration, mm water day\(^{-1}\)

\( ET \) - total site evapotranspiration, mm water day\(^{-1}\)

\( E_{surf} \) - evaporation from the surface layer canopy store, mm water day\(^{-1}\)

\( E_{unsat} \) - evaporative losses extracted from unsaturated zone of the soil column, mm water day\(^{-1}\)
CHAPTER 1

INTRODUCTION

Preliminary Discussion

In this introduction the basic problem which motivated the research is presented. The scope of the research conducted for this dissertation is presented as a subset of the broad and exhaustive series of problems addressed during the Boreal Ecosystem Atmosphere Study (BOREAS) Experiment [Sellers et al., 1994]. Furthermore, the BOREAS experiment is described. This field experiment served as the source for much of the data used in the dissertation. Lastly, the organization of the subsequent chapters in this dissertation is discussed.

In addition to this chapter, the dissertation consists of four chapters related to scientific papers published or in preparation and two chapters describing additional research. Notation lists and references can be found at the end of each chapter. A summary notation list is available at the beginning of the dissertation. Finally, a preliminary discussion is provided with each chapter that corresponds to a research paper.

1.1 Needs Analysis

The Boreal ecosystem covers a circumpolar region with a southernmost point of approximately 48°N latitude and a northern boundary defined by the tree line as depicted in Figure 1.1. The ecosystem contains approximately 11% of global forested land area [Bonan and Shugart, 1989] and 43% of carbon stored in soil worldwide [Schlesinger, 1993]. There is evidence that the Boreal carbon balance is closely related to global atmospheric CO₂ concentrations [Ciais et al., 1995; D’Arrigo, 1987]. Climate warming may result in a reduction in the extent of the Boreal
Figure 1.1: The circumpolar Boreal ecosystem. The BOREAS study region was located in the central Canadian Boreal ecosystem. (Source: NASA GSFC).
forest as well as the carbon within the remaining forest [Neilson and Marks 1994; Tans et al 1990]. Both of these factors may lead to an increase in atmospheric CO$_2$ concentrations [Rizzo and Witken 1992]. There is a need to understand controls on the Boreal carbon cycle and to use this knowledge to develop methods capable of detecting changes in carbon cycling due to shifts in climate.

A substantial portion of the Boreal ecosystem is covered by mesic conifer stands [Bonan and Shugart 1989]. For example, over 75% of the BOREAS study region, shown in Figure 1.2, is covered by mesic conifer stands [Steyaert et al 1997]. These stands typically consist of a sparse overstory over a surface layer of mosses and peat. Soil and moss moisture content are related to net carbon fluxes at the soil surface in Boreal peatlands [Waddington and Roulet 1996] and conifer stands [Goulden and Crill 1997]. A drop in soil moisture contents in peatlands typically results in an immediate increase in soil respiration [Goreham 1991] followed by a gradual increase in overstory productivity [Paavilainen and Paivanen 1997]. Changes in precipitation patterns or soil temperatures due to potential global warming may reduce soil moisture content and therefore shift the Boreal ecosystem carbon budget from a sink to a source of atmospheric CO$_2$ [Pastor and Post 1988]. A method of incorporating climate and structural controls on carbon, water and energy cycles in Boreal conifer stands is needed in order to quantify both soil and overstory responses to both present and future climates.

The large surface area of the Boreal ecosystem underlines its significance as the surface boundary layer of climate models [Betts et al 1996]. The central Canadian Boreal ecosystem has been observed to generate boundary layer heights typically found in arid deserts [Margolisi and Ryan 1997a] while still retaining a sufficiently high level of surface moisture contents to support peatland formation. This suggests that evaporative losses from Boreal land surfaces may be inhibited in the presence of high evaporative demand. There is a need to understand the mechanisms which act to inhibit ET and to determine if there are spatial ET variations at fine spatial scales which may be of significance to regional ecosystem flux models. The need to investigate surface controls on ET is also motivated by the strong relationship between ET and canopy assimilation [Abdenbi et al 1994] and because ET is the most significant loss
Figure 1.2: The Canadian Land Cover Map depicting the Canadian Boreal ecosystem and the spatial extent of the BOREAS study region and Northern and Southern Study Areas. 
(Source: NASA GSFC from Canadian Forestry Service)
component of the water budget during the growing season [Romanov 1968].

Boreal forests and peatlands are often drained to promote silviculture and agriculture [Paavilainen and Paivanen 1997]. While much of the Finno-scandinavian Boreal ecosystem is now managed, the Canadian and Russian boreal ecosystems still contain large tracts of unmanaged, old-growth, stands [Bonan and Shugart 1989]. There is a need to develop and characterize methods which can estimate spatial patterns of carbon and water budgets at regional and watershed scales under existing conditions and during future anthropogenic disturbances.

Numerical models of ecosystem processes have been applied to address the three needs identified above. However, none of the existing models have explicitly included spatial variations in moss surface layer hydrology at scales finer than 1 km. Therefore, there is a need to examine the controls exerted by the surface moss layer, and spatial variations in soil moisture related to the moss cover, on coarse (1 km) scale water and carbon flux from mesic conifer stands.

1.2 Research Questions

The objective of the dissertation is to address the following question:

Do controls on spatial variations in moss and soil hydrological processes at fine (< 1 km) spatial scale contribute to coarser (≥ 1 km) spatial scale, ecosystem responses such as ET and NEP?

Two applied problems must be solved before this question can be addressed:

i) to identify and map the scales of significant variation in moss surface water budgets within Boreal conifer stands;
ii) to develop and validate a model of carbon and water budgets which can be used to assess the need of fine scale parameterizations of moss type and associated soil hydrologic properties for estimation of coarse scale ecosystem fluxes.

In-situ studies have demonstrated that the moss surface of swamps and peatlands exhibit significant spatial variations in moisture content and evaporation and that lateral flow occurs within peatlands with slopes less than 1° [Waddington and Roulet 1994]. The spatial scales at which these variations exist in mesic Boreal conifer stands are not well documented. Spatial patterns in water budgets within stands at scales below 1 km are typically ignored by existing regional ecosystem flux models applied to Boreal ecosystems. A method for mapping these patterns is required to provide spatially explicit fine scale flux model parameterizations and to identify fractional coverage within intermediate scale parameterizations. In addition, a model of ecosystem fluxes is required to test the explicit fine scale parameterization against both intermediate spatial scales (mixture distributions in a stand) and coarse spatial scales (spatially uniform parameters over a stand). Finally the model must be evaluated against in-situ measurements of processes within carbon and water budgets to determine its bias and precision.

1.3 The BOREAS Experiment

One of the primary objectives of the BOREAS experiment was to develop a better understanding of atmosphere-land surface interactions in the Boreal ecosystem. This understanding could then be used to assess the role of the ecosystem during potential global changes. Measurements were conducted for four years with ongoing studies beyond the scope of this dissertation. Two issues were identified as priorities for study:

i) to improve ecosystem process models which describe the exchanges of radiative energy, water, heat, carbon and trace constituents within the boreal forest and between the forest and the atmosphere;
2) to develop methods for applying the process models over large spatial scales using remote sensing and other integrative modelling techniques.

This dissertation addresses both of these issues.

The BOREAS experiment focussed on spatial scale dependent controls exerted by surface and atmospheric parameters on ecosystem water, carbon and energy budgets. In-situ point and local measurements were performed at four mature conifer study sites as well as auxiliary conifer sites. Broadleaf, fen and young conifer sites were also instrumented. However, treatment of these sites was beyond the scope of this dissertation. Satellite and airborne remote sensing platforms were used to monitor ecosystem fluxes (e.g. CO$_2$ flux) and characterize spatial patterns of structural (e.g. leaf area index) and categorical information (e.g. land cover). The experimental design included spatially coincident measurements at each of the study sites for flux model parameterization. Microclimate forcing data and ecosystem responses such as ET and NEP were simultaneously acquired at the study sites. Detailed information regarding these measurements can be found at the Oak Ridge National Laboratory Data Assimilation Centre and in special issues of the *Journal of Geophysical Research - Atmospheres* [Sellers et al. 1997] and *Tree Physiology* [Margolis and Ryan 1997b].

The BOREAS study region covered a square region with sides of 1000 km located in the central Canadian Boreal ecosystem as shown in Figure 1.2. The BOREAS northern study areas (NSA) represented the lower productivity, temperature limited, northern boundary of the Canadian Boreal ecosystem while the southern study area (SSA) was at the southern boundary defined by disturbance and moisture limitations [Margolis and Ryan, 1997b].

Figure 1.3 indicates the range of spatial scales of measurement and analysis embedded in the study region. One goal of the BOREAS experiment was to develop methods for estimating ecosystem fluxes over the entire study region extent. The dissertation research focussed on scaling fluxes from leaf to plot scale as this was considered the first step in addressing the regional scaling problem. The majority of the dissertation research was conducted over the four
Spatial scale of measurement and analysis within the BOREAS ent. The majority of measurements and modelling conducted in the ion were limited to the tower flux site and process scale.

NSAS GSFC).
1 km² conifer study sites corresponding to the plot scale. Supplementary descriptions of the study sites are included in the chapters within the dissertation. Detailed descriptions of the plots selected and the BOREAS study region in general can be found in the Boreas Experiment Plans [Sellers et al 1994].

1.4 Scope of Research

Four mature conifer sites (stem ages ranging from 40 years to 95 years [Sellers et al 1994]), approximately 1 km² in area, were used for all modelling applications in this dissertation as they were the only mature coniferous regions within the BOREAS experiment where sufficient data was available for model parameterization. Two of the stands represented dry conifer sites dominated by Pinus banksiana Lamb. while the other two stands represented mesic conifer sites dominated by Picea mariana (Mill.) BSP. Mesic and dry stands were paired in each of the two study areas. Analysis of field measurements and model results was typically limited to the 1994 growing season due to the lack of reliable winter time forcing and validation data and the substantially lower system fluxes during the winter period. The exception was measurements of sub-canopy water budgets and canopy cover performed at the SSA wet conifer site during the 1996 growing season.

The initial task of the research was to describe the spatial variation in sub-canopy hydrological stores and fluxes over a range of spatial scales within selected stands. Variations in hydrological processes exist over a continuous range of spatial scales within natural landscapes. Limitations in sampling resources, as well as the discrete nature of the ecosystem flux model used in this study, prompted the use of soil survey polygons to define a fine scale partitioning within each study site. Soil polygons were mapped manually by other BOREAS scientists [Veldhuis 1997; Anderson 1997] using 1:50000 air photographs and gridded at 10 m resolution. The 10m resolution was required given in-situ indications of substantial variation in moss and soil moisture content at scales between 100m and 10m at the wet conifer sites. Information from the soil maps and in-situ measurements [Cuenca et al 1997; Chen 1996] suggested
negligible spatial variations in both surface moisture and overstory leaf area within the two dry conifer sites. Soil maps and mensuration data from the two mesic conifer sites were supplemented with in-situ measurements of canopy cover and moss moisture content.

While the fine scale soil maps would be sufficient when addressing the problem statement over each of the study stands, they did not address the practical difficulty of mapping within-stand hydrological patterns over regional extents. The scope of this dissertation was expanded to explore the feasibility of remote sensing methods of mapping surface wetness patterns within stands. The exploration was limited to the use of mid infra-red reflectance imagery due to the availability of calibrated LANDSAT TM data. For simplicity, the remote mapping method assumed the concurrent availability of leaf area maps and a uniform tree dimensions and morphology within the stand. Validation of the remote mapping method was conducted over a single mesic conifer stand due to the lack of fine resolution soil maps over other mesic conifer regions in the NSA and the lack of leaf area maps in the SSA.

The need to quantify the role of scale dependent controls of water budgets on stand scale ET and NEP while keeping other forcing functions and ecosystem parameters fixed suggested that an approach based only on in-situ measurements would not be feasible. Instead a numerical ecosystem flux model was developed based on physical principles, literature review and in-situ observations. For the purpose of the dissertation problem, the model served as a measurement device to quantify the impact of the spatial scale of the representation of surface hydrology on stand level fluxes. A daily time step model provided diagnostic estimates of ET and NEP. In this regard, the model differed from fully prognostic soil-vegetation-atmosphere-transfer (SVAT) models. A diagnostic model was deemed sufficient since the goal of the research was to identify scaling effects rather than to predict surface fluxes. Furthermore, a diagnostic model satisfies the practical need of regionalising estimates of surface fluxes given local climate forcing data. The model did not incorporate canopy growth but treated biomass and stomatal parameters as fixed through the growing season. Modelling inter-annual variability in ecosystem behaviour was also beyond the scope of this study.
Validation of a number of flux model components was performed to reduce the likelihood of over fitting to a single stand level flux or storage component. The model was applied to conifer sites with disparate soil moisture conditions and climates to provide a cross-validation of its representativeness of other conifer regions in the Canadian Boreal ecosystem.

The validated model was applied at each study site using one of three spatial scales of surface wetness parameterizations within a stand: fine scale, intermediate scale and coarse scale. The fine scale treatment used 10 m resolution soil maps to define local water table depth and moss cover. Estimates of ET from the fine scale model trials were compared to tower based and sub-canopy eddy correlation measurements to determine model bias and precision. The intermediate scale treatment consisted of a nonspatial distribution of the two most prevalent soil moisture/moss cover (wetness) classes. The coarse scale treatment used a uniform wetness parameterization consisting of the dominant wetness class. This treatment represents the conceptual model of the land surface most commonly adopted by regional flux models. Time series of modelled ET and NEP generated using intermediate and coarse spatial scale parameterizations were compared to the fine scale model responses to estimate scaling controls on stand level fluxes (i.e. at 1km²).

1.5 Organization of the Dissertation

This dissertation consists of four research papers, each associated with a chapter, and two additional chapters corresponding to material presented at conferences. For convenience a list of the chapters together with the central research question investigated in each chapter is provided:

Chapter 2. Spatial patterns of understory water budgets and canopy cover in mesic Boreal conifer stands: How does moss moisture content differ as a function of either moss functional group (sphagnum or feather moss) or spatial location within a selected mesic conifer forest study site?
Moss moisture content controls evaporation from moss surfaces. Information regarding spatial variations in moss moisture content for typical mesic Boreal conifer stands is needed to determine the length scales of significant variation in surface form and process that may need to be addressed by flux models applied at these sites.

Chapter 3. The reflectance of *Pleurozium schreberi* as a function of moisture content: Is moss moisture content related to top of moss reflectance and how strong is this relationship relative to other variations in top of moss reflectance?

This chapter investigates the relationship between moisture content and top of moss reflectance for *Pleurozium schreberi*, a dominant surface cover in better drained mesic conifer sites. The laboratory study includes a replicate design to quantify the level of variation in moss reflectance due to uncontrolled factors. The ability to determine moss moisture content using top of moss reflectance would facilitate mapping regions of different moss type for flux model parameterization.

Chapter 4. Mapping surface wetness in Boreal conifer stands using mid-infrared reflectance: What is the relationship between top of moss and top of canopy reflectance and can this relationship be inverted to estimate moss moisture content?

This chapter relates top of moss reflectance to top of canopy reflectance given knowledge of canopy cover. The relationship was developed for mature *Picea mariana* stands representative of the two OBS sites. Extending the relationship to other stands was beyond the scope of the dissertation. The study was necessarily model based due to the difficulty in controlling moisture content and canopy cover in conifer stands within the BOREAS site. The study also explored inversion of the modelled relationship to estimate surface moisture for regions given *a priori* knowledge of canopy cover and stand structure.

Chapter 5. A spatially distributed model of overstory and surface water budgets in Boreal conifer stands: What is the expected bias and precision error of model estimates of
water budgets components when parameterized with in-situ data and without back-calibration to observed responses?

This chapter determines if a flux model parameterized with observed data and including a spatially variable distributed hydrologic sub-model is capable of providing accurate and precise estimates of water budget components in Boreal conifer stands. The flux model was applied at four Boreal conifer sites and validated with available eddy flux measurements of ET, soil moisture and moss moisture. The goal of this study was to quantify the uncertainty of model estimates of ET when using the finest spatial scale surface moisture parameterization.

Chapter 6. Effects of spatial scale of hydrologic parameterization on modelled ET: What is the difference in ET estimated by the same model using a fine scale versus a coarser scale hydrologic and moss parameterization? Is this difference significant relative to fine scale model precision?

This chapter investigates whether a coarser scale hydrologic parameterization than that used in Chapter 5 results in significant differences in ET in comparison to model estimates when using a fine scale parameterization. The comparison makes use of the precision estimates from fine scale model validation to determine the significance of observed differences between fine and coarser scale hydrologic parameterizations. The presence of significant differences due to scaling would suggest that coarse scale flux models applied over Boreal conifer stands may require either a parameterization for sub-1km variations in surface moisture or calibration to a fine scale model or surface observations.

Chapter 7. On the use of remotely sensed surface moisture information to improve model NEP estimates in mesic Boreal conifer landscapes: What is the difference in modelled NEP based on fine versus coarse scale moss and soil hydrologic parameterizations at a selected mesic conifer site?

This chapter investigates the impact of the spatial scale of hydrologic parameterization and
moss type distribution has on model estimates of NEP. Existing vegetation and soil carbon budget models, developed for Boreal conifer stands, were embedded within the flux model described in Chapters 5 and 6. In addition, remotely sensed surface wetness information, mapped using the methodology described in Chapter 4, was used to parameterize the flux model. As such, this paper represents an integration of a number of the dissertation components to determine if the spatial scale of hydrologic parameterization may be an important factor in defining an accurate and precise model of Boreal NEP.
1.6 References


Sellers, P.J., F.G. Hall, R.D. Kelly, A. Black, D. Baldocchi, J. Berry, M. Ryan, K.J.Ranson, P.M. Crill, D.P. Lettenmaier, H. Margolis, J. Cihlar, J. Newcomer, D. Fitzjarrald, P.G. Jarvis,


Veldhuis, H., Soil mapping of the NSA sub-areas and tower flux sites. BOREAS Staff data set, BOREAS Information System, 1997.

CHAPTER 2

SPATIAL PATTERNS OF UNDERSTORY WATER BUDGETS AND CANOPY COVER IN MESIC BOREAL CONIFER LANDSCAPES

Preliminary Discussion

This chapter corresponds to a paper by the same title currently in preparation. The paper was motivated both by a previous study [Price et al 1996] identifying the significance of moss evaporation to total system ET and by the lack of moss carpet parameterizations in concurrent and previous Boreal ecosystem flux models.

Objectives

The paper builds upon the work of Price et al [1996] by addressing three objectives:

i) to answer scientific questions regarding spatial patterns of moss moisture content and canopy throughfall within a mesic conifer stand typically considered spatially uniform from a regional modelling perspective:

ii) to document field measurements of water budget components within mesic Boreal conifer stands over a range of spatial scales for a period representative of a growing season;

iii) to identify spatial correlations between overstory data coincident with water budget measurements of surface moisture content, evaporation and canopy interception.
Relationship to Dissertation Chapters

The scientific questions in this paper addressed the need to quantify differences in moss carpet water budgets between paired sphagnum and feather moss plots. They also emphasized the need to estimate the relative spatial variation in moisture content and throughfall within and between small (100 m²) plots within a 1 km² study site. Answers to these questions were required to identify an appropriate spatial scale of wetness information for parameterizing surface water budgets in the flux model presented in Chapters 5 and 7. Information regarding persistent surface wetness patterns in mesic conifer stands also motivated a remote sensing wetness mapping effort to identify these patterns [Fernandes et al 1996 (Chapter 3); Fernandes et al 1997 (Chapter 4)].

Field measurements of moss moisture content and throughfall were required for model validation and parameterization. The data from this paper document persistent spatial differences in moisture content between feather moss and sphagnum moss carpets within mesic Boreal conifer stands. Concurrent flux model applications had either assumed these stands had a uniform moss cover or completely ignored mosses. This knowledge provided a rationale for incorporating a moss understory layer in the flux model.

The absence of fine scale correlations between canopy cover and both surface moisture and estimated evaporation supported the common flux model assumption that stand structure could be assumed well mixed within soil map polygons and justified the use of mixture distributions of mosses within each polygon. The alternative of a flux model parameterization requiring explicit moss mapping within polygons as small as 10 m² would have required a new in-situ mapping effort together with a substantial increase in the number of fine scale partitions for each model run.

Statement of Original Work

The text, charts and figures were produced by the present author. The second and fourth
authors provided editorial comments.

The initial field sampling plan was defined by the second and fourth authors with contributions by all authors. Measurements were made by all authors. Conversion of in-situ weights into water equivalent depths was performed by the third author with data verification by the present author.

Statistical analyses, discussions and conclusions were entirely the work of the present author. Conclusions regarding paired feather moss and sphagnum plots and comparisons of throughfall and moss moisture relationships between stands at extremes of Boreal climates represent original contributions to the literature. This study provided conclusive evidence of persistent differences in moisture status between feather moss and sphagnum moss regions. This evidence has helped motivate both the distributed stand level modelling efforts in the thesis and a larger BOREAS follow on plan to investigate means of mapping moss layers in Boreal conifer stands.

References


Spatial patterns of understory water budget components and canopy cover in mesic Boreal conifer landscapes


Abstract

The Boreal ecosystem represents a significant proportion of the forested regions worldwide and contains the largest soil carbon pool of all biomes. Examination of carbon and water budgets suggest that the Boreal ecosystem may be currently acting as a carbon sink by accumulating soil organic matter in wet boreal landscapes. Peat and moss carbon fluxes have been related to moisture status which in turn is chiefly governed by throughfall inputs and evaporation. Measurements of the mean and variation of throughfall, moss evaporation and moss moisture status were conducted over a range of spatial scales, on a daily basis, at sites at the southern and northern extremes of the Canadian boreal ecosystem. There was no evidence of significant differences between sites in the functional relationship between throughfall and precipitation. However, there were significant differences in mean throughfall at plots along a 1 km transect at one of the sites. Canopy cover explained much of the between plot variation in throughfall. Most of the variation in canopy cover existed below 20 m length scales suggesting that fine spatial resolution estimates of cover would be necessary to map these patterns. Site mean moss moisture content differed by more than 25.2 mm water and by over 40% relative moisture between sphagnum and feather moss covered regions. The coefficient of variation in moss moisture content, based on measurements on 35 feather moss turf lysimeters, each approximately 15 cm square, increased with decreasing moisture content. This suggests the need to parameterize spatial distributions of moss moisture in models with non-linear responses to low moisture contents. Moss evaporation was strongly correlated to moss capacity, as indicated by maximum moisture content and not significantly correlated to canopy cover. Parameterization of canopy cover and moss type at scales finer than 1 km may be a required for
an accurate and precise description of the dominant spatial variations in moss water budgets in mesic Boreal conifer stands.

2.1 Introduction

The Boreal ecosystem covers 11% of the land surface [Bonan and Shugart 1989] and contains 43% of the carbon stored in soils worldwide [Schlesinger 1991]. Mesic conifer stands cover most of the undisturbed regions of the Boreal landscape [Steyaert et al 1997; Shugart 1992; Paavilainen and Paivainen 1997] and contain the majority of soil carbon in the ecosystem due to low decomposition rates in the cool wet soil column [Bonan and Korzuhkin 1989]. In the Canadian Boreal ecosystem, such stands typically consist of a sparse, clumped, *Picea marina* (Mill.) BSP (black spruce) dominated overstory; a carpet of feather mosses, sphagnum mosses, and lichens; a peat layer ranging in depth from approximately one meter to tens of meters; and an underlying, relatively impermeable, clay layer [Halliwell and Apps 1997a,b,c; Anderson 1997; Veldhuis 1997]. Variations in soil carbon and water stores and fluxes within such stands occur at length scales ranging from 1 m to 1 km and are correlated with moss species [Frego and Carleton 1995; Goulden and Crill 1997], microtopography [Waddington and Roulet 1994], and site productivity and nutrient status [Racey 1989; Zoladeski et al 1995]. This study specifically considers variations in water budgets between and within two moss functional groups, feather moss and sphagnum, in a selected 1 km² mesic Boreal conifer site at the southern edge of the Canadian Boreal ecosystem. The study also compares measurements at the study site and measurements at another mesic conifer site at the northern edge of the Boreal ecosystem [Price et al 1996].

The water budget of the overstory canopy (\(\theta_{\text{over}}\)) and live moss carpet (\(\theta\)) can be written as:

\[
\frac{d\theta_{\text{over}}}{dt} = P - \tau_s - \tau - ET
\]

\[
\frac{d\theta}{dt} = \tau_s + \tau + q_{\text{in}} + w_{\text{unsat}} + D - E - q_{\text{drain}} - q_{\text{out}}
\]
Figure 2.1 describes the conceptual model of the water balance of the live moss carpet adopted in this study. Symbols in the figure and the text are defined in the Notation section. Following convention, $d \Theta_{net}/dt$ is termed net canopy interception ($I$) when dealing with precipitation events. Throughfall ($\tau$) is the dominant source of water input to moss layers, especially in minerotrophic regions dominated by feather moss [Busby and Whitfield 1978]. There have been a number of studies characterizing $\tau$ in conifer stands (see review in Price et al [1996]) although studies in Boreal *Picea mariana* stands, especially those exploring the co-variation of $\tau$ and $\Theta$, are uncommon.

Price et al [1996] monitored water fluxes through *Picea mariana* canopies and underlying feather moss carpets at three 400 m² sites at the northern edge of the central Canadian Boreal ecosystem as part of the Boreal Ecosystem Atmosphere Study (BOREAS) [Sellers et al. 1994]. Their results indicate that during the growing season:

i) Throughfall was approximately 67% of gross precipitation ($P$) with the total site coefficient of spatial variation (c.v.) of $\tau$ inversely proportional to mean $\tau$.

ii) Feather moss live layer turfs exhibited a maximum absolute moisture content ($\Theta$) ranging from 3.7 mm water to 4.7 mm water with drainage or lateral flow reaching negligible levels the day after rain events.

iii) Net canopy interception ($I$) plus moss evaporation ($E$) was 41% of $P$; with $E$ comprising 23% of $P$.

While their study provides useful information for parameterising and validating ecosystem flux models in wet Boreal conifer sites there are a number of outstanding research questions which needed addressing:
Figure 2.1: Conceptual model of moss and canopy water fluxes with the SSA-OBS. Boxes indicate overstory and live moss canopy stores. Fluxes are represented by arrows. Stemflow (\( r_s \)) was negligible. Capillary rise from the unsaturated soil moisture store to the live moss turf (\( w_{\text{unsat}} \)) only occurs with sphagnum mosses. Lateral flows (\( q_{\text{in}} \) and \( q_{\text{out}} \)) and vertical drainage (\( q_{\text{drain}} \)) are negligible in feather mosses 24 hours after rain events [Price et al 1996]. Net distillation (\( D \)) was assumed negligible for all mosses over the daily measurement period.
1. Is the observed $\tau$ versus $P$ relationship similar in mature mesic conifer stands at both northern and southern extremes of the Boreal ecosystem?

Ecosystem flux models have been applied at wet Boreal conifer sites in both the BOREAS Northern Study Area (NSA) and Southern Study Area (SSA) located at the northern and southern extremes of the central Canadian Boreal ecosystem [Frolking et al 1996; Cooper et al 1997; Kimball et al 1997; Nijssen et al 1997]. The mesic conifer sites (labelled Old Black Spruce, OBS) are dominated by a Picea mariana overstory and a surface moss carpet separated into regions dominated by either feather mosses or sphagnum mosses. Results from the RHESSys model suggest that total site evapotranspiration at the SSA-OBS site was almost twice that of the NSA-OBS during the 1994 growing season (Chapter 5). Sensitivity analysis indicated that RHESSys based evapotranspiration estimates are sensitive to the parameterized relationship between $\tau$ and $P$. The absence of between site differences in this relationship would simplify flux model applications over similar mesic conifer stands.

2. What is the typical difference in moisture content between sphagnum and feather moss turfs within the study site?

Feather mosses can gain only small amounts of water by lateral recharge or by distillation of vapour from the underlying soil layer [Price et al 1996]. In contrast, sphagnum mosses are capable of extracting sufficient water by capillary rise to satisfy evaporative demand [Romanov 1968]. Empirical studies indicate significant differences in heat and carbon fluxes between sphagnum and feather moss covered regions within the NSA-OBS stand [Goulden and Crill 1997]. Measurements of vapour fluxes in sphagnum and feather moss regions under the same conditions of evaporative demand are also required. The gravimetric methods used in this study prevent direct measurement of vapour fluxes during periods of recharge or drainage. Feather moss evaporation is estimated after drainage. However, the potential for capillary rise in sphagnum turfs prevented estimation of sphagnum evaporation rates with the experimental method. In light of this limitation, this study compares moisture content, rather than evaporation, between sphagnum moss and feather moss turfs under similar climate forcing.
Fortunately moss surface conductance to vapour flux is chiefly governed by moisture content [Williams and Flanagan 1997] suggesting that large differences in moisture content may be indicative of large differences in evaporation for turfs under similar evaporative demand.

3. What are the dominant spatial scales of variation of $C$, $\tau$, $\theta$, $S$ and $E$ within a mesic conifer landscape?

Price et al [1996] provides some data regarding the spatial variation of $E$ and $\tau$ within two 400 m$^2$ plots within the NSA. However a description of the partitioning of variance between spatial scales lower than 10 m, which are likely below the resolution of mapping and modelling methods, and spatial scales between 10 m and 1 km, corresponding to the scale of remotely sensed image data sources and ecosystem flux models, is required.

4. To what extent are sub-canopy water budget components correlated with canopy cover?

It may be possible to reduce the uncertainty in difficult to map spatial patterns of sub-canopy stores and fluxes by relating them to canopy structural properties, such as leaf area index ($LAI$), which are easier to map remotely. Previous studies [Busby and Whitfield 1978; Skre et al 1983] demonstrated that moss vapor and carbon fluxes are related to both $\theta$ and incident photosynthetically active radiation (PAR) at the scale of a single moss turf. These results prompt the need to determine the strength of co-variations of sub-canopy fluxes and stores to canopy cover over coarser spatial scales.

In addition to addressing the above research questions the data in this paper will be of use to future modelling studies to quantify residuals between site scale ecosystem flux model estimates and plot scale observations of understory water budgets. These residuals may provide information regarding the ability of flux models to realistically represent controls on moss moisture content and vapour fluxes.
2.2. Method

2.2.1 Study Area

The majority of measurements reported in this study were acquired at the SSA-OBS site, approximately 50 km north of Prince Albert, Saskatchewan, Canada (53.2°N 105.7°W). The site represents a typical mature, mesic, Boreal conifer stand at the southern edge of the central Canadian Boreal ecosystem [Sellers et al 1997]. The overstory was dominated by a mature Picea mariana overstory separated into two horizontal strata distinguished by moss type [Sellers et al 1994]. The spruce/feather moss stratum consisted of a relatively productive mature Picea mariana overstory with a basal area of 30 m² ha⁻¹ and maximum height near 10 m, together with some Pinus banksiana and Larix laricina. This strata was imperfectly to poorly drained with a 5 cm to 20 cm deep organic humic layer, covered with feather moss (Pleurozium schreberi, Hylocomium splendens, Dicranum polysetum) and lichens (Cladonia cornuta and Cladina sp.), over a loam-clay mineral soil layer. The spruce/sphagnum stratum overstory was dominated by Picea mariana stems with a basal area of 10 m² ha⁻¹ and maximum height near 6 m. This stratum was typically poor to very poorly drained with a peat layer ranging from 50 cm to 120 cm. covered with Sphagnum spp. mosses, over a clay soil layer. More information regarding the site can be found in Halliwell and Apps [1997a,b,c]. Selected understory water budget measurements, reported in Price et al [1996], at a feather moss dominated Picea mariana stand in the NSA are also included for between site comparison.

Three spatial scales are considered during data analysis:

i. study site - a region containing a set of plots spanning an area of approximately 10⁶ m² which is typically considered a uniform site by regional ecosystem flux models.

ii. plot - a contiguous area on the order of 20 m² which is representative of the finest resolution feasible for remote mapping of canopy or moss properties.
iii. measurement - a spatial extent corresponding to the spatial support of measurement devices (e.g. throughfall gauges, turf lysimeters, and optical leaf area meters) whose sampling resolutions range from $10^{-2}$ m$^2$ to $10^1$ m$^2$.

A nested spatial sampling plan was used to characterize the variations at the three spatial scales. Seven ‘moss’ plots, each approximately 20 m$^2$, were located along a 1 km transect in the vicinity of the SSA-OBS flux tower as shown in Figure 2.2. The transect also extended along a perceived wetness gradient from upland spruce/feather moss at plot M1 to a region classified as ‘Treed Muskeg’ [Halliwell and Apps, 1997a], representative of the spruce/sphagnum stratum, at plot M7. Two additional 225 m$^2$ throughfall plots, T1 and T2, were located within the site and two rain gauges were sited in clearings near the transect. The irregular spacing of the plots along the transect reflects the need to find both sphagnum and feather moss cover within each plot. Sphagnum was only found in isolated hollows in the upland plots while extensive carpets of sphagnum covered in “Treed Muskeg” plots. In contrast, feather moss and lichens dominated the upland plots and were only found on ridges in the “Treed Muskeg” regions.

### 2.2.2 Measurement of Moss Moisture Content and Throughfall

Moss turf measurements reported in this study correspond to the photosynthetically active (live) layer where water fluxes are large [Price et al 1996]. Each moss plot had 5 live layer feather moss turf (L) lysimeters, 5 throughfall gauges (one within 10 cm of each lysimeter) and one nearby live layer sphagnum turf lysimeter. The throughfall plots contained 30 throughfall gauges and two stem flow gauges. Lysimeters and gauges were randomly located, under the constraint of a minimum 1 m spacing; except for throughfall gauges in moss plots which were paired with L lysimeters. Gauge locations were not changed during the study. Detailed information regarding the locations of gauges within each plot can be found in Fernandes [1997].
Figure 2.2: Plot locations within the SSA-OBS site. There were seven moss plots (M1-M7), approximately 20m² in area, each containing 5 feather moss turf lysimeters and 1 sphagnum turf lysimeter. Plot locations were selected to ensure both sphagnum and feather moss turfs under similar canopy cover. The throughfall plots, T1 and T2, contained catch gauges to supplement the 5 gauges in each moss plot. The LAI transect consisted of 3 parallel tracks, separated by 20 m, extending 320m from the flux tower. Raw projection in UTM Zone 13 co-ordinates. Symbols not to scale.
Measurements were performed daily and after rain events, when possible, between July 6\textsuperscript{th} 1996 and August 13\textsuperscript{th} 1996; although throughfall measurements were only recorded after rain events. In most instances the daily measurements were conducted between 10:00 am and 1:00 pm local time. Measurements were made at all gauges and lysimeters at a given plot before moving to another plot. There were six precipitation free days during which moss moisture content measurements were not performed due to logistical difficulties (day of year 197.198.205.212.218.222). As a result, the observations presented in this paper represent measurements of understory water budget components over a total of 16 precipitation free days and 17 days with precipitation during the 39 day duration of the field study.

Each turf lysimeter consisted of a 15cm x 15cm fine mesh tray upon which a manually extracted live moss turf was placed. Monofilament wires were attached to the sides of the tray and the turf and tray were then replaced in the pit from which the turf was extracted. Weighing was performed by lifting the lysimeter by the wires and placing it on a calibrated electronic balance located on a level platform within the plot. The precision of the balance was +/- 0.1 g for weights below 1 kg and +/-0.5 g for weights above 1 kg. The lysimeter was then replaced in the same pit. At the end of the field measurement period each lysimeter was bagged in polyethylene and placed in a plastic cooler. The extracted lysimeters were removed from the bags and oven dried at 50°C until the turfs desiccated (the water loss rate was negligible). The drying was initiated two days after bagging the lysimeters.

Moss absolute moisture content was estimated by subtracting the oven dry weight from field measurements of the lysimeter weight. Absolute moisture content was converted into water equivalent depths using the measured surface area of the cube shaped turfs. The relative precision of the absolute moisture content measurements due to weighing errors is inversely proportional to moisture content. Relative precision was estimated to be better than +/- 0.5% of the measured absolute moisture content, for moisture contents over 1 mm water. The precision error in the estimated surface area was approximately +/-15 cm\textsuperscript{2}; chiefly due to uncertainties in defining the boundary in the moss turf. The uncertainty in surface area results in a relative precision error in reported water equivalent depth of approximately +/- 7%.
Assuming additive weighing and surface area errors suggests a total relative precision error of under +/-8% for typical levels of moisture content.

Relative moisture content was estimated by assuming that the maximum observed absolute moisture content was a reasonable estimator of the true saturation moisture content. This assumption was supported by the fact that, for each turf, absolute moisture contents within 5% of the maximum were observed during a number of large precipitation events. A 5% error in maximum moisture content would result in an error of less than +/-0.05% in relative moisture content for all of the reported measurements. This suggest that errors in relative moisture content are dominated by errors in the absolute moisture content weight: which is also very small until the turf is near dessication.

Throughfall was measured using cylindrical plastic containers, 10 cm in diameter, placed in the moss carpet so that the orifice was flush with the carpet surface. The low wind speeds at the moss surface suggest turbulence has a negligible effect on throughfall estimates. Splash losses from the containers were not quantified but the presence of the overstory likely attenuated drop intensity so as to reduce these losses. Gross precipitation was measured using a gauge with 20 cm plastic funnel placed level with the top of grasses growing in a forest clearing (approximately 30 cm in height). Care was taken to ensure that field of view of the 45 degree cone above the gauge was unobstructed. Stemflow was measured over 3 randomly selected stems in each throughfall plot by using plastic collars wrapped around stems and attached to covered reservoirs. However, no stem flow was observed over the entire measurement period. The same result was reported by Price et al [1996] at a NSA site.

Sphagnum evaporation was not estimated as the experimental design did not permit separation of capillary rise and moss evaporation. In contrast, feather mosses do not typically exhibit significant lateral or vertical net water flux during dry periods [Price et al 1996]. The absence of feather moss recharge during dry periods suggested that spatial patterns in net turf water loss ($E^*$) patterns would be similar to spatial patterns of $E$. $E^*$ was computed for measurements where there was at least 24 hours separation from the preceding rain event. In only one rain
free day (day of year 200) was $E^*$ censored due to negative net water loss values at a number of turfs.

2.2.3 Measurement of Structural Properties

Plot locations were mapped by tape and compass relative to the flux tower base. The flux tower was georeferenced using global positioning system measurements by BOREAS staff [Snell 1994]. Plot boundaries were chosen a priori to represent the likely fetch of understory gauges (on the order of 10 m$^2$). Stem diameter at breast height ($dbh$) was measured for all stems to estimate plot basal area density. Upper hemispherical canopy cover, $C_u$, was measured at each lysimeter and throughfall gauge with a canopy densitometer. The field of view of the densitometer theoretically extended over an infinite distance at the horizon: resulting in a spatial support extending past the immediate canopy and perhaps past the edges of the plot. A horizontal projected canopy cover index ($C_h$) was estimated using stem counts and allometric measurements of crown diameter. This index was equivalent to an estimate of total crown area projected on the horizontal without consideration of crown overlap within the plot and of crowns bordering the outside of the plot. The $C_h$ estimates were included both due to the difficulty in defining the spatial support of the densitometer and the possibility that $C_u$ may overestimate the projected canopy cover in the path of incident irradiance or precipitation. A LAI-2000 meter (Li-Cor Corporation, Lincoln, Nebraska) was used to determine effective leaf area ($\mathcal{C}_l$) at plots M2 and M3 together with similar measurements by Chen [1996] within 5 meters of plots M3, M4 and M5. Chen [1996] shows that $\mathcal{C}_l$ is related to the plant area index ($\mathcal{C}_c$), using a clumping factor and allometric relationships, in a manner that is relatively spatially invariant within the SSA-OBS site. Coincident estimates of $C_h$ and $\mathcal{C}_c$ [Chen, 1996] suggest within crown densities on the order of 10 m$^2$ plant area per m$^2$ $C_h$. The high within crown $\mathcal{C}_c$ prevents precipitation from penetrating through crowns without striking foliage. Instead drops are typically intercepted and then drip or evaporate.
2.3 Observations and Analysis

Analysis of variance (ANOVA), analysis of co-variance (ANCOVA) and test of differences in means for populations with unequal variances were applied to address the research questions. All of these tests assume that measurements within plots represent independent and identically distributed randomly selected samples from normal populations. Tests for normality were conducted and power transformations applied when appropriate. A 1 m minimum spacing was enforced between turfs within a plot to reduce the extent of spatial dependance between samples due to explicit lateral connectivity. The possibility of spatial dependence together with the use of a single study site to quantify water budget patterns suggests that the within plot measurements may be pseudo-replicated [Hurlbert 1984]. The lack of independent replicates suggests that significance levels of differences between plots or between sites are indicative of the strength of the observed differences at the sampled regions only and may not apply to other study sites. Furthermore, the possibility of pseudo-replication also suggests that tests for significant differences between plots or sites are strictly only valid in terms of testing for TYPE II errors (i.e. the likelihood of observing no difference when a significant difference exists). As a result f-statistics and actual significance levels are included to describe the magnitude of the observed difference between treatments.

2.3.1 Gross Precipitation

Precipitation events were defined as having a minimum 1 hour interval of no precipitation before and after the event. Difficulties in accessing the site at night likely resulted in some short events being grouped together so that the minimum interval between events could be as high as 24 hours. Figure 2.3 shows a time series and histogram of the gross precipitation recorded at the SSA-OBS. Eighteen precipitation events were measured between DOY 186 to DOY 224 with 13 of them below 2.5 mm water. There was no obvious temporal pattern in event depths although the presence of any pattern was not expected given the short monitoring period.
Figure 2.3: Histogram (a.) and time series (b.) of gross precipitation events at SSA-OBS. There were a total of 18 events recorded during DOY 185 and DOY 225. The maximum aggregation period was 24 hours for overnight events. Daytime events were recorded 1 hour after precipitation ceased.
2.3.2 Canopy Structural Properties

The SSA-OBS site was selected by the BOREAS science team to represent a spatially uniform, poorly drained, mature conifer site [Sellers et al 1994]. However, substantial variation in site productivity was observed both within and between plots. Figure 2.4 provides estimates of the mean and standard deviation of measured $dbh$, $\rho_{stem}$, $\rho_{total}$, $C_h$, and $C_h$ within each moss plot in the SSA-OBS, as well as averaged over moss plots at the SSA-OBS site and the NSA-JLK site. The c.v. of within $dbh$ was on the order of 1.0 indicating either age or productivity variations within plots. Tree ring counts of 11 stems in the SSA-OBS [Halliwell and Apps. 1997c] indicated a range of 70 to 117 rings. This suggests that the majority of stems were mature and that variability in productivity may be due to local edaphic and competitive conditions.

The ratio of plot total projected crown area to plot area, $A$, was used to determine $C_h$.

Allometric relationships between $dbh$ and $cd$ were developed, as part of the current study, using data for BOREAS black spruce stands published in Halliwell and Apps [1997b]:

\[
\begin{align*}
\text{dominant} & \quad cd &= 14.4dbh - 0.3 \quad r^2 = 0.615 \quad s.e. = 0.65 \quad n = 113 \\
\text{codominant} & \quad cd &= 12.0dbh + 0.133 \quad r^2 = 0.571 \quad s.e. = 0.58 \quad n = 166 \\
\text{intermediate} & \quad cd &= 15.4dbh + 0.187 \quad r^2 = 0.531 \quad s.e. = 0.48 \quad n = 97 \\
\text{suppressed} & \quad cd &= 16.0dbh + 0.215 \quad r^2 = 0.630 \quad s.e. = 0.37 \quad n = 31
\end{align*}
\]

The linear fits are statistically significant ($p<0.01$) and estimated slopes and intercepts are significantly different ($p<0.01$) from zero. The $r^2$ and standard error (s.e.) values suggest that the precision of a single $cd$ estimates was low. However, estimation of $C_h$ involves summing $cd$ over 15 to 35 stems in a plot. The summation increases the precision of plot mean $C_h$ estimates by a factor of 3.9 to 5.9 respectively. As Figure 2.4 indicates, $C_h$ exceeded 100% in most instances since overlap of crowns within and along the border of plots was not accounted.
Figure 2.4: Structural characteristics of each moss plots of the overall SSA-OBS and of NSA-JLK site. Refer to text for definitions of parameters. One standard deviation bars included where appropriate.
for. As such, $C_h$ was used as an index of horizontal projected crown cover rather than as an unbiased estimate of actual horizontal projected crown cover. The constant within and between site clumping factor observed by Chen [1996] suggests that overlap may not vary significantly in space. Furthermore, the plots were selected within larger regions of similar canopy cover to minimize boundary effects on $C_h$ estimates.

Figure 2.5 indicates that both $C_h$ and $C_u$ were linearly related to $X_d$; with Pearson sample correlation coefficients of 0.98 ($p=0.002, n=5$) and 0.91 ($p=0.017, n=5$) respectively. The lower precision for the $C_u$ versus $X_d$ fit may be due to differences in spatial support between measurement methods. The field of view of the densitometer extends over a complete upper hemisphere while the LAI-2000 field of view is limited to a cone extending from +/- 75° of the vertical. In addition, $X_d$ was estimated as the average of three LAI-2000 recordings while the plot mean $C_u$ represents an average over at least 10 gauge or lysimeter locations. The large field of view of the densitometer, together with the greater within plot sample size, decreases between plot differences in $C_u$ if the majority of variation in cover and leaf area occur at length scales finer than the field of view of the densitometer. The presence of significant fine scale variation in cover was supported by a within plot $C_u$ +/- 1 standard deviation interval approximately equal to the range of plot mean $C_u$ across the site. Between plot trends in $C_u$ were similar to trends in $C_h$. However, differences between plots were less pronounced for $C_u$. Again, this may be due to the coarse spatial resolution of the densitometer measurements. The averaging effect of the densitometer is further supported by data from Chen et al [1997] showing a 50% lower range in $X_d$ from the hemispherical photograph estimates (which use a method similar to the densitometer for leaf area measurement) in comparison to the LAI-2000 at the SSA-OBS. Chen et al [1997] do not report correlation coefficients between hemispherical photographs based cover estimates and LAI-2000 estimates but examination of their data show precision comparable to the precision of the relationships in Figure 2.5.

Figure 2.4 suggests that the c.v. of within plot $C_u$ was inversely proportional to plot mean $C_u$. The lack of spatial independence of within plot $C_u$ measurements prevented application of an analysis of variance to test the significance of between plot variations in canopy cover. Instead,
Figure 2.5: $C_u$ and $C_h$ versus $L_e$. Bars indicate +/-1 sample standard deviation for $C_u$. A single $L_e$ measurement was provided at five moss plots using a LAI-2000 leaf area meter. Five $C_u$ measurements were performed within each moss plot using a canopy densitometer (one measurement above each turf lysimeter). $C_h$ was estimated by using measured stem properties and allometric estimates of crown cover. Linear fits are included.
a discrete Haar wavelet transform [Daubchies, 1989] was used to identify dominant spatial scales of variance of $\mathcal{V}$. Chen [1996] provided measurements every 10 m along three parallel 300 m transects radiating from the SSA-OBS flux tower and separated by 10 m from each other. The mean value of $\mathcal{V}$ along each transect was removed from measurements along the transect so that the Haar coefficients were equivalent to the variance at a given spatial frequency [Csillag and Kabos 1996]. Figure 2.6a shows the percentage of signal variance represented by each Haar wavelet period. With the exception of two outliers, variance increased linearly with a halving of spatial frequency suggesting both a fractal $\mathcal{V}$ pattern and a monotonic increase in the variation of $\mathcal{V}$ as scale becomes finer. Figure 2.6b shows the best fit Haar basis function along one of the transects computed using a wavelet packet decomposition [Wickerhauser 1994]. In general, most of the spatial variation in $\mathcal{V}$ occurs at length scales at or below 20 m.

### 2.3.3 Canopy Throughfall

Figure 2.7a indicates that site mean $\tau$ can be predicted with minimum bias assuming exact knowledge of $P$. Linear fits were used to relate $P$ and $\tau$ recorded for each event at both SSA-OBS and NSA-JLK sites:

$$
\begin{align*}
\text{SSA-OBS} & \quad \tau = 0.747 P & \rho^2 = 0.98 & \text{s.e. slope} = 0.022 & n = 18 \\
\text{NSA-JLK} & \quad \tau = 0.819 P & \rho^2 = 0.99 & \text{s.e. slope} = 0.017 & n = 9
\end{align*}
$$

(4)

Figure 2.7b indicates that the variance of $\tau$ measurements within a site was proportional to $P$ but the c.v. in $\tau$ was inversely proportional to $P$. A similar trend for c.v. in $\tau$ was also observed at the NSA-JLK site [Price et al. 1996]. The similarity of the $\tau$ versus $P$ relationship between the SSA-OBS and NSA-JLK sites supports the use of a single throughfall parameterization for ecosystem flux models applied to mature *Picea mariana* stands with canopy cover similar to the two study sites.
**Figure 2.6**: Discrete Haar wavelet transform analysis of $F$ measurements along three 320 m transects in SSA-OBS. $F$ data from [Chen 1996]:

a) Spatial frequency partitioning of variance in $F$: The Haar wavelet period indicates the spatial frequency while the energy is equivalent to the $F$ variance at the corresponding Haar period.

b) Spatial/spatial frequency plot of best Haar basis functions for $F$. The dark rectangles indicate the spatial frequency with the largest $F$ variance at a given location in the transects.
Figure 2.7: Summary of site $\tau$ versus $P$ for 18 events at the SSA-OBS and 9 at the NSA-JLK site. Fitted relationships for SSA-OBS indicated by solid lines. Figure (a): Site mean and standard deviation of $\tau$ on a logarithmic scale. The figure indicates that the $\tau$ vs. $P$ relationship was similar between SSA-OBS and NSA-JLK. Figure (b): c.v. of $\tau$; both versus $P$ on logarithmic scale. This suggests that, for both sites, the within site variation in $P$ was inversely proportional to $P$. 
Equation 4 does not permit description of within site patterns of $\tau$. Chi-square tests for normality were conducted within plot T2 to examine the suitability of applying an ANOVA to the moss plot data. The moss plots were not tested for normality since there were insufficient $\tau$ gauges to generate relative frequency histograms meeting a minimum bin count of 4 samples for each event. Figure 2.8 indicates evidence against the hypothesis that $\tau$ was normally distributed within plot T2 for most events. While the small sample size may contribute to the lack of normality there is a pronounced deviation from normality for events with $P$ between 1.78 mm water and 2.4 mm water. Figure 2.7b indicates that the c.v. of $\tau$ also decreases sharply above 2.4 mm $P$. Fine scale variations in $\tau$ due to the onset of drip around 2 mm $P$ may explain these observations since gauges under the canopy should experience very low $\tau$ until the canopy saturates. The possibility that deviations from normality are related to the onset of substantial canopy drip suggests that the mean canopy moisture capacity for the plot may be near 2 mm water. Actual plant area was not measured during this study; however, the mean $\rho$ of 4.6 reported by Chen [1996] suggests a specific canopy capacity in the vicinity of 0.44 mm water $\rho^{-1}$. Througfall observations were separated into two blocks during subsequent analysis corresponding to the hypothesized canopy capacity threshold: events less than 2.4 mm water (low $P$) and events greater than 2.4 mm water (high $P$).

The general deviation from normality was of concern for further statistical analysis. The spatial distribution of measurement scale $\tau$ within the site was typically skewed left for low $P$ events and right for high $P$ events. The skewness may be explained by the lower bound of no interception and the upper bound of interception defined by canopy capacity. Ideally, different transformations could have been applied for each event. However, this would have been tedious and would have complicated analysis of pooled event data. Power transformations with exponents of 0.5 and 0.9 provided the best fit to a normal distribution for pooled $\tau$ measurements for low $P$ and high $P$ blocks respectively.
Figure 2.8: Pearson chi-square statistic (5 degrees of freedom) testing the fit to a normal distribution for measurements of $r$ for 30 gauges within plot T2. Dashed line indicates $p=0.95$ threshold of 11.07 in support of the hypothesis that was no significant difference between the observed $r$ values and a normal distribution fit. The large number of violations of this hypothesis at 2mm $P$ may indicate the point at which canopy rain capacity was just exceeded so that some crowns were dripping while there was no drip at crowns slightly below capacity.
A two-way ANOVA with replicates was performed on each block's transformed $\tau$ data to test the hypothesis that there were no between plot or between event differences in $\tau$. While the event factor was not controlled and included a number of similar events (see Figure 2.9) it was adopted to represent the expected environmental control on spatial throughfall patterns with time. The ANOVA found evidence at a significance level of less than 0.02 of between plot differences between plots for both low $P$ and high $P$ blocks. The standard error of the difference between means after inverse transformation was 8.2% relative to site mean $\tau$ for events greater than 2.4 mm and 0.24% relative to site mean $\tau$ for events below 2.4 mm. Figure 2.9 shows, for each plot, the relative difference between plot $\tau$ and site mean $\tau$ averaged over all events together with the +/-1 standard deviation intervals of the relative difference. The common assumption in ecosystem flux models of spatially uniform $\tau$ within a site could result in relative errors of over 50% in $\tau$ at plot scale. The ANOVA indicates some evidence ($p=0.04$) of differences in spatial $\tau$ patterns between events for small events and little evidence ($p=0.85$) for large events.

### 2.3.4 Moss Moisture Content

Figure 2.10 shows the site mean and variance of $\theta$ for sphagnum and feather moss between DOY 185 and DOY 225. The mean value of site mean $\theta$ over the measurement period was 4.17 mm water (range [1.7 mm water, 7.5 mm water]) for feather moss turfs and 35.4 mm water (range [12.6 mm water, 60.7 mm water]) for sphagnum moss turfs. The upper bound of feather moss $\theta$ is between 160% and 200% larger than corresponding estimates reported for the NSA-JLK and NSA-OBS site [Price et al 1996]. This suggests that moss turf canopies were deeper in SSA-OBS. This may be due to higher irradiance and temperatures in the SSA, although the lack of co-located canopy cover data with the NSA moss measurement sites prevents testing of this hypothesis.
Figure 2.9: Difference in mean $\tau$ of moss plots within the SSA-OBS relative to site mean for small ($\leq 2\text{mm water}$) and large ($>2.4\text{mm water}$) events. Solid lines indicate +/- 1 standard deviation intervals over all events. Statistical significance tests indicated significant differences in between plot $\tau$ for both small and large events. There were 18 events during the measurement period of which 12 were below 2.4 mm water.
Figure 2.10: In-situ moss live layer moisture contents at the SSA-OBS during 1994. Solid symbols indicate site mean moisture content while bars indicate +/- 1 standard deviation intervals for measurements within the site. Moisture content was measured for sphagnum turfs (n=6) paired with feather moss turfs (n=35) paired within plots so as to minimize variations due to differences in evaporative demand.
The minimum observed difference between site mean $\theta$ of sphagnum and feather moss over all measurement dates was 25.2 mm water. The strong dependance of moss surface conductance to vapor and carbon fluxes on $S$ [Williams and Flanagan 1997] suggests that identifying controls on spatial patterns in $S$ may be of importance for modelling these fluxes. Site mean $S$ was 0.65 for feather moss turfs and 0.80 for sphagnum moss turfs when averaged over the measurement period. Figure 2.11 relates site mean $S$ of feather moss turfs to site mean $S$ of sphagnum turfs. The figure includes the +/- 95% confidence intervals of the difference between these two values estimated using unequal variance t-tests on each measurement date. Site mean $S$ for paired feather moss and sphagnum turfs exhibited a strong linear relationship with a Pearson correlation coefficient of 0.86 ($p<0.01; n=27$). The range of sphagnum $S$ was four times smaller than that of feather moss, with the sphagnum $S$ values significantly larger than feather moss $S$ except for cases where all mosses were near saturation. Williams and Flanagan [1997] show that vapor conductance is proportional to $S$ for both moss types: with sphagnum conductance greater than or equal to feather moss conductance at the same value of $S$. The use of paired moss turfs suggests that the evaporative demand between sphagnum and feather moss turfs within a stand was similar. Therefore, the higher site mean $S$ for sphagnum moss turfs is more likely to be due to the sphagnum mosses gaining water by lateral or capillary recharge rather than to higher feather moss evaporation.

The current measurements and previous evidence of capillary rise in sphagnum turfs [Romanov 1969] supports the need to include a lateral recharge mechanism between drier feather moss sites and wet sphagnum sites in models applied to wet Boreal conifer stands if one wishes to preserve the soil water balance and still represent patterns of vapor or carbon fluxes. Furthermore, if drainage from feather moss contributes to recharge of sphagnum moss areas the correlation observed between their moisture contents may be an expression of actual dependance between these two regions. The length scales of interspersed feather moss and sphagnum patches ranged from tens of meters to under a meter. This suggests that the lateral flow between feather moss and sphagnum patches could occur fast enough to supply sphagnum evaporation.
Figure 2.11: Diamonds indicate site mean $S$ of sphagnum versus site feather moss for the SSA-OBS. The linear fit between site mean $S$ for sphagnum and feather moss (solid line) indicates that sphagnum $S$ is consistently higher than feather moss $S$ during the same time period. +/- 95% confidence intervals of Difference in $S$ (dashed lines) indicates that the differences between site mean sphagnum and feathermoss $S$ at measurement scale increases to over 0.4 during dry periods.
Partitioning the land surface into sphagnum and feather moss regions does not explain all of the variation in \( S \) over the study site. Figure 2.12 shows the c.v. of \( S \) versus mean \( S \), over the site, for each moss type. The trend in the c.v. between moss types is similar, with a near constant level of the absolute variance of \( S \) at 0.10, irrespective of site mean \( S \). However, sphagnum mosses do not exhibit as large a range in \( S \) and therefore exhibit substantially lower spatial variability in \( S \) than feather mosses under similar environmental and canopy conditions.

The multiple feather moss turfs within each plot permitted examination of the partitioning of the spatial variation in feather moss moisture content between and within plots. Figure 2.13 shows the \( f \)-statistic, the ratio of the between plot to the average within plot variation, for both relative and absolute moisture content. The scatter in the \( f \)-statistic is large when mosses are near saturation, with within plot variation ranging from over twice that of between plot variation to under half the between plot variation. However, at low site mean \( S \), the scatter in the \( f \)-statistic is substantially lower; with both the variation in \( S \) and in \( \theta \) slightly larger within than between plots. While the existence of between plot variation in wetness was expected given the sampling design, the substantial within plot variation may be of significance to efforts at remote sensing patterns of moss moisture content.
Figure 2.12: Comparison of trends in site c.v. of $S$ vs. site mean $S$, together with linear fits, for feather moss and sphagnum turfs. The fitted lines suggest that both moss types experience a similar increase in relative variation in $S$ as the site dries down. The range of observed site mean $S$ for feathermoss extended from saturation to near dessication; while sphagnum site mean $S$ does not drop below 0.6.

feathermoss (— ; c.v. $S = -0.457 \text{ mean } S + 0.5872$; $r^2=0.72$, $n=40$);
sphagnum (---- ; c.v. $S = -0.5933 \text{ mean } S + 0.6368$; $r^2=0.5547$, $n=32$);
Figure 2.13: f-statistic of between to within plot variation in relative and absolute moisture content for feather moss turfs in SSA-OBS. The f-statistic is equivalent to the ratio of the between plot variation over the average within plot variation; corrected for loss in degrees of freedom due to parameter estimates. A linear fit is provided for pooled θ data. The poor fit ($r^2=0.49$) suggests that the partitioning of variation in θ does not change substantially during dry downs. The f-statistics for S suggests approximately equal between to within plot variance for low S but indicates large differences in variance partitioning for large S. The large S measurements were typically during rainy periods suggesting that differences between f-statistics for large S may be related to the impacts of antecedent moisture conditions and precipitation depth on patterns on S.
2.3.5 Feather Moss Evaporation

The average of feather moss $E^*$ over all valid measurement dates and samples within the SSA-OBS was 0.75 mm water day$^{-1}$. Coincident figures of overstory ET were not available at the time of the study. However, total $E^*$ was 26% of observed $P$, which suggests that it is likely an even larger fraction of site total ET. Figure 2.14 shows that, over the entire growing season, the average $E^*$ at a given plot differed by at most 0.14 mm water day$^{-1}$ from the site mean $E^*$. However, the f-statistic comparing the variation in between to within plot $E^*$ on any given day ranged from 1.1 to 8.2 with an average value of 3.8. This suggests that controls on between plot $E^*$ (such as canopy cover and variations in moss canopy depth) may be required to explain spatial patterns of $E^*$ across the site.

2.3.6 Correlations Between Throughfall, Moss Moisture, Evaporation and Cover

Pearson correlation coefficients between $r$, $C_w$, $C_h$ and parameters related to feather moss moisture content were computed at both plot and measurement gauge scales. Plot scale correlation coefficients ($\rho$) over 0.50 are indicated in bold in Table 2.1. The two estimates of canopy cover only showed a $\rho$ of 0.64 due to the previously mentioned differences in spatial support for the measurements. However, both canopy cover estimates were strongly correlated to $r$. This suggests that canopy cover may explain a substantial portion of the significant between plot differences in $r$ that were observed at the site. The correlation between canopy cover and $r$ likely represents a functional dependance between interception and foliage area. Figure 2.15 suggests that $\xi_c$, which can be mapped remotely [Chen and Cihlar 1996], may be used to describe spatial variations in $r$ between plot sized regions within a stand.

A linear prediction of $r$ as a function of $\xi_c$ and $P$ was estimated for the SSA-OBS:

$$r = 6.13 - 2.9\xi_c + 0.77P \quad n = 72 \quad r^2 = 0.96 \quad (5)$$
Figure 2.14: Plot mean feather moss $E^*$ over all valid dates during the measurement period at the SSA-OBS. The site mean $E^*$ was 0.75 mm water day$^{-1}$. The maximum difference in plot mean $E^*$ was approximately 0.25 mm water day$^{-1}$ while the maximum deviation from the mean $E^*$ was approximately 14 mm water day$^{-1}$. 
Figure 2.15: Relationship between growing season average $\tau$ and $\zeta$ for five of the seven moss plots within the SSA-OBS over which $\zeta$ was measured. $\zeta$ was measured during the middle of the field period with a LAI-2000 meter positioned within 5 m of the plot center. $\tau$ values represent averages over 5 gauges within each plot and over the 18 precipitation events. The linear fit suggests that within site variations in $\tau$ may be partially explained by canopy cover.

Linear fit: $\tau (\%) = -39.6 \zeta + 162.43$, $r^2 = 0.76$, standard error = 0.02, n=5.
Ideally, this relationship could be used to estimate spatial patterns of $\tau$ on an event basis. However, the relationship is only valid of $\mathcal{L}$ over 2.12 (the minimum observed plot mean $\mathcal{L}$) in order to ensure non-negative $\tau$. In addition, the standard errors for the intercept and $\mathcal{L}$ multiplier were large (2.17 and 0.96 respectively) due to the limited number and range of $\mathcal{L}$ observations. In contrast, the standard error of 0.02 for the $P$ multiplier reflects the precision of the relationship between $\tau$ and $P$ documented in Equation 4. The additional uncertainty due to the $\mathcal{L}$ information may not warrant application of Equation 5 without additional data over plots spanning a wider range of $\mathcal{L}$.

Both $\tau$ and canopy cover were not correlated to $E^*$. In addition, correlations above 0.5 between $\tau$ and $\theta$ or $S$ were only observed for $P$ below 5 mm water. However, as expected from laboratory studies [Williams and Flanagan 1996] $E^*$ exhibited strong correlations with indicators of moss wetness. The absence of strong correlations between plot means of canopy cover and $E^*$ and between $\tau$ and $E^*$ suggests that, over the 1994 growing season, feather moss evaporation may be limited by the moss canopy capacity, $\theta_{\text{max}}$, rather than by either evaporative demand or precipitation inputs. This hypothesis is supported by the high correlation between $E^*$ and $\theta_{\text{max}}$. It is possible that during very dry periods, or over other sites with a larger range in canopy cover, a stronger correlation may exists between canopy, $\tau$ and $E^*$.

Table 2.2 shows that, at measurement scale, significant correlations were only present between parameters describing the same process (e.g. $\tau$ and $\tau < 5mm$ or $S$ and $\theta$). The absence of high measurement scale correlations suggests that it may be difficult to map measurement scale variations in throughfall or moss moisture parameters using canopy cover information.
Table 2.1. Correlation coefficients for plot means of selected parameters. Canopy cover measurements were conducted between DOY 220 and 225. $E^*$ values represent averages over valid rain free dates. $\tau$ values represents averages over all rain events or over rain events with $P<5\text{mm}$. Moisture measurements represent mean values over all dry and rainy dates for feather moss turfs within plots. Values over 0.5 indicated in bold.

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Table 2.2. Correlation coefficients of measurement scale values of selected parameters. Canopy cover measurements were conducted between DOY 220 and 225. $E^*$ values represent averages over valid rain free dates. $\tau$ values represents averages over all rain events or over rain events with $P<5\text{mm}$. Moisture measurements represent mean values over all dry and rainy dates for feather moss turfs within plots. Values over 0.5 indicated in bold.

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<td>0.64</td>
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2.4 Conclusions

The conclusions and recommendations are separated according to the research question addressed:

1. Is the observed $\tau$ versus $P$ relationship similar in mature mesic conifer stands at both northern and southern extremes of the Boreal ecosystem?

Site mean $\tau$ was linearly related to $P$ with an increasing c.v. of within site $\tau$ with decreasing event size. The site mean $\tau$ versus $P$ relationship was similar for the SSA-OBS and NSA-JLK sites; even though the NSA-JLK site had far fewer stems and the sites were at opposite extremes of the latitudinal range of the Boreal ecosystem. The similarity in $\tau$ versus $P$ relationships between sites may be due in part to the a priori selection of mature Picea mariana stands or may indicate that the sites were larger than the dominant spatial scales of controls on this relationship in such stands.

2. How large is the difference in moisture content between sphagnum and feather moss turfs within the study site?

Sphagnum turfs always exhibited a larger $\theta$ than paired feather moss turfs. The difference in site mean $\theta$ never fell below 25.2 mm water while site mean $S$ was, on average, 25% larger in sphagnum turfs than feather moss turfs. The higher $S$ for sphagnum turfs, in comparison to feather moss, together with the co-occurrence of sparse canopies with sphagnum cover may explain in-situ observations of higher carbon and vapor fluxes in sphagnum regions [Goulden and Crill 1997]. Numerical models that estimate carbon and vapor fluxes in Boreal ecosystems may require a parameterisation for the proportion, if not the spatial organization, of moss cover type. An evaluation of the extent to which a model of fluxes in Boreal conifer stands is physically realistic should also include the extent to which estimated patterns of $\theta$ and $S$ match
field observations.

3. What are the dominant spatial scales of variation of $C$, $\tau$, $\theta$, $S$ and $E$ within a mesic conifer landscape?

A wavelet decomposition of $\zeta$ suggests that most of the variation in canopy cover existed at length scales at or below 20 m (plot scale). Evidence of substantial within plot variation in $C$, even with the averaging effect due to the densitometer field of view, supports the presence of substantial within plot scale variations in canopy cover. It is of note that the $\zeta$ transects did not extend over the entire site. It is possible that there was another dominant scale of spatial variation in canopy cover, perhaps corresponding to soil substrate and moisture status, that exceeds the wavelength of the 300 m $\zeta$ transects. The $C_h$ measurements suggest a higher canopy cover at the moss plots further from the flux tower (e.g. M2 and M3). However, the moss plots do not represent an exhaustive sample of the spatial pattern of canopy cover and the high $C_h$ moss plots may simply correspond to isolated regions with high canopy cover.

Plot $\tau$ differed from between 2% to 60% of the site mean $\tau$ when comparing averages over the measurement period. A two way ANOVA test suggests that plot mean $\tau$ did not change substantially over time. There was evidence at a significance level better than 0.02 of differences in between plot $\tau$ averaged over the measurement period suggesting between plot variation was substantial. The between plot differences may be due to between plot differences in canopy cover.

The coefficient of variation in $S$ was inversely proportional to site mean $S$ for both feather moss turfs and sphagnum turfs. The substantial variations in site mean $S$ at lower $S$ values may be of significance to models of moss fluxes since controls on moss conductance may be non-linear during low moisture regimes [Williams and Flanagan 1996]. Site mean $S$ for sphagnum turfs did not fall below 0.6 over the measurement period suggesting that a parameterization of
spatially variable water budgets may not be warranted within sphagnum dominated regions. In contrast, feather moss site mean $S$ dropped as low as 0.2. The relatively large c.v. of $S$ (50%) at low site mean $S$ suggests that some regions of the feather moss surface may have approached dessication at this point. As such, a parameterization for variations in feather moss moisture status may be warranted in models which consider moss moisture controls on moss fluxes.

Between plot variations in feather moss $\theta$ and $S$ were not substantially larger than within plot variations during dry periods suggesting that the increase in moss moisture content variability during dry downs occurs over both plot and site length scales. In contrast, between plot variations in $E^*$ were substantially larger than within plot variations. Differences in canopy cover between plots is one possible explanation for the between plot $E^*$ variations since sparse canopies should result in higher moss surface irradiance. However, the absence of a correlation between $E^*$ and the canopy cover measures seems to contradict this hypothesis. Instead, the strong correlation between $E^*$ and both $\theta_{\text{max}}$ and $\theta$ suggests that spatial patterns in feather moss evaporation are controlled more by the amount of moisture held in the moss canopy rather than by evaporative demand. Further in-situ measurements of moss water and energy budgets are required to verify this hypothesis.

5. **What is the co-variance of water budget components with canopy cover?**

Over 50% of the variance of $\tau$ at the measurement and plot scale was explained by patterns of canopy cover. In contrast, feather moss parameters such as $\theta$, $\theta_{\text{max}}$, $S$ and $E^*$ showed weak correlations to canopy cover at measurement and plot scale. The temporal average of $E^*$ was strongly correlated to most moss moisture content parameters at plot scale and uncorrelated with all parameters at measurement scale. The lack of measurement scale correlation may be due to the addition of within plot variations in evaporative demand due to fine scale canopy cover variations.

Over the observation period, site mean $\tau$ was slightly higher at the SSA-OBS site than at the
NSA-JLK site (26% of \( P \) versus 23% of \( P \)). The high correlation between canopy cover and \( \tau \) suggests that remotely sensed LAI maps could help to identify spatial variations in \( \tau \). ‘Whole system’ interception defined as overstory interception plus \( E^* \) comprised 53.1% of \( P \) at SSA-OBS in comparison to 41% of \( P \) at NSA-JLK. This suggests that moss evaporation is a significant source of total evaporation from this mesic Boreal conifer stand. The actual proportion of ‘whole system’ interception may be even higher if sphagnum mosses evaporation is higher than feather moss evaporation. The higher sphagnum \( S \) and maximum vapour conductance in comparison to feather mosses suggests that sphagnum mosses may display higher evaporation than feather mosses under the same evaporative demand. Testing of this hypothesis is inhibited by difficulties in measuring sphagnum evaporation rates in-situ without breaking capillary connections to the underlying peat while still accounting for the amount of capillary recharge.

Further research is also required to determine if parameterizations of within feather moss variations in moisture content may improve model based flux estimates. To this end estimates of the distribution of moss type and moss capacity within mesic Boreal conifer landscapes are required. Similarly, the impact of parameterizing spatial patterns of throughfall controls in flux models based on maps of leaf area or canopy cover should be assessed. Finally, coincident in-situ measurements of moss surface energy and water budgets and moss conductance should be conducted to address the lack of correlation between \( \tau \) and \( E^* \) and between canopy cover and \( E^* \).
2.5 References


CHAPTER 3

THE REFLECTANCE OF *Pleurozium schreberi* AS A FUNCTION OF MOISTURE CONTENT

Preliminary Discussion

This chapter corresponds to a paper published in the Proceedings of the 25th IEEE Geoscience and Remote Sensing Conference [Fernandes et al 1996]. The paper was motivated by empirical measurements reported in Chapter 2 and in Price et al [1996] identifying the moss carpet as a significant source of total ET in Boreal conifer stands. The paper was also motivated by laboratory evidence [Williams and Flanagan 1996], in-situ studies [Waddington and Roulet 1996; Goulden and Crill 1997] and the modelling study presented in Chapters 5 and 6 that suggest that a description of spatial variations in moss carpet hydrologic properties within a forest stand may be useful for accurate estimates of stand ET. Remote methods of monitoring patterns of moss moisture contents over large spatial extents have yet to be developed. The focus of this paper was on investigating the relationship between feather moss moisture content and reflectance in wavelengths currently available on orbital remote sensing platforms.

Objectives

This paper follows and extends the work of Vogelmann and Moss [1993] who related sphagnum moisture content to mid-infrared reflectance by:

i) relating feather moss reflectance in visible, near-infrared (NIR) and mid-infrared (MIR: also called infra-red, IR, reflectance in the paper) wavelengths to moisture content

ii) determining the expected signal-to-noise ratio of the moisture content versus reflectance

67
relationships by performing a replicate experiment within and between moss turfs

iii) examining the extent to which the laboratory observations matched preliminary field
reflectance data.

The first two objectives dealt with defining an empirical forward model relating feather moss
moisture content to reflectance in wavelengths of orbital remote sensing devices (e.g. LANDSAT TM). The study found that feather moss turfs exhibited a regular increase in MIR reflectance with decreasing moisture content; with far greater dynamic range than the typical variation of MIR reflectance between or within turfs at the same moisture content. This relationship was similar to that found by VogelMann and Moss [1993] and was expected given the decrease in water absorption in MIR wavelengths during drying. The expected increase in red reflectance with drying due to chlorosis was not observed until dessication. Prolonged conditions of very low moisture feather moss content were not observed at the SSA-OBS during the experiment conducted in Chapter 2. This suggests that feather moss red reflectance would typically not change due to in-situ moisture content variations.

**Relationship to Dissertation Papers**

In addition to motivating this study, the in-situ observations of moss moisture content presented in Chapter 2 verified that the expected dynamic range of top of moss reflectance would likely be sufficient to discriminate between saturated and dry mosses. This would be useful for discriminating between saturated and dry mosses and between sphagnum mosses, which remain near saturation, and feather mosses, which dry down in the absence of rain.

The evidence of a strong relationship between moss moisture content and top of moss reflectance motivated a subsequent study, described in Chapter 4, which focussed on the use of MIR reflectance imagery to identify in-situ moss moisture patterns and moss functional groups.
Statement of Original Work

The text, charts and figures were produced by the present author. The third and fifth authors provided editorial comments regarding grammar and sentence phrasing.

Research questions, laboratory measurements, statistical analyses, discussions and conclusions were entirely the work of the present author. In-situ data was provided by the second author.

This paper represents original contributions in its characterizations of the spectral reflectance of feather mosses as a function of moisture content and in its quantification of the typical variation of spectral reflectance between moss turfs.

References


The Reflectance of *Pleurozium schreberi* as a Function of Water Status and its Implications on Understory Reflectance Variations for BOREAS Sites

Richard Fernandes, H. Peter White, Derek R. Peddle, John R. Miller, Lawrence E. Band

Abstract

A controlled laboratory experiment was conducted to test the null hypothesis that the nadir reflectance of *Pleurozium schreberi* (a feather moss) in the red ($\rho_{\text{RED}}$), near-infrared ($\rho_{\text{NIR}}$), and infrared ($\rho_{\text{IR}}$) bands is not a function of live layer moisture content. Reflectance spectra were acquired from replicate moss turfs over five dry down stages ranging from 4.8 g water/g moss (g/g) to 0 g/g. Replicate spectra showed a maximum 13.5% increase in $\rho_{\text{RED}}$; almost no significant change in $\rho_{\text{NIR}}$; and an over 20% increase in $\rho_{\text{IR}}$. However, $\rho_{\text{RED}}$ increases due to drying were less than 2% until dessication; suggesting that chlorosis would not normally affect $\rho_{\text{RED}}$ under typical field moisture contents. Inter-replicate differences in reflectance were often larger than dry down differences. NIR understory reflectance measured in a moss dominated BOREAS site showed a significant seasonal change in $\rho_{\text{NIR}}$ which is not likely due to moisture variations.

3.1 Introduction

A large proportion of the northern boreal forest consists of *Picea mariana* Mill. BSP (black spruce) stands with a moss dominated understory [Bonan and Shugart 1989]. The low canopy cover of black spruce stands suggests that factors influencing understory reflectance should be identified both to assist remote sensing efforts and to parameterize carbon flux models. Field measurements of *Pleurozium schreberi* dominated understories indicated some seasonal variations in nadir reflectance [White et al 1995]. The relationship between moss moisture contents and changes in surface nadir reflectance ($\rho$) has not been investigated. This study represents an initial controlled
experiment to determine if \( \rho \) variations observed in the field could be driven by, or even supplemented by, variations due to moisture content.

3.2 Purpose and Hypotheses

The purpose of the experiment was to determine the relationship between moss moisture content and moss reflectance. The experiment also addressed the lack of controlled characterizations of \( \rho \) of *Pleurozium schreberi* and feather moss in general. Finally, the experiment provided information regarding the relative magnitude of between treatment versus between replicate variations of \( \rho \). The experiment measured \( \rho \) over a large number of bands. However, for convenience, hypotheses referred to LANDSAT TM bands \( \rho_{\text{RED}} \) (630 nm to 690 nm), \( \rho_{\text{NIR}} \) (760 nm to 900 nm) and \( \rho_{\text{IR}} \) (1550 nm to 1750 nm).

The null hypothesis was that \( \rho_{\text{RED}}, \rho_{\text{NIR}}, \rho_{\text{IR}} \) of the surface of a live layer of *Pleurozium schreberi* is not related to live layer moisture content. The lack of controls and monitoring of other moss characteristics prohibited the definition of an alternate hypothesis that attributed changes in \( \rho \) to moisture alone. An additional null hypothesis that the between replicate differences in \( \rho \) are not significantly less than the treatment differences was also tested. If \( \rho \) varied more between replicate rather than between treatments one would suggest that factors other than moisture may also cause variations in \( \rho \). It should be noted that the significance tests are only strictly applicable to the moss turfs measurements performed in this study. More replicates of moss turfs from other regions in the Boreal ecosystem would be required to extend these results to other moss covered regions.

3.3 Materials and Methodology

The laboratory experiment used three turfs (A,B, and C) of live moss. The turfs were harvested near the end of a prolonged rain event at a *Pinus sylvestris* stand at approximately 78° W longitude and 43°40' N latitude in Ontario, Canada. Each turf had a 20cm long x 20cm wide x 8cm deep live
layer. The turfs were acclimatized to the laboratory room for 24 hours. Loose litter was removed from the turf surfaces. The live layer of each turf was removed and mounted on a pre-weighed mesh platform. A fourth turf (D) represented desiccated moss. This turf had been harvested at the BOREAS Northern Old Black Spruce (NOBS) field site and oven dried at 50°C until desiccated.

The York University BRDF facility was used to acquire radiance measurements. A 1000W halogen lamp with a collimated beam provided illumination at a 45 degree zenith angle. An ASD field spectrometer measured target nadir radiance in 1 nm bands from 350 nm to 1750 nm. A 2" field of view lens was used with the spectrometer giving a 2.5 cm diameter target size. A Spectrolon panel was used as a white reference.

Turfs A.B. and C dried down in four stages (including the initial wet stage) over a period of 30 hours. A table fan on its lowest setting was used to speed drying. In contrast to the dry down turfs, Turf D was desiccated by oven drying at 50 degrees C and periodically weighing until the turf mass dropped by less than 1% of the mass at saturation. Turf D was assumed representative of all turfs at desiccation. The Spectrolon panel radiance was measured at the start of each dry down stage. Each turf was weighed and nine non-overlapping radiance measurements of the turf surface were acquired during each dry down stage. The ρ spectrum corresponding to a radiance measurement was estimated using the Spectrolon panel radiance measurement for the dry down stage. Mean spectra were computed for each set of nine ρ spectra.

3.4 Observations and Analyses

Figure 3.1 shows the mean spectra for A at each dry down stage. Tables 3.1.3.2, and 3.3 give the mean and standard deviation of mean ρRED, ρNIR, and ρIR for A, B, and C. A "*' symbol is indicated beside measurements which provided evidence against the null hypothesis that there is no difference between reflectance at a given dry down stage compared to the initial wet stage at a 95% significance level. A "**" symbol is indicated besides stages where there was evidence against the null hypothesis that replicates A and B have the same mean reflectance at a 95% significance level.
C started at a higher initial moisture content and was not used for testing the second null hypothesis. A and B had almost identical initial moisture contents of 3.4 g/g and 3.27 g/g and dried to 1.25 g/g and 1.06 g/g respectively. C started at a moisture content of 4.8 g/g and dried down to 1.47 g/g. The moisture contents measured were lower than the range of 14.6 g/g to 1.27 g/g measured at the NOBS site during August 1994 and the field dry down rates were lower than those observed in the laboratory. However, moisture contents and dry down rates observed in the lab were similar to those reported at other black spruce sites [Skre et al 1985].

Figure 3.1 and Table 3.1 indicate a statistically significant increase in $\rho_{RED}$ on the order of 1% prior to dessication. At desiccation (stage 5) a 14.5% increase in $\rho_{RED}$ in comparison to the stage 1 was noted. The increases in $\rho_{RED}$ were likely due to a reduction in red absorption due to chlorophyll depletion bought about by moisture stress [Busby and Whitfield 1977]. Figure 3.2 shows moss dominated understory mean $\rho$ at the BOREAS Southern "Old Black Spruce" (SOBS) site. The slight increase in $\rho_{RED}$ over the growing season may be due to moisture differences rather than seasonal changes.
Table 3.1 Mean and standard deviation of $p_{\text{red}}$ during dry down. Three moss turfs (A, B & C) were dried over five stages from near saturation (stage 1) to near dessication (stage 4). Stage 5 corresponded to a single over dried turf. A total of 9 non-overlapping spectra were sampled from each turf to estimate the mean and standard deviation.

<table>
<thead>
<tr>
<th>Stage</th>
<th>$p_{\text{red}}$</th>
<th>1σ</th>
<th>$p_{\text{red}}$</th>
<th>1σ</th>
<th>$p_{\text{red}}$</th>
<th>1σ</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.23</td>
<td>2.95</td>
<td>0.18</td>
<td>2.69</td>
<td>0.13</td>
</tr>
<tr>
<td>2**</td>
<td>3.49*</td>
<td>0.15</td>
<td>4.10*</td>
<td>0.23</td>
<td>4.01*</td>
<td>0.26</td>
</tr>
<tr>
<td>3**</td>
<td>3.31</td>
<td>0.26</td>
<td>4.42*</td>
<td>0.33</td>
<td>4.11*</td>
<td>0.39</td>
</tr>
<tr>
<td>4</td>
<td>3.68*</td>
<td>0.14</td>
<td>4.03*</td>
<td>0.28</td>
<td>4.09*</td>
<td>0.31</td>
</tr>
<tr>
<td>5</td>
<td>16.3*</td>
<td>0.91</td>
<td>16.3*</td>
<td>0.91</td>
<td>16.3*</td>
<td>0.91</td>
</tr>
</tbody>
</table>

* indicates a significant difference between the turf at Stage 1 and at the current stage.
** indicates a significant difference between samples from turf A and B at the indicated stage.

Table 3.2 Mean and standard deviation of $p_{\text{air}}$ during dry down. Refer to Table 3.1 for additional details.

<table>
<thead>
<tr>
<th>Stage</th>
<th>$p_{\text{air}}$</th>
<th>1σ</th>
<th>$p_{\text{air}}$</th>
<th>1σ</th>
<th>$p_{\text{air}}$</th>
<th>1σ</th>
</tr>
</thead>
<tbody>
<tr>
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<td>2.1</td>
<td>26.3</td>
<td>0.53</td>
<td>29.8</td>
<td>1.1</td>
</tr>
<tr>
<td>2**</td>
<td>24.4</td>
<td>1.2</td>
<td>29.4*</td>
<td>1.7</td>
<td>35.1*</td>
<td>2.4</td>
</tr>
<tr>
<td>3**</td>
<td>20.8</td>
<td>1.4</td>
<td>28.1</td>
<td>1.6</td>
<td>35.8*</td>
<td>2.1</td>
</tr>
<tr>
<td>4**</td>
<td>21.8</td>
<td>1.0</td>
<td>25.9</td>
<td>1.4</td>
<td>33.3*</td>
<td>2.1</td>
</tr>
<tr>
<td>5</td>
<td>29.3*</td>
<td>1.5</td>
<td>29.3*</td>
<td>1.5</td>
<td>29.3*</td>
<td>1.5</td>
</tr>
</tbody>
</table>

* indicates a significant difference between the turf at Stage 1 and at the current stage.
** indicates a significant difference between samples from turf A and B at the indicated stage.

Table 3.3 Mean and standard deviation of $p_{\text{ir}}$ during dry down. Refer to Table 3.1 for additional details.

<table>
<thead>
<tr>
<th>Stage</th>
<th>$p_{\text{ir}}$</th>
<th>1σ</th>
<th>$p_{\text{ir}}$</th>
<th>1σ</th>
<th>$p_{\text{ir}}$</th>
<th>1σ</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1</td>
<td>11.3</td>
<td>0.57</td>
<td>9.2</td>
<td>0.83</td>
</tr>
<tr>
<td>2**</td>
<td>28.1*</td>
<td>1.6</td>
<td>24.7*</td>
<td>1.4</td>
<td>38.3*</td>
<td>1.6</td>
</tr>
<tr>
<td>3</td>
<td>30.8*</td>
<td>2</td>
<td>31.4*</td>
<td>2.7</td>
<td>43.4*</td>
<td>3.1</td>
</tr>
<tr>
<td>4</td>
<td>31.3*</td>
<td>1.3</td>
<td>34.4*</td>
<td>1</td>
<td>40.7*</td>
<td>2.4</td>
</tr>
<tr>
<td>5</td>
<td>39.6*</td>
<td>1.6</td>
<td>39.6*</td>
<td>1.6</td>
<td>39.6*</td>
<td>1.6</td>
</tr>
</tbody>
</table>

* indicates a significant difference between the turf at Stage 1 and at the current stage.
** indicates a significant difference between samples from turf A and B at the indicated stage.
Figure 3.1: Mean *Pleurozium schreberi* nadir reflectance at five dry-down stages. Reflectance spectra correspond to the mean reflectance of nine non-overlapping measurements acquired from Turf A (stages 1 through 4) and an oven dried turf (stage 5). Moisture content ranged from near field capacity for stage 1 to dessicated at stage 5. Refer to the text for moisture contents. Spectra indicate a regular and large increase in infra-red reflectance (1400nm to 1750nm) with drying. (Stage is indicated on the right side of each spectra).
Figure 3.2: Mean reflectance of moss dominated sunlit understory in the BOREAS Southern OBS site during middle and late growing season. The understory consisted of a mixture of feather moss, herbs and needle litter.
Figure 3.1 and Table 3.2 indicate a significant change in $\rho_{\text{NIR}}$ only between stage 1 and 2 and only for B and C. Both A and B show no evidence against the null hypothesis that $\rho_{\text{NIR}}$ did not change with dry down between stages 1 to 4. C showed evidence against this null hypothesis at all stages. There was evidence against the null hypothesis that there are no replicate differences at all stages. The large inter-replicate differences in $\rho_{\text{NIR}}$ suggested that moisture differences were not the primary cause of $\rho_{\text{NIR}}$ variations during dry down. Cellulose and lignin in plant matter give rise to scattering in NIR [Knipling 1970]. The large inter-replicate $\rho_{\text{NIR}}$ variations may be due to differences in moss shoot density and needle litter density in the turfs. Figure 3.2 shows a large increase in $\rho_{\text{NIR}}$ over the growing season at the SOBS site. This increase may be due to organic matter such as needles that were trapped in the moss surface.

Figure 3.1 and Table 3.3 indicate that there was evidence against the null hypothesis that moisture is unrelated to $\rho_{\text{IR}}$ at all dry down stages for all replicates. A 30% absolute increase in $\rho_{\text{IR}}$ was noted between stage 1 and 4. In addition, Figure 3.1 indicates that the increase in $\rho_{\text{IR}}$ is monotonic with decreasing moisture content. Only stage 2 showed evidence against the null hypothesis that there were no inter-replicate differences in $\rho_{\text{IR}}$.

3.5 Conclusions

The turfs tested spanned a plausible range of moisture contents and dry down rates. There was evidence against the null hypothesis that moss moisture content and nadir reflectance are not related in $\rho_{\text{RED}}$; no evidence in $\rho_{\text{NIR}}$; and strong evidence in $\rho_{\text{IR}}$. The absolute magnitude of the change in $\rho_{\text{RED}}$ was near 1% until desiccation, at which point it jumped to over 10%. There was a monotonic increase in $\rho_{\text{IR}}$ of up to 30% during dry downs.

There was infrequent evidence against the null hypothesis that there are no inter-replicate differences in $\rho_{\text{RED}}$ and $\rho_{\text{IR}}$; while there was strong evidence with $\rho_{\text{NIR}}$. It was suggested that the inter-replicate differences in $\rho_{\text{NIR}}$ are due to differences in structural organic matter, such as...
needles, trapped in the moss. The increase in $\rho_{\text{NIR}}$ observed in the field may be due to an increase in needle litter and understory herb cover later in the growing season.

The very small changes in $\rho_{\text{RED}}$ during drying, coupled with canopy absorption in $\rho_{\text{RED}}$, suggest that both ecosystem flux models and remote sensing models need only consider moisture driven changes in $\rho_{\text{RED}}$ at the onset of dessiccation. Coincident in-situ measurement of moss moisture status and reflectance could be performed to determine the cause of seasonal changes in $\rho_{\text{IR}}$. Additional replicates would permit analysis of the proportion of $\rho$ variation due to moisture alone. Significant changes in understory $\rho_{\text{IR}}$ due to moisture may have an effect on understory net radiation, surface heating, and top of canopy radiance. The observed relationship between moss moisture status, if supported by further dry down measurements, could be incorporated in remote sensing models and may give information regarding spatial variations of surface moisture if atmospheric and canopy related effects can be modeled.

3.6 References


CHAPTER 4

MAPPING SURFACE WETNESS IN BOREAL CONIFER STANDS USING MID-INFRARED REFLECTANCE

Preliminary Discussion

This chapter corresponds to a talk presented at the American Geophysical Union 1997 Winter Meeting under the title [Fernandes et al 1997]. The research was motivated by the need to map persistent surface wetness patterns within mesic Boreal conifer stands. Soil surveys undertaken during the BOREAS experiment indicated substantial spatial variations in soil and moss water budgets within mesic conifer study sites. Chapter 2 documents substantial differences in moisture contents between sphagnum and feather moss regions within a 1 km² mesic conifer study site (the SSA-OBS). Measurements at the NSA-OBS site [Goulden and Crill 1997] demonstrated differences in energy and carbon fluxes between regions of different moss types within the study sites. Chapters 5 and 6 of this dissertation demonstrate that flux model accuracy is significantly higher with a spatially variable moss layer in comparison to other models using a uniform moss layer or no moss layer. These results suggest that a remote means of mapping surface wetness and moss functional groups may be of use for accurate regional estimates of Boreal ecosystem fluxes.

Objectives

The study related top of moss MIR reflectance to top of canopy reflectance and used previous information relating moss moisture content to top of moss reflectance to estimate moss surface wetness remotely. A numerical modelling approach was used due to the difficulty in acquiring coincident in-situ moss moisture content, overstory structural and top of canopy reflectance data. The model selected [Myneni et al 1992] had been previously validated in northern conifer stands and was adopted as a preliminary means of addressing following objectives:
i) to integrate relationships between moisture content and top of moss reflectance for sphagnum and feather moss;

ii) to use observed parameters describing a candidate mesic conifer stand to define a model based top of moss versus top of canopy reflectance transfer function without calibration to observed top of canopy reflectance;

iii) to define and apply an inverse model relating top of canopy reflectance to moss moisture content so as to map moss moisture and moss type (sphagnum or feather moss) in regions with independent canopy information.

The first objective demonstrated that both feather moss and sphagnum moisture content versus reflectance relationships were remarkably similar; even though the two data sets were acquired using different apparatus, illumination and regional sources of moss samples.

The second objective demonstrated the use of standard measurements of allometric and optical properties of Boreal conifer stands to generate a plausible forward reflectance model without calibration to observed top of canopy reflectance. Calibration was avoided as it would hamper application of the reflectance model over regional extents where in-situ validation data would not be available. There was insufficient coincident information on canopy and moss properties to permit complete model validation; especially given that true validation would require observations over a number of illumination conditions. Instead the model was used as a means of providing a preliminary indication of the dynamic range of the moisture-content versus top of canopy reflectance in comparison to the moisture content versus top of moss reflectance relationship.

The third objective made use of a LANDSAT TM scene to demonstrate the mapping of surface wetness and moss type using model based MIR inversion. Difficulties were encountered in comparing the inverted moss maps with manually produced maps due to differences in the concept of spatial support for mapping regions (e.g. regular pixel grids versus mixture distributions within
The MIR method demonstrated the ability to provide remote estimation of the proportion of sphagnum and feather moss within a study plot. However, the accuracy of the estimated proportion was sensitive to the threshold chosen for defining the maximum possible feather moss moisture content. Therefore the precision of the estimated proportion was low due to difficulties in mapping canopy cover.

**Relationship to Dissertation Papers**

This study used the in-situ evidence of differences between sphagnum and feather moss regions presented in Chapter 2 together with model based evidence of the need to parameterize these differences, reported in Chapter 5 and 6, to define the problem of mapping surface wetness patterns in mesic Boreal conifer stands. The moss map was incorporated into the NEP modelling study reported in Chapter 7 to demonstrate the possibility of replacing in-situ soil maps with remotely sensed moss maps.

**Statement of Original Work**

Components of the research related to application of the reflectance model using existing data sets were contributed by the present author. The reflectance model represents a slightly modified version of the model presented by Myneni et al [1992]. Original development of a crown clumping effect within the reflectance model was performed by the present author. Data sets provided by other BOREAS science teams are cited. This was the only study within the BOREAS experiment which has currently produced a remote map of moss type and spatial wetness. Finally the physically based inverse model estimation of moss moisture content represents an original and necessary contribution to the field of environmental monitoring in Boreal ecosystems.
References


MAPPING SURFACE MOISTURE AND MOSSES IN BOREAL ECOSYSTEMS USING MID-INFRARED REFLECTANCE IMAGERY

4.1 Introduction

The Boreal ecosystem extends over a circumpolar region of approximately 20 million km² [Bonan and Shugart 1989]. A shift in the Boreal carbon budget from a sink or weak source of atmospheric CO₂ to a strong source has been hypothesized in response to current and predicted global warming [Goreham 1991, Solomon and Leemans 1997]. This shift may increase the already high levels of atmospheric CO₂ present due to anthropomorphic inputs [Keeling et al. 1996] and hence be of concern to humanity.

Goreham [1991] hypothesized that the chief mechanism responsible for a shift in the Boreal carbon budget would be an increase in soil respiration due to drainage of moss covered peat soils. The substantial decrease in soil organic matter observed after peatland drainage provides anecdotal evidence in support of this mechanism [Paavilainen and Paivanen 1997]. However, it is also possible that an increase in aboveground productivity could balance losses of soil carbon. Aboveground productivity increases of 100% have been observed in Boreal conifer stands following drainage [Paavilainen and Paivanen 1997]. In addition, analysis of satellite data has indicated a lengthening of the growing season at the northern edge of the Boreal ecosystem corresponding to climate warming trends [Myneni et al. 1997]. A rigorous test of the hypothesis that soil organic matter losses would exceed productivity gains under climate change or severe anthropomorphic disturbances requires an accurate model of Boreal ecosystem carbon, energy and water cycles. Furthermore, spatial variations in climate and surface conditions within the Boreal ecosystem require that the model has sufficient input information to be applied over regional extents.

One aspect of the Boreal Ecosystem Atmosphere Study (BOREAS) was to develop regional models of Boreal ecosystem carbon, water and energy budgets together with remote sensing methods for parameterizing these models over regional extents [Sellers et al. 1995]. The BOREAS study region
covered a 1000 km x 1000 km area in Saskatchewan and Manitoba, Canada as depicted in Figure 4.1. Two intensive study areas of approximately 1000 km² were defined at the northern and southern extents of the study region to capture latitudinal climate extremes and attendant shifts in ecosystem state. The study areas are depicted in Figure 4.1 as the Northern Study Area (NSA) and Southern Study Area (SSA). Figure 4.2 indicates soil drainage classes over the NSA mapped using manual air-photo interpretation and in-situ survey [Veldhuis 1997]. Land cover mapping indicated that wet conifer sites covered between 83% and 91% of the land surface in both the study areas and the entire study region [Steyart et al 1997]. The predominance of the wet conifer class, together with the absence of significant spatial wetness variations within dry conifer stands and burnt regions, limited the focus of the current study to mapping properties of wet conifer stands. The inset in Figure 4.2 provides an example of the substantial spatial variations in wetness within the NSA Old Black Spruce (OBS) wet conifer stand selected for intensive study in this research.

In the remainder of this section the relationship between surface wetness patterns and fluxes within wet conifer stands is reviewed; research questions regarding remote mapping of these spatial variations are presented; and an outline of the manner in which the rest of this paper addresses the research questions is provided.

4.1.1 Relationship Between Surface Wetness Patterns and Fluxes

Boreal wet conifer stands are distinguished from other conifer stands in their low overstory biomass and in the presence of a continuous carpet of mosses and lichens over a well developed layer of peat [Shugart 1992]. Chapter 2 describes measurements at a 1 km² study site in the SSA (the SSA-OBS), summarized in Figure 4.3, that suggest that moss moisture content is significantly different between two major moss functional groups. Inundated and saturated regions within both OBS study sites contained either bare peat or Sphagnum spp. mosses and typically corresponded to mean water table depths of less than 0.10 m during the growing season [Veldhuis 1997. Anderson 1997]. Better drained regions were covered by feather mosses such as Pleurozium schreberi, Typhnum nitens and Hyclonium splendens and typically corresponded to mean water table depths between 0.50 m and 2.0 m during the growing season.
Figure 4.1: Canadian land cover map indicating the BOREAS study region and Northern Study Area and Southern Study Area. The study areas were selected by the BOREAS science teams to represent the northern and southern extremes of the central Canadian Boreal forest ecosystem. The sturdy areas were chosen for the application of ecosystem flux models and for investigations dealing with mapping of required model parameter fields. Observations from both study areas are used to support forward reflectance model development. In situ data from a wet conifer site in the SSA was used to determine typical moss moisture contents. Surface wetness maps were only generated over the NSA due to the lack of calibrated satellite imagery over the SSA. (Source: NASA GSFC)
Figure 4.2: Drainage class map in the NSA and the NSA-OBS site. The maps were generated by air photographs, in-situ monitoring and soil pits. The OBS map included soil pits and in-situ measurements for all soil polygons and was provided gridded at 10m resolution. The NSA map relied extensively on air-photo interpretation and was provided gridded at 30m resolution. Each soil polygon included a mixture distribution of up to three soil cover strata (e.g. well drained feather moss, poorly drained sphagnum and very poorly drained inundated areas).

(Source: Veldhuis, 1997 from in-situ survey and air-photos).
Figure 4.3: In-situ live layer mean and +/- 1 standard deviation of moisture content of sphagnum (n=6) and feather moss turfs (n=35) at the SSA-OBS site during 1994. Sphagnum and feather moss turfs were paired to account for variability in throughfall and evaporative demand.
Laboratory experiments have indicated that the *Sphagnum* sp. (section acutifolia) mosses, common in Boreal conifer stands, have as much as 100% higher conductance to vapour flux and 350% higher conductance to CO$_2$ flux than *Pleurozium schreberi* at equal moisture contents [Williams and Flanagan 1996]. This data, together with substantially higher sphagnum moisture contents *in-situ* support the potential for larger fluxes from sphagnum regions in comparison to feather moss regions under similar forcings of radiation and temperature. Field measurements within the NSA-OBS found gross production at sphagnum surfaces to be 150% greater than that from feather moss surfaces [Goulden and Crill 1997]. Studies in other wet conifer stands have also linked spatial variations in moss moisture content to variations in CO$_2$, CH$_4$ and vapour fluxes [Waddington and Roulet 1994, den Hartog et al 1994]. Sellers et al [1997] concluded that the primary control on carbon accumulation in peat and moss is drainage. This conclusion, when placed in context of estimates that Boreal peatlands store 43% of worldwide soil carbon [Schlesinger 1991], suggests that knowledge of surface wetness and moss cover patterns may be a prerequisite for accurate models of carbon and water balances in the Boreal ecosystem.

4.1.2 Research Questions

Wet conifer stands covered over 75% of the BOREAS study area [Steyaert et al 1997] and therefore represent an important target for mapping applications. In-situ measurements and model based analysis of vapour fluxes (presented in chapter 5 and Chapter 6) have identified the need for information regarding spatial variations in moss species cover and moss moisture within wet conifer stands as small as 1 km$^2$. This need motivated the following research questions regarding the use of remote sensing methods suitable for mapping information regarding moss patterns over Boreal ecosystem:

Is it possible to map the spatial pattern of moss moisture content over wet conifer sites at fine (30m) resolution?
Is it possible to identify the area covered by each moss functional group (*Sphagnum* spp. versus feather mosses such as *Pleurozium schreberi*), over a selected 1km² wet conifer site, using 30m resolution reflectance imagery?

4.2 Scope of Study

This study is an exploratory, proof of concept, investigation of one method for mapping surface moisture patterns in Boreal conifer stands. The relationship between moss moisture content and top of moss reflectance ($\rho_{TOM}$) is specified. A method for estimating surface moisture content by inverting a physically based model of MIR top of canopy (TOC) reflectance ($\rho_{MIR,TOC}$) is developed. The inverse model sensitivity to input parameters is characterized and its performance when mapping surface moisture and moss cover fractions at the NSA-OBS site is reported.

The scope of the study was intentionally limited to make use of available data sets. Calibration to observed top of canopy (TOC) reflectance for the forward canopy reflectance model and to moss cover type or moss moisture patterns for the inverse model was not permitted. Logistical difficulties in acquiring coincident reflectance, canopy structure and moss moisture data over the field of view of remote sensing instruments limited model validation to a basic exploration of model plausibility. The further complication of natural variations in illumination conditions, especially due to forest fires, supported the suggestion that this study should be considered a feasibility study for further in-situ and remote data acquisition.

4.2.1 Spatial Scope

This study is limited to the NSA due to the lack of surface validation data and calibrated reflectance imagery in the SSA and other locations in the BOREAS study region. Only wet conifer stands were considered given that they cover approximately 90% of the NSA [Steyart et al 1997]. It was further assumed that the conifer overstory consisted completely of *Picea mariana* stems with spatially uniform diameter at breast height (*dbh*) and associated allometric properties to simplify parameterization of the forward reflectance model.
Dry conifer sites, with dominant species other than *Picea mariana*, were not treated in this study. In-situ monitoring within these stands indicated low spatial variations in soil moisture [Cuenca et al 1997] and spatially uniform moss/lichen cover [Veldhuis 1997, Anderson 1997, Halliwell and Apps 1997]. In addition, Chapter 6 demonstrates that the model based estimates of ET at dry conifer sites did not differ significantly between parameterizations using a single patch of soil and lichen cover versus multiple patches corresponding to spatial patterns of surface cover mapped in-situ.

A single wet conifer site, the NSA-OBS, was chosen as a representative site for forward model parameterization. This site was also chosen given coincident calibrated reflectance imagery and in-situ soil wetness maps. A number of similar sites were used to explore the plausibility of the forward model. These sites, surveyed during the BOREAS [Loechel et al 1997] and Superior National Forest Study [Hall et al 1992], provided allometric and reflectance data over a range of mature Boreal *Picea mariana* stands. Validation of the inverse model was only performed at the NSA-OBS site due to the lack of fine resolution (10 m grid) soil maps over other mature wet conifer regions. Nevertheless an unvalidated map of surface moisture for all regions in the NSA containing mature wet conifer stands was also produced.

### 4.2.2 Temporal Scope

A single LANDSAT TM reflectance image, acquired on June 16 1995, was available for this study. The image was acquired six days after a 1.5 mm water precipitation event. Observations at the OBS sites, reported in Chapter 2, suggested that the feather moss moisture content was likely below 1.5 g water/g moss (g/g) and the sphagnum moisture content above 6 g/g during the image acquisition. Ideally, multiple images, during different stages of dry downs, could have been analysed to reduce errors in model inversion. However, the physically based model approach adopted in this study precluded the use of available uncalibrated reflectance imagery or imagery over a time span of years due to the potential for changes in canopy conditions. Mapping canopy cover and changes in canopy cover with time was beyond the scope of this paper. The lack of calibrated reflectance data coincident with in-situ moss moisture measurements also limited validation efforts.
4.3 Review of Optical and IR Remote Sensing of Moisture Content

This section reviews methods for remote estimation of moss surface moisture content ($\theta$) in Boreal conifer stands over regional extents. Constraints to this estimation problem are identified. Methods for indirect estimation of $\theta$, for example by estimating surface temperature or moss species, are discussed. The use of reflectance in visible and infrared wavelengths to directly measure moisture status of mosses is examined. Active radar sensors are not discussed as they are reviewed elsewhere [Wei 1995] and were the subject of a parallel BOREAS investigation [Saatchi et al 1995]. Finally, reasons supporting the selection of the 1.55 $\mu$m to 1.75 $\mu$m MIR reflectance band for moisture mapping are provided.

4.3.1 Indirect Estimation of Moisture Status

Broad band visible and infrared (IR) radiance sensors such as LANDSAT TM and System Probataire l’Observation Terrestrielle (SPOT) offer sufficient spatial resolution and coverage to resolve sub-grid (<1 km) patterns over large regions. The sub-monthly overpass period is sufficient for at least annual updates of moss cover type after scenes obscured by cloud or forest fire cover are discarded. Visible and near-infrared (NIR) reflectance data has been combined with thermal radiant surface temperature data to estimate surface moisture status [Nemani et al 1993]. This technique assumes that surface radiometric temperatures are related to aerodynamic temperature which controls sensible heat fluxes and indirectly, other components of the energy budget [Norman et al 1995]. Mahrt et al [1997] found that this assumption was violated over wet conifer sites within the BOREAS study region. Mosses exhibit significant (10°C) jump in surface temperature when they are dry [den Hartog et al 1994]. This temperature jump could be identified by thermal infra-red sensors. However, feather mosses desiccate infrequently while sphagnum mosses were not observed to drop below 50% relative moisture content during the field study reported in Chapter 2. The lack of frequent or spatially extensive desiccated conditions suggests that reliable monitoring could not be guaranteed. Furthermore, detecting moss temperature shifts requires correction for overstory contributions to at-sensor radiant temperature. Czajowski et al [1997] reported that at a regional level over the BOREAS study region the use of normalized difference vegetation index and radiometric
temperature to infer air temperature resulted in errors as large as +/- 15 K. These errors, attributed to sub-pixel clouds, standing water, and smoke particles, would likely also cause difficulties if the same remotely sensed parameters were used for mapping surface moisture status.

Narrow band (less than 5 μm) optical sensors may be capable of identifying mosses based on absorption phenomena in the NIR and MIR regions of the spectrum [Bubier et al 1997]. Knowledge of moss type may provide information regarding the persistent spatial differences in moss moisture reported in Chapter 2 and information regarding water table depth related to moss cover type. However, calibrated fine spectral resolution data were not available over the NSA at the time of this study. There are also no calibrated orbital narrow band sensors available for civilian use with spatial resolution comparable to LANDSAT TM and SPOT. In addition, it is not clear how the overstory might mask these features since most canopy reflectance models make use of broad band component reflectance.

4.3.2 Direct Measurement of Moisture Status

Surface moisture may also be estimated directly from optical information rather than inferring moisture from surface temperature data or by mapping moss functional types with narrow band information. Three major factors which determine the effectiveness of given wavelengths for moisture estimation are reviewed in this section.

Factor 1: Sensitivity of the relationship between reflectance and moss moisture.

Results from a laboratory dry down study shown in Figure 4.4 suggested that feather mosses do not exhibit significant changes in visible and NIR reflectance until complete dessication [Fernandes
Figure 4.4: Reflectance of *Pleurozium schreberi* and *Sphagnum cuspidatum* as a function of live layer moisture content. Feather moss moisture content indicated at right axis. Sphagnum data from Vogelmann and Moss [1994].

He curves indicate an increase in MIR reflectance for both sphagnum and feather moss during dry down. However, only the sphagnum turfs increased in red and NIR reflectance before desiccation. Each curve represents the mean of 3 (sphagnum) to 27 (feather moss) spectra. The feather moss spectra were acquired using a 45 degree illumination angle and a nadir view angle. Information regarding illumination and view geometry were not provided for the sphagnum spectra.
et al 1996]. Complete dessication was not observed in-situ at the SSA-OBS and was only observed towards the end of the growing season in the presence of a 30 year low in precipitation at the NSA-OBS site (unpublished observations by the author). Laboratory studies with needle and broad leaf species have also indicated that visible. NIR and MIR reflectance of leaves and branches are relatively insensitive to changes in moisture content unless significant moisture stress occurs [Hunt and Rock 1989]. Rather, sub-canopy scale reflectance in these bands has been related to chemical [Middleton et al 1997] and structural [Goel and Quin 1994, Williams 1994] aspects of canopy elements.

MIR leaf and branch reflectance are controlled by similar mechanisms as in NIR as well as by the amount of liquid water held on or in vegetation [Gates 1965, Knipling 1970]. Laboratory studies have demonstrated that the characteristic decrease in MIR reflectance of leaves, needles and branches with increasing moisture content is predominantly due to absorption phenomena of liquid water molecules [Tucker 1980]. Both sphagnum and feather mosses exhibit a similar relationship between MIR reflectance and live layer water content [Vogelmann and Moss 1993, Fernandes et al 1996]. Unlike branches, where MIR response varies with structural properties, Fernandes et al [1996] observed no statistically significant differences in moss reflectance across replicate sample turfs of different maximum moisture capacities. The pooled data from both sphagnum and feather moss reflectance data, shown in Figure 4.5, were used to derive a negative exponential relationship between moss moisture content and top of moss MIR reflectance \( \rho_{TOM,MIR} \) given in Equation (1). The negative exponential form agreed with the theoretical relationship expected if water absorption rather than scattering phenomena controlled changes in \( \rho_{TOM,MIR} \) [Gao and Goetz 1995].

\[
\rho_{TOM,MIR} = 0.80 \exp(-0.7\theta) + 0.0529 \quad r^2 = 0.78 \quad n = 18
\]  

Factor 2: The range of in-situ moisture contents.

Conifer canopies do not exhibit sufficient changes in leaf moisture content to generate detectable signals in optical or IR wavelengths unless exposed to extreme water stress [Hunt and Running 1991]. No such water stress conditions were observed in BOREAS wet conifer sites [Dang and
Figure 4.5: Top of moss MIR (1.55 μm - 1.75 μm) reflectance as a function of relative moisture content. The fitted curve suggests that, except for desiccated turfs, both sphagnum and replicate feather moss turfs exhibited a similar relationship between moss relative moisture content and moss surface MIR reflectance. The negative exponential relationship was expected given that liquid water is a strong absorber of MIR radiation. Sphagnum spp. data [Vogelmann and Moss, 94]. Feather moss data reported in Fernandes et al [1996] for Pleuroziunm schreberi (Pleur.) turfs.
Margolis 1997]. In conifer stands the relationship between sub-canopy and TOC reflectance is typically dominated by factors other than foliage moisture content; such as canopy, illumination and sensor geometry [Norman et al 1985, Williams 1994]. In contrast, results presented in Chapter 2 suggest that feather mosses often exhibit in-situ variations in $\theta$ from under 1.0 g/g to over 6.0 g/g. This range in $\theta$ is sufficient to drive changes in $\rho_{TOC,MIR}$ of over 30% based on Equation 1.

The low variability in overstory MIR reflectance due to changes in overstory moisture content together with the large and regular increase in $\rho_{TOC,MIR}$ with drying suggests that, given an adequate model of overstory structural effects on surface MIR reflectance, one might be able to estimate moss moisture content. The lack of sensitivity of $\rho_{TOC,red}$ and $\rho_{TOC,NIR}$ to moss moisture content may also permit estimation of overstory canopy properties independently of moss moisture content.

**Factor 3: The signal to noise ratio for model based retrieval of understory reflectance.**

The signal to noise ratio of TOC reflectance estimates is also an important consideration for mapping moss moisture remotely. Studies before the launch of LANDSAT 5 recommended the 1.55 $\mu$m to 1.75 $\mu$m MIR band for mapping surface moisture over the 1.42 $\mu$m-1.56 $\mu$m MIR band due to lower atmospheric absorption in the first region [Tucker 1980]. Assessment of radiometric correction of LANDSAT TM data suggested absolute errors on the order of 0.5%, 0.5% and 1.5% for $\rho_{TOC,red}$, $\rho_{TOC,NIR}$ and $\rho_{TOC,MIR}$ respectively [Moran et al 1992]. These absolute errors resulted in relative errors of 10%, 2% and 5% for $\rho_{TOC,red}$, $\rho_{TOC,NIR}$ and $\rho_{TOC,MIR}$ with a bare moss surface of average moisture content.

Over and above the physical considerations in favour of using MIR wavelengths for moisture mapping, the continuous 20 year record of co-registered multi-band LANDSAT TM imagery together with information from future sensors with similar spectral coverage would simplify the quantification of long term changes in Boreal overstory structure and surface moisture.
4.4. Modelling the relationship between Moss Moisture Content and TOC Reflectance

A model based approach for extending the relationship between $\theta$ and $\rho_{TOC:MR}$ was adopted in this study. A review of canopy reflectance models which have been applied to conifer stands is provided in this section. A 3-dimensional hybrid radiative transfer-geometric optics model relating $\rho_{TOC:MR}$ to $\rho_{TOC:MR}$ is described. The parameterization of the model for mature *Picea mariana* stands is documented. An exploratory analysis of the plausibility of the forward model is conducted using helicopter based reflectance observations. Finally an inversion method which permits estimation of $\theta$ from $\rho_{TOC:MR}$ is discussed.

4.4.1 Review of Canopy Reflectance Models

Canopy reflectance models with a physical basis are typically described as either geometric-optics (GO) models, radiative transfer (RT) models or hybrid RT-GO models. These models relate illumination geometry, canopy structure and canopy element reflectance to TOC reflectance. Early efforts at forward reflectance modelling in conifer stands applied existing 1-D or 2-D RT models developed for homogenous or row spaced agricultural canopies [e.g. Ross and Nilson 1968, Suits 1972, Verhoef 1984. Nilson and Kuusk 1989]. These models were not successful in conifer stands due to clustering of needles within shoots, clumping of shoots in crowns and, as in Boreal conifer stands, clumping of crowns within stands.

GO models clump foliage within crown envelopes and assume that these envelopes act as regions which reflect a fraction of incident photons according to the principles of geometric optics [Li and Strahler 1985, Jupp et al 1986. Jasinski and Eagleson 1990, Strahler and Jupp 1990. Wells and Norman 1990]. All of these models decompose forest stands into four fractions: sunlit crown, shaded crown, sunlit background and shaded background. While the GO models validate reasonably well in uniform conifer stands planted in regular patterns they did not perform well in mapping crown cover or density in natural stands [Woodcock et al 1994]. Hall et al[1995] applied the model of Jasins and Eagleson [1990] to a number of Boreal conifer stands dominated by *Picea mariana* overstory canopies and sphagnum moss carpets. Hall et al [1995] showed that observed reflectance
measurements fell within the cone in red-NIR spectral space defined by GO model end-member fractions. Their reflectance model may not be applicable to the current mapping problem since:

i) The GO model red-NIR trajectory had a V-shape: starting with high $\rho_{\text{red}}$ and $\rho_{\text{NIR}}$ for bare, sunlit sphagnum understory; decreasing in both $\rho_{\text{red}}$ and $\rho_{\text{NIR}}$ with increasing canopy cover until the shadow end-member was approached; and then increasing to almost 30% $\rho_{\text{NIR}}$ while exhibiting almost no change in $\rho_{\text{red}}$. However, in-situ observed $\rho_{\text{NIR}}$ of conifer stand do not noticeably increase at ANY point with increasing canopy cover. It is likely that the GO model did not realistically explain within crown shadowing effects due to clumping.

ii) The GO model did not include multiple scattering which has been observed to account for over 20% of mid-infrared scattering within conifer canopies [Myneni et al. 1988].

iii) A between crown clumping factor was not included, although evidence in Boreal forest canopies suggests strong clumping phenomena [Chen and Cihlar 1995]

iv) The GO models did not explicitly account for diffuse irradiance.

GO models were later modified to permit transmission through crowns [Roujean et al. 1992, van Leeuwen et al. 1997]. However, the amount of transmission was typically calibrated using in-situ data [Soffer 1995] or off-line 1-D R-T models [van Leeuwen et al. 1997, Hall et al. 1997]. The calibrations permitted fitting to observed red-NIR scattergrams, but resulted in end-members which may not have been valid at other sites. Rosema et al. [1992] included a between crown clumping factor in a GO model which was later augmented by Chen and LeBlanc [1998] to include within crown clumping. The GO models with clumping offer some promise in characterizing bi-directional reflectance distribution functions in optical wavelengths when multiple scattering is low and reflectance of canopy elements are somewhat stable, such as in healthy stands.

Nilson and Peterson [1991] used a GO model similar to that of Chen and LeBlanc [1998] to describe single scattering together with a RT model to describe multiple scattering within crowns. Their
model showed precise, although biased, estimates of observed reflectance in managed Boreal conifer stands. Nilson and Peterson [1991] suggested that the systematic underestimation of actual reflectance was due to errors in leaf, bark and understory reflectance. However a later study using the same model indicated that the underestimation was due to the absence of a within crown clumping parameterization [Nilson and Peterson 1994]. This suggestion was supported by a comparison of in-situ measurements of branch and crown reflectance which suggested that while the reflectance of tightly packed branches increased with increasing branch area, crown reflectance deceased with increasing plant area [Williams 1994] Four significant factors which explained the crown reflectance behaviour were identified:

i. shadowing, but to a lesser extent than in the visible region, due to multiple scattering and higher component reflectance;
ii. absorption of radiation by material other than needles;
iii. differences in illumination of branch level and canopy level targets;
iv. clumping of needles on branches.

The R-T model of Myneni et al [1995] included explicit computation of multiple scattering, separate consideration of direct and diffuse illumination and needle clumping to address these four issues. The model was validated against several sets of field data including a managed conifer stand. Importantly, the model was completely physically based and did not require calibration of canopy element reflectance or structural properties to observed TOC reflectance. The model was later extended to include both an understory and an overstory in addition to using a GO soil scattering algorithm to fit hot-spot effects in visible wavelengths [Myneni et al 1995]. This hybrid RT-GO model was able to fit observed visible and IR TOC reflectance in natural conifer stands but has not been tested in Boreal conifer stands. Appendix I describes the model in detail together with the modification of between crown clumping added as part of the dissertation research. The remainder of this section applies the model to describing the relationship between surface and TOC reflectance in Boreal conifer stands.
4.4.2 Reflectance Model Parameterization

This section describes the parameterization of the reflectance model for a single baseline run appropriate for illumination conditions during the overpass of the LANDSAT TM data used in this study and for wet conifer sites similar to the NSA OBS. The LANDSAT TM scene for which the model was parameterized was acquired at 10:38 am local time during clear sky conditions (EROS Data Centre cloud level 0) with a solar zenith angle of 39° from the vertical. On the basis of the clear sky conditions and the morning overpass, diffuse irradiance was assumed to total 10% of total irradiance in optical and IR wavelengths.

Baseline trials assumed a nadir view zenith angle. Additional trials with view zenith angles of plus and minus 8° were used to test the sensitivity of modelled reflectance to the location of the target stand relative to the centre of the LANDSAT TM scene.

Model parameterization was separated into structural and reflectance properties. Reflectance parameters are documented in Table 4.1 and are assumed independent of structural properties documented in Table 4.2. The overstory was assumed to represent mature Picea mariana (Mill.) BSP stems with a diameter at breast height of 8 cm while the understory was assumed to consist of Ledum groenlandicum and similar herbs which had planophile leaves as noted in Halliwell and Apps [1997].

The RT-GO model used a spatially explicit placement of tree crowns in a 10 x 10 grid of 1 m resolution cells. The grid was assumed to repeat in the same placement pattern past its boundaries. Overstory stems were located by randomly selecting the centre of a clump of stems within the lattice cell locations on the moss surface. A clump size was then randomly selected using a Poisson distribution with a mean clump size of 3 stems. Unfilled adjacent lattice cells were then assigned stems until the required clump size was reached or until all eight nearest neighbours were occupied with stems. This method represents an approximation to a true double Poisson process necessitated by the discrete nature of the lattice cells. The mean clump size of 3 stems was chosen arbitrarily.
However, it is more realistic than assuming that stems with wet conifer stands are distributed with no clumping effect. In addition, within crown clumping of shoots was specified based on a reduction of the leaf extinction coefficient by a factor of 0.7, as observed in-situ by Chen [1996]. Each model run reported in this paper represents the mean reflectance from 50 trials using random realizations of tree stem placements. The choice of 50 trials was dictated by computational limits. However, the use of an ensemble of realizations reduced the likelihood that the modelled reflectance was biased (especially with low crown cover) due to chance occurrences of tree stem clump configurations.

**Table 4.1** RT-GO model component reflectance parameters. Parameters represent averages over all age classes of needles and stem/branch sizes.

<table>
<thead>
<tr>
<th>Property</th>
<th><em>red</em></th>
<th><em>NIR</em></th>
<th><em>MIR</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Overstory leaf hemispherical reflectance†</td>
<td>0.047</td>
<td>0.39</td>
<td>0.17</td>
</tr>
<tr>
<td>Overstory leaf hemispherical transmittance†</td>
<td>0.023</td>
<td>0.39</td>
<td>0.15</td>
</tr>
<tr>
<td>Understory leaf hemispherical reflectance‡</td>
<td>0.054</td>
<td>0.5</td>
<td>0.41</td>
</tr>
<tr>
<td>Understory leaf hemispherical transmittance‡</td>
<td>0.058</td>
<td>0.42</td>
<td>0.33</td>
</tr>
<tr>
<td>Stem/branch hemispherical reflectance†</td>
<td>0.037</td>
<td>0.1</td>
<td>0.21</td>
</tr>
<tr>
<td>Stem/branch hemispherical transmittance†</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

†Hall et al [1992]. ‡Middleton et al [1997]
Table 4.2 RT-GO model structural parameters as a function of stem $dbh$. The $dbh$ increments were selected to represent low, medium and high productivity Picea mariana stands reported by Hall et al [1992] and Halliwell and Apps [1997]. Data sources from which parameters were derived are specified. The NSA-OBS site corresponded to a mid-productivity Boreal wet conifer site.

<table>
<thead>
<tr>
<th>Property</th>
<th>$dbh$ 4cm</th>
<th>$dbh$ 8cm</th>
<th>$dbh$ 14cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overstory height (m)$^\dagger$</td>
<td>4</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td>Foliage clumping parameter$^\ddagger$</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Branch silhouette area index (m$^2$ branch area / m$^2$ horizontal projected area)$^\ddagger$</td>
<td>1.3175</td>
<td>1.1296</td>
<td>0.8477</td>
</tr>
<tr>
<td>Overstory crown depth (m)$^\dagger$</td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Overstory crown diameter (m)$^\dagger$</td>
<td>0.62</td>
<td>1.09</td>
<td>1.82</td>
</tr>
<tr>
<td>Understory plant height (m)$^\S$</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Overstory leaf inclination distribution$^\ddagger$</td>
<td>uniform</td>
<td>uniform</td>
<td>uniform</td>
</tr>
<tr>
<td>Overstory leaf azimuth distribution$^\ddagger$</td>
<td>uniform</td>
<td>uniform</td>
<td>uniform</td>
</tr>
<tr>
<td>Understory leaf inclination distribution$^\S$</td>
<td>planophile</td>
<td>planophile</td>
<td>planophile</td>
</tr>
<tr>
<td>Understory leaf azimuth distribution$^\S$</td>
<td>uniform</td>
<td>uniform</td>
<td>uniform</td>
</tr>
<tr>
<td>Stem/branch orientation distribution$^\ddagger$</td>
<td>uniform</td>
<td>uniform</td>
<td>uniform</td>
</tr>
<tr>
<td>Overstory plant area density (0.5 * m$^2$ plant area/ m$^2$ horiz. proj. crown area)$^\S\S$</td>
<td>6.917</td>
<td>5.9303</td>
<td>4.45</td>
</tr>
<tr>
<td>Understory leaf area index (0.5 * m$^2$ plant area/ m$^2$ ground area)$^\S$</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

$^\dagger$Halliwell and Apps [1997] and Hall et al[1992]. $^\ddagger$Chen [1996]. $^\S$Unpublished in-situ data. $^\S\S$ Chen [1997] and unpublished crown cover data [J.M. Chen]

4.4.3 Reflectance Model Evaluation

The forward model was executed over all combinations of canopy cover (in steps of 10%) and understory reflectance (in steps of 5%) using the baseline parameterization. Figure 4.6 compares modelled and observed TOC reflectance for Picea mariana stands in $\rho_{\text{red}}\rho_{\text{NIR}}$ spectral space. The $\rho_{\text{red}}\rho_{\text{NIR}}$ space was selected for validation to reduce the possibility of $\rho_{\text{TOM}}$ variations due to differences in understory moisture content across validation sites. The curves indicated in Figure
4.6 correspond to isolines of $\rho_{TOMLIR}$. Hollow symbols along the isolines correspond to 10% increments in $C_o$, increasing from right to left. The exception was that 0% $C_o$ was replaced by 5% due to a discontinuity in model response when all canopies were removed. $\rho_{TOMLred}$ was not perturbed given its stability for moss understories [Fernandes et al 1996].

Isolines progressed from reflectance values close to that of a bare understory with 5% $C_o$ to a critical point at approximately 0.0125 $\rho_{TOK,red}$ and 0.12 $\rho_{TOK,NIR}$ with 100% $C_o$. The critical point was approached from below for isolines of $\rho_{TOMLIR}$ lower than the critical $\rho_{TOK,NIR}$ and from above for isolines of higher $\rho_{TOMLIR}$. The presence of a critical point, typically absent for 100% canopy cover in other reviewed models, may be a result of including the recommendations of Williams [1994] into the Myneni model.

Observed TOC reflectance from the BOREAS [Loechel 1997] and Superior National Forest (SNF) [Hall et al 1992] studies were superimposed on the isolines in Figure 4.6 to explore the model plausibility. The observations were acquired from a helicopter mounted radiometer at an altitude of approximately 100 m and a field of view (FOV) corresponding to a patch of approximately 25 m in diameter. A number of caveats were required before comparison of observed and modelled reflectance:

i) The target may not have corresponded exactly to surface measurements of $C_o$ due to difficulty in navigating the helicopter and due to differences in the spatial support of $C_o$ measurements and the radiometer FOV;

ii) Illumination conditions were not recorded during observations. Atmospheric correction code incorporating surface radiometer measurements were used to compute TOC irradiance. However local forest fires and haze may have substantially distorted the BOREAS reflectance estimates [Walthall, Charles personal communication];

iii) Solar zenith angles differed by as much as 10° from the 39° assumed in the model runs;
Figure 4.6: Red-NIR scattergram of modelled and observed TOC reflectance for dbh 8cm *Picea mariana* stands with $\rho_{TOM,red}$ at 0.05. Isolines correspond to reflectance model responses (after 50 trials at each canopy cover level corresponding to different canopy clumping realizations) to constant $\rho_{TOM,NIR}$; * symbols correspond to helicopter observations [Hall et al 1992, Loechel et al 1997]. Helicopter observations typically had a 25 m diameter field of view. Differences in illumination conditions between helicopter observations and the model runs and in-situ variability of stem dbh may explain the substantial variation in observed $\rho_{TOM,NIR}$. 
iv) The model assumed clear sky illumination conditions with 10% diffuse reflectance which may not have applied for all observations or uniformly across spectral band:

v) Measurements of $\rho_{TOM:NIR}$ were not performed at each site at the time of TOC measurements making it impossible to determine which isoline should apply to a given observation.

Nevertheless, it was encouraging that most TOC reflectance measurements corresponded to isolines within the range of in-situ $\rho_{TOM:NIR}$ measurements (0.15 to 0.30) [White et al 1995]. In addition, the agreement of TOC reflectance measurements with the critical point without any calibration to reflectance at the sites supports the model validity.

The observations with $\rho_{TOK:RED}$ values over 0.02 corresponded to very sparse stands, having $dbh$ values less than 4 cm, for which the $dbh$ 8 cm baseline model runs may not be entirely representative. The higher $\rho_{TOK:RED}$ for very sparse canopies may also be due to patches of lichens which typically have significantly higher $\rho_{TOM:red}$ than sphagnum and feather mosses [Bubier et al, 1997]. There was one outlier with almost 0.30 $\rho_{TOK:MIR}$ which was acquired near a forest fire where IR irradiance and reflectance may have been enhanced by scattering from smoke particles.

Figure 4.7 shows the modelled $\rho_{TOK:MIR}$ versus $\rho_{TOM:MIR}$ and $C_a$ for the baseline run. The response surface includes $C_a$ values ranging from 5% to 100% for completeness. However, $C_a$ ranged from 30% to 60% in most wet conifer stands with very few stands having a $C_a$ in excess of 80% [Chen, J. unpublished data]. The response surface shows a linear decrease in $\rho_{TOK:MIR}$ with decreasing $\rho_{TOM:MIR}$ since the uncollided understory reflectance source dominated the understory TOC radiance source. The response surface also shows a concave, curvilinear decrease in $\rho_{TOK:MIR}$ with increasing $C_a$. This agrees with the observed phenomenon of smaller changes in reflectance with changes in cover with dense canopies where shadowing of the understory does not change substantially [Nilson and Peterson 1994, Hall et al 1992]. The presence of a smooth response surface was encouraging for model inversion.
Figure 4.7: Modelled $\rho_{TOC,MIR}$ as a function for overstory crown cover and $\rho_{TOM,MIR}$ for dbh 8 cm Picea mariana stands. The model response surface represents the mean TOC MIR for 50 trials at each indicated interval of crown cover and moss MIR reflectance. Each trial used a single realization of a clumped configuration of crowns within a 10m x 10m grid embedded in a radiative transfer-geometric optics reflectance model [Myneni et al 1992].
Figure 4.8 shows the baseline model MIR response using isolines of constant canopy cover. Figure 4.8 suggests that model inversion would be ill-posed without knowledge of canopy cover. For example, a $\rho_{TOK: MIR}$ of 0.10 could correspond to a 20% $C_o$ with a $\rho_{TOM: MIR}$ of 0.15 or a 60% $C_o$ with a $\rho_{TOM: MIR}$ of 0.35. In addition, Figure 4.8 also indicates that model inversion would not be possible with observed $\rho_{TOK: MIR}$ near 0.07. Unfortunately, observed $\rho_{TOK: MIR}$ was often close to 0.07 as shown in Figure 4.9. Figure 4.9 indicates that the baseline model, when parameterized using a range of $\rho_{TOM: MIR}$ appropriate for mosses, covered the range of observed $\rho_{TOK: MIR}$. The model response shown in Figure 4.9 does not cover the entire range of observed $\rho_{TOK: NIR}$ as only model responses for a single value of 0.25 $\rho_{TOM: NIR}$ were displayed for demonstration purposes. However, an assessment of model plausibility considering both Figure 4.9 and Figure 4.7 indicates that the model may be capable of describing observed TOC reflectance given reasonable values of TOM reflectance.

The $dbh$ 8 cm trials were labelled as the baseline trial as they most closely matched the OBS study sites within the BOREAS region. The model was also executed with a selection of perturbations of the baseline parameterization:

i) $dbh$ 8 cm with 1.0 $LAD_u$;
ii) $dbh$ 4 cm;
iii) $dbh$ 4 cm with 1.0 $LAD_u$;
iv) $dbh$ 8 cm with 8° view zenith angle.

A $dbh$ 14 cm perturbation was performed but results are not reported here as it always exhibited smaller differences from the baseline than a $dbh$ 4 perturbation. The lower sensitivity to $dbh$ overestimation rather than underestimation was due to the reduction in the dynamic range of TOC MIR reflectance with increasing stem size caused by an increase in mutual shadowing. In addition a 0 $LAD_u$ trial was not reported given that the understory herbs and other broadleaf species were present in all stands [Halliwell and Apps 1997].
Figure 4.8: Modelled $\rho_{TOC,MIR}$ as a function $\rho_{TOM,MIR}$ along overstory canopy cover isolines for $dbh$ 8 cm *Picea mariana* stands. The figure shows a sub-set of the response surface of Figure 4.7. The intersection of all curves near a $\rho_{TOM,MIR}$ of 7% indicates that inversion may not be possible for TOC reflectance of around 6%.
Figure 4.9: NIR-MIR scattergram of modelled and observed TOC reflectance for dbh 8cm *Picea mariana* stands with $\rho_{TOM,NIR}$ set at 0.25. Isolines correspond to constant $\rho_{TOM,MIR}$; * symbols correspond to helicopter observations [Hell et al 1992, Loechel et al 1997]. Variability in crown cover and stem dbh within the 25 m diameter field of view of helicopter observations make comparison to sparse in-situ canopy cover data difficult. The substantial variation in observed TOC MIR may be due to variations in moss moisture content.
Figure 4.1a indicates that increasing $LAD_u$ results in a decrease in $\rho_{TOC:MIR}$. The magnitude of the $LAD_u$ perturbation effect was proportional to understory reflectance. The most likely explanation for this trend is that an increase in $LAD_u$ increases soil shading so that the brighter the soil the greater the difference in the soil source. The maximum modelled absolute difference in $\rho_{TOC:MIR}$ due to the $LAD_u$ perturbation was approximately 0.04.

Figure 4.1b indicates a stand with $dbh$ 4 cm stems, representing a low productivity region, would result in modelled $\rho_{TOC:MIR}$ with an absolute difference less than 0.02 from the baseline estimates. The absolute value of the difference between the baseline and the perturbation increased from almost no difference for very low $\rho_{TOC:MIR}$ to 0.02 for a $\rho_{TOC:MIR}$ of 0.60. The perturbation resulted in a higher $\rho_{TOC:MIR}$ with canopy cover below 50% since more of the bright moss surface (relative to a dense canopy MIR reflectance of 0.10) was visible. Unexpectedly, the perturbation resulted in a lower $\rho_{TOC:MIR}$ with canopy cover above 50%. While one would expect lower absorption with small stems, the actual leaf area density of the $dbh$ 4 cm stems was higher than the $dbh$ 8 cm stems since the measurements of leaf area density were performed by dividing observed leaf area per unit ground area by observed crown area per unit ground area. The low productivity of the $dbh$ 4 cm sites likely resulted in a few very dense crowns in an otherwise empty region (i.e. high clumping of foliage within crowns). In any event canopy cover over 50% was not observed for $dbh$ 4 cm stands (J. M. Chen. personal communication, unpublished data).

Figure 4.11a compares the baseline response to a more realistic perturbation than those shown in Figure 4.10. It was noticed in the field that stands corresponding to higher $LAD_u$ had sparse, low productivity overstory cover. A perturbation taking into account the co-variation of $LAD_u$ and site productivity resulted in a modelled absolute difference approximately equal to the sum of the differences (including signs) due to perturbations shown in Figure 4.10. As a result, the expected difference in MIR response was about 50% lower for canopy cover over 50% and was below 0.02 for canopy cover less than 50%. Once more, the absolute difference between the baseline and perturbed model responses was proportional to $\rho_{TOC:MIR}$. 
Figure 4.10: TOC MIR absolute error given by the difference in modelled reflectance between a baseline trial using dbh 8 cm stems and a $LAD_{u}$ of 0.5 and:

a) a baseline trial but with 1.0 $LAD_{u}$;
b) a trial using $dbh$ 4 cm stems with parameters specified in Table 4.2
Figure 4.11: TOC MIR absolute error given by the difference in modelled reflectance between a baseline trial using dbh 8 cm stems and a $LAD_u$ of 0.5 and:

a) a trial using dbh 4 cm stems specified in Table 4.2 but with 1.0 $LAD_u$;
b) a baseline trial but with $+8^\circ$ view zenith angle.
Figure 4.11b indicates the view angle perturbations representative of LANDSAT TM imagery would result in an order of magnitude smaller differences than perturbations dealing with surface parameters.

In summary, the sensitivity analysis suggested that typical errors in stand structure parameterization (except for canopy cover) taking into account the covariance in $LAD_o$ and overstory stem size would result in absolute errors in $\rho_{TOK, MIR}$ of under 0.02. Furthermore, the absolute error was proportional to $\rho_{TOM, MIR}$ so that the relative error in $\rho_{TOK, MIR}$ (not shown in the figures for brevity) ranged from 20% for full canopy cover to under 1% for canopy cover below 5%. The relative error in $\rho_{TOK, MIR}$ for the typical range of 60% $C_o$ to 20% $C_o$ was less than 10% and 1% respectively.

### 4.4.4 Reflectance Model Inversion

The mean modelled value of $\rho_{TOK, MIR}$ for all 50 replicates of each baseline trial was inverted to allow specification of $\rho_{TOM, MIR}$ given $C_o$. The inverse of Equation (1) was then used to transform the $\rho_{TOM, MIR}$ values into estimates of $\theta$. A cubic spline was fit to the space defined by related $\rho_{TOK, MIR} \cdot C_o$ and $\theta$ with a root mean square error of less than 0.005 reflectance units. The spline surface resulted in negative $\theta$ estimates for some combinations of $\rho_{TOK, MIR}$ and $C_o$. However, the hypothetical combinations of dense canopies and $\rho_{TOK, MIR}$ that resulted in negative modelled $\theta$ estimates were physically unrealistic given the forward model estimates of canopy cover attenuation of $\rho_{TOM, MIR}$.

Figure 4.12 shows the response surface for $\theta$ after limiting the cubic spline surface to non-negative values. The surface shows a monotonic increase in $\theta$ with decreasing $\rho_{TOK, MIR}$ and $C_o$. The absence of undulations or jumps in the surface increases the robustness of the inverse model to errors in parameters or calibration of $\rho_{TOK, MIR}$.

Figure 4.13 presents the data in Figure 4.12 using $C_o$ isolines. Isolines which exhibit a large dynamic range in $C_o$ exhibit a small range of valid $\theta$ and vice versa. As a result the range for useful model inversion was limited to $\theta$ less than 6g/g and $C_o$ less than 60%. The restriction on $\theta$ indicated that it would not be possible to track moisture dynamics of sphagnum mosses unless they desiccated.
Figure 4.12: Estimated live moss moisture content given canopy cover and nadir $\rho_{TOM,MIR}$. The relationship represents a cubic spline fit to a look-up table relating canopy cover and $\rho_{TOM,MIR}$ to moss moisture content. The look-up table was generated by combining an empirical relationship between moss moisture content and a modelled relationship between $\rho_{TOM,MIR}$ and $\rho_{TOM,MIR}$ using a3-D RT-GO reflectance model [Myneni et al 1995]. The region with an estimated moisture content of 0 g/g correspond to negative model based estimates. This region was limited to 0g/g based on the forward model response surface that indicated that high canopy cover and high $\rho_{TOM,MIR}$ was not possible for the observed range of $\rho_{TOM,MIR}$. 
Figure 4.13: Inverse model estimates of moss moisture as a function of $\rho_{TOC,MIR}$ along isolines of overstory canopy cover for the baseline stand parameterization corresponding to dbh 8 cm stems. The inverse relationship was defined by fitting a cubic spline surface to the combination of the $\rho_{TOM,MIR}$ vs. $\rho_{TOC,MIR}$ relationship and the $\rho_{TOM,MIR}$ vs. moss relative moisture content relationship. The figure suggests the inverse model may be useful for mapping moss moisture contents with canopy cover less than 60% and moss moisture contents less than 6 g water/g moss.
Fortunately, feather moss stands never exhibited values of $\theta$ over 6 g/g and as previously mentioned $C_u$ rarely exceeded 60% over a stand.

Figure 4.14a indicates that over the range of typical canopy cover (20%-60%) the model predicted that the absolute error in $\theta$ due to a 10% relative error in measuring $\rho_{TX:MR}$ was less than 0.5 g/g. This relationship between errors in $\rho_{TX:MR}$ and $\theta$ can also be used to indicate the equivalent inverse model error due to parameterization errors in the forward model. For example the forward model relative errors due to joint uncertainty in stem dbh and $LAD_u$ was approximated as less than 10% for typical stands. This uncertainty would then suggest an absolute model inversion error of 0.5 g/g if the incorrect stand parameters were used to define the inverse relationship. While this reasoning is not exact since it assumes a linear error function, the smooth forward and inverse model response surfaces support its validity for stands similar to the baseline stand.

Figure 4.14b indicates that a 10% error in $C_u$ would result in an absolute error on the order of 0.5 g/g in inverted $\theta$ over typical canopy cover conditions. The remote mapping of $C_u$ is an active research area. Chen and Cihlar [1996] suggest errors on the order of +/-20% in estimates of leaf area index from LANDSAT TM imagery. The precision of the $C_u$ statistic used in the model is at least as poor as the leaf area index uncertainty since $C_u$ was related to leaf area index using an estimated multiplicative factor equivalent to the within crown leaf area density. A linear extrapolation of the error trend levels in Figure 4.14b results in a minimum estimate of absolute error in $\theta$ of +/-1 g/g due to typical uncertainties in $C_u$.

The large number of model parameters resulted in large precision errors if all uncertainties in model parameters and image calibration were additive. A tentative error budget for a pixel with a baseline stand of 50% cover (see Table 4.3) suggests worst case absolute precision errors on the order of +/-3.35 g/g. If however, $\theta$ estimates from individual pixels were aggregated over regions where model errors or calibration errors were random the uncertainty could be reduced substantially. Furthermore, if the region over which the model was applied exhibited a constant systematic error, the pattern of relative $\theta$ may still be sufficiently precise. In-situ validation over a number of forest stands is required to determine the extent to which model inversion errors are additive or cancel out.
Figure 4.14: Modelled absolute error in $\theta$ (for non-negative baseline $\theta$) with baseline stand parameterization due to:

a) 10% relative error in $\rho_{TOC,MIR}$;
b) 10% absolute error in overstory canopy cover.

The response surfaces suggest an absolute error on the order of 0.5 g/g for a 10% error in either $\rho_{TOC,MIR}$ or in overstory canopy cover for a canopy cover under 60%.
In the absences of a thorough in-situ evaluation it is suggested that, over the extent of a single LANDSAT TM pixel, sources of error are not likely random and should be treated as additive. As such, the inversion algorithm was more suited for identifying dry versus saturated pixels rather than providing precise estimates of moss moisture content.

Table 4.3: Tentative error budget for baseline model inversion assuming a 40% overstory canopy cover. The sources of error include selected areas of uncertainty in model parameters and in satellite imagery. The absolute error in $\rho_{\text{TRK:MIR}}$ indicates an error in the forward reflectance model due to the source of error. With the exception of $C_o$, the absolute error in moisture content was estimated by assuming linearity of the forward error formation process over the range of possible $C_o$ and $\rho_{\text{TRK:MIR}}$. Previous analysis of error response surfaces support the linearity assumption. The Euclidean error corresponds to the root mean square of the individual error terms.

<table>
<thead>
<tr>
<th>Source of Error</th>
<th>Absolute Error in $\rho_{\text{TRK:MIR}}$</th>
<th>Absolute Error in $\theta$ (g/g)$^+$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_o$</td>
<td>N/A</td>
<td>1</td>
</tr>
<tr>
<td>Stem size (dbh 4cm)</td>
<td>0.005</td>
<td>0.25</td>
</tr>
<tr>
<td>$LAI_o$</td>
<td>0.01</td>
<td>0.5</td>
</tr>
<tr>
<td>Image calibration</td>
<td>0.01</td>
<td>0.5</td>
</tr>
<tr>
<td>Foliage reflectance</td>
<td>0.02$^+$</td>
<td>1</td>
</tr>
<tr>
<td>View angle error</td>
<td>0.0025</td>
<td>0.1</td>
</tr>
<tr>
<td>Total Error</td>
<td></td>
<td>3.4</td>
</tr>
<tr>
<td>Euclidean Error</td>
<td></td>
<td>1.6</td>
</tr>
</tbody>
</table>

$^+$Estimated by model inversion for $C_o$ and by assuming linearity in forward error formation process for other sources of error (i.e. 10% forward error = 0.5 g/g inversion error)

$^+$Assumes 20% relative error in reflectance measurements and a 1:1 relationship between $\rho_{\text{TRK:MIR}}$ to reflectance errors. The second assumption is pessimistic as $\rho_{\text{TRK:MIR}}$ is always smaller than foliage reflectance.
4.5 Mapping Surface Wetness within the BOREAS NSA

The inverse reflectance model was applied to imagery of the BOREAS NSA. The data used with the inverse model is described. The inverse model based estimated moisture map over the entire NSA and over the NSA-OBS site is presented. Possible sources of error in the NSA moisture map are discussed. A visual comparison of moisture patterns and a quantitative comparison of moss fraction within the NSA-OBS is provided.

Analysis of the inverse model suggested that the ideal time at which to acquire MIR data would be later in a dry down. Observations presented in Chapter 2 suggest that after four to five days without rain feather mosses typically reached their lowest moisture content of below 1 g water /g moss while sphagnum moss moisture content was over 5 g water /g moss. While these observations were performed at the SSA-OBS similar trends were observed for feather mosses at the NSA-OBS. Data for sphagnum mosses were not available for the NSA-OBS. However, the presence of capillary recharge to sphagnum mosses suggests that they are likely to remain near saturation in undisturbed state irrespective of spatial differences in evaporative demand. Figure 4.15 shows a $\rho_{TOK: MIR}$ image derived by Hall et al [1997] from a LANDSAT TM image, acquired on 16. June. 1995. covering all of the BOREAS NSA. The scene was corrected, by BOREAS staff, to reflectance using surface measurements of atmospheric properties within the 6S radiative transfer code [Moran et al 1997]. A land-cover map, generated from the same image [Hall et al 1997], was used to mask out regions within the reflectance image which were not covered by conifer stands or open fens.

Figure 4.16 shows an overstory leaf area index ($LAI_o$) image of the NSA derived from a LANDSAT TM scene acquired on 9. June. 1994 [Chen and Cihlar 1996]. This image was used to specify $C_o$ by assuming that within crown leaf area density was identical to the value assigned for a dbh 8 cm stand. There were two reasons supporting the assumption that the $LAI_o$ image was representative of canopy cover a year later when the reflectance imagery was acquired. Firstly the $LAI_o$ image was derived from the same sensor and at approximately the same time in the growing season as the reflectance image. Secondly, forest fires and harvesting were suppressed in the NSA during the BOREAS experiment.
Figure 4.15: Estimated $\rho_{\text{Landsat}} (1.55 \, \mu m \text{ - } 1.75 \, \mu m)$ for the BOREAS NSA derived from LANDSAT TM [Hall et al, 1997]
Grey level is proportional to reflectance although image has been histogram equalized for presentation. Bright white regions correspond to open canopy regions including roads, transmission line right of ways and burn scars.
Figure 4.16: Estimated LAI over the BOREAS NSA [Chen and Cihlar 1996]. The estimation algorithm used a regression relationship between the simple ratio ($\rho_{440}/\rho_{665}$) and observed LAI over a number of auxiliary sites. The image
The $LAI_n$ data and land cover classification were co-registered to the reflectance image to facilitate model inversion. Co-registration errors were approximately 30 m root mean square (RMS), 1 standard deviation, for both $LAI_n$ and land cover images. A 3 by 3 pixel square window (approximately 90 m x 90 m) has been used in the $LAI_n$ estimation algorithm [Chen and Cihlar 1996]. This likely resulted in a smoothing of the $LAI_n$ estimates in sparse canopies or at edges between fens or clearings and dense canopies.

The MIR inversion method was applied to all unmasked pixels in the MIR reflectance image using the baseline stand parameterization. Inversion errors may have been greater in pine stands with substantially taller stems and higher crown bases than the baseline stand and in rich fens where the moss cover was obscured by sedges which have erectophile leaves rather than the planophile leaves characteristic of broadleaf understories in wet conifer stands. Figure 4.17 shows a map of $\theta$ over the NSA estimated by MIR inversion. The absence of temporally coincident maps of in-situ measurements of $\theta$ over the NSA precluded validation of this map. However, potential sources of error included:

i) errors in $LAI_n$ due to the window based $LAI_n$ estimation method (maximum expected error of 4.0 $LAI_n$ units);

ii) errors in $LAI_n$ due to noise in the relationship between $LAI_n$ and reflectance imagery (+/-20% absolute error in $LAI_n$);

iii) errors in the land cover classification product (around 25% misclassification);

iv) registration errors with $LAI_n$ or land cover images (30 m RMS, 1 standard deviation error, although local errors could be larger);

v) deviations in stand characteristics from the baseline model assumptions (discussed under model sensitivity).
A smaller spatial extent, the NSA-OBS site, was selected to further assess the impact of some of these errors. While misclassification of land cover was not treated using this approach, the substantial within stand variation in stem size and moss cover provided a useful test of moisture mapping performance.

Figure 4.18 shows the input image layers, the estimated moisture content image and a map of drainage classes generated by in-situ survey. The $LAI_s$ image was produced by overlaying a forest cover mask developed using a thresholded air photograph on the NSA $LAI_s$ image. This modification was intended to compensate for the loss of spatial resolution in the NSA $LAI_s$ image due to the window based algorithm used to estimate $LAI_s$. The TM5 image indicates that well drained regions with high $LAI_s$ had lower estimated mid-infrared reflectance than poorly drained regions with sparse canopies.

The moisture map shows $\theta$ proportional to grey level so that the brightest regions corresponded to $6g/g$ and the darkest regions to $0g/g$. Thresholding of the moisture map was used to label feather moss and sphagnum regions. Numerical approximations to the Gamma distributions shown in Figure 4.19 were used to determine the threshold that resulted in a minimum classification error of 6.85% (assuming a Gaussian distribution of errors in moisture content about the threshold with a standard deviation of 1.6 $g/g$ suggested in Table 4.3). Figure 4.19 also compares the probability of classification error for a given moisture content threshold based on the assumed Gamma distributions versus the empirical classification error at the NSA-OBS site as a function of threshold (both error estimates are truncated at a reasonable upper bound for the threshold and are only estimated at discrete threshold levels). The empirical error assumed that the estimates of 55% sphagnum and 45% feather moss cover by Harden et al [1997] were accurate.

Both the theoretical and empirical minimum value for classification error occurred with a threshold near 3.0 $g/g$. However, the empirical error sensitivity to this threshold was much greater than the theoretical sensitivity. This suggests that, at this site, mapped feather moss and sphagnum moss regions are not as well separated in $\rho_{MIR,IR}$ as suggested by the model sensitivity analysis. The negative correlation between cover and site drainage may explain the lack of separation since a wet
Figure 4.18. Comparison of estimates of surface moisture at NSA-OBS. All maps shown on a ratio (a,b,c) or ordinal (d) scale proportional to gray level.

(a) original MIR reflectance image (0-1);
(b) LAI image (0-5.9 m² leaf area m² ground);
(c) MIR inversion (0-6 g water/g moss) and
(d) drainage class map estimated by in-situ survey (moderately drained shown as black to very poorly drained shown as white).

Images have been not been enhanced so as to preserve spatial patterns of each mapped quantity.
Figure 4.19: Inverse model error assessment. Probability density functions (Pdf) of absolute moisture content given moss type (sphagnum - Sphag. or feather moss - F. moss) using Gamma distributions fitted to observed moisture contents. Moisture content data were recorded at the SSA-OBS site for periods at least four days after a rain event. See Chapter 2 for details regarding measurement methods. The absolute error rate corresponds to the classification error at the NSA-OBS as a function of the threshold moisture content separating sphagnum from feather mosses. The theoretical error represents the expected classification error assuming a constant inverse model error represented by a Gaussian error distribution with a 1.6 g/g 1 standard deviation interval.
spaghnurn region with a sparse canopy would have a similar $\rho_{TIX:MR}$ as drier feather moss region with a denser canopy. $LAI_o$ uncertainty, $LAI_o$ smoothing and mis-registration of the $LAI_o$ and TM5 images also decrease $\rho_{TIX:MR}$ separability between mosses. In addition, the size of sphagnum and feather moss patches may have been below the 30 m resolution of the TM sensor. The coarse spatial resolution of the soil map polygons prevented assessment of the potential for mixed pixel errors.

### 4.6 Conclusions and Recommendations

#### 4.6.1 Conclusions

Laboratory studies provided strong evidence that a single exponential decay relationship is sufficient to relate moss MIR reflectance to increases in moss moisture content for both feather mosses and sphagnum mosses. The invariance of this relationship between mosses substantially simplified the problem of mapping moss moisture content to one of identifying TOM MIR reflectance.

A 3-D RT-GO model was able to provide plausible estimates of TOC reflectance given adequate knowledge of canopy structural and reflectance properties. The model exhibited a critical point, at high canopy cover conditions, observed in empirical data but not predicted by other reflectance models. Unlike other reviewed reflectance models the RT-GO model did not require calibration to observed TOC reflectance but made use of measurable stand properties. In this sense, the physically based model was useful for assessing the relationship between moss wetness and top of canopy reflectance. Parameterization of spatial variations in these parameters based on remotely sensed data sources may be difficult. The use of multi-date imagery and the incorporation of surface based information constraining the joint distribution of canopy characteristics and moss cover may reduce the impact of errors in stand parameters on the MIR inversion technique.

The remainder of the conclusions address the specific research questions presented in this study.
Is it possible to map the spatial pattern of moss moisture content over wet conifer sites at fine (30m) resolution?

Evaluation of the MIR inversion method suggested it was sensitive to typical in-situ moisture content variations with sparse canopies (below 60% cover). Fortunately most boreal wet conifer stands fall under the category of sparse canopy stands. While the inversion method had sufficient sensitivity over the range of typical moss moisture contents and overstory canopy cover its precision was poor with a tentative estimate of +/-1.60 g/g absolute precision error for a pixel representative of a baseline stand with 50% canopy cover. The largest sources of uncertainty were errors in canopy cover and image calibration. Both of these factors were not within the scope of the model but are external data products. It is possible that the precision of relative moisture maps may be higher given that image calibration errors would be uniform over larger regions. Finally, aggregation of individual pixel moisture estimates may also increase model precision by averaging over model errors caused by variations in structural and reflectance properties of canopies.

Is it possible to identify the spatial pattern of moss functional type (*Sphagnum* spp. versus feather mosses such as *Pleurozium schreberi*) over wet conifer sites at fine (30m) resolution?

The precision of the moisture mapping method, together with the large separation in moisture contents and $\rho_{\text{TM5:MIR}}$ between sphagnum and feather mosses during dry periods, suggest that it may be possible to map pixels which contain reasonably homogenous moss functional type with knowledge of canopy cover. However, application of the moisture mapping method to the NSA-OBS site indicated two significant problems with the MIR inversion method for both moisture mapping and moss type identification. The first problem was uncertainties in canopy cover due to precision errors in the $LAI_o$ estimation algorithm, the coarse spatial scale of the $LAI_o$ data, and misregistration of $LAI_o$ and TM5 imagery. The second problem was the strong negative correlation between canopy cover and understory wetness (sphagnum moss proportion) which resulted in a low overall dynamic range in $\rho_{\text{TOC:MIR}}$ across the landscape. As a result, the spatial variation in the MIR signal was attenuated by the canopy.
4.6.2 Recommendations

The RT-GO forward model should be further validated using co-incident in-situ measurements of canopy cover, moss type, surface moisture, $\rho_{TOM:IR}$ and $\rho_{TOC:MIR}$. This in-situ monitoring could be used to determine the extent to which model errors contribute to inversion errors in accuracy and precision.

The MIR inversion method suffers from the need for accurate and precise $LAI_s$ data and the low dynamic range in the spatial $\rho_{TOC:MIR}$ signal between dry feather moss and wet sphagnum regions. Errors due to $LAI_s$ uncertainty could be minimized by considering temporal trajectories of $\rho_{TOC:MIR}$ at the same spatial location. Furthermore, field based calibration of moss type and overstory cover could serve to condition the inversion algorithm on $LAI_s$ as well as on MIR reflectance. In this manner, regions with dense canopies could be assigned feather moss cover even if the canopy attenuation of MIR results in a $\rho_{TOC:MIR}$ similar to a very wet sphagnum site.

4.7 References


Veldhuis, H., Soil mapping of the NSA sub-areas and tower flux sites, BOREAS Staff data set. BOREAS Information System, 1997.


A SPATIALLY DISTRIBUTED MODEL OF OVERSTORY AND SURFACE WATER BUDGETS IN BOREAL CONIFER STANDS

Preliminary Discussion

This chapter represents a manuscript in preparation that was motivated by:

i) scientific issues identified in the dissertation problem statement dealing with hydrological budgets and ET in Boreal conifer stands:

ii) observations, reported in Chapter 2, of substantial moss evaporation and significant, persistent, spatial differences in moss moisture contents within a mesic Boreal conifer stand:

iii) the availability of data within the framework of the BOREAS experiment that facilitated parameterization of an ecosystem flux without substantial calibration at selected study sites where validation measurements of water fluxes and stores are available:

v) the absence of a moss understory layer and spatially distributed soil hydrology with current model implementations at the same BOREAS study sites.

Objectives

The objectives of this paper were to:

i) document a modified version of RHESSys (Regional Hydro-Ecological Simulation System) [Band et al 1993] that includes a moss layer and other components specifically designed to
represent controls on water budgets in Boreal conifer stands:

ii) parameterize RHESSys with documented literature values and in-situ measurements while minimizing calibration to eddy flux measurements of vapour fluxes:

iii) assess model accuracy and precision given field observations and to compare model performance to results reported by con-concurrent modelling studies at the same site:

iv) identify model sensitivity to input parameters which are likely to exert significant controls on vapour fluxes.

**Relationship to Dissertation Research**

In-situ observations reported in Chapter 2 motivated the inclusion of a spatially variable moss layer in RHESSys. Relationships derived from these observations were used to parameterize interception and moss capacities and to validate moss moisture content.

Two related studies dealing with mapping surface wetness patterns in Boreal ecosystems [Fernandes et al 1996, 1997 (Chapters 3 and 4)] were conducted in response to the evidence from this chapter that suggests that incorporation of a spatially variable moss layer in RHESSys can result in accurate estimates of ET.

Chapter 6 in this dissertation makes use of the model to test the effect of scaling surface moss cover and hydrologic parameterizations on estimates of stand level ET. The precision estimates generated in this paper are used in the scaling study to quantify the significance of differences in ET due to scaling. The strong interrelationship between water and carbon budgets in Boreal forests also motivated a preliminary modelling study on net ecosystem production scaling in wet conifer stands, presented in Chapter 7.
Statement of Original Work

Text, figures and tables were entirely contributed by the present author. Comments and corrections were provided by the other authors.

The new version of RHESSys presented in this chapter was designed and engineered by the first two authors based on the RHESSys model developed by the third author [Band et al 1991], in collaboration with researchers at the Numerical Terradynamics Simulation Group, University of Montana, Missoula. The following model components were chiefly designed and engineered by the present author:

i) sparse canopy radiation sub-model including a clumping factor;
ii) two stream radiation which accounts for both direct and diffuse radiative transfer;
iii) separation of leaf and stem area;
iv) moss water and energy budgets;
v) physically based vertical soil water budget which includes a variable vertical porosity

Model parameterization, and data analysis were primarily contributions of the first author. The other authors offered substantial constructive criticism. The third author assisted in the formulation of research questions and conclusions.

This chapter includes a number of original contributions to Boreal ecosystem science. This study incorporates measurements describing structural and functional parameters derived at the same sites in an ecosystem flux model without adjustment of measured parameters. While other studies have validated models using overstory ET and soil moisture, the present study also includes understory ET and moss moisture validation. In addition, this study includes a sensitivity analysis of the modified RHESSys using observed evapotranspiration as a diagnostic. The paper also represents the first application of TOPMODEL to Boreal conifer stands with moss layers, vertically decaying soil porosity and flow paths without no-flux boundary conditions. Most importantly, this study and the results from Chapter 6, suggest that unbiased
flux model estimates of ET in wet Boreal conifer stands may require a spatially variable moss parameterization at a scale finer than 1km. This result is significant given that mesic conifer stands cover over 75% of the BOREAS study area land surface and that current ecosystem flux models developed for these stands do not consider fine scale spatial variations of moss parameterizations.

References


A Spatially Distributed Model of Overstory and Moss Water Budgets in Boreal Conifer Stands

Richard A. Fernandes, Christina L. Tague, Lawrence E. Band

5.1 Introduction

The Boreal ecosystem covers a circumpolar region extending from a southernmost point of approximately 48°N latitude to the northern hemisphere tree line. The ecosystem is comprised of upland forests, forested peatlands, fens, open water bodies and regenerating post-burn areas that together total approximately 11% of the Earth’s land cover [Bonan and Shugart 1989]. The Boreal ecosystem is estimated to contain 43% of the carbon stored in soil worldwide [Schlesinger 1991]. There is interest as to the current and potential role of the Boreal ecosystem as a source of methane [Bartlett and Harris 1993], a source or sink of atmospheric CO₂ [Goulden et al 1997] and as to its potential effects on atmospheric general circulation [Margolis and Ryan 1997]. Over regional and local extents the role of disturbance, both natural and anthropogenic, on the storages and fluxes of the Boreal ecosystem is of concern to wetland conservation [Mitsch and Gosselink 1993, pp. 367-411], agricultural and forest productivity [Paavilainen and Paivanen 1997, p. 21] and the quantity [Ivanov 1981] and quality of runoff [Mitsch and Gosselink 1993, pp. 367-411]. A pressing concern is to determine how potential shifts in the hydrologic regime, dominated by evapotranspiration (ET), would feed back to the peatland soil moisture and groundwater level, and hence to the carbon budget.

ET plays a significant role in energy, water, chemical and carbon budgets of the Boreal ecosystem and has been labelled the most important hydro-physical process in peatlands during the growing season [Romanov 1968, p. 151]. Surface controls on ET have been suggested as a factor which promotes the growth of atmospheric boundary layers heights similar to deserts over forested Boreal land surfaces in Canada [Betts et al 1996]. ET constitutes between 60% to
100% of the annual losses in the water balance of Boreal peatlands [Romanov 1968, p. 151]. This suggests that ET may play a significant role in controlling soil moisture; especially during dry-downs when runoff is low. Soil moisture controls on net ecosystem productivity drive much of the spatial variation in observed CO₂ and CH₄ flux over a range of spatial scales in mesic Boreal landscapes [Waddington and Roulet 1996]. Temporal variations in water and carbon budgets occur as a result of disturbances and climate variations. Drainage of forested Boreal wetlands in Finland resulted in annual aboveground production increasing from 2.3 tonnes C ha⁻¹ yr⁻¹ before drainage to 4.4 tonnes C ha⁻¹ yr⁻¹ 50 years after drainage [Paavilainen and Paivanen 1997, p. 36]. Changes in aboveground biomass due to shifts in productivity or harvesting have feedbacks to the water budget. For example, removal of forest cover resulted in a 100% increase in annual runoff and a 30mm increase in water table height over three years [Paavilainen and Paivanen 1997, pp. 99-100]. This suggests that changes in ET and carbon flux caused by disturbances or climate change may be interrelated.

This paper focuses on the development and testing of a diagnostic, daily time-step, ecosystem flux model. RHESSys (Regional Hydro-Ecological Simulation System) [Band et al 1993], modified to represent processes specific to Boreal ecosystems. The most significant modification is the inclusion of a spatially variable understory moss layer coupled to a distributed hydrologic model (TOPMODEL [Beven and Kirkby 1979]). The primary research question addressed is whether RHESSys, when applied to selected Boreal conifer sites, using parameters measured in-situ, is capable of estimating ET with a precision that falls within the level of uncertainty in validation data.

5.1.1 Review of Previous Work

Numerical models that estimate ET in Boreal forests range in spatial scale from coarse scale climate and ecosystem flux models [Kite et al 1994] to site specific energy budget models [Romanov 1966, pp. 167-177; Laflleur and Rouse 1990]. The need to test a model at fine spatial scale over a number of Boreal conifer sites constrains this review to sub-grid scale ecosystem flux models which could potentially be parameterized using remotely sensed information rather
than calibrations to other local ET estimates. Sub-grid scale models of Boreal CO₂ flux have been tested over a number of sites [Bonan 1991; Bonan 1992; Hunt and Running 1992]. Similar models of ET have only recently been tested over a range of Boreal sites under the auspices of the Northern Wetlands Study (NOWES) [Roulet et al 1992], the Northern hemisphere climate Process land-surface Experiment (NOPEX) [Lundin and Halldin 1994a,b] and the BORéal Ecosystem Atmosphere Study (BOREAS) [Sellers et al 1994]. For brevity we only review modelling studies performed within BOREAS.

A number of the ecosystem flux models applied within the BOREAS study area have not always represented observed spatial variations in surface moisture, bryophyte cover and associated co- variations in canopy cover at spatial scales finer than 1 km. Bonan and Davis [1997] found that ET was consistently underestimated by their model at dry conifer sites during dry downs. Kimball et al [1997a] matched total ET without significant bias across selected conifer and deciduous stands over the growing season using a single patch model without an explicit moss layer. However, they used model parameters that differed substantially from in-situ measurements of canopy conductance and maximum soil moisture capacity. They also suggested that within site heterogeneity may be a factor responsible for differences between measured and modelled CO₂ fluxes using the same model [Kimball et al 1997b]. Nijssen et al [1997] included fine scale (sub-1km) topographic information when applying an energy budget model over a mature black spruce stand. They reported a bias in modelled ET fluctuating between 0% to 20% of mean growing season ET and a root mean square error of over 50% of mean growing season ET. The topographic data used in their study was generated by the present authors from 1:50000 scale maps. The suitability of this topographic data for describing controls on spatial patterns of soil or moss moisture was not evaluated. Nijssen et al [1997] also suggested that their assumption of a bare soil surface was not physically realistic. Cooper et al [1997] explored the difference between model based ET estimates with spatially uniform and spatially variable surface parameterizations. The finest spatial scale of 1km ignored the substantial variation in within site moss cover and moisture content observed in-situ (e.g. Chapter 2, Veldhuis [1997], Anderson [1997], Harden et al [1997]). In addition, Cooper et al [1997] did not validate the model against measurements. Therefore their results are conditional.
on the fine scale model being accurate. The absence of a moss parameterization in all of the reviewed studies underlines the need to evaluate the performance of an ecosystem model using a realistic surface parameterization at fine spatial scales where validation data is available.

The BOREAS modelling studies cited above often relied on parameters not measured in-situ; in part due to the desire to evaluate model performance before a complete set of field data was available. It is possible that the degrees of freedom afforded by chosen parameters may reduce the physical basis behind the explanatory power of a given model. Reported model performance may then not be representative of regions in space or time over which the model is applied. In this study every effort was made to use parameters based on in-situ measurements and to identify parameters chosen from the literature or by calibration.

5.1.2 Research Questions

A diagnostic ecosystem flux model, such as RHESSys, serves as a tool for regionalising estimates of ET by scaling relationships calibrated over needles, branches, or small plots within study sites (and possibly in the laboratory) to patches of characteristic land surface cover represented by selected study sites. The availability of field data for the BOREAS region minimizes the need for selecting parameters values from typically sparse or uncertain literature data and also reduces the extent of model calibration. The need for a fine spatial scale baseline model for testing model scaling behaviour motivated the following research questions:

1. What is the accuracy and precision of RHESSys estimates of ET over selected Boreal conifer stands relative to eddy flux estimates when the model is parameterized using the finest spatial scale data available?

2. How well does RHESSys estimate corollary surface state variables such as surface moisture or understory ET?

3. What is the sensitivity of modeled ET to uncertainties in parameters controlling overstory
The emphasis of this study is to define, parameterize and test a daily time step diagnostic flux model of ET over a set of mature Boreal conifer sites using data measured during the BOREAS campaign. The expected level of accuracy, precision, and uncertainty of the fine scale diagnostic model is intended as a benchmark for future evaluation of coarser scale model applications and for investigating the possibility of simpler models.

5.2 Scope

The scope of this study is defined in three aspects:

- spatial and temporal extents;
- the methods used for estimating and validating ET;
- and the spatial and temporal resolution of the model and input parameters.

5.2.1 Spatial and Temporal Extent

This study relied on field data acquired from four mature conifer sites, each approximately 1 km², in the BOREAS study area. The sites were designated as the Old Black Spruce (OBS) and Old Jack Pine (OJP) sites in either the Northern Study Area (NSA) or Southern Study Area (SSA). The sites are briefly described in Table 5.1 in terms of the components represented in the conceptual model upon which RHESSys is based. Full site descriptions, including information regarding understory herb cover and secondary strata not included in the current conceptual model are provided in Sellers et al [1994, 1995], and Halliwell and Apps [1997a,b,c]. Conifer sites were chosen given that both 1 km resolution Advanced Very High Resolution Radiometer (AVHRR) classification and 30m resolution Landsat Thematic Mapper (TM) classifications indicated conifers cover between 83% and 95% of the forested BOREAS study area [Steyart et al 1997]. Dry conifer regions, similar to the OJP sites, cover less than 10% of the
region. However, they were included in the study as they represent a potential successional outcome within post-burn regeneration sites. Modelling deciduous sites was beyond the scope of this study both due to the additional complexity of describing phenological trends and the fact that the central and northern BOREAS study area is dominated by conifers [Steyart et al 1997].

The temporal extent of RHESSys application was limited to the 1994 calendar year. Forcing climate data was not available for the entire winter period at some sites and had to be filled in with data from meteorological stations within the same study area. The year chosen was exceptionally dry and warmer than normal in the NSA and slightly wetter and cooler than normal in the SSA [Sellers et al 1997]. The pronounced dry downs observed in the NSA and heavy rainstorms in the SSA permitted testing RHESSys under different climate regimes.

Table 5.1. Description of BOREAS tower flux sites modelled. The four sites correspond to mature stands dominated by *Picea mariana* (OBS) and *Pinus banksiana* (OJP) located at the northern (NSA) and southern (SSA) edges of the central Canadian Boreal ecosystem. The overstory at each site included sub-dominant strata containing the dominant species at the other conifer sites as well as *Alnus crispa* (Alder) or *Larix laricina* (Tamarack). These strata, together with seasonable herb dominated understories, were not included in the RHESSys conceptual model for simplicity. The surface layer describes the cover adjacent to the mineral soil surface. The mineral soil layer was assumed homogenous within sites with the exception of a spatially variable water table depth. The reader is referred to Halliwell and Apps [1997a,b,c] and the sources cited in the table for more detailed physical descriptions.

<table>
<thead>
<tr>
<th>Site</th>
<th>Dominant over-story</th>
<th>Surface Layer†</th>
<th>Soils</th>
</tr>
</thead>
<tbody>
<tr>
<td>NSA-OBS</td>
<td><em>Picea mariana</em> (Mill.) BSP</td>
<td>13% Brown Moss &amp; Sedges, 34% <em>Sphagnum sp.</em> mosses, 53% Feather mosses</td>
<td>Very poorly drained Humic Organic Cryosol</td>
</tr>
<tr>
<td>NSA-OJP</td>
<td><em>Pinus banksiana</em> Lamb.</td>
<td>100% Bare soil and lichens</td>
<td>Rapid drained Orthic Dystric Brunisol</td>
</tr>
<tr>
<td>SSA-OBS</td>
<td><em>Picea mariana</em> (Mill.) BSP</td>
<td>4% Brown Moss &amp; Sedges, 40% <em>Sphagnum sp.</em> mosses, 56% Feather mosses</td>
<td>Poorly drained Gleyed Regosol</td>
</tr>
<tr>
<td>SSA-OJP</td>
<td><em>Pinus banksiana</em> Lamb.</td>
<td>90% Bare soil and lichens, 10% Feather mosses</td>
<td>Moderately well drained Orthic Eutric Brunisol</td>
</tr>
</tbody>
</table>

† From Anderson [1997], Harden et al. [1997] and Veldhuis [1997].
The limited temporal extent implies that accuracy and precision estimates are specific to the conditions prevailing during 1994 and that multi-year analysis should be performed in future work. Model spin up was performed using repetitive application of the 1994 forcing functions at the NSA-OJP and the SSA sites. Model spin up was performed using repetitive application of data from January 1 1994 until September 1996 for the NSA-OBS. The additional data was included to minimize the impacts of biases in initial soil moisture due to the exceptionally dry 1994 period.

**5.2.2 Methods Used for ET Estimation and Validation**

ET may be estimated by mass balance, energy balance or direct measurement [e.g. Oke 1996]. Cuenca et al [1997] estimated ET over the NSA-OJP site using a mass balance approach. They arrived at a 60% overestimate in daily ET during the mid and late growing season in comparison to tower flux measurements; possibly due to spatial variations in soil moisture at the site. In the current study mass balance measurements were limited to validating soil moisture and parameterizing canopy throughfall.

Direct measurements of vapour fluxes, using eddy correlation methods, were available at all four study sites [Baldocchi et al 1997, Jarvis et al 1997, Fitzjarrald and Moore 1997, Goulden et al 1997]. Top of canopy vapour flux measurements were performed at all of the sites during the 1994 growing season. Understory vapour flux measurements were also performed at the OJP sites. Both top of canopy and understory eddy correlation sensors were located at the centre of the selected sites. Issues dealing with the representativeness and error levels of these measurements are discussed in later in this chapter and the above citations.

The energy balance method solves for ET by estimating all other significant components of the energy balance of evaporating surfaces [e.g. Budyko 1958]. RHESSys performs a daily time step diagnostic estimation of latent heat flux from patches within each site by using simplifying assumptions and measured data to constrain the other energy budget components. Specifically, the Penman-Monteith combination equation [e.g. Oke 1996] is separately applied to the
overstory and understory canopy layers. The use of the Penman-Monteith equation eliminates
the need to resolve sub-daily changes in canopy temperature in response to diurnal trends in
vapour fluxes and net radiation. In addition, the model assumes that, over a daily time step, net
longwave radiation has a negligible effect on modelled latent heat fluxes as also assumed in other

The simplifications in energy and water budgets adopted by RHESSys reflect the fact that it is
not designed for prognostic estimation of fluxes or precise diagnostic estimates of sub-daily
fluxes. Rather, RHESSys is intended as a tool to examine scale dependent controls of surface
parameters on modelled fluxes over weekly or seasonal periods. Diagnostic energy budget
equations were specifically adopted to increase the extent to which factors not included in
scaling treatment are controlled. The daily time step and simplified energy budget reflect the
desire to eventually apply the model over large regions where sub-daily forcing data may not be available. RHESSys is not intended as a replacement for prognostic surface water budget models
that operate at sub-daily time steps (e.g. TOPLATS [Peters-Lidard et al 1997], DHVSM
[Wigmosta et al 1994]). Rather, the purpose of this study is to determine the extent to which the
simplifications involved in RHESSys energy and water budgets permit accurate and precise
estimation of weekly and seasonal water budgets within selected Boreal conifer stands.

5.2.3 Spatial and Temporal Resolution of Fields

RHESSys was executed using a diurnal time step. In some cases, information describing the
sub-daily variation in measured fluxes was included (e.g. daytime rain duration). RHESSys was
parameterized using data mapped at a maximum spatial resolution of 10m. Site soil maps,
provided at 10m resolution, included information on local water table depths and also permitted
estimation of the type of surface cover. Leaf area maps were also available for the NSA sites at
30m spatial resolution and gridded at 10m resolution during parameterization. All other
parameters were assumed dependent on these two maps (e.g. plant area was set as a constant
multiple of leaf area) or were assumed spatially uniform over the study sites. The fine scale
partitioning of RHESSys at each study site was defined by patches corresponding to soil map
polygons. Aggregation of both input parameters and within site model partitions to patches was adopted since the actual specification of soil map properties was performed for each polygon rather than each 10m grid square cell over which the map was gridded.

5.3 Conceptual Model of Controls on ET

This section describes RHESSys as modified for Boreal forests. The most significant difference from the previous version of RHESSys model [Band et al. 1993] is the addition of a surface vegetation layer to represent mosses and lichens. The current model also includes a prognostic canopy short wave radiation sub-model which accounts for canopy clumping, for the ratio of leaf area to plant area and for differences in transmission of direct and diffuse irradiance within the canopy. The modifications also include a physically based description of vertical soil column hydrology based on theoretical work by Eagleson [1978] and existing numerical models [Famiglietti and Wood 1994, Wigmosta et al. 1994]. The following description of RHESSys explicitly states simplifying assumptions within energy and water budgets. These assumptions are included to provide a faithful documentation of RHESSys and do not imply that the in-situ processes actually follow the assumptions. Furthermore, many of the assumptions are typical of similar daily time step ecosystem flux models and represent the limited availability of high temporal resolution forcing data over regions not instrumented for research purposes.

5.3.1 Accounting of ET

Figure 5.1 indicates an example of the within site partitioning scheme used during this study. Each study site is partitioned into N patches corresponding to unique soil map polygons. Each patch consisted of an overstory vegetation layer, a surface vegetation layer and a mineral soil layer. The overstory vegetation species was assumed to match the dominant species at the site. The complexity of including sub-dominant species in the overstory layer was beyond the scope of this study. The understory herb layer common in the OBS sites was not modelled. The potential significance of this herb layer and of variations in species within the overstory layer
was implicitly considered in later analysis of the sensitivity of site ET to canopy conductance and canopy leaf area. The assumptions regarding a uniform overstory species and the lack of a herb layer have also be adopted by other daily time step diagnostic models applied to the same study sites [Frolking et al. 1996, Kimball et al. 1997]. RHESSys was modified to include a surface vegetation layer (representing mosses, lichens or litter) which varies between patches and within patches by specifying non-spatial component mixture distributions. It should be noted that although Figure 5.1 represents the patches as being explicitly located in space for presentation purposes, RHESSys does not locate the patches explicitly in space. The total site ET is then defined as the area weighted sum of overstory ET and soil and surface E in each patch $i$ assuming that the contribution from each of the $j$ surface vegetation layer mixture components is proportional to its fractional cover $f_{ij}$:

$$ET_{site} = \frac{1}{a_{site}} \sum_{i=1}^{n} a_i \left[ E_{i,overstory} + T_{i,overstory} + E_{i,soil} + \sum_{j=1}^{J} (f_{ij} \times E_{i,j,surface}) \right]$$  \hspace{1cm} (1)$$

Simplified energy budgets of layers are computed in order of overstory, understory and then soil surface. Transmitted direct irradiance, diffuse irradiance and throughfall of rain and snow are assumed uniform over the surface and soil layers in each patch due to the lack of information regarding the explicit location of the surface layer mixture components. Figure 5.2 provides a schematic of modelled with site energy and water fluxes using a simplified 2 patch site. The estimation of these fluxes, together with the assumptions adopted, is discussed below.
Figure 5.1. RHESSys spatial partitioning scheme. Each modelling site is partitioned into patches that correspond to regions of distinct soil and surface properties. Patches are not located in a spatially explicit manner (although the figure shows them as such for convenience). The soil column and overstory layer within each patch are considered spatially uniform. The surface layer can consist of a mixture of component cover types, of specified fractional cover within the patch, that are not explicitly located in space. Vertical fluxes within a patch are assumed independent of neighbouring patches with the exception of changes in the water table depth. The patch local water table depth is modelled using an algorithm based on TOPMODEL [Beven and Kirkby 1979] which relates a patch specific soil topographic index to the site mean soil topographic index.
Figure 5.2: RHESSys within site partitioning scheme for a two patch example. Selected energy budget fluxes are indicated for Patch 1. Selected water budget stores and fluxes are indicated for Patch 2. Both energy and water fluxes are assumed to be patch specific and are computed separately for the overstory layer, surface layer components and the soil column. Patch and site water table depths are indicated by dashed lines and are computed based on water budgets of all patches within the site by applying TOPMODEL [Beven and Kirkby 1979].
5.3.2 Radiation Balance

Net radiation is estimated for each layer assuming that the net longwave flux was negligible as in Kimball et al [1997a] and as in previous implementations of RHESSys [Band et al 1993]. This assumption may be valid when estimating fluxes on a daily basis. Furthermore, incoming longwave radiation was not measured at the OBS sites. Net shortwave radiation is estimated prognostically with separate direct and diffuse streams:

\[ Q^* = S^* + D^* \]  

(2)

Overstory \( S^* \) is computed as in Liu et al [1996] by integrating the effect of diurnal changes in solar path length. Their method includes a clumping factor to account for non-random plant area distributions common with sparse Boreal canopies. Overstory \( D^* \) from interception of incident top of canopy and backscattered surface irradiance is estimated using Beer's law with a 15% reduction in overstory \( \rho_{proj} \) to account for within overstory multiple scattering [Chen et al 1997]:

\[ D^* = [D \downarrow (1 - \alpha_D) + S \downarrow \beta] \exp(\kappa \cdot 0.85 \cdot \rho_{proj}) \]  

(3)

The mixture fraction weighted albedo of the surface layer components, \( \beta \), is used to estimate upwelling scattered direct irradiance. Upwelling scattered diffuse irradiance is assumed negligible as it was estimated as an order of magnitude lower than \( D^* \) using a canopy radiative transfer model developed by Myneni [1991]. Surface layer \( Q^* \) is estimated by assuming no transmittance to the underlying mineral soil. This assumption is reasonable for feather moss layers [Skre et al 1983] and likely also valid for sphagnum layers given that their canopies are substantially deeper than those of feather moss turfs (unpublished observations by the author). The assumption of complete surface layer short wave extinction was also applied to lichen and litter layers as in Band et al [1993].

Empirical data suggest the magnitude of instantaneous heat fluxes in the upper soil layer and the
surface layer ranges from 5% to 30% of net radiation for Boreal fens and sparse wet conifer sites [Romanov 1968; Lafleur and Roulet 1992; den Hartog et al 1994; Wessel and Rouse 1994; Kim and Verma 1996]. Measurements of soil heat flux were not available at the study sites at the time of writing. However, the co-variation of heat capacity with soil moisture content was of concern when estimating net radiation for these layers. Specifically, while the diurnal average $G^*$ is often assumed to be small [Kimball et al 1997a; Band et al 1993], the daytime heat flux may indicate an energy sink that is not negligible in comparison to surface layer $Q^*$. A diagnostic $G^*$ estimate was implemented as a compromise between the need to control for heat flux variations between wet and dry patches and the a priori decision to use a diurnal time step model. $G^*$ was estimated using measured surface and soil temperature. An exponential decay of temperature with depth was assumed as in [Oke 1987, p. 46]. The additional assumption of negligible heat flux at a diurnal damping depth at which soil temperature is measured results in:

$$G^* = z_d C_{soil} (\overline{T}_{sundown} - \overline{T}_{sunrise}) \times (1\text{day})^{-1}$$

Soil temperature measurements were provided at one location within each OJP site. The absence of significant spatial variation in surface moisture patterns [Cuenca 1997] within the OJP sites suggests the single measurement may be sufficient to reduce the bias in assuming no soil heat flux common in daily time step models [Kimball et al 1997a; Band et al 1993]. The OBS sites included soil temperature measurements within both a well drained feather moss region and a very poorly drained sphagnum region. Soil heat capacity is estimated using modelled soil moisture content and literature values of soil physical parameters [Oke 1996]. The soil heat flux correction was implemented to remove an obvious likely bias in soil heat flux between inundated and well drained regions within the OBS sites. The issue of prognostic heat flux estimation was beyond the scope and need of the dissertation questions.

5.3.3 Actual Evaporation

Actual daily evaporation from each vegetation layer component is defined as the minimum of potential evaporation and the rain stored in the canopy. Daily precipitation is assumed to
replenish canopy storage, before evaporation is accounted, using:

$$\theta_c(t) = \theta_c(t-1) + \min(\theta_{c,specific} \cdot \phi - \theta_c(t-1), I_p) \cdot \text{day}$$  \hspace{1cm} (5)

Daily potential interception is given using a bi-linear relationship with a breakpoint calibrated from throughfall observations (unpublished data documented in Fernandes [1997]):

$$I_p = \begin{cases} 
i_p \cdot I_\downarrow & I_\downarrow < I_o \\ 
i_1 \cdot I_\downarrow & \text{else} \end{cases}$$  \hspace{1cm} (6)

The instantaneous potential overstory evaporation rate is estimated using the Penman-Monteith equation [e.g. Oke 1996] assuming negligible canopy resistance to vapour flux and assuming no coupling between overstory and surface:

$$E_{\text{overstory}} = \frac{\Delta \times Q^* + C_p \times \rho_{\text{air}} \times \text{vpd} \times g_a}{\rho_{\text{water}} L_v (\Delta + \gamma)}$$  \hspace{1cm} (7)

The instantaneous potential evaporation rate for a given surface layer component was estimated using the Penman-Monteith combination equation with the canopy conductance replaced by an empirical surface layer canopy conductance term:

$$E_{\text{surface}} = \frac{\Delta \times (Q^* - G^*) + C_p \times \rho_{\text{air}} \times \text{vpd} \times g_a}{\rho_{\text{water}} L_v (\Delta + \gamma (1 + g_a / g_c))}$$  \hspace{1cm} (8)

The assumption of uncoupled overstory and understory evaporation has been used in previous implementations of RHESSys [Band et al 1993] and is adopted in this study due to the difficulty
in specifying within canopy coupling terms given the a priori limitation of daily microclimate forcing data.

The instantaneous evaporation rate for a vegetation layer during rain free periods, $E_{\text{dry}_r}$, is estimated using measured daytime mean $vpd$ with Equation 7 for the overstory and Equation 8 for the surface layers. The instantaneous evaporation rate for a vegetation layer during rainy periods, $E_{\text{rainy}_r}$, is estimated using the same equations but with a $vpd$ of 10 Pa to reflect high humidity. Rainy period evaporation has been indicated by water budget measurements in northern conifer stands [Tallaksen et al 1996] and was included based on its presence in other canopy water budget models [Calder 1996]. Daily total rainy period evaporation, $E_{\text{rainy}}$, is estimated by scaling the instantaneous rate, $E_{\text{rainy}_r}$, by the daytime rain duration; with $E_{\text{rainy}}$ limited to the canopy storage after accounting for precipitation inputs. Daily total dry period evaporation, $E_{\text{dry}_r}$, is assumed to follow rainy period evaporation until the canopy storage for the given layer component is depleted. Daily total overstory evaporation is then given by the sum of $E_{\text{rainy}}$ and $E_{\text{dry}_r}$ for the overstory layer or the surface layer component under consideration.

Diurnal time step models often assume constant overstory and surface aerodynamic conductances [Kimball et al 1997a; Band et al 1993]. This assumption does not correct for differences in canopy structure or canopy density. Site specific growing season means of observed drag coefficients, for both overstory and surface, are used to determine aerodynamic conductance for each layer given top of canopy wind speed:

$$g_a = \left( u \times c_d \right)^2 \quad (9)$$

The sensitivity of site ET to $c_d$ is reported in Section 5.5.3. However, $g_a$ for the overstory were typically high enough (over 0.10 ms$^{-1}$) for the Penman-Monteith equation to predict almost complete coupling ($vpd$ driven ET) with the atmosphere for the overstory. In contrast understory $g_a$ was typically low enough (under 0.01 ms$^{-1}$) to result in almost complete decoupling
(radiation driven ET) with the atmosphere. It should be noted that, even if only a rough estimate of \( c_d \) was available, Equation 9 still represents an improvement on the assumption of constant \( g_a \) by permitting some sensitivity to wind speed.

Aerodynamic conductance is increased by a factor of 2 when patches contain moss surface layers with below 10% relative moisture content. This simulates the development of unstable profiles due to heating of dry moss surfaces. The purpose of this correction is to remove the obvious bias in assuming stable profiles with dry moss surfaces that can reach 10°C above air temperature [den Hartog 1994]. The alternative of applying a stability correction based on estimation of the Richardson number [eg. Oke 1996. p. 261] requires accurate knowledge of moss surface temperature: which is outside the scope of this study.

Conductance to evaporation from surface layer components and the soil column is modelled as being proportional to relative moisture content of the layer component or the soil column. Williams and Flanagan [1997] established a linear relationship between live moss relative moisture content and moss surface conductance to vapour flux for both Sphagnum sp. and a mixture of feather moss:

\[
g_c = g_o + g_1 \left( \frac{\theta_c}{\theta_{c, \text{max}}} \right)
\]

where, \( g_o \) and \( g_1 \) are empirical coefficients dependent on the moss functional group. Canopy conductance of litter and lichen mats is assumed to have a similar linear relationship as supported by Schaap and Bouten [1997]. Soil surface conductance is assumed to be linearly related to unsaturated zone moisture content as in Kelliher et al [1986] except for soils under mosses where it is considered zero [Kershaw and Rouse 1971; Chung and Horton 1987].

Sphagnum moss surfaces are conceptually modelled as being able to extract water from the soil column via capillary rise [Romanov 1968; Laine 1984; Price 1997]. In keeping with the conceptual model that sphagnum mosses act as a conduit for water from the soil column,
evaporative losses from sphagnum are replenished by capillary rise, labelled as $w_{\text{surf}}$ at a rate equal to the capillary rise rate within the unsaturated zone. This assumes steady state flow between the saturated zone, unsaturated zone and sphagnum moss turf as required by the unsaturated zone capillary rise model described in Section 5.3.5. This implies that the storage within the sphagnum mosses typically remains near saturation since any depletion in storage is matched by recharge via capillary rise.

5.3.4 Actual Transpiration

The overstory daily transpiration rate is estimated using:

$$T_{\text{overstory}} = T^* (t_{\text{dryt}} - t_{\text{rain}} - \frac{E_{\text{dry}}}{E_{\text{dry}}})$$

The instantaneous overstory transpiration rate, $T$, is estimated by the Penman-Monteith combination method with non-zero canopy conductance using the estimated overstory $Q^*$:

$$T = \frac{\Delta \times Q^* + C_p \times \rho_{\text{air}} \times vpd \times g_a}{\rho_{\text{water}} L_v (\Delta + \gamma (1 + g_a / g_c))}$$

Overstory canopy conductance is specified as:

$$g_c = \mathcal{L}^* (g_{\text{cuticular}} + g_s)$$

and stomatal conductance estimated using a measured maximum conductance, $g_{s,\text{max}}$ and multiplicative control factors [Jarvis 1976]:
Table 5.2 lists the control factors and their sources. Direct APAR is estimated by integrating the modified Beer's law equation specified by Liu et al [1996] over a uniform vertical distribution of plant area as in Rastetter et al [1992]. Diffuse APAR was estimated as in Norman [1982]. Both the direct and diffuse APAR estimation methods assume an exponential extinction of PAR within the canopy which was supported by field data [Dang et al 1997]. The predawn leaf water potential was estimated as the soil column water potential in the rooting zone by assuming hydrological equilibrium along the pathway from rooting zone to the leaves.

Control factor $f_1$ represents a daily analog to a similar instantaneous relationship commonly used to represent leaf stomatal response to APAR [Jarvis, 1976]. The use of a canopy mean APAR in $f_1$ was supported by observations that leaf level conductances were not significantly different between upper and lower regions of the over-stories at the study sites [Brocks et al 1997].

Control factor $f_2$ is a daily analog to observed instantaneous leaf level responses [Dang et al 1997] for mature *Picea mariana* (Equation 15b) and *Pinus banksiana* (Equation 15c) life forms. The analogs, shown in Figure 5.3, represent calibrated fits to ET weighted average instantaneous control factors using tower flux observations at the NSA-OBS and SSA-OJP [Baldocchi et al 1997; Goulden et al 1997]. It is of note that the control factors used by Kimball et al [1997a] were significantly different from the daily factors presented in Equations 15a, 15b and 15c while their model still provided unbiased estimates of ET for the BOREAS sites. One explanation for the success of their model may be their use of a single bucket hydrological model with very large water capacity (over 20 mm) that may have prevented premature drying of regions mapped as feather moss in the fine resolution soil maps.

\[ g_s = g_{s,max} f_1(\text{APAR}) f_2(vpd) f_3(T_{day}) f_4(T_{min}) f_5(\psi_{hwp,predawn}) \]  

(14)
Table 5.2: Stomatal environmental control factors. The equations represent multiplicative factors on $g_{c, max}$ ranging from 0 to 1. All equations use daytime mean measured meteorological data representative of the overstory. Equations 15a, 15b and 15c include constants which have been adjusted to represent daytime mean rather than instantaneous values by fitting to daily ET weighted means of half hourly estimates of the same control factor. Equations 15d, 15e and 15f were not adjusted as they were developed for daily time step meteorological data.

\[
f_1(\text{APAR}) = \frac{\text{APAR}-\text{APAR}_0}{\text{APAR}+\text{APAR}_{0.5}} \quad (15a)^6
\]

\[
f_2(\text{vpd}) = c_1 + c_2 \text{vpd} \quad (15b)^7
\]

\[
f_3(\text{vpd}) = c_1 + \frac{c_3}{(1 + c_1 \text{vpd} / 1000)} \quad (15c)^7
\]

\[
f_3(T_{day}, T_{max}) = \left( \frac{T_{day} - T_{coef}}{T_{opt} - T_{coef}} \right) \times \left( \frac{T_{max} - T_{day}}{T_{max} - T_{opt}} \right) \times \left( \frac{T_{max} - T_{opt}}{T_{opt} - T_{coef}} \right) \quad (15d)^7
\]

\[
f_4(T_{min}) = 1.0 + 0.125 \times T_{min} \quad (15e)^7
\]

\[
f_5(\psi_{lwp, predawn}) = \frac{\psi_{lwp, predawn} - \psi_{min}}{\psi_{max} - \psi_{min}} \quad (15f)^8
\]

\(^6\) Running and Coughlan [1988]; \(^7\) Calibration to daily aggregation using Dang et al. [1997]; \(^8\) Kimball et al. [1997a]
Figure 5.3: Half hourly ET weighted control factor (---), calibrated daily control factors (—––), daily control factors using daily means values for arguments to Equations 15a 15d (—–) and control factors of Kimball et al [1997a] (——). The calibrated daily control factors were generated by synthesizing growing season mean diurnal curves of forcing data and observed ET at a half-hourly resolution. The half hourly daily control factors were computed and aggregated using ET weighted averages. The functional form for each half-hourly control factor was then calibrated to match the half-hourly ET weighted control factor. This calibration was only performed at the NSA sites; with the SSA sites assuming the calibrated control factors of the NSA site with matching overstory species.
The use of ET weighted control factors also addresses the difficulty in temporal scaling of leaf-level in-situ measurements for daily time step models [Running 1994]. While the use of observed ET represents a form of forward calibration it should be noted that the weighting was defined by the mean diurnal ET trends over an entire growing season and does not represent a weighting optimized for each daily time step. Furthermore, the forward weighting does not include a specific adjustment based on observed residuals between modelled and observed ET. In fact, the constraint of using in-situ measurements of instantaneous leaf conductance parameters serves to constrain the choice of daily time step canopy conductance parameters.

5.3.5 Soil Water Budget

The patch soil column conceptual model consists of a single, variable depth, unsaturated zone over a saturated zone as shown in Figure 5.4. This assumes that perched water tables caused by frost lenses or layered mineral deposits do not interact with the surface water table so as to exert controls on ET. A constant amount of residual soil moisture is assumed unavailable for drainage or transpiration as in other Boreal hydrology models [Kimball et al 1997a, Nijssen et al 1997].

Unsaturated Zone

The unsaturated zone soil water budget is estimated as:

\[
\frac{d\theta_u}{dt} = I + w - q_{\text{drain}} - E_{\text{soil}} - T_{\text{overstory}} - w_{\text{surface}}
\]  

(16)

The infiltration rate, \(I\), is assumed equal to the throughfall from the surface canopy layer given the high surface sorptivity and saturated conductivities of peat and sand found in the study sites [Cuenca et al 1997].

The capillary rise rate to the unsaturated zone, \(w\), is set at zero when the unsaturated zone is
Figure 5.4: Soil column hydrology conceptual model. The soil column is partitioned into an unsaturated zone of time varying depth over a saturated zone. The column is bounded below by an impermeable layer and above by either bare soil or a moss or lichen layer together with an overstory canopy. Net lateral saturated zone runoff \( q_{\text{net}} \) is estimated using TOPMODEL and is equivalent to lateral outflow less lateral inflow. Vertical fluxes between the unsaturated and saturated zone include drainage to the saturated zone and capillary rise from the saturated zone. Vertical fluxes to the surface include overstory transpiration, bare soil evaporation and water extracted by sphagnum mosses to replace evaporative losses. Infiltration includes all vertical recharge to the unsaturated zone. Surface runoff occurs when the water table depth exceeds the detention store capacity.
above field capacity, equal to the rate required to reach field capacity while the water table depth is less than the capillary fringe depth (defined by the air entry pressure head) and otherwise estimated using the method defined by Familigetti and Wood [1994] based on Eagleson [1978]:

\[
 w = \begin{cases} 
 \max(\theta_f - \theta_u, 0) & \text{if } z_v \leq \psi_{ae} \\
 \frac{1 + 1.5/(1 + 3b)}{(z_v - \psi_{ae})^{2+3b}} & \frac{K_{sat}(z_v)\psi_{ae}^{2+3b}}{(z_v - \psi_{ae})^{2+3b}} & \text{if } z_v > \psi_{ae} 
\end{cases}
\]

where \( b \) is given by Brooks and Corey [1964]. The Familigetti and Wood method is used since it can be parameterized with soil physical parameters fitted to in-situ measurements [Cuenca et al. 1997]. A similar method based on the Eagleson conceptual model has also been used at the study sites in a parallel modelling study [Nijssen et al. 1997]. The in-situ validation of either method with peat soils found in Boreal conifer stands remains to be performed. However, capillary rise in peat soils has been observed in forested peatlands of the former Soviet Union [Romanov 1969].

Drainage from the unsaturated zone is estimated assuming gravity drainage to field capacity in one day limited to the minimum of the unsaturated vertical hydraulic conductivity based on mean unsaturated zone moisture content and the saturated vertical hydraulic conductivity at the water table. Vertical saturated hydraulic conductivity was assumed to decay exponentially with depth as observed in mineral soils [Beven 1984] and peats [Hoag and Price 1995; Romanov 1968]:

\[
 K_{sat}(z) = K_{sat}(0) \exp(-m_z z) 
\]

Field capacity is estimated as a numerical approximation to the following integral equation:
\[
\theta_{fc} = \int_{0}^{z_c} \eta(z) S(\psi = [z_v - z]) \, dz
\]  

(19)

Unsaturated vertical hydraulic conductivity, \( K(S) \) and soil moisture content as a function of matric potential, \( S(\psi) \), are estimated using equations presented by Brooks and Corey [1964] for peats and by van Genuchten and Nielsen [1985] for sandy soils. Both estimates of \( S(\psi) \) were modified so that \( S \) was set to 1 in the capillary fringe as expected empirically.

The effective porosity profile is assumed to decay exponentially with depth as observed for Boreal peats [Ivanov 1981] and expected with lacustrine soils [Kirkby 1997]:

\[
\eta(z) = \eta(0) \exp(-c_\eta z)
\]  

(20)

Bare soil evaporation, \( E_{e,nb} \), is estimated as the minimum of the bare soil potential evaporation determined using the Penman-Monteith equation and the maximum bare soil exfiltration (equivalent to bare soil evaporation) rate, \( E_{exfl} \), given by Wigmosta et al [1994]:

\[
E_{exfl} = \left[ \frac{8\eta_{avg}(z_v)K_{sat,avg}(z_v)\psi_{ac}}{3(1 + 3M)(1 + 4M)} \right]^{1/2} \left[ S \right]^{(1/2, M)+2} \sqrt{t_{day}}
\]  

(21)

where \( M \) is a function of the Brooks and Corey Parameters, \( \eta(z_v) \) and \( K_{sat,avg}(z_v) \) are the mean porosity and hydraulic conductivity of the unsaturated zone respectively and the product of the two bracketed terms estimates the sorptivity.

Water extracted by capillary rise to surface sphagnum moss cover is accounted for as \( w_{surface} \). The amount of water extracted is given by the computed capillary rise rate from the saturated to unsaturated soil zone, \( w \), limited by the maximum moisture capacity of the moss canopy. This assumes that capillary rise between the moss layer, unsaturated zone and saturated zone occurs at a steady state flow rate.
Saturated Zone

RHESSys makes use of a method based on TOPMODEL [Beven and Kirkby 1979] to estimate sub-surface runoff and subsequent changes in within site water table depths due to runoff or vertical recharge to the saturated zone. The TOPMODEL framework models saturated zone soil water flow based on a kinematic wave runoff model together with a number of other assumptions [Beven and Kirkby 1979, Kirkby 1997]. The essential assumption for the purpose of this study is that the shape of the water table over a study site is invariant with time with the exception of cases of saturation excess. Patch detention store height controls the amount of saturation excess permitted before surface runoff occurs. TOPMODEL also assumes that lateral transmissivity decays as an exponential function of the product of the water equivalent depth to the control volume representing the upper boundary of the region of lateral runoff and a spatially invariant value $m$. TOPMODEL was modified to include a variable vertical porosity, as commonly found in Boreal peats and as previously used in Alaskan tundra peatlands [Ostendorf 1996] and Boreal conifer stands in Sweden [Seibert et al 1997].

The use of study sites which are not hillslopes in the hydrological sense required an adjustment to the analytical form of TOPMODEL. The net site lateral runoff, $q_{net}$, is specified as a time varying boundary condition for each study site to give:

$$\frac{ds_{v,site}}{dt} = q_{net} + \frac{1}{a_{site}} \sum_{i=1}^{N} a_i (q_{drain,i} - w_i) \quad (22)$$

Equation 22 is solved for $ds_{v,site}/dt$ numerically by estimating $q_{net}$ as in Kirkby [1997]:

$$q_{net} = \exp(-\lambda_{site})\exp(-s_{v,site}/m) \quad (23)$$

The water equivalent depth to the saturated zone is updated for each patch by:
\[ s_{\varphi,i} = s_{\varphi,site} + m(\lambda_{site} - \lambda_i) \]  

where \( \lambda_{site} \) is the parameterized area weighted mean of the patch soil-topographic index represented by \( \lambda_i \) [Beven and Kirkby 1979]. Net surface runoff is estimated as all ponded water above a specified detention store.

### 5.4 Model Parameterization

Daily forcing data were aggregated from 15 minute resolution measurements at the OJP sites (BOREAS staff, BOREAS Information System) and 30 minute resolution measurements at the OBS sites [Goulden et al 1997; Jarvis et al 1997]. The OJP forcing data had been previously screened by BOREAS staff and filled in with data from the nearest surface meteorological station (within 30 km). Missing data at the OBS sites were replaced from the OJP site in the same study area. Forcing data included day length, precipitation water equivalent depth, daytime rain duration, direct and diffuse shortwave and PAR irradiance; daily average air and soil temperatures; daytime average air temperature, \( vpd \) and wind speed; daily and nighttime minimum and maximum air temperatures; and the ratio of daily to seasonal site mean leaf area.

Spatially uniform, time invariant, parameters are given in Tables 5.3 and 5.4 for overstory layers and patch soil columns respectively. A number of parameters were derived using data published on the BOREas Information System (BORIS) [Sellers et al 1995]. The spatially variable parameters described in the rest of this section include: overstory leaf area index (LAI), ground surface cover type, soil topographic index, detention store, moss water capacity, and rooting depth.

A 30 m resolution Landsat TM based overstory LAI image [Chen and Cihlar 1996] was co-registered to each NSA site with sub-pixel accuracy and precision. This image was then corrected for registration and mixed-pixel errors at each site by overlaying with a forest/non-
forest classification derived from a crown cover map generated by thresholding digitized air photographs. Landsat TM based LAI was not available for the SSA. Instead, forest cover maps [Halliwell and Apps 1997a] were used to indicate regions of “Treed Muskeg” versus mature upland conifer within each site. The LAI images at the NSA sites were adjusted so that the forested region LAI matched the mean LAI over the growing season measured on the surface by Chen [1996]. The SSA-OBS had two identifiable modes in LAI measured at the surface which were assigned to “Treed Muskeg” (lower mode) and mature forested (upper mode) regions based on an overlay of the measurement transects on the forest cover map for the site. Substantial uncertainty (15%-25% relative precision error) existed in LAI estimates with a bias of approximately -10% in comparison to destructive methods [Chen et al 1997].

Detailed soil maps were provided for each study site using mapping units corresponding to contiguous polygons with a finest resolution of 10 m [Veldhuis 1997; Anderson 1997]. The soil maps identified a number of surface microtopes (e.g. fen, bog, sandy ridges) within a single mapping unit, together with microtope fractional cover and water table depth, without explicitly mapping the microtopes within the mapping unit. Four functional surface cover types were mapped: sphagnum fens or bogs, feather moss covered upland areas, lichens and litter, and bare soil. The criteria for mapping each surface cover type is described in Table 5.5 while spatially invariant parameters are provided in Table 5.6.
Table 5.3: Overstory parameters that are assumed spatially uniform over each study site. The parameters were specified by in-situ measurements already published or currently archived in the BOREAS Information System. In cases where measurements were not available at all study sites, the same measurement at the most representative similar study site was used.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NSA-OBS</th>
<th>NSA-OJP</th>
<th>SSA-OBS</th>
<th>SSA-OJP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A^*$</td>
<td>4.57</td>
<td>1.89</td>
<td>4</td>
<td>2.64</td>
</tr>
<tr>
<td>$\Omega^*$</td>
<td>0.71</td>
<td>0.82</td>
<td>0.7</td>
<td>0.71</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$L/\phi^*$</td>
<td>0.84</td>
<td>0.72</td>
<td>0.84</td>
<td>0.68</td>
</tr>
<tr>
<td>$\alpha_N \cdot \alpha_{N,PAR}$</td>
<td>0.10,0.036</td>
<td>0.12,0.042</td>
<td>0.10,0.038</td>
<td>0.11,0.040</td>
</tr>
<tr>
<td>$\alpha_D \cdot \alpha_{D,PAR}$ (TF-03)</td>
<td>0.10,0.036</td>
<td>0.12,0.042</td>
<td>0.10,0.038</td>
<td>0.11,0.040</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\theta_{c,specific}$</td>
<td>0.2 mm water</td>
<td>0.2 mm water*</td>
<td>0.2 mm water*</td>
<td>0.2 mm water*</td>
</tr>
<tr>
<td>$i_0,i_1$</td>
<td>0.4,0.2</td>
<td>0.5,0.05*</td>
<td>0.4,0.2*</td>
<td>0.28,0.28*</td>
</tr>
<tr>
<td>$I_0$</td>
<td>5 mm water*</td>
<td>5 mm water*</td>
<td>5 mm water*</td>
<td>5 mm water*</td>
</tr>
<tr>
<td>$c_d$ canopy</td>
<td>0.288**</td>
<td>0.222 (TF-05)</td>
<td>0.122**</td>
<td>0.148**</td>
</tr>
<tr>
<td>$c_d$ surface</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>$g_{sat}^{cellular}$**</td>
<td>0.00005 ms$^{-1}$</td>
<td>0.00005 ms$^{-1}$</td>
<td>0.00005 ms$^{-1}$</td>
<td>0.00005 ms$^{-1}$</td>
</tr>
<tr>
<td>$g_{sat,max}$</td>
<td>0.0005 ms$^{-1}$</td>
<td>0.00125 ms$^{-1}$</td>
<td>0.0005 ms$^{-1}$</td>
<td>0.00125 ms$^{-1}$</td>
</tr>
<tr>
<td>APAR$_0$</td>
<td>0.20 umol photon m$^{-2}$s$^{-1}$</td>
<td>100, 353 umol photon m$^{-2}$s$^{-1}$</td>
<td>0.20 umol photon m$^{-2}$s$^{-1}$</td>
<td>100, 353 umol photon m$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>APAR$_{0.5}$</td>
<td>photon m$^{-2}$s$^{-1}$</td>
<td>photon m$^{-2}$s$^{-1}$</td>
<td>photon m$^{-2}$s$^{-1}$ (TE-04)</td>
<td>photon m$^{-2}$s$^{-1}$ (TE-04)</td>
</tr>
<tr>
<td>$c_1$, $c_2$, $c_3$</td>
<td>-0.2304,0.9967 Pa$^{-1}$, N/A</td>
<td>0.476, -0.052 Pa$^{-1}$, 0.147 Pa$^{-1}$</td>
<td>-0.2304, 0.9967 Pa$^{-1}$, N/A</td>
<td>0.476, -0.052 Pa$^{-1}$, 0.147 Pa$^{-1}$</td>
</tr>
<tr>
<td>$T_{opt}$, $T_{max}$</td>
<td>15 °C,35 °C, 15 °C, 35 °C, 15 °C,35 °C, 15 °C</td>
<td>15 °C,35 °C, 15 °C,35 °C, 15 °C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$T_{min}$**</td>
<td>-10 °C</td>
<td>-10 °C</td>
<td>-10 °C</td>
<td>-10 °C</td>
</tr>
<tr>
<td>$\Psi_{max}$, $\Psi_{min}$</td>
<td>-0.25 MPa, 4.75 MPa</td>
<td>-1.25 MPa, -2.25 MPa</td>
<td>-0.25 MPa, -1.25 MPa</td>
<td>-0.25 MPa, -1.25 MPa</td>
</tr>
</tbody>
</table>


Parameters without references were assumed identical to the same parameter at the other study area.
Table 5.4: Soil column parameters that are assumed spatially uniform over each study site. van Genuchten parameters were provided at OJP sites [Cuenca 1997]. OBS sites did not make use of in situ measurements conducted in the mineral soil layer [Cuenca 1997] since the peat layer is typically the active layer for lateral soil moisture fluxes [Romanov 1968]. The site mean wetness index, $\lambda_{wte}$, was calibrated based on literature values of maximum sub-surface lateral runoff (OBS sites) or by maximizing model fit to observed soil moisture at sites where spatial variations in soil moisture were not substantial (OJP sites).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NSA &amp; SSA OBS</th>
<th>NSA-OJP</th>
<th>SSA-OJP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{sat}(0)$, m day$^{-1}$</td>
<td>17.28$^+$</td>
<td>1.0$^-$</td>
<td>1.0$^-$</td>
</tr>
<tr>
<td>$m$, m water$^{-1}$</td>
<td>0.035$^+$</td>
<td>0.054$^-$</td>
<td>0.054$^-$</td>
</tr>
<tr>
<td>$\eta(0)$</td>
<td>0.8$^+$</td>
<td>0.21$^-$</td>
<td>0.385$^-$</td>
</tr>
<tr>
<td>$c_p$, m$^{-1}$</td>
<td>0.4328$^+$</td>
<td>2.476$^+$</td>
<td>1.65$^+$</td>
</tr>
<tr>
<td>$b$</td>
<td>0.25$^+$</td>
<td>5.0$^+$</td>
<td>5.0$^+$</td>
</tr>
<tr>
<td>$\psi_{wtr}$, m</td>
<td>0.2$^+$</td>
<td>0.128$^-$</td>
<td>0.128$^-$</td>
</tr>
<tr>
<td>$\lambda_{wte}$</td>
<td>6.907**</td>
<td>3.10$^*$</td>
<td>1.00$^*$</td>
</tr>
<tr>
<td>van genuchten n</td>
<td>N/A</td>
<td>1.56$^-$</td>
<td>1.56$^-$</td>
</tr>
</tbody>
</table>

$^+$Romanov [1968], $^-$Cuenca [1997]. $^+$Halliwell and Apps [1997b]. *calibrated to observed soil moisture. ** based on observed lateral flow rates in peatlands [Waddington and Roulet 1996]
Table 5.5: Criteria for mapping surface layer component cover type. Four cover types were specified to capture the dominant variations in controls on surface fluxes between and within study sites and to limit the demands on model parameterization. Features listed were determined from available soil maps at the study sites [Anderson 1997, Veldhuis 1997] and represent the only spatial maps of surface layer cover types available at the sites at the time of writing. The Fen/Water cover type was specifically indicated on the soil maps. Bare soil regions were identified as being neither bog or fen and having a surface material of mineral soil with a shallow LFH (Live-Fabric-Humic) layer. Feather moss regions were separated from sphagnum regions by LFH layer thickness and water table depth under the assumption that sphagnum regions correspond to substantial peat development in poorly drained regions. The classification represents an attempt to provide a documented, objective relationship between soil map features and surface cover categories suitable for model parameterization. Validation was not performed in-situ, but it is of note that the suite of features representative of each cover type were always consistent in providing the same cover type label.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Bare Soil</th>
<th>Feather moss</th>
<th>Sphagnum</th>
<th>Fen/Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFH Layer thickness</td>
<td>&lt;0.2 m</td>
<td>&lt;0.2 m</td>
<td>&gt;0.2 m</td>
<td>N/A</td>
</tr>
<tr>
<td>Humus/Peat thickness</td>
<td>&lt;5 cm</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Mode of deposition of parent material</td>
<td>Anthropogenic or Glacio-fluvial or Glacio-lacustrine</td>
<td>Bog or Fluvial or Glacio-fluvial or Organic</td>
<td>Bog or Fluvial or Organic</td>
<td>Fen</td>
</tr>
<tr>
<td>Local surface form</td>
<td>Neither bog or fen</td>
<td>Bog</td>
<td>Bog</td>
<td>Fen</td>
</tr>
<tr>
<td>Surface Material</td>
<td>Mineral soil</td>
<td>Mineral or Organic soil</td>
<td>Organic soil</td>
<td>Organic Soil or Water</td>
</tr>
<tr>
<td>Drainage class</td>
<td>Very Rapid to Well</td>
<td>Moderately Well to Poor</td>
<td>Poor to Very Poor</td>
<td>Very Poor</td>
</tr>
<tr>
<td>Depth of water table, average</td>
<td>&gt;20 cm</td>
<td>N/A</td>
<td>&lt;75 cm</td>
<td>&lt;20 cm</td>
</tr>
</tbody>
</table>
Table 5.6: RHESSys parameter values for surface layer component cover types. Feather moss and sphagnun interception parameters were based on measurements by the authors at the OBS study sites. Moss conductance parameters were measured using samples acquired in-situ by other BOREAS science teams. The lichen parameters were assumed to correspond to those for a sparse feather moss canopy. This assumption recognizes that both lichens and feather mosses are incapable of extracting soil moisture and often tend to occur in mixtures within upland Boreal conifer sites [e.g. Halliwell and Apps 1997a]. Moss heat capacity when dry was assumed equivalent to organic peat moss due to insufficient data for heat capacities of moss species. Modelled moss heat capacity was chiefly controlled by moss moisture content.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bare Sand</th>
<th>Lichens</th>
<th>Feather moss</th>
<th>Sphagnum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{w}^{\text{water}}$ $\cdot$ m water (unit area)$^{-1}$</td>
<td>porosity</td>
<td>0.0005$^{*}$</td>
<td>0.0044$^{*}$</td>
<td>0.02$^{*}$</td>
</tr>
<tr>
<td>$g_{o}$, ms$^{-1}$</td>
<td>**</td>
<td>0.0011$^{*}$</td>
<td>0.0011$^{**}$</td>
<td>0.0040$^{**}$</td>
</tr>
<tr>
<td>$g_{l}$, ms$^{-1}$ (m water)$^{-1}$</td>
<td>**</td>
<td>0.011$^{*}$</td>
<td>0.011$^{**}$</td>
<td>0.040$^{**}$</td>
</tr>
<tr>
<td>$i_{0}$, $i_{1}$</td>
<td>N/A</td>
<td>0.70.7$^{*}$</td>
<td>0.70.7$^{*}$</td>
<td>1.01.0$^{*}$</td>
</tr>
<tr>
<td>$\alpha_{l}$, $\alpha_{S}$</td>
<td>0.25.0.25 $^{**}$</td>
<td>0.25.0.25 $^{**}$</td>
<td>0.10.0.10 $^{**}$</td>
<td>0.10.0.10 $^{**}$</td>
</tr>
<tr>
<td>$C$, dry. Jm$^{-3}$K$^{-1}$</td>
<td>1280000$^{*}$</td>
<td>58000$^{*}$</td>
<td>58000$^{*}$</td>
<td>58000$^{*}$</td>
</tr>
</tbody>
</table>

$^{*}$Corresponds to mean layer thicknesses; $^{*}$as feather moss; $^{*}$Fernandes [1997]; $^{**}$Williams and Flanagan [1996]; $^{**}$ Price et al. [1997]; $^{**}$ Miller et al. [1997]; $^{*}$ Oke [1997]; $^{**}$ as in Kelliher et al. [1986].
Observed spatial patterns of water table depths [Veldhuis 1997; Anderson 1997] were used to estimate patch soil topographic index relative to the mean value for the site as in Seibert et al [1997]. The mean site soil topographic index was estimated by calibration to observed soil moisture for the OJP sites. The indication of substantial spatial variation in soil moisture within the OBS sites precluded the use of soil moisture observations for calibration of $\lambda_{w-e}$. Instead, $\lambda_{w-e}$ was defined as 6.907 so as to produce a $q_{sat}$ at saturation of 1 mm water day$^{-1}$ based on Equation 23. Baseflow rates are not easily measured from sites that are not hillslopes. However, maximum sub-surface flow rates in other Boreal wetlands suggest an upper bound of 1 mm water day$^{-1}$ is reasonable in the absence of additional information [Waddington and Roulet 1996]. The sensitivity of modelled ET to the calibrated $\lambda_{w-e}$ is explored in Section 5.5.3.

Rooting depth in the OBS sites was related to water table depth using an empirical relationship [Lieffers and Rothwell 1987]. The absence of substantial spatial variation in the ground water table over the OJP sites together with the low variation in measured rooting depths supported the use of a uniform rooting depth set at the mean depth observed in soil pits at each site [Halliwell and Apps. 1997b].

The hummocky OBS sites retain water in surface detention over saturated regions. Detention store height was estimated as half the height from hollow top to hummock height characteristic of a given land surface form provided on the soil maps. Heights were sampled at a single location within the NSA-OBS and 8 locations along a 500m transect in the SSA-OBS and were compared to literature values to arrive at typical detention store heights for each land surface form listed in Table 5.7. Specific detention store capacity was estimated by assuming unimpeded surface runoff above half the detention height and an hypsometric integral of 0.25 at this point, typical for cylindrical hummock and hollow profiles [Ivanov 1981]. The detention store capacities were not considered precise given the natural variability in drainage networks within Boreal wetlands [Peters et al 1995]. However, detention stores were included in RHESSys to reduce the obvious bias in assuming no detention store capacity in current models applied to the OBS sites and in the previous version of RHESSys. In-situ measurements of the length scales of hummocks were not recorded at the study sites. However, observations made by the author
suggest substantial variation below the 10 m resolution of the available soil maps. Such short length scale variability is also supported by observations in other peatlands [Ivanov, 1981].

Sphagnum and feather moss specific water capacity was estimated using field observations of moss moisture capacity and live moss depth together with estimates of moss depth provided in soil maps. Lichen and litter layer capacity was assumed to be identical to the capacity of an equivalent depth of feather moss. Fens and open water regions were assumed to have the same surface capacity as the maximum observed value for sphagnum.

Table 5.7: Estimated surface detention storage. Detention storage was defined as the maximum negative soil moisture deficit before surface runoff was assumed to take place. This is in contrast to previous versions of RHESSys [Band et al 1993] which assumed surface runoff from a patch as soon as a negative soil moisture deficit was computed for that patch. The land surface form feature was provided in soil maps at the sites [Anderson 1997; Velduis 1997]. Specific detention store capacity was estimated from in-situ observations of height from low to high points within each surface form at the OBS sites and from the literature cited. Capacity was assumed to correspond to the hypsometric integral at half the estimated height after which runoff was assumed to commence. The capacities fall within literature estimates derived from observations at other peatland sites.

<table>
<thead>
<tr>
<th>Land surface form</th>
<th>Specific detention store capacity, cm water</th>
<th>Literature estimates(^t). cm water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hummocky</td>
<td>10</td>
<td>6 to 17</td>
</tr>
<tr>
<td>Veneer Bog</td>
<td>5</td>
<td>3.5 to 6</td>
</tr>
<tr>
<td>Collapse Scar Fen</td>
<td>10</td>
<td>3 to 15</td>
</tr>
<tr>
<td>Peat plateau bog</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>Palsa Bog</td>
<td>10</td>
<td>6 to 17</td>
</tr>
<tr>
<td>Undulating</td>
<td>1</td>
<td>0 to 1.5</td>
</tr>
<tr>
<td>Level</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>Inclined</td>
<td>0</td>
<td>N/A</td>
</tr>
</tbody>
</table>

\(^t\) Price et al. [1996], Romanov [1968] and Ivanov [1981].
5.5 Results and Discussion

Simulated values of total ET, surface E, and moss and soil column moisture content were compared to eddy flux observations at towers located at the centre of each study site. Vapour flux comparisons were performed using 3-day averages since the daily time step model could not represent overnight storms. RHESSys results are compared with results from other models, without moss layers, applied at the same sites. This comparison is also useful in assessing the performance of RHESSys when constrained by the large proportion of parameters measured in-situ.

Estimates of closure of the site energy budget were provided at some sites as an indication of the precision of eddy flux measurements. For example, at the SSA-OJP, measured energy budget components underestimated top of canopy $Q^*$ by 9.4 Wm$^{-2}$ (13%) on average and overestimated understory $Q^*$ by 7 Wm$^{-2}$ (67%) [Baldocchi and Vogel 1996]. If all of this uncertainty was explained by latent heat flux one would expect errors on the order of 0.33 mm water day$^{-1}$ for the overstory and 0.25 mm water day$^{-1}$ for the understory. Taking the SSA-OJP errors to be indicative of all sites suggests worst case uncertainties in eddy flux ET on the order of 25% of total ET and 100% of understory ET. Also, eddy flux measurements only applied to flux generated from a spatial footprint upwind of the anemometer. Kaharabata et al [1997] suggested an elliptical footprint for overstory eddy flux sensors with a major axis on the order of 0.5 km and a minor axis on the order of 0.1 km which gave substantially lower coverage than the 1km$^2$ patches used in parameterizing RHESSys. The smaller footprint may have contained surface moisture conditions which were not representative of the entire site. Aircraft based eddy flux ET estimates showed biases compared to tower estimates (-12% at SSA-OBS; 9% at NSA-OBS; 32% at SSA-OJP; 139% at NSA-OJP) [DesJardins et al 1997]. The large positive biases at the OJP sites were hypothesized to be the result of siting the flux tower in the driest area of the site combined with the smaller flux footprint of the tower in comparison to the aircraft.

Two statistics were computed to quantify accuracy and precision errors in model estimates of growing season site total ET. The bias error is defined as the ratio of the difference between
model estimates and measured values versus the sum of the measured values over all days in the growing season with sufficient measurements to permit estimation 3-day averages:

\[
\text{bias} = \frac{1}{\sum_{\text{days}D} \sum_{\text{days}D} (\text{ET}_{\text{TRUE},D} - \text{ET}_{\text{MODELLED},D})}
\]

(25)

This error measure is useful in quantifying model performance in predicting seasonal total of ET. The bias error is also significant in that it would not likely be removed by spatial averaging over large regions of the same cover type. As such, the bias error is important in suggesting the effectiveness of using RHESSys to estimate regional patterns of ET assuming available forcing data. Precision error is estimated using the mean absolute error (MAE). The MAE is estimated by first subtracting the bias error, expressed in units of water equivalent depth, from RHESSys total ET estimates and then computing the mean absolute difference between corresponding RHESSys and eddy flux ET estimates divided by sum of the measured values:

\[
\text{MAE} = \frac{1}{\sum_{\text{days}D} \sum_{\text{days}D} |\text{ET}_{\text{TRUE},D} - \text{ET}_{\text{MODELLED},D} - \frac{\text{bias}}{\# \text{days}D} \sum_{\text{days}D} \text{ET}_{\text{TRUE},D}|}
\]

(26)

Both bias and MAE are expressed as a percentage of mean measured ET to facilitate between site comparison and to implicitly incorporate an ET weighting of individual residuals.

5.5.1 Comparison of Total ET

Figure 5.5 provides scatter plots of RHESSys versus eddy flux estimates of site ET with corresponding time series shown in Figure 5.6. The figures suggest unbiased estimates of ET at all but the NSA-OJP site. Figure 5.7 indicates that residuals between modelled and observed total ET at the NSA-OJP site are typically above 30% of eddy flux ET at all levels of eddy flux ET. The absence of a similar positive bias at the other sites suggests that this systematic difference is not a function of the model but may be a function of the forcing data or of the
Figure 5.5: Scatter plots of modelled versus eddy flux ET estimates at study sites. Points indicate 3-day averages of both observed and modelled site ET over periods when eddy flux data was available (SSA-OBS: DOY 145-255; NSA-OBS: DOY 77-321; SSA-OJP: DOY 156-256; NSA-OJP: DOY 165-255).

The NSA-OJP results indicate a persistent bias which may be related to differences cover between the fetch of eddy flux observations and the entire site. The NSA-OBS results include a number of days with ET<0.5mm corresponding to early and late in the growing season.
Figure 5.6: Time series of 3-day averaged RHESSys and eddy flux site ET estimates at study sites for the 1994 growing season. RHESSys results were generated by spinning-up using 1994 data for 4 years prior to recording modelled fluxes.
Figure 5.7 Scatter plots of residuals between RHESSys and eddy flux estimates of site ET expressed as a percentage of observed ET. Eddy flux measurements were acquired at a flux tower sited at centre of each 1 km diameter study area by Fitzjarrald and Moore [1997] (NSA-OJP), Goulden et al [1997] (NSA-OBS), Baldocchi et al [1997] (SSA-OJP) and Jarvis et al [1997] (SSA-OBS). Residuals compare 3-day averages of RHESSys and eddy flux site ET over dates during the 1994 growing season with consecutive eddy flux data.
position of the eddy flux tower within the site. Residuals for the other three site are typically under 40% of measured ET with the exception of residuals at eddy flux ET levels less than 0.5 mm at the NSA-OBS. As Figure 5.6 indicates, these low ET periods occur late in the growing season. At this point in the growing season overstory transpiration is substantially reduced. The days with the largest residuals at the NSA-OBS correspond to periods during or immediately after precipitation events. There were substantial uncertainties in model parameterization of throughfall since the in-situ coefficient of variation of throughfall was typically over 40% for event less than 5mm (Price et al [1997], Chapter 2). The late growing season residuals at the NSA-OBS may also be due to increased spatial and temporal variability in soil temperatures due to freezing and thawing late in the growing season and due to use of a snow estimation algorithm based on air temperature rather than observed snowfall.

Figure 5.8 summarizes the bias and MAE for each of the study sites. ET bias at the OBS sites and the SSA-OJP site was below 5% for the 1994 growing season dates with eddy flux data. Figure 5.7 suggests that bias was not a function of ET magnitude; with the possible exception of the SSA-OBS. The time series shown in Figure 5.6 indicate infrequent, but substantial, underestimates at the SSA-OBS site (DOY 230-235; DOY 250) and overestimates at the NSA-OBS site (DOY 290-295). These errors may be due to errors in canopy interception and evaporation as they occurred during or after precipitation events. A -1.2% bias was observed at the SSA-OJP without substantial residuals excepting two periods between DOY 168-172 and DOY 205-210 which are discussed later. ET at the NSA-OJP site was overestimated at all magnitudes with a growing season average bias of 37%. Figure 5.7 indicates that the large NSA-OJP bias persisted over the entire growing season rather than only during isolated periods.

RHESSys biases at each site correspond to biases found in comparing aircraft versus tower eddy flux estimates of ET [DesJardins et al 1997] both in direction and magnitude of bias. This suggests that the RHESSys biases may be partially explained by differences in surface controls on ET between the RHESSys study site domains and the tower flux footprints. Lack of closure of tower flux energy budgets may also have contributed to the positive biases observed at the NSA-OJP.
Figure 5.8: Bias and MAE for RHESSys estimates of study site ET in comparison to eddy flux estimates. The bias error indicates the total error in modelled ET over all eddy flux measurements within the 1994 growing season at each study site. The large NSA-OJP bias may be due to systematic differences between the eddy flux fetch surface cover and the cover within the site. The MAE provides an estimate of relative precision error once bias error is removed. The similarity of MAE values suggests that RHESSys was not over-fitted to any given site. Refer to Equations 25 and 26 in the text for formulae for bias and MAE.
MAE levels were between 13% and 22% for all sites. Absolute precision did not substantially vary with ET rate for the NSA sites and the SSA-OBS. In contrast, the SSA-OJP site ET was estimated with lower precision at higher ET rates. Examination of the SSA-OJP overstory ET times series indicated a substantial overestimate in ET between DOY 168-172 during a period of intermittent rainfall. Systematic discrepancies in tower flux and modeled ET during and immediately after rain events were also noted with results from an hourly time step flux model [Nijssen et al 1997]. The overestimates may be due to errors in canopy interception parameters, errors in rainfall inputs, lack of parameterizations for drip due to gusts, errors in eddy flux sensors during rainy periods, or a lack of a characterization of stable atmospheric regimes in the model. In addition, substantial underestimates in ET occurred during a dry-down between DOY 205-210. The discrepancy may be due to errors in modelling unstable aerodynamic turbulence regimes during dry periods. It should be noted that sap flux measurements were also on the order of 0.5 mm/day lower than eddy flux estimates of $T_{\text{overstory}}$ (estimated by Baldocchi et al [1997] who subtracted understory flux measurements from overstory measurements during dry periods).

With the exception of the NSA-OJP, the bias and MAE are on the order of uncertainties in eddy flux ET estimates described in Section 5.5. The bias errors are smaller than biases reported between aircraft eddy flux data although these are only indicative of the instances of the overflights. Bias errors were of the same order of magnitude as other modelling studies for the same sites and time periods [Nijssen et al 1997, Kimball et al 1997a]. The MAE's were comparable to the 24% discrepancy between sap flow and eddy flux transpiration estimates at the SSA-OJP [Baldocchi et al 1997]. Table 5.8 presents root mean square error (R.M.S.E.) and ratio of the R.M.S.E. to the mean observed flux (C.V.) for validation periods at each site to facilitate comparison of precision between RHESSys estimates and those published elsewhere. The C.V. for RHESSys estimates was on average 10% lower in absolute terms (range 2% to 17% lower) than C.V.'s calculated from Nijssen et al [1997] and Kimball et al [1997a].
Table 5.8: Summary of RHESSys study site ET estimates. Estimates are summarised over the growing season (21 May, 1994 to 21 September 1994) and the 1994 calendar year. Precipitation includes both rain and snow observed at each site. Site ET was only validated during the growing season suggesting that the annual site ET is only a preliminary estimate for water budget purposes. Understory ET includes both fluxes from soil, moss and ponded water. The R.M.S.E. of growing season site ET is provided from comparison with other model based estimates at the same site. The C.V. in Site ET indicates modelled variation in site ET during growing season periods where eddy flux data was available.

<table>
<thead>
<tr>
<th></th>
<th>NSA-OBS</th>
<th>NSA-OJP</th>
<th>SSA-OBS</th>
<th>SSA-OJP</th>
</tr>
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<tbody>
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<td>Site Precipitation†</td>
<td>375</td>
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<td>419</td>
<td>433</td>
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<td>353</td>
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<tr>
<td>Overstory ET‡</td>
<td>114</td>
<td>104</td>
<td>115</td>
<td>156</td>
</tr>
<tr>
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<td>24</td>
<td>19</td>
<td>34</td>
<td>57</td>
</tr>
<tr>
<td>Overstory T‡</td>
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</tr>
<tr>
<td>Understory T‡</td>
<td>25</td>
<td>35</td>
<td>44</td>
<td>31</td>
</tr>
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<td>R.M.S.E. Site ET*</td>
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<td>0.37</td>
<td>0.36</td>
</tr>
<tr>
<td>C.V. Site ET*</td>
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<td>0.37</td>
<td>0.2</td>
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</tr>
<tr>
<td>Number of days*</td>
<td>78</td>
<td>50</td>
<td>76</td>
<td>57</td>
</tr>
</tbody>
</table>

†January, 1994 to 31 December, 1994; ‡21 May, 1994 to 21 September 1994; *days with complete eddy flux ET data; all values in mm water.
5.5.2 Comparison of Understory ET and Soil and Surface Moisture

The major difference between RHESSys and other models applied to the same sites is the presence of a spatially variable moss or lichen layer in RHESSys. A comparison of RHESSys estimates of understory ET with understory eddy flux measurements at the OJP sites is provided in Figure 5.9. Application of the error measures in Section 5.5.1 to understory ET, rather than site total ET, resulted in biases of 2.1% and 6.98% and MAE's of 15.8% and 30.3% at the NSA-OJP and SSA-OJP sites respectively. The slight overestimate in understory ET may be due to regions of deeper lichen mats and feather moss (10% of the SSA-OJP site) which were not present within the fetch of the understory eddy flux sensor. The level of precision is similar to that of the total ET estimates and within the uncertainty of using a single eddy flux sensor to validate site averaged understory ET.

Soil moisture was measured at a number of depths at 5 neutron probe tubes along 10m transects near the centre of each of the OJP sites [Cuenca et al 1997]. Figure 5.10 presents RHESSys and neutron probe estimates (averaged over a depth of 0.75 m) of soil moisture at the OJP sites. The 0.75 m depth was chosen since it represented the extreme rooting zone depth at these sites. Estimated soil moisture was within 1 standard error of measured soil moisture. Soil moisture was underestimated during the first dry down sequence at both site and during major precipitation events at the SSA-OJP site. These errors were not easily attributable to TOPMODEL since the soil moisture recession curves are parallel to observed dry down curves. Biases in soil moisture immediately after large rain events may be due to absolute errors in throughfall that are typically proportional to the event size [Fernandes 1997].

Figure 5.11 compares RHESSys estimates of moss moisture content in turfs located 25 m away from the NSA-OBS flux tower to two measurements of feather moss live layer moisture content. Modelled moisture content falls within measurements with the exception of an overshoot at DOY 248. The use of only two 10 cm square moss turfs located within 5 m of each other suggests that the overshoot may be due to a difference in modelled and actual throughfall at the turfs. The modelled moisture content dry-down curves falls within the observed curves indicating that
Figure 5.9: Observed versus modeled NSA-OJP (a) and SSA-OJP (b) understory ET. Observations were provided from understory eddy flux sensors. Modelled ET was estimated using the patch co-located with the understory sensor. The low precision of the modelled ET may be due to local variations in climate forcings within the site and also due to the absence of a spatially distributed understory momentum flux model.
Figure 5.10: Observed vs. modeled NSA-OJP (a) and SSA-OJP (b) soil moisture. One standard deviation intervals for observations are included. Modelled values were taken from the patch co-located with the measurements within each site. Modelled moisture content refers to the estimated moisture content assuming a uniform relative moisture content in the unsaturated zone until the capillary fringe (where complete saturation was assumed). Observed data represent the mean of soil moisture contents estimated at five depths between 0 and 75 cm at 5 spatial locations by Cuenca et al [1997].
Figure 5.11: Modeled and observed feathermoss live layer moisture content within the NSA-OBS. Model estimates correspond to a patch co-located with the two life moss turfs. The model overshoot at DOY 248 is likely due to differences in throughfall at the turfs and throughfall estimated at the patch. The moss canopy conductance model had a non-linear cut-off for low moisture contents, resulting in the flat modelled moisture contents between DOY 235 and DOY 245 when applied at a daily time step.
understory ET may be represented without significant bias for the feather moss sites. Sphagnum moisture contents were not measured at the NSA-OBS. However, modelled sphagnum moisture content were always within the range of moisture contents observed at the SSA-OBS site in the 1996 season. Nijssen et al [1997] provide model based estimates of soil and understory evaporation for three of the study sites. Assuming that soil evaporation in their model is equivalent to RHESSys understory ET, the difference between the RHESSys and the results from Nijssen et al [1997] is -30 mm water at the NSA-OBS; -17 mm water at the SSA-OBS; and 60 mm water at the SSA-OJP between 21 May, 1994 and 21 September, 1994. These differences amount to relative differences on the order of 50% to 100% of modeled understory ET. It is possible that the model of Nijssen et al[1997] compensates for underestimates in understory evaporation with evaporation from an understory herb layer. However, their conceptual model of understory and surface ET contains a stomatal control that has a negative feedback proportional to atmospheric vapour pressure deficits in contrast to bryophytes and bare soil which do not change vapour or carbon flux conductance in response to vapour pressure deficit. The lack of significant bias between RHESSys and eddy flux estimates of understory ET lend support to the implementation of a spatially variable understory moss and lichen layer as recommended by Nijssen et al [1997].

5.5.3 RHESSys ET Sensitivity

Model parameters related to controls on overstory or surface conductance were perturbed by +/- 25% of the baseline values (except for $\lambda_{\text{site}}$ which was perturbed to produce a +100%/ -50% change in maximum lateral net runoff) at each site. Most overstory parameters listed in Table 5.3 were tested. Sensitivity to the stomatal conductance model was tested by perturbing maximum stomatal conductance rather than perturbing the many parameters within each scaling function given in Equations 15a through 15e. All of the soil column parameters listed in Table 5.4 and the detention store depth were perturbed assuming a uniform bias in the parameter value over the site. Moss surface parameters from Table 5.6 were also tested.

Table 5.9 summarizes model sensitivity to only those parameters which resulted in a bias or
MAE greater than 5%. Parameters which resulted in a bias or MAE comparable to or greater than the error between modelled and eddy flux ET estimates include controls on radiation interception and water interception in the overstory and moss water capacity. The dependance of Boreal ecosystem flux models on canopy leaf area has been identified [Bonan 1993]. However, Table 5.9 indicates that RHESSys has substantial sensitivity to parameters which may not be easily mapped; such as $g_{\text{c,max}}$, moss moisture capacity, and canopy interception. It should be noted that before the completion of the BOREAS data set $g_{\text{c,max}}$ was assumed to be 0.001m/s for all life forms [e.g. Kimball et al 1997a,b]. This assumption, if used in RHESSys, would result in differences of -50% for the OBS sites and +12.5% for the OJP sites in comparison to in-situ measurements used in this study. Switching climate forcing data between OJP and OBS towers in the same study areas (except for soil temperatures) also resulted in significant bias or precision errors at all sites. These large residuals due to switching forcing data between sites separated by less than 10 km may pose difficulties when applying RHESSys over larger regions and may also impact similar diagnostic flux models applied to Boreal conifer stands.

Modelled ET was not extremely sensitive to growing season albedos. This is encouraging for large scale albedo mapping initiatives and is in contrast to the sensitivity of climate models to snow pack albedo [Betts and Ball 1997]. In addition, modelled ET was not highly sensitive to $\lambda_{\text{exe}}$ for OBS sites. The lack of bare soil exfiltration at the OBS sites supported this observation. However, even the bare OJP soil columns did not exert as strong a control on modelled ET as overstory or surface layer canopy parameters. This result is encouraging since the net runoff estimates were defined from literature values for maximum lateral flow or from site specific calibration to soil moisture.
Table 5.9: Summary of RHESSys ET sensitivity analysis. Bias and MAE due to a +/-25% perturbation in specified parameters are reported. Both sensitivity measures are expressed as ET weighted percentages (rounded to nearest integer) of three day averaged RHESSys ET estimates using baseline conditions. Values in bold are of similar magnitude as errors between the baseline RHESSys (using parameters in Tables 5.3, 5.4 and 5.6) and eddy flux ET.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NSA-OBS Bias MAE</th>
<th>SSA-OBS Bias MAE</th>
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<td>-1/1 1/1</td>
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<td>4 29</td>
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</tbody>
</table>

5.5.4 Discussion

Table 5.8 summarizes SVAT model estimates of total, overstory and understory ET between May 21, 1994 and September 21, 1994 following Nijssen et al [1997]. Table 5.8 also includes modelled total ET and measured precipitation for 1994. Precipitation during the 1994 growing season was approximately 20% lower at the NSA-OBS site in comparison to the NSA-OJP site even though they were less than 10 km apart. This difference in precipitation may be due to differences in rain gauge configuration given the proximity of the sites. These measurement differences should be kept in mind, together with the model MAE and mode sensitivity to parameter uncertainties, when interpreting the data in Table 5.8 and when comparing this data to results from other models.
RHESSys estimates suggest ET constituted between 72% to 83% of annual water losses from mesic conifer sites and between 47% to 67% of annual water losses from the dry conifer sites. Kimball et al [1997a] reported modelled annual ET losses between 10% to 14% lower in absolute terms. The lack of significant biases during the growing season for both their model and RHESSys suggests that the higher loss fractions estimated in this study may be due to increased runoff or evaporation outside the growing season. Evaluation of runoff has yet to be performed as it requires a validated ET model but it is possible that the absence of mosses or lichens and depression storage in the Kimball et al [1997a] model resulted in higher runoff and lower annual ET than RHESSys. Nijssen et al [1997] modelled ET losses between May 21, 1994 and September 21, 1994 as between 51% to 57% of precipitation for the study sites. The absence of a moss layer in their model may explain the similarity in their estimates of ET loss fractions at wet and dry conifer sites as well as the substantially lower values of modelled ET at the OBS sites in comparison to RHESSys estimates. Nijssen et al [1997] include a vascular understory in their conceptual model of the OBS sites. Their model estimates that this vascular understory contributed between 30% to 50% of total ET during the growing season. While their parameterizations likely overestimates understory $\zeta$ (set at 2.0 for all sites although our unpublished data suggest values below 1.0) the absence of an understory vascular layer in the RHESSys may explain the negative bias at the SSA-OBS in Table 8. Differences in total ET between the RHESSys and Nijssen et al [1997] may also be due to their use of overstory $\zeta$ values that differed by over 25% from in situ measurements by Chen et al [1997] and maximum stomatal conductances over 250% higher than those measured in-situ by Dang et al [1997].

RHESSys estimates of overstory ET were 50% higher at the SSA-OJP site in comparison to the NSA-OJP site. This difference is chiefly due to an increase in $E$ at the SSA-OJP in comparison to the NSA-OJP. The increase in $E$ is likely due to the higher $\mathcal{P}$ and irradiance at the SSA-OJP site. Overstory $T$ differed by less than 15% of the across site average growing season total with a range of less than 14 mm water over the growing season. The low sensitivity of $T$ to the increased irradiance in the SSA suggests that overstory canopies were well coupled with the atmosphere so that $vpd$ demand dominated the net radiation component in the Penman-Monteith model of overstory transpiration. The substantially lower between site variation in $T$ compared to
E suggested that negative feedback of \textit{vpd} on stomatal conductance may balance the increase in evaporative demand in the SSA versus the NSA. Kimball et al [1997a] estimate the ratio of overstory T to total ET between 10\% to 15\% higher (absolute) than RHESSys estimates. Differences in \( g_{\text{t max}} \) and stomatal conductance control factors may explain some of this bias. In addition, Kimball et al [1997a] did not specify if they separated \( z \) and \( \theta \). Including both leaf and plant area results in a decrease in understory irradiance without an increase in APAR on needles in the overstory.

RHESSys estimates suggest that the soil and surface layer percentage of total ET was 31\% at the NSA-OJP site: 23\% at the SSA-OJP sites; 38\% at the NSA-OBS site; and 51\% at the SSA-OBS. The moss or lichen surface sub-models does not include a \textit{vpd} control on surface conductance to vapour fluxes typical of boreal conifer over-stories [Dang et al 1997, Kimball et al 1997a]. The low aerodynamic conductance at the surface also substantially reduces the impact of \textit{vpd} on surface evaporation and suggests that understory \( E \) are chiefly controlled by irradiance and relative moisture content. The higher moss surface moisture levels at the OBS sites, together with the similarity in overstory T between OBS and OJP sites, explains the higher understory \( E \) proportion of total ET at mesic conifer sites. The modelled lower understory \( E \) proportion of total ET at the SSA-OJP and NSA-OBS sites in comparison to their counterparts in the other study areas may be due to reduced irradiance caused by higher overstory LAI.

It is of note that RHESSys is capable of describing the substantial difference in water table depths and moss moisture contents between sphagnum and feather moss dominated regions while still providing unbiased total site ET estimates. This level of physical realism in surface moisture content may be essential for modelling surface runoff [Burt et al 1990] or surface CO\(_2\) fluxes [Goulden and Crill 1997].
5.6 Conclusions and Recommendations

Comparison of RHESSys and eddy flux estimates of site ET indicated negligible bias error at the NSA-OBS and SSA-OJP sites. The -4.4% bias at the SSA-OBS site may have been due to the lack of an understory vascular herb layer or due to insufficient spatial information regarding the co-occurrence of LAI and surface wetness fields. There was a substantial (39%) positive bias in the estimation of ET at the NSA-OJP site. The consistency of this bias at all ET rates, together with the presence of a positive bias between aircraft and eddy flux measurements at the site, suggested a systematic underestimation of site ET by the eddy flux tower. The underestimate may be due to the tower being sited in a dry region of the site or due to measurement errors at the tower.

The precision error in total ET as measured by the MAE was approximately the same as the +/-25% precision error of eddy flux measurements. Substantial errors in precision during and immediately after precipitation events may be due to errors in either: throughfall; characterization of atmospheric stability; or in eddy flux measurements during wet conditions. It is likely that precision in total ET estimates was limited by the RHESSys daily time step, by parameter errors, and by the simple soil heat flux and atmospheric stability estimators used.

Validation of understory ET indicated unbiased estimates at the OJP sites with errors in precision comparable to overstory estimates. The precision errors were attributed to the uncertainties in modelling understory aerodynamic conductance together with the small fetch of understory ET sensors. While the precision errors were large in relative terms they were likely within the 100% relative uncertainty in the understory eddy flux estimates. The absence of significant bias in understory ET was in contrast to results from models without a moss or lichen layer. Soil moisture content at the OJP sites was estimated within 1 standard error of observed moisture contents within the rooting zone. However, soil moisture was underestimated immediately after rain events. These underestimates may be due to the comparison of instantaneous soil moisture measurements over a 10 m transect and a daily time step model of the entire site for the purposes of describing a dynamic profile drainage. RHESSys accurately estimates low moisture regimes
where soil water controls on transpiration and exfiltration are strong. The additional complexity of a vertically resolved unsaturated zone may only be warranted for forecasting soil thaw or peak flows. Feather moss moisture contents were similar to field observations although a larger spatial sampling of moss moisture contents is required for further assessment of modelled moss moisture content. It is significant that RHESSys captures within site differences in moisture contents between sphagnum and feather moss regions given current observations of persistent and substantial differences in moisture contents and surface conductances between these two surface cover types.

An investigation of model sensitivity to a 25% or larger perturbation in parameter values supports the need for accurate estimates of conductances and $\xi$ (or moisture capacity) for both overstory and moss canopies. The importance of $\xi$ for accurate estimation of surface fluxes has been emphasized in numerous studies including investigations in the Boreal ecosystem. However, the significance of the surface layer parameterization is emphasized by the RHESSys sensitivity analysis and growing season ET totals. Encouragingly, sensitivity to the TOPMODEL site mean soil-topographic index was low in the OBS sites. The OJP sites showed some precision errors due to uncertainties in the site mean soil-topographic index; possibly due to soil moisture controls on overstory transpiration and bare soil evaporation at these sites.

RHESSys offers equivalent or improved performance in estimating total ET over the study sites in comparison to other models while also offering reasonable descriptions of understory ET and soil moisture. Importantly, the majority of RHESSys parameters were measured in-situ with no parameters calibrated so as to directly increase model fit to observed ET. The availability of the numerous constraining parameters at the study sites represents a best case scenario for model parameterization. Of note was the requirement for soil temperature measurements to determine soil heat flux. The results reported raise a number of questions which drive specific recommendations for future research:
1. Would other diagnostic flux models previously applied to the BOREAS sites show similar performance if parameterized with recently available overstory data used in this study?

A comparison of diagnostic flux models applied to the BOREAS sites with finalized parameter values would serve to indicate if conceptual differences in models (e.g. a moss layer) explain differences in model performance. In addition, consensus in sensitivity and estimated fluxes and state variables between validated models would increase the confidence in the results reported in this study.

2. What is the relative importance of and surface wetness information to the estimation of ET with the ecosystem flux model?

Comparison of the current spatially distributed model with other single patch models indicate differences in understory ET and overstory T. RHESSys could be used to determine the change in ET estimates as a function of the spatial scale of the joint distribution of and understory parameters. In addition, the possibility that an area threshold exists where model estimates using simple mixture distributions of parameters are not substantially different from model estimates using distributions which capture fine scale covARIATIONS between parameter fields should be tested.

3. Are the moss moisture and ET estimates representative of the spatiotemporal pattern observed in-situ?

This study provided a provisional validation of moss moisture content using only two sets of turfs. Moss moisture was monitored during 1996 [Fernandes 1997] over a 500 m transect at the SSA-OBS which would permit validation of spatial patterns of moss moisture content when the corresponding tower flux and meteorologic forcing functions are available.

4. Are there differences in net ecosystem production (NEP) between single patch and
spatially distributed RHESSys parameterization of the mesic conifer study sites?

In-situ [Waddington and Roulet 1996, Goulden and Crill 1997] and laboratory [Williams and Flanagan 1996] studies suggest that variations in moss moisture content and moss species may explain and control variations in surface carbon fluxes. In addition, the fact that the majority of the carbon in Boreal forests is stored in peat together with in-situ [Paavilainen and Paivanen 1997] observations relating drainage to soil carbon fluxes suggests that it may be necessary to accurately estimate spatiotemporal variations in soil moisture content to estimate site NEP. Ecosystem flux models, such as RHESSys, could be used to explore the interrelationship between spatial variability in water and carbon budgets.

The lack of substantial bias in ET at the OBS sites and the SSA-OJP site supports the use of RHESSys to explore the impact of assumptions regarding the spatial variability of the surface layer on ET. Further validation of RHESSys should be performed over study sites representing conifer stands at different levels of productivity and moisture content, over other land surface types such as deciduous stands and fens and at the watershed level. These studies could be used to determine if RHESSys can generate unbiased estimates of ET over local and regional extents. Studies using longer time periods of forcing and validation data are also required to quantify the significance of temporal variation in controls on site ET. The existing sensitivity analysis identifies the need for accurate and precise maps of leaf area index, overstory species and surface cover type. Chen and Cihlar [1997] generated an LAI map for the NSA using LANDSAT-TM data. However, a surface moisture map generated using remotely sensed imagery would facilitate parameterization of the relative proportion of surface cover types between and within mesic and upland conifer sites. The sensitivity analysis should be expanded to stomatal conductance sub-model parameters not considered within this study given the need to estimate daily weighted stomatal conductance control functions. Finally, the application of a diagnostic model requiring a large number of in-situ parameters and forcing functions may not be feasible over large extents. The possibility of using RHESSys to calibrate simpler models should be explored to facilitate estimates of ET over extents larger than the 1 km diameter sites investigated in this study.
5.7 References


Halliwell, D.H. and M.J. Apps, BOREal Ecosystem-Atmosphere Study (BOREAS) biometry and


Jarvis, P.G., J.M. Massheder, S.E. Hale, J.G. Moncrieff, M. Rayment and S.L. Scott, Seasonal variation in carbon dioxide, water vapour, and energy exchanges of a boreal black spruce forest,


Peters, D.L., J.M. Buttle, C.H. Taylor, and B.D. LaZerte, Runoff production in a forested,


Running, S.W. and E.R. Hunt Jr., Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models, in *Scaling Physiological*


Veldhuis, H., Soil mapping of the NSA sub-areas and tower flux sites, BOREAS Staff data set. BOREAS Information System, 1997.


CHAPTER 6

COMPARISON OF MODELLED ET AS A FUNCTION OF SPATIAL SCALE OF HYDROLOGICAL PARAMETERIZATION

6.1 Introduction

Chapter 5 discussed the application and validation of RHESSys, a spatially distributed ecosystem flux model, at four Boreal conifer study sites. RHESSys produced unbiased estimates of understory E and total ET at three of the four sites when using a fine spatial scale soil and moss parameterization. There was also evidence that the substantial bias in total ET observed at the NSA-OJP may have been due to a mismatch in the fetch of the eddy flux tower and the characteristics of the entire 1km diameter site. RHESSys was also found to have similar or higher levels of accuracy and precision in comparison to other models applied at the same sites when evaluated with eddy flux stand level ET measurements.

Chapter 2 reported evidence of substantial spatial variation in moss moisture content, both between feather moss and sphagnum regions and within feather moss regions, at the SSA-OBS. In addition, a survey of both moss cover and water table depth at the NSA-OBS [Harden et al, 1997] suggested that feather moss covered regions were related to deeper water tables than regions dominated by sphagnum mosses. However, RHESSys is the only model applied to these sites that currently includes a spatially variable moss layer and preserves observed differences in relative water table depths between sphagnum and feather moss regions. The ability of other models to match total ET without the complexity of a spatially variable moss and soil parameterization raises two questions:

1. Does a model that provides unbiased estimates of total ET with a fine spatial scale parameterization of moss and soil hydrology (e.g. RHESSys) produce significant differences in
ET when using coarser spatial scale parameters?

2. To what extent is total ET sensitive to spatial variations in moss and soil hydrology at the wet and dry conifer sites?

This chapter directly addresses the first question. In doing so, it also quantifies the sensitivity of site ET to spatial variations in surface hydrologic parameters under the assumption that the model is a realistic representation of physical controls on within site fluxes. While the model based assessment is limited by fine scale model accuracy and precision, the alternative of manipulating the site to remove variations in surface hydrology is likely not feasible. In addressing these two questions, this chapter also evaluates the need for the fine scale maps of moss and soil hydrological parameters and the need for the additional model complexity required to make use of this spatial information.

The chapter consists of three subsequent sections:

i) a description of the model scaling treatments;

ii) results summarizing differences in estimated ET between fine and coarser scale treatments;

iii) conclusions and recommendations regarding the impact of the spatial scale of hydrological parameterization on RHESSys estimates of ET at the study sites.

6.2 Model Scaling Treatments

The treatments represent the application of RHESSys using a marginal aspect of the joint spatial distribution of ecosystem parameters associated with maps of water table depth, surface layer cover type and leaf area. The leaf area aggregation reflects the typical coarse scale parameterization in existing ecosystem model applications at the same study sites (reviewed in
Chapter 5) that assume that both overstory and understory parameters are uniform within patches of characteristic wetness conditions. Furthermore, spatial maps of leaf area were not available at two of the sites (SSA-OBS and SSA-OJP) to permit scaling of surface wetness while preserving spatial variation in leaf area. Finally, the fixing of leaf area independent of surface cover would not represent a realistic model parameterization if leaf area co-varies with site moisture and nutrient conditions.

Three different scaling treatments were defined:

i) **fine scale:**

Soil maps, produced by in-situ survey [Anderson 1997, Veldhuis 1997], were used to define fine scale partitions. The soil maps consisted of polygons, corresponding to microtopes of characteristic soil and surface layer cover, mapped on a 10 m regular grid. Between one to three soil strata were associated with each polygon. The strata were not explicitly defined in space but were associated with an estimated fractional cover within the polygon. The strata included descriptions of soil surface cover, moss or lichen canopy depth, water table depth and sufficient data to infer soil surface cover and detention store. Surface layer cover fractions were estimated from soil map attributes based on the method presented in Chapter 5. The cover fractions were used to define a mixture distribution of non-spatial surface cover components within each patch.

Ground based measurements of leaf area were acquired within each site along three 300m transects [Chen 1996]. Chen and Cihlar [1997] also produced a spatial map of leaf area in the NSA by calibrating a 30 m resolution LANDSAT TM scene, acquired early in the 1994 growing season, to surface measurements of leaf area over auxiliary sites within the NSA. The algorithm for estimating leaf area from the LANDSAT scene used a 3 pixel window around each original pixel to estimate scene reflectance and then generated an estimate of leaf area based on a non-linear regression fitted using the surface leaf area measurements [Chen and Cihlar 1997]. Examination of the leaf area maps over the NSA study sites suggested that the 3 pixel window obscured some open canopy regions. A forest/non-forest map was generated for each NSA study
site by thresholding 1:50,000 air photos scanned with a resolution of approximately 5m per pixel. The forest cover map was then imposed on the LANDSAT based leaf area images for each NSA study site to censor non-zero leaf area estimates in non-forested areas. Biases between the site mean LANDSAT based leaf area and surface based leaf area measurements were also noticed. The biases were removed by scaling the edited leaf area images so that the mean leaf area in regions of canopy cover matched the mean value of the ground based measurements.

Spatial maps of leaf area were not available for the SSA. Surface leaf area measurements at the SSA-OJP site suggested a coefficient of variation of less than 25% over three 100m transects. The low spatial variation in leaf area at the SSA-OJP supported the assumption of a uniform leaf area over the site for the fine scale parameterization. The non-spatial distribution of leaf area measurements at the SSA-OBS site indicated two distinct modes. In-situ observations by the author and personal communication with the leaf area measurement team (Kris Inmanen, Department of Physics, York University; Jing Chen, Applications Division, Canada Centre for Remote Sensing) suggested that the upper mode corresponded to well drained feather moss covered regions; while the lower mode was assumed to correspond to poorly drained sphagnum regions. The leaf area corresponding to these modes was assigned to the each soil map polygon on the basis of moss cover (the SSA-OBS soil map polygons did not define multiple strata so there was only one moss cover type in each polygon). While these assumptions remain to be verified they represent a preliminary method of capturing spatial variations in leaf area over the soil map polygons within the SSA-OBS.

The lack of fine spatial resolution leaf area maps at all sites supported the decision to use a map of the mean leaf area within each soil moisture polygon as the finest spatial scale leaf area data. The use of separate fine scale partitions for each possible combination of 30m resolution leaf area maps and 10m grid resolution soil map polygons would have necessitated a fine scale model partitioning on the order of 10 m grid resolution. Instead, the soil polygons were chosen for the fine scale partitions since the true spatial support for the leaf area and soil polygons was likely much coarser than 10m.
ii) **intermediate scale**: This treatment consisted of a single patch for each unique surface layer cover type within the site. Soil and overstory properties within a patch with a specified moss cover were estimated using a weighted average of fine scale properties within each soil polygon. Mapped properties within a soil polygon were weighted by the fraction cover of the specified moss type and by the polygon area. The weighted values were then summed over all patches within the site. This site level sum was then divided by the total of the patch weighting factors over the site. The intermediate treatment was included to determine if a simple partitioning scheme that explained the dominant variation in moss and water table patterns was sufficient to reduce scaling errors.

iii) **coarse scale**: This treatment consisted of a single patch over the site. The surface cover of this patch was specified as the cover having the greatest area (weighted by soil map polygon area and cover fraction for polygons with mixtures of surface cover) within the site. Overstory leaf area was estimated by weighting the leaf area within each soil map polygon by the polygon area and cover fraction of the surface cover type represented in the coarse scale patch. The use of a single patch eliminated the need for parameterizing relative water table depths. However, the site mean soil topographic index was defined by the area and cover fraction (of the selected dominant surface cover type) weighted soil topographic index of each soil map polygon.

The fine scale treatment represents a best case level of spatial information for regional application of RHESSys. The intermediate scale treatment is equivalent to assuming that the study sites may be considered representative elementary areas (REA) with respect to hydrologic parameterization [Wood 1993]. A REA implies that model responses based on a parameterization using non-spatial mixture distributions do not differ significantly from responses based on a parameterization using explicit spatial patterns corresponding to the distributions. The ability to identify REA's over the extent of study sites would substantially simplify data requirements for model parameterization. For example, registration errors in remote sensing data products or random classification errors in GIS overlays or remotely sensed products may cancel out over a study site so as to reduce the bias in estimates of non-spatial distributions of parameter fields.
The REA implementation still requires unbiased estimates of non-spatial fine scale parameter distributions derived from remote sensing methods, calibration, or a priori information. In addition, the ecosystem flux model must be capable of incorporating the parameter distributions within algorithms defining ecosystem processes. In contrast, the coarse scale treatment assumes that the spatial variability present in soil and surface layer properties within a study site does not have an impact on stand level fluxes. *This assumption may be justified where there is very low spatial variability in the properties or when the functional relationship between these properties and stand level fluxes is either linear or has low sensitivity to variations in surface properties.*

The treatments assume that RHESSys is a valid representation of fine scale ecosystem processes. The validation performed in Chapter 5 suggests that RHESSys can produce unbiased estimates of site ET at three of the four sites. Furthermore, the bias at the fourth site may be due to factors other than model errors. The treatments are evaluated by comparing fine scale and coarser scale modelled vapour fluxes over the entire growing season at the four BOREAS mature conifer study sites. The choice of sites with disparate intrinsic spatial variability in soil moisture and with disparate climates increases the significance of the scaling analysis to regional modelling applications.

The fine scale surface cover categories included: bare soil, lichen, feather moss, sphagnum moss and inundated regions. The lichen layer is defined in RHESSys as a thin, low moisture capacity, feather moss canopy due to the lack of information on lichen water and energy budgets at the study sites. Furthermore, the inundated regions were assumed to correspond to sphagnum moss surfaces with large detention stores defined by the land surface form specified in the soil maps and by the empirical look up table documented in Table 5.7, Chapter 5. These two simplifying assumptions reduced the number of functionally unique surface cover categories to three: bare soil, lichen/feather moss, sphagnum moss/inundated.

The dry conifer sites did not contain sphagnum mosses or inundated regions while the mesic conifer sites did not contain bare soil. As a result, the intermediate scale trials used only two
patches at each site: bare soil and lichen/feather moss at dry conifer sites and lichen/feather moss and sphagnum moss/inundated at mesic conifer sites.

The coarse scale trial used a complete feather moss carpet at the mesic conifer sites. Soil maps at both OJP sites indicated sandy soil with little or no organic layer as the dominant cover type. In situ observations by the author suggested that this cover type exhibited a mixture of bare soil and sparse lichens occurring in irregular patches on the order of 1 m². Given the short length scales of variation between bare soil and lichen the coarse scale trial at the dry conifer sites used a single patch containing a mixture of both cover types in equal proportion. The assumption of an equal proportion of bare soil and lichen was not verified in situ. However, a mixture of bare soil and lichens represented a closer approximation to reality in comparison to the assumption of completely bare soil.

6.3 Observations and Analysis

The period from 21 May, 1994 to 21 September 1994 (124 days) was used for evaluation of scaling responses. This period was selected both due to available forcing data at all study sites and because it represented the bulk of the growing season, when vapour fluxes are largest. The mean difference (bias) and root mean square difference (RMSD) between fine and coarser scale treatments were computed over all days in the evaluation period to quantify the model response to treatments.

Scaling errors are reported for the entire site, for the overstory layer and for the combined surface and soil layers (termed the understory). Scaling errors for the overstory include assessment of ET, E and T. Scaling errors for the surface include assessment of surface layer evaporation that does not result in a recharge from the soil column (i.e. lichen, feather moss and detention store evaporation), labelled as $E_{\text{surf}}$, and surface layer evaporation which results in water extraction from the soil column unsaturated zone (i.e. bare soil evaporation or capillary rise to sphagnum mosses required to satisfy evaporative demand), labelled as $E_{\text{unsat}}$. 
RMSD values are compared to fine scale model root mean square error (RMSE) and mean absolute error (MAE) provided in Chapter 5. The RMSE indicates the total error (accuracy error and precision error) between the fine scale model and eddy flux data at the site. The RMSE includes a bias component due to systematic modelling or eddy flux measurement errors. In contrast, the MAE indicates the precision error for the fine scale model after removing the bias between the modelled ET and eddy flux measurements. The MAE also provides a measure of the significance of the RMSD in comparison to random errors in modelled or eddy flux ET. Scaling bias errors are also reported to diagnose sources of scaling errors.

### 6.3.1 Fine vs. Coarse Scale Comparison

Table 6.1 quantifies the RMSD of modelled fluxes between the fine and coarse scaled treatments at each of the study sites. Table 6.2 provides corresponding estimates of bias errors. Both tables separate errors into components due to errors in $E$ from overstory or moss canopies and due to errors in modelled evaporative losses from the unsaturated soil column (overstory $T$ or $E_{\text{unsat}}$).

The RMSD for total ET was approximately 0.28 mm water day$^{-1}$ at both OJP sites. This figure is 25% lower than the fine scale treatment RMSE at both OJP sites. The RMSD is also 30% lower than the MAE at the SSA-OJP site and approximately 10% lower than the MAE at the NSA-OJP site. Both RMSE and MAE estimates for the fine scale treatment suggest that the RMSD for total ET at the OJP sites lies within model uncertainty.

The low bias errors at the NSA-OJP confirm that the RMSD at this site is not likely due to systematic errors caused by the scaling treatment. There is little evidence of a treatment effect on modelled mean daily total ET or overstory ET at the NSA-OJP. The NSA-OJP also indicates low biases in surface fluxes. This suggests that the high RMSD in NSA-OJP understory fluxes (0.28 mm water day$^{-1}$ for $E_{\text{unsat}}$ and 0.14 mm water day$^{-1}$ for $E_{\text{surf}}$) may be due to differences in the timing of evaporation between treatments; possibly due to the larger spatial variation in lichen layer moisture capacities with the fine scale treatment.
Table 6.1: Root mean square difference (RMSD) of modelled ET, E or T between fine and coarse spatial scale parameterizations for the period 21 May, 1994 to 21 September, 1994 (124 days). The RMSD is partitioned between overstory and soil or surface layers. In addition, water extracted from the soil column (T and $E_{\text{unsat}}$) is distinguished from direct canopy evaporation ($E_{\text{surf}}$ and overstory E). All values are in mm water day$^{-1}$ rounded to two decimal places.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>SSA-OJP</th>
<th>NSA-OJP</th>
<th>NSA-OBS</th>
<th>SSA-OBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>total ET</td>
<td>0.28</td>
<td>0.29</td>
<td>0.50</td>
<td>0.41</td>
</tr>
<tr>
<td>overstory $E + T$</td>
<td>0.02</td>
<td>0.03</td>
<td>0.04</td>
<td>0.00</td>
</tr>
<tr>
<td>$E_{\text{surf}} + E_{\text{unsat}}$</td>
<td>0.26</td>
<td>0.26</td>
<td>0.46</td>
<td>0.41</td>
</tr>
<tr>
<td>overstory $E + E_{\text{surf}}$</td>
<td>0.15</td>
<td>0.14</td>
<td>0.45</td>
<td>0.38</td>
</tr>
<tr>
<td>overstory E</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$E_{\text{surf}}$</td>
<td>0.15</td>
<td>0.14</td>
<td>0.45</td>
<td>0.38</td>
</tr>
<tr>
<td>$T + E_{\text{unsat}}$</td>
<td>0.40</td>
<td>0.31</td>
<td>0.30</td>
<td>0.36</td>
</tr>
<tr>
<td>T</td>
<td>0.06</td>
<td>0.03</td>
<td>0.06</td>
<td>0.00</td>
</tr>
<tr>
<td>$E_{\text{unsat}}$</td>
<td>0.34</td>
<td>0.28</td>
<td>0.25</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Table 6.2: Bias (mean difference) of modelled ET, E or T between fine and coarse spatial scale parameterizations for the period 21 May, 1994 to 21 September, 1994 (124 days). Bias errors are separated into overstory and soil or surface layers. In addition, water extracted from the soil column (T and $E_{\text{unsat}}$) is distinguished from direct canopy evaporation ($E_{\text{surf}}$ and overstory E). All values are in mm water day$^{-1}$ rounded to two decimal places.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>SSA-OJP</th>
<th>NSA-OJP</th>
<th>NSA-OBS</th>
<th>SSA-OBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>total mean daily ET</td>
<td>0.24</td>
<td>0.00</td>
<td>-0.19</td>
<td>-0.22</td>
</tr>
<tr>
<td>overstory $E + T$</td>
<td>0.00</td>
<td>0.02</td>
<td>-0.07</td>
<td>0.01</td>
</tr>
<tr>
<td>$E_{\text{surf}} + E_{\text{unsat}}$</td>
<td>0.24</td>
<td>-0.02</td>
<td>-0.12</td>
<td>-0.23</td>
</tr>
<tr>
<td>overstory $E + E_{\text{surf}}$</td>
<td>-0.12</td>
<td>-0.08</td>
<td>0.04</td>
<td>-0.10</td>
</tr>
<tr>
<td>overstory E</td>
<td>0.00</td>
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<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$E_{\text{surf}}$</td>
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<td>0.04</td>
<td>-0.10</td>
</tr>
<tr>
<td>$T + E_{\text{unsat}}$</td>
<td>0.36</td>
<td>0.08</td>
<td>-0.23</td>
<td>-0.12</td>
</tr>
<tr>
<td>T</td>
<td>0.00</td>
<td>0.02</td>
<td>-0.08</td>
<td>0.01</td>
</tr>
<tr>
<td>$E_{\text{unsat}}$</td>
<td>0.36</td>
<td>0.06</td>
<td>-0.15</td>
<td>-0.12</td>
</tr>
</tbody>
</table>
The SSA-OJP site also shows negligible RMSD and bias errors in overstory fluxes due to the treatment. However, the large understory bias error explains most of the 0.24 mm water day\(^{-1}\) total ET bias error. The increase in \(E_{\text{unst}}\) and drop in \(E_{\text{surf}}\) (lichen/feather moss evaporation) between fine and coarse scale treatments is due to the increased bare soil cover with the coarse scale treatment. The large increase in soil evaporation with a reduction in lichen cover is due to the model based assumption that lichens and mosses completely inhibit bare soil evaporation. While the RMSD for the SSA-OJP does not suggest strong evidence of a coarse scale treatment effect, the bias in soil evaporation may persist if the model is applied over larger dry conifer regions or for longer time periods.

The coarse scale treatment resulted in low overstory ET RMSD and bias values at both OJP and OBS sites. RMSD values for the overstory contributed on the order of 10% of the total RMSD. The similarity in overstory vapour fluxes between fine and coarse scale treatments at the OJP sites may be due to the low level of spatial variation present in the fine scale water table depth patterns. Spatial variations in moss moisture documented in Chapter 2 and spatial variations in water table depths [Veldhuis 1997, Anderson 1997] were substantial at the OBS sites. However, in-situ measurements [Dang et al 1997] and the RHESSys simulations suggest an absence of soil moisture controls on transpiration at the OBS sites. The low sensitivity of modelled transpiration to the typically high relative soil moisture contents found at the OBS sites explains the weak coarse scale treatment effect on modelled overstory ET. The presence of a small negative bias at the NSA-OBS may be due to a reduction in transpiration due to increased drainage caused by the use of a soil topographic index corresponding to feather moss regions.

In contrast to overstory ET, both total ET RMSD and understory E RMSD are substantially higher at the OBS sites in comparison to the OJP sites. The RMSD in total ET was 0.41 mm water day\(^{-1}\) at the SSA-OBS and 0.50 mm water day\(^{-1}\) at the NSA-OBS. These levels are higher than model RMSE levels of 0.37 mm water day\(^{-1}\) and 0.23 mm water day\(^{-1}\) at the SSA-OBS and NSA-OBS respectively. The MAE at the OBS sites is approximately equal to the RMSE and therefore also lower than the RMSD at these sites. The similar magnitude of RMSD and model precision errors at the SSA-OBS suggests evidence of a treatment effect on modelled total ET.
There is even stronger evidence at the NSA-OBS given that the RMSD for total ET is over 150% larger than model precision errors.

The majority of treatment differences at the OBS sites are concentrated in moss surface layer evaporation and soil evaporation. Table 6.1 indicates that RMSD values for understory E comprised over 90% of RMSD for total ET. In contrast, modelled understory E ranged from 25% to 33% of total ET. For example, the understory E RMSD of 0.46 mm water day$^{-1}$ at the NSA-OBS site and 0.38 mm water day$^{-1}$ at the SSA-OBS site are approximately 75% of daily average understory E estimated by the fine scale model.

Examination of bias components shows that the coarse scale treatment resulted in a drop in E$_{\text{unsat}}$ and overstory T at the NSA-OBS. The drop in unsaturated zone evaporative losses is likely due to two factors: the higher soil topographic index of the feather moss site and dry 1994 growing season at the NSA-OBS leading to a lowering of the water table and a subsequent reduction in overstory T and capillary recharge to sphagnum turfs; and the absence of sphagnum mosses that are capable of extracting water from the soil column via capillary rise. The SSA-OBS did not exhibit a drop in overstory T; possibly due to higher precipitation inputs. Nevertheless, the SSA-OBS also exhibited a drop in both E$_{\text{unsat}}$ and E$_{\text{surf}}$. The drop in E$_{\text{surf}}$ was likely due to the lower relative moisture content of feather mosses in comparison to sphagnum mosses resulting in lower surface conductance in vapour fluxes when specifying a complete feather moss cover. This suggests that underestimating the proportion of sphagnum moss cover may lead to an underestimate in understory fluxes in mesic conifer sites. Furthermore, the significance of understory E to total ET at the OBS sites suggests that the coarse scale treatment may also produce large errors in site level ET.

6.3.2 Fine versus Intermediate Scale Comparison

Table 6.3 compares model results between fine and intermediate scale parameterizations at all sites. Table 6.4 lists bias errors between fine and coarse scale treatments at each site. The RMSD for total ET is 0.164 mm water day$^{-1}$ at the SSA-OJP and 0.216 mm water day$^{-1}$ at the NSA-OJP.
Table 6.3: Root mean square difference (RMSD) of modelled ET, E or T between fine and intermediate spatial scale parameterizations for the period 21 May, 1994 to 21 September, 1994 (124 days). The RMSD is partitioned between overstory and soil or surface layers. In addition, water extracted from the soil column (T and $E_{\text{unsat}}$) is distinguished from direct canopy evaporation ($E_{\text{surf}}$ and overstory E). Values are in mm water day$^{-1}$ rounded to two decimal places.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>SOJP</th>
<th>NOJP</th>
<th>NOBS</th>
<th>SOBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>total ET</td>
<td>0.16</td>
<td>0.22</td>
<td>0.13</td>
<td>0.24</td>
</tr>
<tr>
<td>overstory E + T</td>
<td>0.01</td>
<td>0.03</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>$E_{\text{surf}} + E_{\text{unsat}}$</td>
<td>0.16</td>
<td>0.19</td>
<td>0.12</td>
<td>0.24</td>
</tr>
<tr>
<td>overstory E + $E_{\text{surf}}$</td>
<td>0.15</td>
<td>0.09</td>
<td>0.37</td>
<td>0.36</td>
</tr>
<tr>
<td>overstory E</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$E_{\text{surf}}$</td>
<td>0.15</td>
<td>0.09</td>
<td>0.37</td>
<td>0.36</td>
</tr>
<tr>
<td>$T + E_{\text{unsat}}$</td>
<td>0.05</td>
<td>0.20</td>
<td>0.30</td>
<td>0.28</td>
</tr>
<tr>
<td>$T$</td>
<td>0.02</td>
<td>0.03</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>$E_{\text{unsat}}$</td>
<td>0.02</td>
<td>0.18</td>
<td>0.28</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Table 6.4: Bias (mean difference) of modelled ET, E or T (all in mm water day$^{-1}$) between fine and intermediate spatial scale parameterizations for the period 21 May, 1994 to 21 September, 1994 (124 days). Bias errors are partitioned between overstory and soil or surface layers. In addition, water extracted from the soil column (T and $E_{\text{unsat}}$) is distinguished from direct canopy evaporation ($E_{\text{surf}}$ and overstory E). Values are in mm water day$^{-1}$ rounded to two decimal places.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>SSA-OJP</th>
<th>NSA-OJP</th>
<th>NSA-OBS</th>
<th>SSA-OBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>total ET</td>
<td>0.10</td>
<td>0.03</td>
<td>0.08</td>
<td>0.05</td>
</tr>
<tr>
<td>overstory E + T</td>
<td>-0.01</td>
<td>0.02</td>
<td>-0.03</td>
<td>0.00</td>
</tr>
<tr>
<td>$E_{\text{surf}} + E_{\text{unsat}}$</td>
<td>0.11</td>
<td>0.01</td>
<td>0.11</td>
<td>0.05</td>
</tr>
<tr>
<td>overstory E + $E_{\text{surf}}$</td>
<td>0.07</td>
<td>0.04</td>
<td>0.15</td>
<td>0.11</td>
</tr>
<tr>
<td>overstory E</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>$E_{\text{surf}}$</td>
<td>0.07</td>
<td>0.03</td>
<td>0.15</td>
<td>0.11</td>
</tr>
<tr>
<td>$T + E_{\text{unsat}}$</td>
<td>0.03</td>
<td>-0.01</td>
<td>-0.07</td>
<td>-0.06</td>
</tr>
<tr>
<td>$T$</td>
<td>-0.01</td>
<td>0.01</td>
<td>-0.03</td>
<td>0.00</td>
</tr>
<tr>
<td>$E_{\text{unsat}}$</td>
<td>0.04</td>
<td>-0.02</td>
<td>-0.04</td>
<td>-0.06</td>
</tr>
</tbody>
</table>
This represents a drop in scaling error of up to 40% in comparison to the coarse scale treatment error. As with the coarse scale treatments, the intermediate scale treatment does not result in significant differences in modelled total ET at the OJP sites.

The intermediate scale treatment resulted in a 50% lower bias error in understory evaporation at the SSA-OJP in comparison to the coarse scale treatment error. This suggests that a two patch representation that separates bare soil and feather moss/lichen regions may reduce bias errors in modelled understory evaporation even in sites with low spatial variability in water table depths.

In contrast to the coarse scale treatment, the RMSD for the intermediate scale treatment was similar between OBS and OJP sites. The RMSD values of 0.13 mm water day⁻¹ at the NSA-OBS and 0.244 mm water day⁻¹ at the SSA-OBS are well within the RMSE and MAE levels at the NSA-OBS and SSA-OBS respectively. Therefore there is little evidence of significant differences between the fine and intermediate scale treatment at the OBS sites in terms of daily total ET.

As with the coarse scale treatments, none of the sites showed significant RMSD for overstory ET. The OJP sites also did not exhibit large RMSD or bias errors for modelled understory vapour fluxes with the intermediate scale treatment. This was expected given the low spatial variability in water table depths within regions of the same surface cover type.

Examination of bias errors at the OBS sites indicates overestimates of $E_{surf}$ of over 0.10 mm water day⁻¹. These errors are partially balanced by co-incident underestimates in $E_{unsat}$. The $E_{surf}$ overestimates may be related to the effect of aggregation spatial patterns of water table depths on the rate of capillary rise to sphagnum turfs. The mapped growing season mean water table depths [Anderson 1997, Veldhuis 1997] for fine scale soil polygons dominated by sphagnum ranged from 5 cm to 75 cm. The aggregated water table depth for the intermediate scale sphagnum patch was approximately 25 cm. However, the capillary rise parameters for sphagnum turfs and the rooting depths for the overstory were fixed at the fine scale values. The drop in water table depths for relatively wetter sphagnum regions would reduce both capillary rise to
sphagnum layers ($E_{\text{unsat}}$) and overstory $T$ in comparison to the fine scale treatment. The reduction in capillary rise to sphagnum also results in an increase in moss canopy evaporation ($E_{\text{surf}}$) to meet evaporative demand at the moss surface. Nevertheless, biases between $E_{\text{surf}}$ and $E_{\text{unsat}}$ do not completely cancel; suggesting other treatment effects on other processes are also involved in explaining the bias in $E_{\text{surf}}$. An examination of the effect of treatments on within site processes was beyond the scope of this study.

6.4 Conclusions and Recommendations

6.4.1 Conclusions

There was no evidence that either scaling treatment resulted in significant differences in overstory mean daily ET in comparison to the fine scale treatment. This suggests that, for overstory vapour fluxes, a coarse scale parameterization at 1 km resolution may be sufficient for mature Boreal conifer stands.

In contrast there was evidence suggesting that understory $E$ differs between coarse scale versus fine scale treatments at all sites. Bare soil evaporation was significantly higher in single patch OJP sites, between fine and coarse scale treatments, due to the absence of a lichen layer that acts as a mulch to inhibit soil evaporation. Both understory mean daily $E_{\text{surf}}$ and $E_{\text{unsat}}$ differed significantly between coarse and fine scale model treatments at the OBS sites. These differences were likely due to the absence of sphagnum mosses in the coarse scale parameterization and the increase in site runoff due to the use of a site soil topographic index corresponding to regions of well drained, feather moss covered, patches.

The intermediate scale parameterization resulted in minor differences in total and overstory ET in comparison to the fine scale treatment. The intermediate scale treatment exhibited substantial precision errors in $E_{\text{unsat}}$ and $E_{\text{surf}}$ at the OBS sites. However, the RMSD in total understory evaporation was over 40% lower in comparison to the coarse scale treatment error. It is possible
that the two patch intermediate scale treatment may have been compensating for the reduction in variability in water table depths (which governs capillary recharge to sphagnum mosses) by shifts in modelled sphagnum moss canopy evaporation.

6.4.2 Recommendations

A more detailed model analysis is required to determine if the observed residuals are concentrated during certain periods or in certain spatial regions corresponding to specific fine scale moss and soil characteristics.

Intermediate scale models may be useful for estimation of total site ET but should be carefully validated if realistic simulation of controls on understory E is also required. The potential for cancelling errors in understory vapour fluxes suggests that intermediate scale model performance may not always accurately describe the actual physical controls on within site fluxes. Further analysis of treatment effects on modelled understory fluxes and storages is required to identify the source of the positive bias in E_{surf} at the OBS sites between intermediate and fine scale treatments.

The large coarse scale treatment errors suggests that models of Boreal conifer ET that use single patches at 1 km scale should be benchmarked and/or validated against finer spatial scale models and in-situ observations.

The observed scaling effects on vapour fluxes suggests that the impact of the scaling treatments on estimates of carbon fluxes should also be investigated.

The large differences in modelled fluxes between parameterizations using different estimates of moss cover and water table depths suggests that methods for mapping mixture fractions of moss cover within wet Boreal conifer stands should be investigated. The relationship between moss cover and relative water table depths should also be investigated in-situ given the difficulty in remote mapping of soil moisture patterns in moss covered regions.
6.5 References


CHAPTER 7

ON THE USE OF REMOTELY SENSED SURFACE MOISTURE INFORMATION TO
IMPROVE MODEL NEP ESTIMATES IN MESIC BOREAL CONIFER LANDSCAPES

Preliminary Discussion

This chapter corresponds to a manuscript in preparation based on research conducted for the
Vegetation/SPOT for Northern Applications project. The chapter was motivated by:

i) the need to represent controls on site net ecosystem production (NEP) due to physical
processes within soil, moss and overstory layers in a wet Boreal conifer stand:

ii) empirical evidence at the study site [Goulden and Crill 1997] and in other Boreal wetlands
[Waddington and Roulet 1996] indicating significant differences in soil carbon fluxes between
sphagnum and feather moss regions;

iii) laboratory evidence [Williams and Flanagan 1996] suggesting that moss moisture content
exerts strong controls on moss carbon budgets together with in-situ measurements, reported in
Chapter 2. indicating characteristic differences in moss water budgets related to moss type;

iv) the need to provide regional estimates of Boreal NEP for the purposes of determining the role
of the ecosystem in global carbon budgets.

The research in this paper differs from current NEP models in mesic Boreal conifer stands that
do not incorporate spatially variable moss layers or surface hydrologic parameterizations [Bonan
Objectives

The primary objective of this research was to determine whether a diagnostic flux model, RHESSys [Band et al 1993], that includes a parameterization of spatial variations in moss surface cover and associated soil moisture patterns results in significant differences in estimated NEP in comparison to the same model using a spatially uniform moss and soil moisture parameterization. A number of additional objectives regarding the ability to model NEP using remotely sensed data products were also addressed:

i) to demonstrate the use of remote sensing methods of parameterizing moss surfaces in ecosystem process models;

ii) to validate RHESSys estimates of carbon fluxes at a site where it has already been validated in terms of vapour fluxes;

iii) to determine if an intermediate scale parameterization of hydrological partitioning based on non-spatial mixture distributions of moss classes is sufficient to provide unbiased estimates of stand level NEP.

The scope of this study was limited to a single mesic conifer study site in the BOREAS NSA due to the lack of leaf area maps or calibrated reflectance imagery in the SSA. Dry conifer sites were not considered as they do not exhibit substantial spatial variation in surface moisture conditions associated with water table depths or moss cover. The soil carbon model of Frolking et al [1996] was incorporated within RHESSys. This provided ideal conditions for evaluating the hypothesis of spatially uniform moisture conditions adopted in the Frolking model. The current version of RHESSys also includes the daily time step overstory carbon budget model used in BIOME-BGC [Running et al 1993].

The study also investigated whether the site could be considered a representative elementary area with respect to wetness and moss patterns; that is, whether the use of non-spatial mixture
distributions of these patterns within RHESSys model is sufficient to provide similar NEP estimates as a spatially explicit parameterization. The ability to generate unbiased NEP estimates using mixture distributions would reduce the significance of either registration errors or random errors in remotely sensing algorithms or devices.

**Relationship to Dissertation Research**

This study represents an integration of all four previous dissertation papers. The central question regarding the role of the moss layer and its spatial variation on stand level NEP was motivated by the evidence, presented in Chapter 2, of persistent differences in moss wetness associated with moss type. The remotely sensed moss map used in the NEP model parameterization was produced by reflectance model inversion to estimate top of moss reflectance [Fernandes et al 1996 (Chapter 3)] and observations relating top of moss reflectance to moss moisture content [Fernandes et al 1997 (Chapter 4)].

The study also parallels the work reported in Chapters 5 and 6; where RHESSys was used to investigate the impact of surface wetness parameterization scale on estimates of stand level ET. Parameters already specified in the ET modelling effort were not adjusted in this study to reduced the possibility that model performance with regard to the carbon cycle was improved at the cost of errors in representation (or lack of realism) in the site water budget.

**Statement of Original Work**

Text, figures and tables were entirely the work of the present author. Comments and corrections were provided by the second author.

The first author and Ms. Christina Tague were responsible for significant modifications to RHESSys. The first author's contribution included integration of the Frolking et al [1996] soil and moss carbon flux model with surface energy, water budgets. The first author's other contributions to RHESSys are detailed in the introduction to Chapter 5. Overstory carbon
budgets were modelled using algorithms provided by the Numerical Terradynamic Simulation Group, University of Montana, Missoula under a collaborative arrangement between Dr. Steve Running and the second author. These existing algorithms were specifically chosen since they have already been validated at the chosen study site while paired with a bucket model of soil column water budgets. The modified version of RHESSys represents the first physically based flux model of NEP with a spatially distributed moss layer applied within a Boreal conifer stand. The comparison of RHESSys with spatially distributed versus bucket hydrologic parameterizations provides a controlled assessment of the sensitivity of the carbon flux sub-models to the scale of moss and hydrologic parameterization.

Data for parameterization and validation of both RHESSys and the remotely sensed moss cover map were provided by other BOREAS researchers and from the literature cited in the text. Both authors were involved in formulating research questions and defining model treatments. The current author performed analysis of observations and provided a discussion of results and conclusions. The second author contributed a critical review of the discussion and conclusion. This study represents an original contribution to the evaluation of the impact of the scale of representation of surface hydrological processes to modelled stand NEP. In addition, the integration of remotely sensed moss maps into an ecosystem flux model represents an original contribution to the application of remote sensing science to environmental analysis in Boreal ecosystems.

References


On the use of remotely sensed surface moisture information to improve model NEP estimates in mesic Boreal conifer landscapes

Richard Fernandes and Lawrence E. Band

Abstract

Mesic conifer stands dominated by *Picea mariana* (Mill.) BSP occupy a significant portion of the land cover in the Canadian Boreal ecosystem. The effect of different spatial parameterizations of surface moss cover and soil hydrology on modelled overstory and surface net ecosystem production (NEP) from a mesic conifer stand is quantified using the RHESSys hydro-ecological model coupled with a surface carbon cycling model presented by Frolking et al [1996]. Model estimates using a 10 m resolution parameterization of surface moss cover and soils suggest a NEP of 0.055 kg m$^{-2}$yr$^{-1}$ (where a positive value indicates a carbon sink) for 1994 with an overstory NEP of 0.218 kg m$^{-2}$yr$^{-1}$ and an understory NEP of -0.166 kg m$^{-2}$yr$^{-1}$. No significant differences in overstory NEP were found with spatially uniform surface parameterizations due to the absence of overstory moisture stress. In contrast, a spatially uniform, well-drained, feather moss surface resulted in a 46% relative decrease in understory NEP; while a uniform poorly drained sphagnum surface resulted in a 2.4% relative increase in understory NEP. The area covered by dry feather moss and wet sphagnum cover was estimated by inverting observed MIR reflectance recorded in a LANDSAT TM scene during a dry-down. An intermediate scale surface parameterization using a single non-spatial patch representing the area covered by each moss type resulted in a negligible change in modelled NEP in comparison to the fine scale parameterization. A two patch representation based on the proportion of moss cover type may be necessary and sufficient for unbiased estimates of surface and total NEP in wet Boreal conifer stands with uniform overstory. The close agreement between the uniform sphagnum patch and the fine scale trial may be due to a balance between coincident overestimation in soil decomposition and moss assimilation. Further research should investigate the relative sensitivity of modelled carbon budgets to uncertainties in the joint distribution of spatial wetness and
biomass and nutrients. This study indicates that surface characterisation using MIR reflectance may be useful in parameterizing diagnostic carbon flux models over the Boreal ecosystem.

7.1 Introduction

The Boreal ecosystem covers a circumpolar region comprised of upland coniferous and deciduous forests, forested and bare peatlands, minerotrophic fens, open water bodies and regenerating post-burn areas which comprise approximately 11% of the Earth's total land cover [Bonan and Shugart 1989]. The spatial organization of land cover types has been found to correlate with climate influences over global extents [Shugart et al 1992] and moisture gradients, nutrient gradients or disturbance patterns over extents represented by transects ranging from 1000 km [Nicholson et al 1996] to 1 km [Gignac et al 1991] to 1 m [Frego and Carleton 1995]. The Boreal ecosystem is distinguished from other biomes in the significant accumulation of soil organic carbon found in its peatland regions. Recent estimates of total carbon in peat range from 10% to 20% of the terrestrial carbon in the biosphere [Paavilainen and Paivanen 1997, p. 14]. There is interest as to the current and potential role of the Boreal ecosystem as a source or sink of atmospheric CO₂ [Goulden et al 1998]. Soil moisture controls on NEP are thought to drive much of the spatial variation in observed CO₂ flux in Boreal peatlands and mesic conifer stands at scales below 1km [Waddington and Roulet 1996, Trumbore and Harden 1997]. It is possible that models which estimate net primary production (NPP) and NEP may need to consider fine (<1km) scale variations in moisture condition and moss cover within mesic Boreal conifer stands. The fact that other carbon modelling studies at the same site under consideration here [Kimball et al 1997, Frolking et al 1996] have used a spatially uniform parameterization of moss cover and site wetness leads us to pose the following research questions

1) Is there is significant difference in total NEP, overstory NEP or understory NEP estimated from a calibrated model which explicitly considers spatial distributions of mosses and hydrologic connections at 10 m resolution versus the same model assuming a spatially uniform moss cover with a bucket hydrologic model?
2) Is there a significant difference in total NEP, overstory NEP or understory NEP estimated by the spatially explicit model and a spatially inexplicit model which uses a two patch parameterization of wet and dry areas mapped using inversion of Landsat TM mid-infrared reflectance (MIR) imagery?

If a significant range in NEP is indicated when comparing fine scale and bucket models then addressing the second research question will help determine if remote sensing methods can be used in conjunction with spatially distributed carbon flux models to describe the spatial variation in carbon fluxes due to variations in site wetness.

7.2 Method

7.2.1 Study Site

The study was confined to a 1 km diameter region surrounding the BOREAS Northern Old Black Spruce (NSA-OBS) flux tower located at 55.879 °N latitude and 98.484 °W longitude near Thompson, Manitoba, Canada. The site was chosen due to the availability of coincident observations required for model parameterization. In addition, land cover mapping over local and regional extents [Steyaert et al 1997] has indicated that a substantial portion of the Canadian Boreal ecosystem is dominated by similar Picea mariana stands (over 50% of undisturbed terrestrial cover). Additional information regarding the study site can be found in Halliwell and Apps [1997a,b,c], Veldhuis [1997] and Sellers et al [1994].

7.2.2 Scaling Treatments

The study site represents one sample along a wide gradient of moisture and stand age. In testing modelled differences between a surface parameterization faithful to the chosen site versus parameterizations representing extreme site wetness conditions we hoped to identify the potential of error with models calibrated to a single site. The extreme conditions also give some idea of the expected range in stand NEP over regions of the Boreal ecosystem not identical to the NSA-OBS
study site.

Four spatial scaling treatments were used in this study:

i) Fine scale - the finest spatial resolution data was used to define both leaf area index (LAI) (30 m resolution) and surface cover and hydrologic parameters (10 m resolution).

ii) Intermediate scale - the fine scale surface cover map was used to aggregate all other parameter maps into a sphagnum covered region and a feather moss covered region. The two regions were assumed to be spatially distinct and connected but were not explicitly located within the study site.

iii) Coarse scale uniform well drained surface - the entire site was assumed to consist of uniform well drained soils covered by feather mosses. LAI and other parameters were assumed uniform at the mean value measured over the site.

iv) Coarse scale uniform poorly drained surface - the entire site was assumed to consist of uniform well drained soils covered by sphagnum. LAI and other parameters were assumed uniform at the mean value measured over the site.

The intermediate scale treatment tested the potential of using simplified surface parameterizations that may be derived from remotely sensed data. The two coarse scale treatments represented extreme surface wetness conditions.

7.2.3 Model Description

Chapter 5 demonstrated that RHESSys, when modified to accommodate Boreal land surfaces, is capable of providing unbiased estimates of vapour fluxes at the NSA-OBS. Stomatal conductance and environmental conditions estimated by RHESSys were applied to an overstory carbon cycling model defined in Biome-BGC [Running and Hunt 1987, Kimball et al 1997] to estimate overstory NPP and maintenance respiration for roots. The soil decomposition model of Frolking et al [1996],
developed specifically for Boreal land surfaces, was incorporated into RHESSys. Both of these two models are briefly described below. Finally, the accounting method used to compute surface and overstory NEP is specified.

**Biome-BGC Overstory Carbon Budget**

Overstory gross primary production (GPP) is defined as the daily sum of gross photosynthesis and daily foliar respiration. Gross photosynthesis is estimated based on the Farquhar biochemical model [Farquhar and von Caemmerer 1982] as presented in Woodrow and Berry [1988] modified so that the maximum rate of electron transport was tied to the maximum carboxylation velocity [Wullschleger 1993]. Photosynthesis is controlled by canopy conductance to CO₂ (estimated as 1.6 times the conductance to vapour fluxes) and absorbed photosynthetically active photon flux density (PPFD) as well as leaf maintenance respiration and daytime averages values for air pressure and temperature. Leaf conductance and PPFD is estimated by RHESSys as described in Chapter 5. Leaf level estimates of gross photosynthesis were then scaled by canopy leaf area under the assumption that variations in PPFD within the canopy are balanced by changes in allocation of leaf nitrogen required for photosynthesis [Evans 1993].

Overstory respiration is estimated as the sum of growth and maintenance respiration. Growth respiration was set as a fixed proportion of the difference between overstory GPP and maintenance respiration. Maintenance respiration was estimated for the fixed size leaf, sapwood, coarse root and fine root carbon pools. Maintenance respiration for each pool was calculated by first specifying the fraction of the carbon lost at a reference air temperature of 20°C. A scaling factor was then applied using an exponential function of air temperature and a specified proportional rate of change for a 10 °C change in air temperature. Leaf respiration was computed separately for day and night periods using observed day and night temperatures. The other compartments used daily average temperature to produce estimates of daily maintenance respiration. Parameters corresponding to the BIOMEBGC carbon flux model for the NSA-OBS are given in Kimball et al [1997].

**Frolking Moss and Soil Carbon Model**
The moss and soil carbon cycling model of Frolking et al [1996] was adopted given that it was specifically developed for the NSA-OBS. The elements of the soil carbon cycling model embedded in RHESSys included foliage litter, fine root litter and humus matter carbon pools. The model assumes that all three pools were at steady state so that decomposition rates do not change the amount of carbon in each pool. Mass loss rates are specified as fixed fractions of pool size scaled by functions of soil temperature and soil moisture content. The Frolking model uses a multi-layer soil column to estimate soil temperatures and moisture content. In contrast, the RHESSys implementation uses measured soil temperature at the diurnal damping depth together with air temperature to estimate the mean soil column temperature within the organic layer. Also, RHESSys estimates soil moisture content assuming no a priori vertical distribution of water within the unsaturated zone. The modelled unsaturated zone soil moisture is assumed to apply to all soil carbon pools unless the soil column is saturated. While this assumption is a departure from the multi-layer Frolking model it was retained given the emphasis on quantifying the effect of lateral rather than vertical differences in soil moisture on modelled NEP. This assumption of a uniform vertical soil moisture distributions within the unsaturated on soil carbon decomposition is unlikely to impact the analysis of spatial scaling effects for three reasons: the large (>1m) difference in water table depths between feather moss and sphagnum regions is likely much larger than differences in unsaturated zone soil moisture within a region of uniform drainage characteristics; the Frolking model used a linear control of soil moisture on respiration until field capacity; and finally, the gross fluxes from soil carbon stores were substantially lower than root and moss carbon fluxes.

The moss carbon cycling sub-model uses an empirical gross photosynthesis model presented by Frolking et al [1996]. Specified maximum assimilation rates (GPP - growth respiration) are scaled by functions of daytime average air temperature, moss relative moisture content and incident PPFD. The scaling functions are assumed identical for feather moss and sphagnum regions. Frolking et al [1996] did not specify a maximum assimilation rate for sphagnum moss. The ratio of maximum assimilation rate between sphagnum and feather moss reported by Williams and Flanagan [1997] is used in the current study to estimate sphagnum maximum assimilation. Moss maintenance respiration is estimated using a fixed respiration rate for an air temperature of 20°C scaled by an exponential temperature response curve and a non-linear water content response curve. Feather moss
response curves given in Frolking et al [1996] are assumed to apply to sphagnum mosses as well due to insufficient data on environmental controls on sphagnum respiration. Laboratory evidence [Williams and Flanagan 1997] supports the assumption that moss relative moisture controls on carbon fluxes are similar between moss type. Moss NPP is defined as moss assimilation less moss maintenance respiration.

**NEP Accounting**

Surface NEP is defined as moss NPP less root maintenance respiration and soil heterotrophic respiration. Overstory NEP is defined as overstory GPP less growth respiration, leaf respiration and sapwood respiration. The assumption of steady state carbon pools may be reasonable for the mature forest stand and short time span used in this study. The specified respiration and moss assimilation parameters are empirical and may not be appropriate for the site. However, the emphasis in this paper is to explore the spatial assumptions in the carbon flux models embedded in RHESSys rather than to evaluate the suitability of the carbon model parameters.

**7.2.4 Temporal Forcing**

The model was applied from March 18, 1994 to December 31, 1994, reflecting the period when soil temperature data was available. Observed forcing functions included precipitation, incoming short-wave radiation, incoming photosynthetically active radiation (PAR), daily minimum and maximum air temperature, daytime average values of air temperature and vapour pressure deficit and wind speed, and soil temperatures at 5 cm, 20 cm, and 50 cm depths at both a dry feather moss site and a wet sphagnum site.

**7.2.5 Biomass and Nutrient Parameterization**

A spatially uniform parameterization of non-foliar aboveground biomass and aboveground compartment (hardwood, sapwood, twigs, leaves/needles) nutrient concentrations was specified based on other BOREAS field data while foliar biomass patterns were defined using leaf area
patterns and a constant specific leaf area. The assumption of uniform overstory biomass should not substantially affect scaling results given the lack of observed water stress [Dang and Margolis, 1997] and given the linearity between respiration rates and standing bias assumed in the Kimball et al [1997] model. The fact that Boreal mesic conifers are nutrient limited [Paavilainen and Paivanen 1997] suggests that nutrients should be proportional to biomass and supports the use of a fixed compartment nutrient concentration. Below ground root biomass was also assumed spatially uniform as in Frolking et al [1996] due to a lack of information regarding spatial biomass distributions. The impact of this assumption on the scaling treatments is discussed in the Observations and Analysis section.

Initial soil carbon pool sizes given in Frolking et al [1997] were assumed to represent site mean values. These values were scaled by the ratio of the patch to site mean organic matter horizon depth to estimate the initial carbon pool for each patch within the site. The assumption that all soil pools were proportional to the organic matter depth was adopted due to a lack of spatial information regarding the size of these pools. Fortunately, modelled heterotrophic respiration was much smaller than moss assimilation, moss respiration and root respiration so that the impact of the assumptions on soil pool magnitudes on scaling results was likely minimal. Moss carbon stores were estimated using species specific carbon stock estimates reported by Harden et al [1997] scaled by the ratio of the patch to site mean live moss layer depth provided in the site soil map.

Leaf area index (LAI) was parameterized using a LANDSAT TM derived estimate [Chen and Chilar 1996] corrected so that the mean leaf area matched the mean leaf area observed using surface measurements [Chen 1996]. Spatially distributed leaf area was only used with the 10 m resolution parameterization. Other model parameters related to energy budgets and stomatal conductance were specified according to the parameters specified for the NSA-OBS site in Chapter 5.

7.2.6 Hydrological Parameterization

Estimation of Water Table Depth
A spatially distributed hydrological model based on TOPMODEL [Beven and Kirkby 1979] is embedded in the RHESSys framework. TOPMODEL assumes that lateral transfer of water occurs so as to preserve the shape of the water table. While this assumption is not exact in peatlands experiencing prolonged dry downs or drainage, TOPMODEL has been shown to provide an unbiased description of soil water dynamics in peatlands and Boreal conifer stands under typical conditions [Ostendorf 1996, Siebert et al 1997]. Figure 7.1 shows the spatial pattern of mean water table depth recorded by Veldhuis [1994], based on in-situ sampling, used to parameterize the TOPMODEL soil topographic index.

A map of moss surface cover was defined using field observations of site characteristics provided by Veldhuis [1997]. Moss cover fractions estimated from the map shown in Figure 7.2 suggested the region had 51% sphagnum/fen and 49% feather moss Harden et al [1997]. The field-based moss cover map was used to estimate mean depth to the water table for each moss cover category using an overlay operation with the observed water tables depths shown in Figure 7.2. However, a separate moss cover map derived using inversion of mid-infrared reflectance was used for model parameterization of surface cover to test the effectiveness of remotely sensed maps.

**Parameterization of Scale Treatments**

The fine scale parameterization consisted of patches corresponding to regions of constant water table depth shown in Figure 7.1; each containing a fractional moss cover defined by overlaying the moss map of Figure 7.2. The intermediate scale parameterization consisted of two patches: one representing a region of sphagnum cover and the other a region of feather moss cover. The relative size of each patch was determined from remote sensing methods described later in the report. The difference in water table depths between patches was specified using the average depth to the water
Figure 7.1: Depth to water table measured by Veldhuis [1994] for one day in the growing season at NSA-OBS site. Depths range from 0-5 cm for black regions to 100-200 cm for white regions using a non-linear enhancement for visualization purposes. Water table depths were estimated by in-situ measurements adjacent to soil pits and then extrapolated based on in-situ survey and air photo identification of surface microtopes.
Figure 7.2: Estimated soil surface cover types over NSA-OBS. The map was produced by applying classification rules provided in Chapter 5, Table 5.5 to a 10 m resolution soil map produced by Veldhuis [1997]. Polygons indicate the dominant surface cover type. The fen/water class was assumed equivalent to inundated sphagnum regions based on in-situ observations by the author indicating an absence of fens within the region. The other polygons included mixtures of both moss types with the indicated type usually covering more than 75% of each soil map polygon depicted in Figure 7.1.
table of regions of the same moss type in Figure 7.2. The two coarse scale parameterizations assumed either uniform feather moss coverage or uniform sphagnum moss cover and by definition assumed a uniform water table depth.

**Specification of Maximum Baseflow Rate**

TOPMODEL also requires specification of a maximum baseflow rate for the ensemble of patches within the site. Both the fine and intermediate scale parameterizations used a maximum baseflow of 1 mm day$^{-1}$ which produced unbiased fits to observed ET (refer to Chapter 5) and matched observed baseflow rates in other Boreal wetlands [Waddington and Roulet 1996]. The maximum baseflow of the uniform feather moss parameterization was set at 2 mm water day$^{-1}$ based on the relative difference in transmissivity of a feather moss region and the mean site transmissivity. The sphagnum only parameterization used a baseflow maximum of 0 mm water day$^{-1}$ to describe the extreme condition of an inundated bog.

**7.3 Remote Estimation of Fraction Moss Cover**

**7.3.1 Relating MIR Reflectance to Top of Moss Moisture Content**

The large extent of the Boreal ecosystem suggests that field surveys of moss cover, such as the map presented in Figure 7.2, would not be feasible for a model applied to either regional or global scales. One method of providing regional moss maps is the use of MIR imagery acquired globally using the LANDSAT TM 5 sensor. The MIR spectral wavelengths between 1.5 um to 1.75 um has been suggested as a useful band for orbital remote sensing of surface moisture [Tucker 1980]. Early studies indicated that, while foliage moisture content was related to MIR reflectance, the signal caused by typical changes in foliage moisture was weaker than the noise due to variations in MIR scattering by leaves and branches [Hunt and Rock 1989]. A replicate experiment was performed to identify within moss species variations in reflectance at different levels of moisture content [Fernandes et al 1996 (Chapter 3)]. Figure 7.3 shows that MIR nadir reflectance is independent
Figure 7.3: Top of moss MIR (1.55 μm - 1.75 μm) reflectance as a function of relative moisture content. The fitted curve suggests that, except for dessicated turfs, both sphagnum and replicate feather moss turfs exhibited a similar relationship between moss relative moisture content and moss surface MIR. The negative exponential relationship was expected given that liquid water is a strong absorber of MIR radiation. Sphagnum data [Vogelmann and Moss, 94]. Feather moss data reported in Fernandes et al [1996] for Pleurozium schreberi (Pleur.) turfs.
between and within moss species. Moss moisture content can be related to top of canopy nadir MIR reflectance by sufficient field calibration or by inverting a canopy reflectance model. Figure 7.4 allows estimation of moss MIR reflectance from top of canopy MIR reflectance based on numerical inversion of a 3-dimensional canopy radiative transfer model developed by Myneni et al [1992] and applied over the entire BOREAS Northern Study Area [Fernandes et al. 1997 (Chapter 4)].

7.3.2 Inversion of Forward Reflectance Model for Moss Moisture Content

Figure 7.4 suggests useful inversions are possible for sparse canopies, which are fortunately common in Boreal ecosystems. Sensitivity analysis of the inverse reflectance model suggested errors in the vicinity of +/-1.6 g water/g moss for a sparse (40% cover) mesic conifer stand [Fernandes et al 1997 (Chapter 4)]. The inverse model was applied to a reflectance calibrated Landsat TM scene acquired on 6 June 1995 provided by Knapp (BOREAS staff), together with the LAI map, to estimate the surface moisture pattern over the study site. The inversion produced a spatial map of surface moisture contents shown in Figure 7.5. In-situ measurements of moisture content in feather moss and sphagnum turfs in a mesic conifer stand during a dry period were used together with the estimated inverse model sensitivity to define the expected error if a threshold was used to transform the moisture map into a map of moss cover [Fernandes et al 1997 (Chapter 4)]. Figure 7.6 suggests that a threshold level between 3.0 g/g and 4.0 g/g should result in a moss classification error of less than 25%. In contrast, the empirical sensitivity to the threshold suggested a change in feather moss fraction from 87% at a threshold of 4.0 g/g to 48% at 3.0 g/g. Examination of the co-occurrence of in-situ moss type and cover suggested that feather moss regions were associated with high forest cover while sphagnum regions were most likely associated with low overstory cover. The denser canopy in feather moss regions acted to reduce the dynamic range of the difference in mid-infrared reflectance between sphagnum and feather moss regions. In addition, the LAI estimate included a 100 m smoothing window. Except for bare patches, sphagnum was typically found in depressions surrounded by ridges with feather moss. While the averaging would bring the canopy cover of both of these regions closer to the mean cover value the sensitivity of the inversion algorithm is much
Figure 7.4: Estimated live moss moisture content given canopy cover and nadir $\rho_{TOM,MIR}$. The relationship represents a cubic spline fit to a look-up table relating canopy cover and $\rho_{TOM,MIR}$ to moss moisture content. The look-up table was generated by combining an empirical relationship between moss moisture content and a modelled relationship between $\rho_{TOM,MIR}$ and $\rho_{TOM,MIR}$ using a 3-D RT-GO reflectance model [Myneni et al 1995]. The region with an estimated moisture content of 0 g/g correspond to negative model based estimates. This region was limited to 0g/g based on the forward model response surface that indicated that high canopy cover and high $\rho_{TOM,MIR}$ was not possible for the observed range of $\rho_{TOM,MIR}$. 
Figure 7.5. Comparison of estimates of surface moisture at NSA-OBS. All maps shown on a ratio (a,b,c) or ordinal (d) scale proportional to gray level.
(a) original MIR reflectance image (0-1);
(b) LAI image (0-5.9 m² leaf area m² ground);
(c) MIR inversion (0-6 g water/g moss) and
(d) drainage class map estimated by in-situ survey (moderately drained shown as black to very poorly drained shown as white).

Images have been not been enhanced so as to preserve spatial patterns of each mapped quantity.
Figure 7.6: Inverse model error assessment. Probability density functions (Pdf) of absolute moisture content given moss type (sphagnum - Sphag. or feather moss - F. moss) using Gamma distributions fitted to observed moisture contents. Moisture content data were recorded at the SSA-OBS site for periods at least four days after a rain event. See Chapter 2 for details regarding measurement methods. The absolute error rate corresponds to the classification error at the NSA-OBS as a function of the threshold moisture content separating sphagnum from feather mosses. The theoretical error represents the expected classification error assuming a constant inverse model error with a Gaussian error distribution having a 1.6 g/g 1 standard deviation interval.
higher for sparse canopies. This suggests that averaging canopy cover would tend to reduce estimates of moisture content in sphagnum regions more than it would increase estimates in feather moss regions. As a result the lower threshold of 3.0 g/g was adopted to map moss types from the surface moisture image. The threshold resulted in 48% feather moss and 52% sphagnum cover which was within 5% of in-situ estimates by Harden et al [1997]. The implication of uncertainty of moss cover fractions to modelling surface fluxes was beyond the scope of this study but represents a major issue for future use of MIR inversion for moss cover mapping. However, it should be recognized that at present there are no other means of remote mapping of moss type using existing orbital sensors.

7.4 Model Results

7.4.1 Model Initialisation

The model did not include a dynamic carbon allocation scheme since the stand under consideration was mature and the simulation duration was less than one year. This suggested that the major transient upon model initialization would be the soil moisture status. Initial water table depths, before snow melt, were set at typical growing season values mapped by Veldhuis [1997]. The unsaturated zone was initialized at field capacity. The snow pack was initialized as the site mean snow pack depth observed with the fine scale simulation after five years of model spin up. Figure 7.7 shows the modelled water table depth for all four parameterizations. The initial transient is limited to a week during the winter period, before snow melt, and was deemed unlikely to effect the conclusions of this study. Furthermore, water table depths prior to snow melt matched levels predicted at the end of the year suggesting they were appropriate for the site. It is also significant that the occurrence of complete saturation of the soil column following snow melt minimizes biases in water budgets in subsequent periods caused by incorrect initial conditions prior to snow melt. While spin up may have provided more accurate water budget estimates before snow melt the aforementioned lack of soil temperature data inhibited the use of these estimates for predicting useful carbon fluxes before March 18, 1994.
Figure 7.7: Modeled site mean water table depth as a function of surface parameterization. Intermediate scale result was not significantly different from the fine scale result. Initial water table depths were initialized at typical growing season depths [Veldhuis 1997] prior to snow melt. The curves suggest that, after a short initial transient, water table depths matched levels observed at year end. The onset of snow melt at DOY 120 resulted in complete saturation for all scaling treatments. This suggests that model estimates after DOY 120 are not likely sensitive to the initial conditions.
7.4.2 Stand NEP and Overstory NPP

Figure 7.8 shows the fine scale modelled stand NEP and its overstory and understory components. NEP values for the period of January 1 1994 to March 18 1994 were assumed equal to the average of the NEP in the week preceding and week following this period since there was insufficient soil temperature data to run the model for the first three months of 1994. The stand annual NEP was estimated as 0.055 kg m$^{-2}$yr$^{-1}$ with an overstory NEP estimate of 0.218 kg m$^{-2}$yr$^{-1}$ and an understory NEP estimate of -0.166 kg m$^{-2}$yr$^{-1}$. Nevertheless it was not possible to conclude that the stand was a carbon source or sink due to substantial uncertainties in field measurements of overstory NPP, model equifinality and the lack of a longer temporal forcing. For example Ryan et al [1997] estimated overstory NPP at 0.252 kg m$^{-2}$yr$^{-1}$ based on field measurements taken in a productive feather moss region of the NSA-OBS site. However, their sampling locations may not be have been representative of the entire site [Goulden et al 1997]. Kimball et al [1997], using essentially the same overstory model with a 100% larger leaf carbon and a leaf carbon to nitrogen ratio of 167 rather than an observed value of 61.7 [Middleton et al 1997], was also able to match observed total NEP at the site suggesting the possibility of cancelling errors in either the conceptual model or its parameterization. Finally eddy flux measurements at the NSA-OBS site indicated a carbon source in 1995 and 1996 suggesting that ecosystem NEP may fluctuate between sink and source at multi-annual time scales due to normal climatic variability [Goulden et al 1997]. Table 7.1 summarizes the modelled NEP components for the four surface parameterizations. While uncertainties in overstory NPP pose problems for estimating total site carbon fluxes, the small range of overstory NEP estimates in Table 7.1 indicate that these uncertainties are not related to spatial parameterization of moss type or surface wetness.
Figure 7.8: Modeled fine scale carbon budget components at NSA-OBS site during 1994. Overstory NEP is defined as canopy net photosynthesis less growth respiration and maintenance respiration from needles, branches and sapwood. Understory NEP is defined as moss net photosynthesis less growth respiration, root maintenance respiration and heterotrophic respiration from soil carbon pools (foliage litter, root litter and humic matter). Total NEP is the sum of overstory NEP and understory NEP. All values represent RHESSys model estimates using the BIOME-BGC [Kimball et al 1997] overstory carbon cycling model and Frolking et al [1996] soil and moss carbon cycling equations together with RHESSys radiation and water budget equations specified in Chapter 5.
Table 7.1: Model estimates of overstory, understory and total NEP (kg C m\(^{-2}\) yr\(^{-1}\)). Positive values indicate sinks of atmospheric carbon. Overstory NEP was defined as canopy gross photosynthesis less growth respiration and maintenance respiration of stem, sapwood and leaf biomass. Understory NEP was defined as moss gross photosynthesis less growth respiration, heterotrophic respiration and maintenance respiration for mosses and overstory roots. Total NEP was defined as the sum of overstory and understory NEP. NEP figures are provided for each of four scaling treatments. The fine scale treatment used 31 patches containing different mixtures of feather moss and sphagnum; the intermediate scale treatment used two patches each corresponding to the total cover or either feather moss or sphagnum; while the uniform moss treatments assumed that the site was representative of surface and overstory conditions typical of the selected moss surface.

<table>
<thead>
<tr>
<th></th>
<th>Fine Scale</th>
<th>Intermediate Scale</th>
<th>Uniform Feather moss</th>
<th>Uniform Sphagnum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overstory NEP</td>
<td>0.218</td>
<td>0.220</td>
<td>0.220</td>
<td>0.221</td>
</tr>
<tr>
<td>Understory NEP</td>
<td>-0.166</td>
<td>-0.192</td>
<td>-0.292</td>
<td>-0.162</td>
</tr>
<tr>
<td>Total NEP</td>
<td>0.055</td>
<td>0.027</td>
<td>-0.071</td>
<td>0.059</td>
</tr>
</tbody>
</table>

7.4.3 Understory NEP and Moss NPP

Table 7.1 also indicates that the differences in surface NEP explains the majority of difference in total NEP which is expected given that the scaling treatment deal with surface parameters and overstory non-foliar biomass and available nutrient concentrations were specified as being spatially invariant. Surface NEP was dominated by a moss sink and a root respiration source as shown in Figure 7.9 for a uniform sphagnum surface. The feather moss regions showed a similar trend although moss annual gross assimilation was approximately a quarter that of sphagnum regions. This result suggests that under present conditions it is more important to identify spatial variations in moss cover than spatial variations in surface controls on soil decomposition. Fortunately the MIR inversion method is capable on identifying moss cover more robustly that moisture content due to the persistent differences in water content between sphagnum and feather mosses.
Figure 7.9: Components of modeled surface carbon budget for a uniform sphagnum surface parameterization. Moss gross photosynthesis is zero in the presence of freezing temperatures and under a snow pack. Moss respiration includes growth and maintenance respiration. Root and moss respiration dominate carbon courses given substantially higher respiration coefficients. Heterotrophic respiration is inhibited by cool, damp soil column that results from the sphagnum parameterization assumption of no subsurface runoff.
The large root respiration source suggests the co-variation of root biomass and surface wetness should be known. The uniform root biomass assumption likely overestimated biomass in low productivity regions characteristically dominated by sphagnum cover and underestimated biomass in higher productivity feather moss regions. Steele et al [1997] monitored five soils cores at each of four random 15m x 15m plots within the study site. They reported that while the coefficient of variation for live root biomass at the study site was 15% the coefficient of variation of annual mean NPP was under 5% for coarse roots and under 2% for fine roots. This suggests that spatial variations in root NEP may not be significant within the study site. Furthermore, the modelled root litter decomposition coefficient was on average 34% greater in feather moss than in sphagnum regions. This suggests that modelled root litter decomposition would increase with a spatially variable biomass parameterization. An increase in feather moss surface decomposition would augment the already substantial differences in understory NEP between the fine scale and single feather moss trials.

The uniform sphagnum parameterization surface NEP is remarkably close to that of the fine scale parameterization. This may be a fortuitous result of using a 0 mm water day\(^{-1}\) baseflow condition for uniform sphagnum, which inhibits sphagnum assimilation. For example, with a 1 mm water day\(^{-1}\) maximum baseflow rate with uniform sphagnum the modelled surface NEP was -0.194 kg m\(^{-2}\) yr\(^{-1}\) and the total NEP was estimated at 0.026 kg m\(^{-2}\) yr\(^{-1}\). This result may explain why other single patch models [Kimball et al 1997, Frolicing et al 1996] are able to achieve reasonable understory NEP estimates by using a very large patch moisture capacity (e.g. 250 mm water) and a low or zero baseflow rate.

Figure 7.10 compares understory NEP between the fine scale treatment and each of the coarser scale treatments. The uniform feather moss cover resulted in a slight overestimate in NEP during winter due to a corresponding overestimate in soil moisture during the winter. The lack of a spatially distributed hydrologic parameterization prevents lateral drainage of water from moist to dry areas and subsequent drainage. The uniform feather moss parameterization showed low precision \((r^2=0.45)\) in matching the fine scale response. The low precision is likely a combination of fluctuations in moss NPP with changes in moss moisture content resulting in a drop in moss
Figure 7.10: Comparison of fine scale parameterization RHESSys surface NEP estimates with coarser scale parameterization RHESSys surface NEP estimates. The uniform feather moss treatment indicates a number of days when modelled surface NEP is substantially lower than the fine scale estimate. The difference is likely due to higher drainage in feather moss regions leading to warm, dry conditions in feather moss turfs and underlying soil column which promote respiration. In contrast the uniform sphagnum treatment shows only a slight tendency to underestimate fluxes during periods of large net inputs or losses. Surface NEP with the intermediate scale treatment, consisting of one sphagnum and one feather moss patch does not differ substantially from the fine scale treatment. Linear trend lines correspond to equations provided in legend. N=291
assimilation together with a larger root respiration in feather moss regions due to higher temperatures and an absence of inundation. The fine scale parameterization did not exhibit such a large temporal variations in moss or soil moisture content due to the presence of sphagnum mosses, which were always near saturation (as demonstrated at a similar mesic conifer stand in Chapter 2) and due to the lower effective site baseflow rate with the presence of sphagnum regions.

The intermediate-scale parameterization showed a negligible bias error and low precision error, $r^2=0.95$, in matching the fine scale parameterization. The low precision error represents a statistically significant ($p<0.01$) improvement in model precision over both uniform surface parameterizations. This suggests that the majority of the variation in surface controls on NEP are captured by identifying two regions corresponding to the area of sphagnum and feather moss cover and allowing lateral transfer of water between these areas. Lateral transfer between these characteristic regions has been documented within the NSA-OBS [Moosavi and Crill 1997].

7.5 Conclusions and Recommendations

The total site NEP for 1994 was estimated as 0.055 kg m$^{-2}$yr$^{-1}$ using the RHESSys model with a fine-scale parameterization using observed and previously published values for surface parameters, spatially uniform biomass and nutrient concentrations. Field studies have indicated that site drainage may increase NEP due to changes in available nutrients and increased rooting depths [Paavilainen and Paivanen 1997, pp. 93-95]. The current study is limited to a steady state system and is not intended to characterise prognostic model performance. Future work should extend the model used in this study to permit dynamic adjustments of canopy and forest floor conditions on multi-annual to decade levels.

A spatially uniform surface parameterization resulted in either significant bias or precision errors in matching a fine-scale parameterization. The spatially uniform sphagnum cover resulted in negligible error in surface NEP in comparison to the fine scale parameterization, but the result
may be fortuitous. The use of a spatially uniform feather moss cover resulted in a relative error in estimated surface NEP of over 200%. An intermediate-scale parameterization with two patches representing wet sphagnum regions and drier feather moss regions resulted in a relative error of approximately 50% in total NEP. The description of moss type was identified as a significant factor in achieving a lower error than for the uniform feather moss comparison due to the dominance of moss assimilation in the surface NEP budget. Moss cover information may be required for accurate model based estimates carbon fluxes within mesic Boreal conifer stands. Further validation of the MIR reflectance inversion method is required to determine if the high sensitivity to the moisture threshold was specific to the chosen site or due to the coarse LAI resolution. The possibility of using multiple dates to identify MIR reflectance trajectories during dry-downs should also be examined. The accuracy of moss species maps may also be improved by using high spectral resolution imagery [Bubier et al 1997].

The estimation of moss surface cover using MIR reflectance data required knowledge of canopy cover and structure. A parallel difficulty is that the carbon flux model presupposed knowledge of biomass and LAI distributions. In general, surface moss cover and wetness, biomass and LAI co-vary across nutrient and moisture gradients [Bonan and Shugart 1989]. This study has demonstrated that knowledge of surface moss cover and wetness is required for accurate estimates of NEP at the moss surface. Additional knowledge of biomass, nutrients and LAI is required for accurate and precise modelling of total NEP. In this regard it may be useful to consider mapping the joint distribution of these surface parameters. The parallel development of methods extending such algorithms to include MIR reflectance for wetness/moss cover estimation may increase the accuracy and precision of carbon flux models making use of remotely sensed parameter fields. Finally, it may be possible to constrain the joint distribution of surface and overstory properties by incorporating ecological constraints derived from observational studies.
7.6 References


Shugart, H.H., Patterns in space and time in Boreal forests. in *A Systems Analysis of the Global*


Woodrow, I.E. and J.A. Berry, Enzymatic regulation of photosynthetic fixation in C3 plants. 

CHAPTER 8

CONCLUSIONS

This section provides conclusions to the major research questions posed in Section 1 of the dissertation. The conclusions are all derived from conclusions in the dissertation chapters. For convenience the research questions are listed before each conclusion.

Chapter 2. Spatial patterns of understory water budgets and canopy cover in mesic boreal conifer stands: Are there significant differences in moss moisture content as a function of either moss functional group (sphagnum or feather moss) or spatial location within a typical wet conifer forest stand?

In-situ measurements indicated substantial differences in absolute and relative moisture content between sphagnum and feather moss; with sphagnum mosses typically holding 5 g water /g moss more than feather mosses in the same location and having a relative saturation which averaged 25% more than feathermoss turfs during the growing season. The difference in absolute moisture content between moss group was present at both plot and site scale and was persistent in time. The difference in relative moisture content was also present at all scales. However, the difference increased further into a dry down.

There was insufficient data to test if their were significant spatial differences in sphagnum moisture content. Site mean feather moss maximum moisture content was over 150% higher at site at the southern edge of the central Canadian boreal ecosystem in comparison to a site at the norther edge. While there were not substantial between plot differences in feathermoss moisture content there was an increase in the variation of within site feathermoss moisture content during a dry down. This fine scale variability in surface moisture during dry periods may need parameterization in models which rely on estimates of moss water budgets.
Chapter 3. The reflectance of *Pleurozium schreberi* as a function of moisture content: Is moss moisture content related to top of moss reflectance and how strong is this relationship relative to other variations in top of moss reflectance?

The moisture content of *Pleurozium schreberi* was related to top of moss mid infrared reflectance by a negative exponential curve which may be explained by liquid water absorption. There was only weak evidence that this relationship varied between moss turfs. This relationship may be useful for monitoring moss moisture content. Top of moss reflectance in red wavelengths was not sensitive to changes of moisture content until complete dessication. Top of moss reflectance in near infra-red wavelengths was not related to moss moisture content.

Chapter 4. Mapping surface wetness in Boreal conifer stands using mid-infrared reflectance: What is the relationship between top of moss and top of canopy reflectance and can this relationship be inverted to estimate moss moisture content?

A preliminary study using a numerical canopy reflectance model suggests that there is an invertible relationship between top of canopy mid infra-red reflectance and moss moisture content. The inverse relationship was only useful for overstory canopy cover less than 60% and moss moisture content under 6 g water/g moss. Application of the inverse relationship suggested that errors in LAI due to spatial smoothing and mis-registration limit the effectiveness of the MIR inversion method to moss cover mapping rather than estimation of moisture content. Furthermore, the negative correlation of moss wetness and canopy cover increased the sensitivity of estimated moss cover proportions to the threshold used to separate sphagnum and feather mosses. Both the use of temporal image sequences as well as the incorporation of *a priori* knowledge of the covariance of moss type and canopy cover may improve the robustness of the inverse modelling method for mapping surface wetness using mid-infrared reflectance.

Chapter 5. A spatially distributed model of overstory and surface water budgets in Boreal conifer stands: What is the expected bias and precision error of ET and understory water budgets estimates generated using a diagnostic daily time step model which includes a
parameterization for fine (<1km) scale variations in soil, moss and canopy parameters?

The RHESSys model, when parameterized with fine spatial scale (< 1 km) soil, moss and canopy information, was able to provide unbiased estimates of total ET and understory water budget components at two wet conifer sites and one dry conifer site without calibration. The expected bias in total ET was on the order of +/-5% of observed ET while precision errors ranged from 13% to 22%. The expected bias at one of the dry conifer sites was substantially higher (+39%) although the eddy flux data used for validation may not have been accurate.

Chapter 6. Effects of spatial scale of hydrologic parameterization on modelled ET: What is the differences in modelled ET estimated by the same model using a fine scale versus a coarser scale hydrologic and moss parameterization? Is this difference significant relative to fine scale model precision?

Coarse scale (1km) parameterizations of hydrology and understory cover at wet and dry conifer sites resulted in significant differences in modelled total ET in comparison to fine (<1km) scale parameterizations. The difference was chiefly explained by differences in understory ET, as modelled scaling controls on overstory E or T were almost negligible. The differences in modelled ET between fine and coarse spatial scale treatments at the dry conifer sites were approximately the same magnitude as the fine scale model precision. However, the differences at the wet conifer sites were up to twice as large as model precision. The use of a two patch parameterization resulted in no significant differences in modelled total ET in comparison to the fine scale results at all sites. Nevertheless a bias of 35% was noticed in the two patch estimate of understory ET at a mesic conifer site. The bias may have been due to a limitation on capillary rise to sphagnum turfs due to aggregation of water table depths over sphagnum dominated regions. Additional in-situ data regarding sphagnum and feather moss water and energy budgets is required to quantify the impact of scaling model parameter fields on modelled understory fluxes. Ideally, this data should be acquired together with measurements required for parameterization of the flux model.
Chapter 7. On the use of remotely sensed surface moisture information to improve model NEP estimates in mesic Boreal conifer landscapes: What is the difference in modelled NEP based on fine versus coarse scale moss and soil hydrologic parameterizations at a selected wet conifer site?

Model estimates using a 10 m resolution parameterization of surface moss cover and soils suggested a NEP of 0.055 kg m$^{-2}$yr$^{-1}$ (where a positive value indicates a carbon sink) for 1994 with an overstory NEP of 0.218 kg m$^{-2}$yr$^{-1}$ and an understory NEP of -0.166 kg m$^{-2}$yr$^{-1}$. No significant differences in overstory NEP were found with spatially uniform surface parameterizations due to the absence of overstory moisture stress. However a spatially uniform, well-drained, feather moss surface resulted in a 46% relative decrease in understory NEP; while a uniform poorly drained sphagnum surface resulted in a 2.4% relative increase in understory NEP. Although a uniform sphagnum surface resulted in negligible NEP differences it should be kept in mind that this parameterization contradicted the physical evidence of approximately 50% feather moss cover and may lead to inconsistencies in the site water budget. In contrast, a two patch, intermediate scale parameterization was able to match the fine scale NEP results for both overstory and understory.

Do controls on fine (< 1 km) spatial scale surface hydrological processes contribute to coarser (≥ 1 km) spatial scale, ecosystem responses such as ET and NEP?

The conclusions listed above support the hypothesis that fine spatial scale variations in moss moisture content, related to moss type (sphagnum versus feather moss), exert controls on understory fluxes which can play a significant role in defining total stand ET and NEP. Furthermore, a two patch parameterization where each patch corresponds to the fractional area covered by each moss type, without requiring a specification of the location of these patches, may be sufficient to provide unbiased model estimates of stand ET and NEP. However, it should be recognized that these final conclusions are conditional on the accuracy, precision and realism of the fine scale RHESSys model. Further validation over a range of site characteristics and over multi-annual periods should be conducted to determine the suitability of RHESSys for
diagnostic flux modelling in Boreal conifer landscape. In addition, information regarding the co-
variation of overstory and surface properties may be necessary if RHESSys is to be applied to
sites with a wider range of productivity than those tested in this study. Finally the impact of
functional variations linked to variations in species and phenological differences related to
responses of different species to environmental factors must be addressed if one wishes to apply
RHESSys over regional extents, throughout the Boreal ecosystem, rather than over the limited
sampling of study sites used in this dissertation.
APPENDIX I - Description of 3-D Radiative Transfer Geometric Optics Model

The 3-D RT-GO model of Myneni et al [1995] was selected to relate $\rho_{TOCMBR}$ to $\rho_{TOMMBR}$. To facilitate model validation independent of surface moisture content the model was also applied to red and NIR reflectance bands. This section provides a brief summary of the model.

The reflectance model combined a discrete implementation of radiative transfer equations describing standard photon scattering phenomenon [Chandrasekar, 1960] modified for anisotropic scattering together with a GO shadowing algorithm. The RT model was implemented on a cubic lattice. The lattice was bounded above by the atmosphere, below by the moss surface and assumed to repeat infinitely in all horizontal directions. The moss surface was assumed to be a Lambertian reflector as supported by observations in-situ [Peddle, Derek personal communication]. The Lambertian surface together with the absence of substantial shading effects between hummocks and hollows during satellite overpasses also supported the assumption that the moss surface was flat. Lattice cells had a uniform height defined by dividing the height corresponding to the top of the overstory ($H_o$) by the number of vertical layers ($N_v$). Each cell along the moss surface corresponded to a potential overstory or understory stem location. The horizontal dimension of the lattice cells were defined as the crown diameter of a typical overstory stem ($D_o$).

Overstory stems were located by randomly selecting the centre of a clump of stems within the lattice cell locations on the moss surface. A clump size was then selected from a Poisson distribution with a mean clump size of 3 stems. Unfilled adjacent lattice cells were then assigned stems until the required clump size was reached or until all eight nearest neighbours were occupied with stems. This method represents an approximation to a true double Poisson process necessitated by the discrete nature of the lattice cells. The mean clump size of 3 stems was arbitrarily chosen however it is likely more realistic than assuming that stems are distributed with no clumping effect. The same method was implemented to specify the location of surface cells containing understory stems based on understory crown cover ($C_u$). Foliage elements were located within columns of lattice cells above surface cells containing a stem. Understory leaf
area was assigned to lattice cells within a column by dividing the specified understory leaf area density ($LAD_u$) and stem area density ($SAD_u$) by the number of cells (beginning above the moss surface) required to reach the specified understory height ($H_u$). Overstory leaf and stem area were assigned in a similar manner given overstory leaf area density ($LAD_o$) and stem area density ($SAD_o$). However, the overstory cells were located within a column by beginning at the top of the lattice cube and filling downwards a sufficient number of cells to span the crown depth ($H_c$). The assumption of uniform $LAD_o$ and $SAD_o$ within a crown was reasonable for Picea mariana stems which typically have few dead branches below the crown and have nearly cylindrical crowns. The distribution of $LAD_u$ and $SAD_u$ across the column of cells corresponding to an understory stem was not an issue as the understory only occupied the cell adjacent to the moss surface.

Foliage elements within a cell were defined as branches holding shoots (for conifers) or leaves. Shoots were further separated into needles and bark area. The branch angle distribution within a cell was assumed to be uniform in azimuth and zenith. Leaf or shoot angle distributions were specified using functional forms for azimuth angle and zenith angle distributions. Needle dimensions and needle orientation relative to shoots was explicitly specified and assumed constant. The shoot or leaf angle distributions were used to evaluate the Ross-Nielson $G$-function [Ross and Nielson, 1968] for each cell containing foliage. The $G$-function was corrected for needle orientation and clumping for cells containing shoots. The corrected $G$-function was used together with specified leaf area and leaf optical properties to determine the fraction of photons entering a cell from a given direction, which were transmitted, reflected or absorbed. Bi-Lambertian phase functions appropriate for leaf, shoot or stem elements [Hapke, 1981] were used to defined the direction along which photons exited the cell after transmission or reflection.

A numerical approximation to the analytical transport equation using Gaussian quadrature was used to approximate interception and scattering functions along a set of discrete ordinates within each cell. An additional set of ordinates was required for each $G$-function and phase function along the direction of direct solar irradiance and selected viewing directions above the canopy.
The amount of uncollided radiation incident in each surface cell was estimated by computing the path integral of the extinction coefficient between each cell at the top of the canopy and the surface cell. For direct solar radiation, the path integral was only computed along the incident solar angle. For diffuse irradiance the path integral was computed over all discrete ordinates and weighted using Gaussian quadrature while assuming a uniform hemispherical distribution of diffuse irradiance.

The proportion of uncollided radiation incident on the surface which left the canopy without further scattering was estimated using a GO model which accounted for overlap between crowns [Li and Strahler, 1992]. The GO model ignored the presence of understory vegetation however the much lower LAD and SAD of the understory in comparison to the overstory supported this simplification. The GO model was applied along all discrete ordinates using the assumption of Lambertian scattering at the moss surface. The GO model was also applied along the view angle to estimate the radiant intensity incident on the viewer which has collided only with the moss surface. The GO model was embedded in the RT model to better characterize the hot-spot effect common in sparse canopies [Privette et al, 1995]. As such it was only used for first scattering from the moss surface source which contributes significantly to this effect.

The path integral of the extinction coefficient along discrete ordinates in the upper hemisphere between each cell within the lattice and each cell at the top of the canopy was computed. This path integral was then used to determine the fraction of first scattered radiant intensity which exiting the canopy without further scattering. A similar path integral along the view angle direction was computed for each lattice cell to estimate the first scattered radiant intensity reaching the viewer.

Radiation which did not leave the canopy after first scattering by either the moss surface or foliage was considered the first collision source within each cell. The first collision source from the moss surface was assumed to originate from a Lambertian surface. The magnitude of this source was determined by applying the GO model. An iterative solution of the discretized radiative transfer equations was then applied to update the within canopy and moss surface
collision sources together with an analysis phase after each iteration to estimate the cumulative multiple scattered irradiance leaving the canopy in the direction of the viewer.

References


