

Uncovering the understudied role of microtopography and ground cover on
evapotranspiration partitioning in high-elevation wetlands in the Canadian Rocky
Mountains

by

Yi Wang

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Examining Committee Membership

The following individuals served on the Examining Committee for this thesis. The decision of the Examining Committee is by majority vote.

External Examiner	Dr. Altaf Arain Professor, McMaster University
Supervisor	Dr. Richard Petrone Professor, University of Waterloo
Internal Member	Dr. Cherie Westbrook Professor, University of Saskatchewan Adjunct Professor, University of Waterloo
Internal-external Member	Dr. Rebecca Rooney Associate Professor, University of Waterloo
Other Member(s)	Dr. John Pomeroy Distinguished Professor, University of Saskatchewan

Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Statement of Contributions

This thesis has been structured in accordance with the manuscript option. Chapters two and three have been published. Chapter four has been submitted and is currently under peer-review. Consequently, should the Chapter 4 manuscript be accepted for publication, it may differ from what is presented in this thesis due to comments and feedback following peer-review.

To ensure coherence and consistency with the overall thesis, minor editorial revisions have been made on the published works. These revisions do not alter the scientific content of the chapters but rather correct typos and adjust formatting, to align with the thesis requirements.

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By signing below, I indicate that I agree with the evaluation of the roles and contributions of the various authors expressed above.

R. Petrone

B. Van Huizen

Abstract

A warming climate is projected to alter hydrological regimes in high mountain regions, including the Canadian Rocky Mountains. Rivers originating from the eastern slopes of the Canadian Rocky Mountains provide up to 90% of streamflow to downstream users in the Saskatchewan River Basin and have shown significant declines in summer discharge. In mid to late summer, as streamflow gradually decreases while water demand for agriculture, industry, and domestic use remains high, this reduction in streamflow imposes considerable stress on water use for various needs in downstream areas.

Wetlands buffer excess water during floods and alleviate water shortage during droughts, making them crucial for sustainable water resource management. With glacial recession, wetlands may become more widespread; however, their hydrological roles are uncertain. Evapotranspiration (ET) represents the total water loss from the wetland surface to the atmosphere through both evaporation and transpiration, which is typically the largest component of the wetland hydrological cycle. Accurately quantifying ET is essential for understanding ecosystem water use patterns, estimating water budgets, and designing sustainable water resource management strategies.

The environmental controls of ET in high-elevation wetlands are currently not well understood. The effects of land surface features such as microtopography, bryophytes, and litter covers, commonly found in these ecosystems, on ground surface evaporation—a component of ET—remain insufficiently explored. This thesis investigated these impacts across three typical high-elevation wetland types on the eastern slope of the Canadian Rocky Mountains: a montane fen (Sibbald), a sub-alpine marsh (Burstall) and a sub-alpine wet meadow (Bonsai). Field measurements of controlled evaporation experiments were conducted over various soil substrates and ground cover types, with and without an overstory willow canopy, during July and August 2021. The results showed that microforms and the overstory willow canopy did not exhibit statistically significant direct impacts on ground surface evaporation. Instead, their influences were indirect, affecting soil temperature profiles and

below canopy microclimates, which in turn influenced ground surface evaporation. Conversely, ground covers, including litter and bryophytes, significantly impacted on ground surface evaporation, with effects varying by site and involving complex interactions with evaporative demand and water availability.

In high-elevation ecosystems, the lack of adequate measurements of energy and water balance components, primarily due to high instrumentation costs and accessibility challenges, hampers understanding of their hydrological processes. While modelling approaches may be convenient and enable the exploration of temporal variability of energy and water fluxes, they require accurate parameterization, and model validation is often unavailable. It remains uncertain whether and how microtopography and ground covers should be integrated into modelling frameworks to enhance the representation of water and energy fluxes of high-elevation wetland ecosystems.

This thesis found that the effects of microtopography on ground surface evaporation were satisfactorily modelled by the Penman–Monteith model and a more complex bryophyte layer model in the Atmosphere-Plant Exchange Simulator (APES), based on soil temperature measured in these microtopographical features. The effects of ground covers and overstory canopy on ground surface evaporation were successfully modelled based on the modelling framework of soil evaporative efficiency (SEE) which is the ratio of actual to potential ground surface evaporation. Given that high-elevation ecosystems generally lack sufficient ground measurements for model calibration and validation, this thesis established a simple approach for modelling the SEE of vegetated surfaces over a range of soil substrates and ground cover types, based on the mass fractions of bryophytes and litter. Additionally, a correction method was developed to account for the effects of an overstory willow canopy on SEE. This novel approach is less parameter-intensive compared to conventional methods and potentially widely applicable beyond the three study sites.

Both the field experiments and the proposed SEE model formulation illustrate that ground covers significantly influence ground surface evaporation, a key component of ET. This

highlights the importance of further studying the effects of ground covers on both ET and its partitioning into evaporation and transpiration at the ecosystem scale. Since field measurements alone are insufficient to fully capture the daily dynamics of ET partitioning, modeling techniques were applied to achieve this goal. To quantify the relative contribution of ground surface evaporation (E) and vascular plant transpiration (T) to wetland ET at a daily scale, part of the newly developed SEE approach, which estimates the surface resistance of bryophytes and litter covered wetland ground surfaces, was incorporated into the widely used Shuttleworth–Wallace (S-W) model. Based on this model, the relative contributions of E and T fluctuated daily in response to meteorological conditions and soil moisture content during the study period. The average daily T/ET ratios for Sibbald, Burstall, and Bonsai were 0.86, 0.46, and 0.61, respectively. When excluding rainy days, the average T/ET ratios were 0.86 for Sibbald, 0.50 for Burstall, and 0.60 for Bonsai. The modified S-W model performed with satisfactory accuracy when compared to field measurements.

Assuming that the modified S-W model accurately captures the fundamental mechanisms driving wetland ET partitioning, this model was employed to simulate daily ET partitioning with varying ground cover fractions to investigate the effects of ground covers on ET and T/ET. The results indicated that bryophytes and litter had a minor impact on the magnitude of T/ET, though their influence may be more pronounced in wetlands with an elevated water table. A literature synthesis was further presented to reveal that wetland ET partitioning is strongly controlled by leaf area index (LAI) and moderated by water table depth. However, due to the absence of surface runoff measurements and continuous groundwater level monitoring, the water balance could not be estimated for each study site. Future research should explore potential interaction effects of water table level with microforms and ground covers as well as possible seasonal variations in their effects on wetland ET. Overall, this research reduced uncertainties associated with land surface heterogeneity in estimating ET and its partitioning in high-elevation wetlands, offered new perspectives for developing ET models, and facilitated the evaluation of ecosystem services and hydrological processes in these ecosystems.

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Dedication

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List of Abbreviations

AIC	Akaike's Information Criterion	MDS	Marginal distribution sampling
ANOVA	Analysis of variance	MLs	Micro-lysimeters
APES	Atmosphere-Plant Exchange Simulator	MSE	Mean square error
a.s.l.	Above sea level	M11	Merlin et al. (2011)'s model
BC	Below canopy	M16	Merlin et al. (2016)'s model
BP	Peat-bryophyte column	NC	No canopy
BS	Soil-bryophyte column	P	Peat column
E	Evaporation	PAR	Photosynthetically active radiation
ET	Evapotranspiration	PET	Potential evapotranspiration
EBR	Energy balance ratio	PLBS	Soil-bryophyte-litter-ground vascular vegetation column
GLMMs	Generalized linear mixed models	PPFD	Photosynthetic photon flux density
HOL	Hollow	P-M	Penman–Monteith model
HUM	Hummock	REML	Restricted Maximum Likelihood
K03	Komatsu (2003)'s model	RMSE	Root mean square error
LAI	Leaf area index	S	Soil column
LBP	Peat-bryophyte-litter column	SEE	Soil Evaporative efficiency
LBS	Soil-bryophyte-litter column	S92	Sellers et al. (1992)'s model
LMMs	Linear mixed models	S & M 92	Modified S92 by Merlin et al. (2011)
LP	Peat-litter column	S-W	Shuttleworth–Wallace model
LSMs	Land surface models	T	Transpiration

List of Symbols

A	Site specific parameter for estimating surface resistance in S92
A_{MLs}	Cross-sectional area of the MLs (cm ²)
B	Site specific parameter for estimating surface resistance in S92
C_c	Coefficient in the S-W model
C_s	Coefficient in the S-W model
c_p	Specific heat of air at constant pressure (J kg ⁻¹ °C ⁻¹)
D	Molecular diffusivity of water vapor in air (m ² s ⁻¹)
d	Zero plane displacement (m)
E_a	Actual evaporation (units vary by chapter)
E_{ij}	Ground surface evaporation from the $i \times j$ treatment group (units vary by chapter)
E_0	Potential evaporation (units vary by chapter)
e_a	Partial pressure of water vapor in air (units vary by chapter)
e_s	Saturation vapor pressure (units vary by chapter)
F_i	Land cover proportion of dominant vascular species
G	Ground heat flux (W m ⁻²)
g	Gravitational constant (9.8 m s ⁻²)
g_s	Stomatal conductance (m s ⁻¹)
g_{sc}	Canopy stomatal conductance (m s ⁻¹)
g_{sl}	Leaf stomatal conductance (m s ⁻¹)
$g_{v,B}$	Boundary layer conductance for H ₂ O from the bryophyte layer to reference point of air (mol m ⁻² s ⁻¹)

$g_{v,BP}$	Total conductance for H ₂ O from the peat surface to air ($\text{mol m}^{-2} \text{s}^{-1}$)
$g_{v,P}$	Molecular transport between the peat surface and the bryophyte layer ($\text{mol m}^{-2} \text{s}^{-1}$)
H	Sensible heat flux (W m^{-2})
h	Matric potential expressed as pressure head (cm)
i	Ground cover treatment (i = P, BP, LP, or LBP in Chapter 2 and i = S, BS, LBS, or PLBS in Chapter 3)
j	Microform levels in Chapter 2 (j = HUM or HOL) and canopy levels in Chapter 3 (j = NC or BC)
K_s	Saturated hydraulic conductivity (cm hr^{-1})
$K(h)$	Unsaturated hydraulic conductivity (cm d^{-1}),
k	Bulk canopy extinction coefficient
k_s	Thermal conductivity of the peat ($\text{W m}^{-3}\text{K}^{-1}$)
LAI_e	Effective LAI
LE or λET	Latent heat flux (W m^{-2})
L_B	Roughness height of bryophyte canopy (cm)
l	Pore-connectivity parameter
M_w	Molar mass of water vapor (18 g mol^{-1})
n	Pore-size distribution index
P	Parameter accounting for the soil thickness and evaporative demand in M11
Precip	Precipitation input (g)
p_a	Ambient pressure of the study site (kPa)
R or R_{specific}	Specific gas constant ($8.314 \text{ J mol}^{-1} \text{K}^{-1}$ or $0.287 \text{ kJ kg}^{-1}\cdot\text{K}^{-1}$)

Re	Reynolds number for H ₂ O
RH _a	Air relative humidity
RH _p	Relative humidity of peat
R _n	Net radiation (W m ⁻²)
R _{ns}	Net radiation at the ground surface (W m ⁻²)
r _a	Aerodynamic resistance under neutral atmospheric condition (s m ⁻¹)
r _{aa}	Aerodynamic resistance between the canopy and the eddy covariance measurement level (s m ⁻¹)
r _{ac}	Bulk boundary layer resistance of the vegetative elements in the canopy (s m ⁻¹)
r _{ah}	Aerodynamic resistance accounting for atmospheric stability conditions (s m ⁻¹)
r _{as}	Aerodynamic resistance between the ground and the mean aerodynamic canopy height (s m ⁻¹)
r _b	Leaf boundary layer resistance (s m ⁻¹)
rho	Spearman correlation coefficient
r _s	Ground surface resistance (s m ⁻¹)
r _{sc}	Bulk stomatal resistance of the canopy
r _{total_ij}	Bulk total resistance of the i × j treatment group (s m ⁻¹)
Sc	Schmidt number for H ₂ O
Se	Effective saturation content
Time	Duration of each round of evaporation experiment (day)
T _a	Air temperature (°C)
T _B	Temperature of the bryophyte layer (°C)

T_s	Surface temperature or soil surface temperature (units vary by chapter)
T_{soil}	Soil temperature ($^{\circ}\text{C}$)
T_p	Peat temperature ($^{\circ}\text{C}$)
u	Wind speed (m s^{-1})
u^*	Friction velocity (m s^{-1})
VWC or θ	Soil volumetric water content
VPD	Atmospheric vapor pressure deficit (kPa)
VPD_c	Vapor pressure deficit at the canopy height (kPa)
ν	Kinematic viscosity of air ($\text{m}^2 \text{s}^{-1}$)
vdd_a	Vapor density deficit of air (kg m^{-3})
W_{after}	Weight of ML samples at the end of each round of evaporation experiment (g)
W_B	Dry weight of the bryophyte biomass in each ML sample (g)
W_{before}	Weight of ML samples at the beginning of each round of evaporation experiment (g)
W_{constant}	Constant dry weight of the sample (g)
W_L	Dry weight of the litter biomass in each ML sample (g)
W_M	Molecular weight of air (29 g mol^{-1})
W_{plate}	Weight of the foil plate for each sample (g).
Z_B	Thickness of the bryophyte layer (m)
z_{oh}	Roughness lengths of the surface for heat transfer (m)
z_{om}	Roughness lengths of the surface for momentum transfer (m)
z_u	The height at which wind speed was measured (m)

α	Inverse of the air-entry value
β_{thermal}	Thermal expansion coefficient
γ	Psychrometric constant (kPa °C ⁻¹)
Δ	Slope of the saturation vapor versus temperature curve (kg m ⁻³ °C ⁻¹)
η	Coefficient accounting for atmospheric stability conditions
θ_a	Air-filled porosity
θ_r	Residual soil water content
θ_s or θ_{sat}	Saturated soil water content
$\theta_{1/2}$	Critical soil water content
κ	von Karman constant
λ	Latent heat of vaporization (units vary by chapter)
μ	Dynamic viscosity (kg m ⁻¹ s ⁻¹)
ρ	Density of the air (units vary by chapter)
τ_p	Tortuosity factor

Chapter 1

Introduction

1.1 Research context

A wetland is a mosaic of diverse habitats with varying extents of vegetation cover, open water, and exposed bare soil (Drexler et al., 2004), where the soil or substrate is at least periodically saturated or inundated with water. According to Cowardin (1979), a wetland is defined by meeting one or more of the following criteria: “(1) *at least periodically, the land supports predominantly hydrophytes; (2) the substrate is predominantly undrained hydric soil; and (3) the substrate is non-soil and is saturated with water or covered by shallow water at some time during the growing season of each year*”.

According to the Canadian Wetland Classification System, wetlands are primarily classified into five classes: bog, fen, marsh, swamp, and shallow water (National Wetlands Working Group, 1997). Bogs and fens are commonly referred to as peatlands, characterized by a layer of soil organic matter that exceeds 40 cm in thickness (Tarnocai, 1980). The major difference between bogs and fens is that bogs are exclusively fed by precipitation, while fens receive water from groundwater or surface water. Marshes and swamps are mineral wetlands that have little or no organic soils. Marsh is dominated by herbaceous plants, and swamp is mainly covered by woody vegetation. In addition, grassy marshes found in sub-alpine zones and higher elevations are often referred to as wet meadows. A wet meadow has minimal or no tree cover and has at least seasonally saturated soils mostly occurring following snowmelt (Keddy, 2010). It is important to note that the Canadian Wetland Classification System does not specifically define "wet meadow", as it was primarily designed to provide a broad framework for describing wetlands across Canada and guiding the development of wetland conservation policies. However, its framework lacks detailed subdivisions within wetland classes. To address this, individual provinces in Canada have developed their own wetland classification systems, which incorporate more detailed subdivisions and conservation policies. For instance, the Alberta Wetland Classification System (Alberta Environment and Sustainable Resource Development (ESRD), 2015), explicitly defines a wet meadow as "*a wetland plant zone found*

in some marshes and shallow water wetlands, dominated by graminoids that tolerate periodically saturated soils and short periods of shallow inundation."

Globally, wetlands are presented in all climate zones ranging from the tropics to tundra (Mitra et al., 2005), covering approximately 6.2% to 7.6% of the global land surface area (excluding Antarctica and glaciated Greenland) (Lehner and Döll, 2004). In Canada, around 36% of the country is covered by wetlands, with marshes and swamps covering approximately 12% and 8%, respectively, and peatlands (including both bogs and fens) covering about 10% (Amani et al., 2019). Despite occupying a small portion of the Earth's land surface, wetlands support disproportionately high numbers of species and provide invaluable ecosystem services including water quality improvement, flood abatement, and carbon management (Zedler and Kercher, 2005). Notably, peatlands occupying only about 2–3% of the Earth's land surface but storing around 25% of the global soil carbon (Turetsky et al., 2015; Yu, 2012), play an important role in nature-based climate change mitigation (Beaulne et al., 2021).

In the Canadian Rocky Mountains, wetlands are typically found in small depressions and floodplains in flat areas or gentle slopes, covering only 3.2% of the area (Alberta Biodiversity Monitoring Institute (ABMI), 2024). Swamps are the most common type, covering 1.0%, followed by open water (0.9%), fens (0.7%), and marshes (0.5%) (Alberta Biodiversity Monitoring Institute (ABMI), 2024). Their water table levels are primarily influenced by snowmelt, resulting in some of these wetlands being wet in the spring and early summer, and drying by late summer (Alberta Biodiversity Monitoring Institute (ABMI), 2024). Compared to boreal wetlands, these wetlands are situated in higher elevation zones, are generally smaller, have limited access, and are largely unaffected by human activity. Some of them may have permafrost or experience higher precipitation, cooler temperatures and greater humidity due to the orographic effect (Cooper et al., 2012). Additionally, the slope and aspect of some wetlands, depending on their location in the mountains, can significantly affect day length, carbon and water fluxes dynamics in growing seasons, and seasonal temperature fluctuations (Cooper et al., 2012; Hrach et al., 2021a; Hrach et al., 2021b).

As climate change exerts pronounced stress on high mountain regions, projected declines in snow cover and glaciers will lead to decreased summer runoff in Western Canada over the 21 century (Hock et al., 2019). Rivers originating from the eastern slopes of the Canadian Rocky Mountains provide up to 90% of streamflow to downstream users in the Saskatchewan River Basin (Martz et al., 2007) and have shown significant declines in summer discharge (Rood et al., 2008). This poses challenges to water availability for downstream communities, particularly in mid to late summer, when streamflow gradually declines while water demand for agriculture, industry, and domestic use remains high. On the other hand, as glaciers recede, wetlands may become more widespread and serve as self-regulated water reservoirs to sustain water supply (Somers and McKenzie, 2020), but their hydrological roles are poorly understood. Particularly, as many high-elevation wetlands rely on snowmelt and become dry in the late growing season, their hydrological processes in response to reduced water availability during this period is largely uncertain. Thus, it is imperative to study the hydrological processes of these mountain wetlands and their responses to changes in environmental conditions. Evapotranspiration (ET) represents the largest water loss from wetlands into the atmosphere, marking it as an important component in the wetland hydrological cycle (Hesslerová et al., 2019). Accurately quantifying ET is crucial for estimating the water budget, understanding water use patterns, designing sustainable water resources management, climate change adaptation, and ecosystem preservation.

ET is the total water loss from both evaporation and transpiration processes. Evaporation refers to the process by which water on various surfaces, such as plant surfaces, soil, and open water, transforms into vapor and then releases into the atmosphere. It is a physical process, primarily driven by evaporative demand controlled by radiative energy, air humidity, surface temperature and wind speed, and surface resistance to water vapor transfer (Allen et al., 1998; Monteith, 1981). Transpiration is the water movement through plants to the atmosphere and is controlled by stomata, the microscopic openings found on the surface of plant leaves and stems that regulate gas exchange between the plant and its environment.

There are many ways to quantify ET across different spatial scales. At the plot level, ET is commonly measured by flux chambers (i.e., a physical enclosure equipped with sensors to measure the traces gas within it) or by a combination of evaporation pans (i.e., a pan filled with water and placed in an open area to expose it to environmental conditions over time which measures the amount of water that has evaporated), lysimeters (i.e., a cylindrical container filled with a column of soil with vegetation growing on it, which can monitor water movement into and out of the soil column), gas exchange analyzers (i.e., a system that encloses a portion of a plant, such as a leaf, in a chamber and monitoring the concentrations of water vapor and other trace gases entering and exiting the chamber), and sap flow sensors (i.e., a set of probes used to measure the movement of sap within the xylem of plants), to measure the water fluxes from water, soil and vegetation. At broader spatial scales, ET is commonly quantified by combining measurements of the water balance components (e.g., using isotopes, rain gauges, flow meters and groundwater wells to measure evaporation, precipitation, surface and sub-surface runoff, and water storage) and complex models based on coupled energy and mass exchange of the soil-vegetation-atmosphere continuum (e.g., the Surface-Vegetation-Atmospheric Transfer (SVAT) models). Drexler et al. (2004) examined the most common methods and models for estimating ecosystem-level ET in wetlands and concluded that no single method stood out as the best for estimating wetland ET. All measurements assumed adequate fetch and homogeneous terrain so that the measurement is representative of the underlying surface (Drexler et al., 2004), however, not all wetlands have homogeneous land surfaces.

It is common to encounter open water, exposed soils, and vegetated patches in high-elevation wetlands in Canadian Rocky Mountains. Peatlands in the mountain region also share the microtopographical features of typical peatlands, such as hummocks (local high points) and hollows (local low points) (Harbert and Cooper, 2017). Some land surface properties, such as the relative coverage of open water (Eichelmann et al., 2018) and vegetation structure (Scarlett et al., 2017) have been recognized as significant factors controlling the spatial and temporal variability of wetland ET. Vegetation composition, distribution, growth, and phenology in

wetlands are predominantly controlled by water table depth and soil nutrient and redox conditions (Dwire et al., 2006; Ridolfi et al., 2006; Rodriguez - Iturbe et al., 2007). Additionally, water table depth also influences soil and open water evaporation, as a near-surface water level supports existences of open water, and enhances capillary rise of groundwater to direct evaporation in the upper soil horizons (Charles, 1987; Chen and Hu, 2004; Cooper et al., 2006). Furthermore, the movement of water through soils is controlled by soil characteristics including particle size, texture, and hydraulic conductivity, and environmental factors like moisture, temperature and pressure gradients (An et al., 2018; Flumignan et al., 2012; Shimojimaa et al., 1996; Wilson et al., 1994; Yang and K. Yanful, 2002). If the substrate is peat soil, water movement is also influenced by factors such as the level of decomposition and the forming material of peat (Rezanezhad et al., 2016). Clearly, the temporal and spatial characteristics of vegetation, groundwater, and soils play important roles in affecting wetland ET. Their effects have been extensively examined and most of them have been well incorporated into the SVAT models like Hydrus-1D (Simunek et al., 2005) and SimSphere (Gillies et al., 1997), and the land surface models (LSM) like CLASS ((Versegny, 1991) and CLM (Lawrence et al., 2019).

Wetlands have additional land surface properties influencing ET that remain insufficiently explored and have not been fully integrated into existing models. These properties include ground covers (e.g., bryophytes and litter) and microtopography (also referred to as microforms). Their impacts on wetland energy, water and carbon fluxes have only recently been acknowledged more broadly by the modelling community, even though a few studies already explored their impacts in northern peatlands several decades ago.

Bryophytes are a group of non-vascular plants that typically grow above soils in moist environments, and in northern peatlands, the most common bryophytes are mosses, like *Sphagnum* species (i.e., peat mosses) and brown mosses (Vitt and House, 2021). These species are also commonly found in high-elevation wetlands in the Canadian Rocky Mountains. They can absorb water from their surroundings through their leaves and stems, and store water from

300 to 500% of their dry weight for extended periods (Bayfield, 1973; Rouse, 2000). However, most of them cannot actively regulate water transport, and rely on their structural and physiological properties to transport water up to their capitula where photosynthesis takes place (Goetz and Price, 2015; McCarter and Price, 2014; Rice and Schneider, 2004; Thielen et al., 2021). Therefore, their influence on evaporation depends on their species composition, life traits, and biomass, as well as the humid or dry conditions of the site (Blok et al., 2011; Goetz and Price, 2015; Kidron and Tal, 2012; Liu and She, 2020; McCarter and Price, 2014; Rice and Schneider, 2004; Thielen et al., 2021; Voortman et al., 2014). Litter is the dead plant material that has fallen onto the ground. It can reduce evaporation by intercepting net radiation (Price et al., 1998), maintaining cooler daytime soil temperatures (Bristow, 1988), keeping constant or even slightly higher soil moisture (Petrone et al., 2001; Price et al., 1998), and decreasing atmospheric mixing within the litter (Hares and Novak, 1992). The effects of litter are also subject to moisture conditions. Peatland microtopographical features, such as hummocks and hollows, are functionally important in creating variations in soil temperature, moisture, oxygen levels and water table dynamics (Courtwright and Findlay, 2011; Kellner, 2001; Stovall et al., 2019; Strack et al., 2006; Sullivan et al., 2007), which, in turn, lead to variations in energy distribution and evaporation in hummocks and hollows (Admiral and Lafleur, 2007a; Kellner, 2001; Moore et al., 2022). Overall, there is strong evidence showing that microtopography and ground covers may play an unignorable role in wetland ground surface evaporation, yet their direct and indirect effects on ET have not been thoroughly investigated. It also remains uncertain how, or even if, these characteristics should be factored into modelling frameworks to enhance the representation of water and energy fluxes of wetland ecosystems.

1.2 The scope and the objectives of the thesis

Lafleur (2008), by compiling 60 studies all over the world on wetland energy and water fluxes, concluded that wetland location had little to do with its ET rates, and the variation in ET rates was largely determined by local climates and wetland characteristics. The review highlighted the necessity for future research in five critical areas: the significance of moss

covers, the requirement for more studies in tropical systems, the inclusion of wetlands in global climate models, the role of microforms in wetlands and their scaling to entire ecosystems, and the scarcity of annual ET measurements (Lafleur, 2008). Over the past 16 years, numerous studies from these fields have emerged, including research on moss evaporation and microforms as discussed earlier, but a complete understanding of the effects of microforms and ground covers on wetland hydrological processes is still lacking. There is a continuing need to enhance our knowledge of how microforms and ground covers affect wetland ET.

In this thesis, controlled experiments were employed to investigate the effects of microforms and ground covers (i.e., bryophytes and litter) on wetland ground surface evaporation. A focus of the investigation was to determine whether and how microforms and ground covers should be factored into modelling frameworks to better estimate ground surface evaporation, ET and the partitioning of ET into evaporation and transpiration for high-elevation wetlands. The field experiments were conducted at three wetlands on the eastern slopes of the Canadian Rocky Mountains, all above 1,400 m above sea level, with each representing the region's common wetland types. Given that field observations for model parameterization and validation are generally limited for high-elevation wetlands, this thesis also aimed to improve model representation of the impacts of microforms and ground covers on wetland ground surface evaporation, ET and the partitioning with minimal number of parameters possible.

This thesis is structured into five chapters, adhering to the manuscript option guidelines at the University of Waterloo. Chapter 1 provides the context, research gaps, objectives and the structure of the thesis. Chapter 2 assesses the impact of microforms on wetland ground surface evaporation and determines their integration into modelling frameworks. Chapter 3 and Chapter 4 examine how ground covers and overstory canopy influence wetland ground surface evaporation. Specially, Chapter 3 develops a parsimonious approach to account for the effects of ground covers and overstory canopy on ground surface evaporation, while Chapter 4 further incorporates this approach into a widely used ET model to estimate daily ecosystem-scale ET and the partitioning of ET into ground surface evaporation and vascular plant transpiration at the daily scale. Chapter 5 concluded the thesis and offered suggestions for future research.

Chapter 2

Effects of microforms on the evaporation of peat-bryophyte-litter columns in a montane peatland in the Canadian Rocky Mountains

2.1 Introduction

Peatlands are the largest terrestrial carbon sink, storing approximately 550 Gt carbon and sequestering 0.37 Gt of CO₂ per year (Mickler, 2021; Turetsky et al., 2014). Their carbon storage is determined by the balance between the carbon gained through vegetation photosynthesis and the carbon loss through vegetation respiration and peat decomposition, which are all strongly influenced by the hydrological conditions of peatlands (Aurela et al., 2007; Strack et al., 2006; Waddington and Price, 2000). For this reason, hydrological conditions of peatlands are crucial for carbon sequestration of these ecosystems. Moreover, accurately quantifying evapotranspiration (ET) is essential for understanding peatland hydrological conditions, as ET, which represents the total water transport from land surface to atmosphere, is a key water balance component and often the largest pathway of water loss in these ecosystems (Price and Maloney, 1994; Streich and Westbrook, 2020; Van Seters and Price, 2001; Wu et al., 2010).

ET includes both evaporation and transpiration, driven by different mechanisms — transpiration through plant physiology and evaporation driven by atmospheric and soil conditions (An et al., 2018; Gilliland, 2002; Shimojima et al., 1996; Stoy et al., 2019; Wilson et al., 1994; Yamanaka et al., 1997). Despite the importance of ET, there is a lack of direct observations of these processes at the ecosystem level (Stoy et al., 2019). Additionally, evaporation from the peatland ground surface may be affected by microforms like hummocks (local high points) and hollows (local low points), due to variations in soil temperature, moisture, and oxygen level within these microforms (Courtwright and Findlay, 2011; Stovall et al., 2019; Strack et al., 2006; Sullivan et al., 2007). However, as of yet, there is a paucity of information on the effects of microforms on peatland ground surface evaporation, despite its relevance for accurately quantifying peatland ET.

The potential effects of microforms on peatland ground surface evaporation may involve more complex interactions with ground covers, such as bryophytes and litter, which reside above the peat soils. The major bryophytes in peatlands are mosses, and most of these mosses cannot actively regulate evaporation (Goetz and Price, 2015). Instead, they rely primarily on capillary rise through their water-conducting pores to evaporate water, a process influenced by temperature and humidity gradients between ground surface and atmosphere (Goetz and Price, 2015; Kellner and Halldin, 2002; McCarter and Price, 2014; Nichols and Brown, 1980). As mentioned earlier, peatland microforms can cause variations in ground surface thermal and moisture conditions, potentially affecting peat-bryophyte column evaporation, though these effects have not been rigorously tested in the field. Further, the presence of bryophytes on peat soils can also modify temperature and moisture conditions of the ground surface. For example, some *Sphagnum* mosses have a high water retention capacity, which allows them to remain wet under dry conditions, leading to higher evaporation (McCarter and Price, 2014). While both bryophytes and microtopography contribute to variations in peatland ground surface thermal and moisture conditions, it remains unclear whether there are interaction or combined effects between microforms and bryophytes on peatland ground surface evaporation.

Unlike bryophytes, the presence of undecomposed litter cover was frequently overlooked in peatland evaporation studies. Litter refers to the dead plant material that has fallen onto the ground, and, in peatlands, often resides above bryophytes when both are present on the ground surface. A limited number of research examining water fluxes in peatlands have found that litter impacts peatland ground surface evaporation. For example, Farrick and Price (2009) found that litter acted as a physical barrier to reduce the upward movement of water vapor, resulting in lower evaporation under litter cover compared to bare peat. This study also found that litter cover helped maintain higher moisture within the soil (Farrick and Price, 2009). Despite the limited studies on peatland litter, research on mulches—similar to undecomposed litter cover—has shown that mulches can help maintain relatively constant soil moisture levels (Petrone et al., 2001), and lower soil temperatures during the day and higher temperatures during the night compared to bare soils (Bristow, 1988). However, most studies on litter or

mulches and their effects on evaporation have been conducted in greenhouses or agricultural sites, with few investigations in natural peatlands where microforms, bryophytes and litter may interact in complex ways to influence evaporation processes.

To better understand the effects of microforms and ground covers on peatland ground surface evaporation, field investigations with controlled experiments focusing on various microforms and ground cover treatments, are essential. These data are crucial for validating and improving evaporation models, which will be useful for estimating peatland ET in the context of changing environmental conditions due to disturbances and climate change. Historically, ground surface evaporation models were primarily developed for bare soil evaporation (Or et al., 2013), and only recently have they begun to incorporate the bryophyte layer. Evaporation from a bryophyte layer can be simulated by one-dimension models (e.g., liquid flow equations or radiation models) when the boundary conditions and hydraulic conductivity of the bryophytes are properly defined (Kellner, 2001; Price et al., 2009). For example, McCarter and Price (2014) applied Hydrus-1D in simulating moss evaporation in peat columns by fitting the water retention and hydraulic conductivity functions of mosses based on the measured values. Launiainen et al. (2015) used the Atmosphere-Plant Exchange Simulator (APES) to model moss evaporation in a boreal forest, where the upper boundary condition of the model was given as a balance between infiltration, soil evaporation and capillary rise to the living mosses. More recently, Park et al. (2018) integrated the Coupled Hydrological and Biogeochemical Process Model (CHANGE) with the bryophyte layer model of APES when applying CHANGE in an arctic region. However, these models generally treat the bryophyte layer as a homogeneous organic layer situated above the soil surface (Launiainen et al., 2015; Park et al., 2018). Without sufficient observations and a comprehensive understanding of the spatial variability in peatland evaporation (Dixon et al., 2017), there remains a gap of whether and how the effects of microforms on the evaporation of a peat-bryophyte column should be incorporated into evaporation models.

To improve the understanding of peatland ground surface evaporation, it is imperative to examine how the evaporation of a peat-bryophyte-litter column varies with peatland

microforms in a natural peatland, whether these variations can be accurately modelled by evaporation models, and whether fine-scale variations are critical when upscaled to the entire peatland ecosystem. To answer the questions, in situ evaporation experiments were conducted in a montane peatland in the Canadian Rocky Mountains during the growing season of 2021. The specific objectives were: (1) to test if the effects of microforms is significant in the evaporation of bare peat, peat-bryophyte, and peat-bryophyte-litter columns; (2) if significant, to identify the key environmental controls that influence the effects of microforms on evaporation from a variety of combinations of peat, bryophytes, and litter; and (3) to investigate if the effects of microforms can be incorporated into evaporation models.

2.2 Study sites and methods

2.2.1 The study site

The study was conducted at Sibbald Peatland (51.06°N, 114.87°W) in the foothills of the Canadian Rocky Mountains, at a mean elevation of 1,490 m a.s.l (Figure 2-1). According to the Canadian Wetland Classification System (National Wetlands Working Group, 1997), Sibbald Peatland can be classified as a fen because its soil organic layer (i.e., peat layer) is greater than 40 cm (Tarnocai, 1980), and it is primarily supplied by groundwater that flows through the surrounding area (Weixelman, 2009). The study site is referred to as Sibbald Fen hereafter. The site has a surface area of approximately 9.3 km², and an aspect slightly south oriented with an elevational change of 34 m. The climate is characterized by warm, dry summers, and cold, snowy winters. The mean air temperature from 1975 to 2008, recorded at the University of Calgary Biogeosciences Institute (station #3053600; ~1,391 m a.s.l.), which is within 10 km of Sibbald Fen, is 3.5 °C. The mean annual precipitation is 639 mm, with approximately one-third of the rainfall occurring during the growing season (June to August).

Dominant vegetation consists of sedges (*Carex* spp., 65%) and willow (*Salix* spp., 23%), and moss species include: *Aulacomnium palustre* (Hedw.) Schwaegr., *Bryum pseudotriquetrum* (Hedw.) Gaertn. et. al., *Calliergon giganteum* (Schimp.) Kindb., *Calliergon richardsonii* (Mitt.) Kindb. in Warnst., *Campylium stellatum* (Hedw.) C. Jens., *Hypnum lindbergii* (Mitt.),

Plagiomnium ellipticum (Brid.) T. Kop., *Pohlia nutans* (Hedw.) Lindb., and *Warnstorfia fluitans* (Hedw.) Loeske (Lei, 2021).

The fen is composed of sedge- or *Sphagnum*-derived peat. Peat thickness is less than 0.5 m at the northern end and increases gradually (up to 6.5 m) towards the center. The upper 0.5 m of peat is composed primarily of decomposing sedges (*Carex* spp.), and from 0.5 to 1.3 m, the peat is dominated by mosses (*Sphagnum* spp.) (Wang et al., 2016). Beneath the peat layer, the soil is characterized as alluvium (sandy gravel and boulders) and black shale of marine origin (1971 Alberta water well drilling report (GIC Well ID 404614)). Details of the hydrology, soil properties, and vegetation of this site have been extensively described by Janzen and Westbrook (2013), Wang et al. (2016), Streich and Westbrook (2019) and Lei (2021).

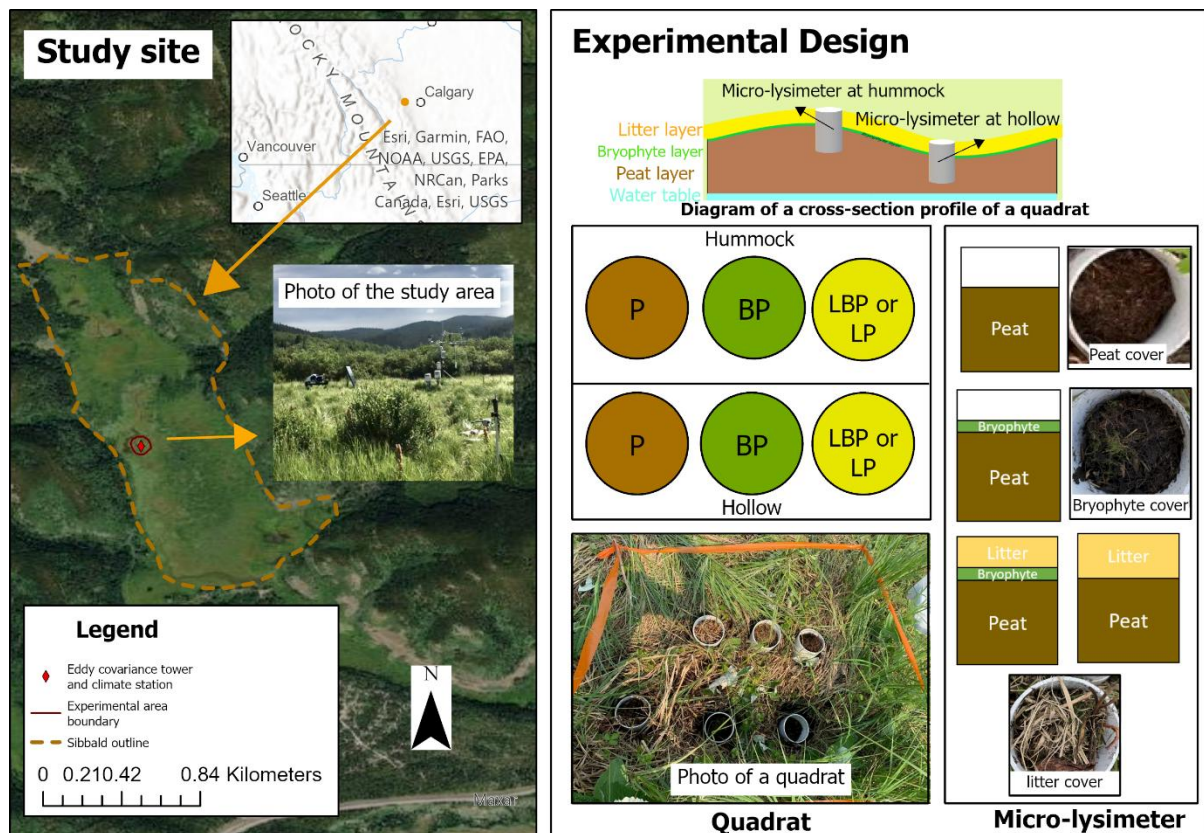


Figure 2-1. Study site location in Alberta, Canada, and illustration of the experiment design.

2.2.2 Evaporation experiment

The evaporation experiments began during the snow-free period on July 12th, 2021, and ended on August 30th, 2021, with a total of six replications (rounds) during this period. In each experiment, six quadrats were randomly distributed, with three under the canopy of willow trees and the others directly exposed to the sun. Each quadrat contained three micro-lysimeters (MLs) located in hummocks and three in hollows (six MLs per quadrat). Two treatment levels, peat (P) and peat-bryophyte (BP), along with one control (peat-bryophyte-litter (LBP)), were randomly assigned to the three MLs in each hummock and hollow within each quadrat. The MLs, which were 10 cm in diameter and 15 cm deep, were constructed from 10.2 × 304.8 cm (4 inches × 10 ft) PVC pipes (IPEX model #003245), following the procedure described by Flumignan et al. (2012).

Before installing the MLs, vascular vegetation at each quadrat was removed by clipping the above-ground biomass. Then, MLs without caps were inserted into the ground using light strokes with a mallet until the upper edge of the MLs was at the ground surface. After that, MLs containing peat-bryophyte-litter columns were carefully removed from the ground, taking care not to disturb the structure of the extracted samples and the remaining pits. The extracted MLs were sealed at the bottom with corresponding PVC pipe caps (IPEX model #650580) to prevent water from draining from the bottom. For MLs under the P treatment, both litter and bryophytes were carefully removed, while for MLs under the BP treatment, only the litter was removed. The average thickness of the bryophyte layer and the litter layer was approximately 5 mm and 5 cm, respectively. After removal, the exterior of the MLs was cleaned with a dry cloth and weighed using an electric laboratory balance (CGOLDENWALL; Max: 3,000 g; resolution: 0.01g) on site. The balance was placed inside a 13 L transparent storage container to prevent turbulent air from affecting the weighing process. After recording the initial weights (W_{before}), the MLs were placed back into their corresponding locations where the column samples were extracted.

In the first round of the evaporation experiment, the MLs were measured two days after installation (denoted as the round 1.1) and were put back to the field for another three days until soil samples were taken back to the lab (denoted as round 1.2). For the remaining five rounds, the weights of MLs were generally measured four days after installation. The final weight of each ML was denoted as W_{after} . Evaporation (E , g d^{-1}) from the MLs was calculated as follows (Flumignan et al., 2012):

$$E = \frac{W_{\text{before}} - W_{\text{after}} + (\text{Precip} \times A_{\text{MLs}})}{\text{Time}} \quad (1)$$

where W_{before} and W_{after} are the weights of the ML samples at the beginning and the end of each evaporation experiment (g), respectively; Precip is the precipitation (cm); A_{MLs} is the cross-sectional area of the PVC pipes (cm^2); and Time is the duration of each evaporation experiment (d).

After the evaporation experiment, samples from the BP and LBP categories were taken back to the Wet Lab at the University of Calgary Biogeoscience Institute to measure the dry weight of bryophyte and litter biomass. Fresh leaves and roots were removed from the samples. Bryophytes and litter were manually identified and sorted, then placed in 3-inch and 9-inch foil plates, respectively. These plates were oven-dried at 70 °C (Fisher SCI, Isotemp incubator 200 series) until the weights were constant (W_{constant}), a process that took around 72 hours in this study. The weights were measured using an electric scale (Sartorius ENTRIS3231-ISUS; Max: 320 g; resolution:0.001 g). In cases where the weights exceeded the maximum capacity of the scale, another electric balance (PG 5002-S Delta Range METTLER TOLEDO; Max: 5100 g; resolution:0.01g) was used instead. The dry weight of the bryophyte biomass (W_{B}) and litter (W_{L}) was calculated as the difference between W_{constant} and the corresponding weight of the foil plate (W_{plate}), as follows:

$$W_{\text{B}}(\text{or } W_{\text{L}}) = W_{\text{constant}} - W_{\text{plate}} \quad (2)$$

where W_B is the dry weight of the bryophyte biomass in each sample (g), W_L is the dry weight of the litter biomass in each sample (g), W_{constant} is the constant dry weight of the sample (g), and W_{plate} is the weight of the foil plate for each sample (g).

In the LBP category, some samples had no apparent bryophytes, so these samples were recategorized as peat-litter (LP). Data from the quadrats located below the willow canopy were also removed to exclude the unnecessary complexity of the plant canopy's effect on evaporation in this study. Therefore, there were a total of four levels of ground cover type ($i = P, BP, LP$ and LBP), and two levels of microform ($j = HUM$ and HOL) in the evaporation experiments. In each round of the experiment, there were three replicates for each treatment (three quadrats per experiment round).

2.2.3 Measurement of environmental variables

Meteorological variables, including net radiation (R_n , $W\ m^{-2}$), air temperature (T_a , $^{\circ}C$), air relative humidity (RH_a , %), wind speed (u , $m\ s^{-1}$) and precipitation (Precip, mm) were continuously measured at a height of 3 m by a weather station located at the center of the sampling area (Figure 2-1). R_n was measured using an NR-Lite2 (Kipp Zonen: Delft, Netherlands), T_a and RH_a were measured using an HMP-155 T/RH probe (Vaisala; Helsinki, Finland), u was measured using an R.M. Young 05103 propeller anemometer (R.M. Young: Michigan, USA), and Precip was measured with a TE525I rain gauge (Texas Electronics: Dallas, USA). Soil heat flux ($W\ m^{-2}$) was measured using the HFP01 soil heat flux plate (HukseFlux: Delft, Netherlands), placed 6 cm below the surface. Soil temperature (T_{soil} , $^{\circ}C$) was continuously measured at 15 cm and 30 cm depths using Type E Thermocouples (Omega Engineering: Connecticut, USA). Soil volumetric water content (VWC) was continuously measured at 15 and 30 cm depths using ECH2O EC-5 sensors (Meter Group, Hopkins, Washington, USA). All these variables were sampled every 30 seconds and averaged every 30 minutes using a CR1000 datalogger (Campbell Scientific: Utah, USA).

In addition, T_{soil} at depths of 5, 10, 20, 30 and 40 cm in both hollows and hummocks within each quadrat was manually measured using a temperature sensor (Type K Thermocouple,

Omega Engineering: Connecticut, USA) at the beginning and end of each evaporation experiment.

2.2.4 Modelling evaporation from hummocks and hollows

In order to investigate the ability of evaporation models to capture the possible fine-scale variations of evaporation influenced by peatland microforms, two widely used models were selected: the Penman–Monteith (P-M) model (Monteith, 1965) and the bryophyte layer model in APES (Launiainen et al., 2015). Although the two models appear different, both are fundamentally based on the Dalton type flux gradient equation for evaporation derived from Fick’s law of diffusion and the bulk resistance scheme. In this equation, evaporation, which is driven by molecular diffusion, is analogous to the flow of electric current through a circuit, with the diffusion coefficient of water vapor quantified by a bulk resistance term, r_{total} (Monteith, 1965; Oke, 2002). By analogy to Ohm’s law, the flux gradient equation for evaporation is expressed as follows (same with the Eq. 18a in Monteith 1965).

$$E = \frac{\rho_a c_p}{\lambda \gamma} \frac{(e_s(T_s) - e_a)}{r_{\text{total}}} \quad (3)$$

where E is the evaporation ($\text{kg m}^{-2}\text{s}^{-1}$), ρ_a is the density of air (kg m^{-3}), c_p is the specific heat of air at constant pressure ($\text{J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$), $e_s(T_s)$ is the saturated vapor pressure at the surface temperature T_s (kPa), e_a is the air vapor pressure (kPa), λ is the latent heat of vaporization (J kg^{-1}), γ is the psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$), and r_{total} is the bulk resistance between the land surface and the height above the land surface where evaporation is measured (s m^{-1}).

Although the P-M model and the bryophyte layer model in APES share the same physical basis, the bryophyte layer model in APES differs by separately calculating the evaporations of the bryophyte layer and underlying peat using the flux gradient equation for each layer. The specific differences between the models are detailed in the following sections.

2.2.4.1 The Penman–Monteith (P-M) model

The P-M model is a combination-type equation that integrates energy balance and mass-transfer theory to estimate evaporation from various surfaces. This model has multiple variants, as listed in Xiang et al. (2020), with the most widely-used variant being the one adopted in FAO Irrigation and Drainage Paper No.56 (Allen et al., 1998). This FAO variant calculates evaporation using variables such as R_n , ground heat flux (G), vapor pressure deficit, surface and aerodynamic resistances, which are derived from Eq. 3 with the assumption of surface energy balance (Monteith, 1981).

In this study, instead of using the FAO variant, a different form of the P-M model was adopted. This form was previously applied in the peat evaporation studies (Kettridge et al., 2013a; Raddatz et al., 2009). This version of the P-M model is presented as the combination of Eq. 4 (which is equivalent to Eq. 3, except that the vapor pressure gradient is replaced by the vapor density gradient using the ideal gas law) and the surface energy balance (Eq. 9 and Eq. 10).

$$E_{ij} = \frac{1000[\Delta(T_{s_{ij}} - T_a) + vdd_a]}{r_{total_{ij}}} \quad (4)$$

where E_{ij} is the evaporation from the $i \times j$ treatment group ($\text{g m}^{-2}\text{s}^{-1}$), Δ is the slope of the saturation vapor density versus temperature curve ($\text{kg m}^{-3} \text{ } ^\circ\text{C}^{-1}$), $T_{s_{ij}}$ is the surface temperature under the $i \times j$ treatment ($^\circ\text{C}$), T_a is the air temperature ($^\circ\text{C}$), vdd_a is the vapor density deficit of air (kg m^{-3}), $r_{total_{ij}}$ is the bulk resistance of the $i \times j$ treatment group (s m^{-1}), and 1000 is the unit conversion coefficient to convert E from $\text{kg m}^{-2}\text{s}^{-1}$ to $\text{g m}^{-2}\text{s}^{-1}$. The choice to use this unit for E is to facilitate the comparison between the P-M model and the bryophyte layer model in APES, because the conductance terms (i.e., the reciprocals of the resistance terms) in the latter were expressed in $\text{mol m}^{-2} \text{ s}^{-1}$.

The calculation for vdd_a is based on the ideal gas law as:

$$vdd_a = \rho_v^* - \rho_v = \frac{M_w(e_s - e_a)}{R(T_a + 273.15)} \quad (5)$$

And the calculation of Δ is based on the FAO Penman-Monteith method (Allen et al., 1998), as follows:

$$e_s = 0.6108 \times \exp\left(\frac{17.27T_a}{T_a + 237.3}\right) \quad (6)$$

$$\Delta = \frac{de_s}{dT_a} = \frac{4098e_s}{(T_a + 237.3)^2} \quad (7)$$

$$e_a = e_s \times \frac{RH_a}{100} \quad (8)$$

where ρ_v^* and ρ_v are the saturated and actual air vapor density (kg m^{-3}), respectively, e_a is the partial pressure of water vapor in air (kPa), e_s is the saturation vapor pressure (kPa), M_w is the molar mass of water vapor (18 g mol^{-1}), R is the gas constant ($8.314 \text{ J mol}^{-1} \text{ K}^{-1}$), T_a is the air temperature ($^{\circ}\text{C}$), RH_a is the air relative humidity (%), and the value 4098 in Eq. 7 comes from the derivative of e_s with respect to temperature T_a ($4098 \approx 17.27 \times 237.3$).

The surface temperature under the $i \times j$ treatment (T_{s_ij} , $^{\circ}\text{C}$) was calculated by inverting the flux gradient equation for sensible heat (Oke, 2002), as shown in Eq. 9. The sensible heat under the $i \times j$ treatment (H_{ij} , W m^{-2}) was calculated based on the assumption of energy balance, as shown in Eq.10.

$$T_{s\_ij} = \frac{\rho_a c_p T_a + r_a H_{ij}}{\rho_a c_p} \quad (9)$$

$$H_{ij} = R_n - G_{ij} - LE_{ij} \quad (10)$$

where ρ_a is the density of air (kg m^{-3}), c_p is the specific heat of air at constant pressure ($1,010 \text{ J kg}^{-1} \text{ }^{\circ}\text{C}^{-1}$), T_a is the air temperature ($^{\circ}\text{C}$), r_a is the aerodynamic resistance (s m^{-1}), R_n is the net radiation measured at the weather station (W m^{-2}), G_{ij} is the calculated ground heat flux under the $i \times j$ treatment (W m^{-2}), and LE_{ij} is the calculated latent heat under the $i \times j$ treatment (W m^{-2}).

m⁻²), which is converted from the measured evaporation (E_{ij} , g) from MLs under various ground covers and microforms.

The ground heat under the $i \times j$ treatment (G_{ij}) was calculated based on the finite-difference form of the heat flow equation (Sharratt et al., 1992):

$$G_{ij} = -k_s \frac{\Delta T_{\text{soil}_{ij}}}{\Delta z_{\text{soil}}} \quad (11)$$

where k_s is the average thermal conductivity of the soil columns during the study period, taken as $0.28 \text{ W m}^{-1}\text{K}^{-1}$, and $\Delta T_{\text{soil}_{ij}}$ (K) and Δz_{soil} (m) are the temperature difference between the two depths (5 cm and 15 cm) and the corresponding depth difference under the $i \times j$ treatment, respectively. The value of k_s was estimated using the inverse form of Eq. 11 and the measured ground heat flux measurements. This value falls within the reported range for the thermal conductivity of peat soils (Zhao et al., 2019). Additionally, due to the lack of T_{soil} measurements under various ground covers, $T_{\text{soil}_{ij}}$ was substituted with T_{soil} measurements from hummocks and hollows, denoted as T_{soil_j} . While T_{soil_j} was measured manually at the beginning and end of each evaporation experiment round, calculating G_{ij} requires continuous T_{soil_j} data. To address this, time series for T_{soil_j} at 5 cm and 15 cm depths were constructed using continuous T_{soil} measurements at 15 cm depth and their linear relationships with discrete T_{soil_j} measurements (Table A1). Since T_{soil_j} at 15 cm depth was not directly measured, it was estimated as the average of T_{soil_j} at 10 cm and 20 cm, based on significant linear correlations between T_{soil_j} and depth (Figure A1).

The resistance term, $r_{\text{total}_{ij}}$, was derived by inverting Eq. 4 using measured evaporation, and then averaged from hummocks and hollows for each ground cover type (i.e., $r_{\text{total}_i\text{-HUM}} = r_{\text{total}_i\text{-HOL}} = r_{\text{total}_i}$). If the P-M model can successfully predict E_{ij} using r_{total_i} and $T_{s_{ij}}$, Δ , T_a and v_{dd_a} , this would confirm the model's ability to capture fine-spatial variations in evaporation caused by different microforms, indicating that these variations are mainly driven by differences in T_s between hummocks and hollows. Conversely, failure to do so would imply that either the P-M model is inadequate in accounting for the fine spatial variations in

evaporation due to microforms, or that other processes, likely related to resistance, are influential and requires further investigation.

2.2.4.2 The bryophyte layer model in APES

Unlike the P-M model, the bryophyte layer model in APES (Launiainen et al., 2015) is a process-based model that separately calculates the resistances and evaporations of the bryophyte layer and the underlying peat. In this study, this model was specifically applied to the BP columns, with the total evaporation calculated as the sum of evaporation from the bryophyte layer (E_{B_BP}) and the underlying peat soils (E_{p_BP}).

The evaporation from the bryophyte layer of the BP columns (E_{B_BP} , $\text{mol m}^{-2} \text{s}^{-1}$) is calculated using the Dalton type flux gradient equation as follows (Launiainen et al., 2015):

$$E_{B\_BP\_j} = \frac{g_{v,B}(e_s(T_{B\_j}) - e_a)}{P_a} \quad (12)$$

where $g_{v,B}$ is the boundary layer conductance for H_2O ($\text{mol m}^{-2} \text{s}^{-1}$), $e_s(T_{B\_j})$ is the saturation vapor pressure (kPa) at the temperature of the bryophyte layer (T_{B_j} , $^{\circ}\text{C}$), e_a is the ambient vapor pressure (kPa), and P_a is the ambient pressure at the study site (84.47 kPa). T_{B_j} is the temperature of the bryophyte layer ($^{\circ}\text{C}$) for microform type j , assumed to be the same as $T_{\text{soil\_}j}$ at 5 mm depth. $T_{\text{soil\_}j}$ at 5 mm was linearly extrapolated based on the soil temperature profile with depth in hummocks and hollows (Figure A1).

The boundary layer conductance $g_{v,B}$ ($\text{mol m}^{-2} \text{s}^{-1}$) for the bryophyte layer was developed based on nine moss species similar to those grow in the study site of this study (Rice et al., 2001) and is computed as follows:

$$g_{v,B} = \frac{\rho_a 10^{-3.18} \text{Re}^{1.61} \text{DSc}^{0.33}}{L_B} \quad (13)$$

where ρ_a is the molar density of air (mol m^{-3}), Re and Sc is the Reynolds and Schmidt numbers for H_2O , respectively, D is the molecular diffusivity of water vapor in air ($\text{m}^2 \text{s}^{-1}$), and L_B is the roughness height of the bryophyte canopy which was assumed to be 0.57 cm based

on the field observation and the study by Rice et al. (2001). Each term in Eq. 13 was calculated as shown below (Rice and Schneider, 2004; Saito et al., 2006; Simunek et al., 1998; Sutherland, 1893):

$$\rho_a = \frac{1000P_a}{W_M R_{\text{specific}} (T_a + 273.15)} \quad (14)$$

$$Re = u \times L_B \times v^{-1} \quad (15)$$

$$Sc = \frac{v}{D} \quad (16)$$

$$D = 2.12 \times 10^{-5} \left(\frac{T_a + 273.15}{273.15} \right)^2 \quad (17)$$

$$v = \frac{\mu}{\rho_a} \quad (18)$$

$$\mu = \frac{1.458 \times 10^{-6} (T_a + 273.15)^{3/2}}{(T_a + 273.15) + 110.4} \quad (19)$$

where R_{specific} is 0.287 kJ (kg⁻¹·K⁻¹), W_M is the molecular weight of air (29 g mol⁻¹), v is the kinematic viscosity of air (m² s⁻¹), μ is the dynamic viscosity (kg m⁻¹s⁻¹), and ρ_a is the air density (kg m⁻³).

Peat evaporation E_{p_BP} (mol m² s⁻¹) was computed as follows (Launiainen et al., 2015):

$$E_{p\_BP\_j} = g_{v,BP} \frac{RH_{p\_j} e_s(T_{p\_j}) - e_a}{P_a} \quad (20)$$

where RH_{p_j} is the relative humidity of the peat (-), T_{p_j} is the temperature of the peat (°C), which was approximated to be the average of $T_{\text{soil\_j}}$ at 5 mm depth (i.e., the top boundary of the peat of a BP column and 15 cm (the bottom of the MLs), $g_{v,BP}$ is the conductance (mol m⁻² s⁻¹) from peat surface to the air, which includes molecular transport in the bryophyte layer ($g_{v,p}$) as well as the boundary layer conductance from the bryophyte layer to reference point in the air ($g_{v,B}$).

Molecular vertical transport in the bryophyte layer was calculated as (Launiainen et al., 2015):

$$g_{v,P} = \frac{1000P_a}{R(T_a+273.15)} \frac{D\theta_a\tau_p}{z_B} \quad (21)$$

where θ_a is the air-filled porosity ($0.9 \text{ m}^3 \text{ m}^{-3}$), τ_p is the tortuosity factor (0.7) derived from Launiainen et al. (2015), R is the universal gas constant ($8.314 \text{ J mol}^{-1} \text{ K}^{-1}$), z_B is the thickness of the bryophyte layer (0.0005 m). The air-fill porosity was calculated based on the bulk density of 0.14 g cm^{-3} that was measured at the same site previously (Karran, 2018) and the density of peat particle of 1.47 g cm^{-3} derived from Redding and Devito (2006).

Convective heat transfer may take place within these layers, as highlighted in Dimitrov et al. (2010); however, it is not accounted for in the model. Since convective heat transfer could influence the conductance terms, its exclusion represents a limitation that should be acknowledged.

The relative humidity of the peat was estimated using the thermodynamic relationship, as follows (Edlefsen and Anderson, 1943; Philip, 1957):

$$RH_{p,j} = \exp \left(\frac{M_{\text{water}} \times g}{R(T_{p,j} + 273.15)} h \right) \quad (22)$$

where $RH_{p,j}$ is the relative humidity of the peat for the microform type j (-), g is the gravitational acceleration (9.8 m s^{-2}), M_{water} is the molecular mass of water ($0.018 \text{ kg mol}^{-1}$), h is the water potential (m), R is the universal gas constant ($8.314 \text{ J mol}^{-1} \text{ K}^{-1}$), and $T_{p,j}$ is the temperature of the peat ($^{\circ}\text{C}$).

The water potential h was estimated from the van Genuchten water retention model with the model parameters derived from Dixon et al. (2017) for peat, which was calculated as follows:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m}, & h < 0 \\ \theta_s, & h \geq 0 \end{cases} \quad (23)$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{\frac{1}{m}} \right)^m \right]^2 \quad (24)$$

where $\theta(h)$ is the soil VWC (-), $K(h)$ is the unsaturated hydraulic conductivity (cm d^{-1}), θ_r and θ_s is the residual and saturated water contents, 0.01 and 0.94, respectively, h is the water potential (cm), α is the inverse of the air-entry value (0.60 m^{-1}), S_e is the effective saturation, n is the pore-size distribution index (1.19), and l is the pore-connectivity parameter (-1.41). K_s is the saturated hydraulic conductivity averaged from the previous study conducted at the same site (1.08 cm hr^{-1}) (Streich and Westbrook, 2019). The parameters, m and S_e , are calculated as follows:

$$m = 1 - \frac{1}{n}, n > 1 \quad (25)$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad (26)$$

In order to understand the mechanism underlying the impact of microforms on evaporation processes from the BP column, the evaporation of the BP column was modelled in two ways. The first approach, denoted as APES_P-M, involves integrating the bryophyte layer model from APES with the P-M model by substituting the total resistance in the P-M model with the total effective resistance (r_{total}^*) calculated based on the sum of $g_{v,P}$, $g_{v,B}$ and aerodynamic resistance (r_a). The method aims to evaluate the compatibility of the resistance terms calculated from the APES model with those of the P-M model. It should be noted that the r_{total}^* is not simply the sum of the reciprocals of $g_{v,P}$, $g_{v,B}$ and r_a ; it is also related to the boundary conditions (e.g., wind speed and soil moisture content at the bryophyte surface) (Launiainen et al., 2015; Rice et al., 2001). It was found that assigning an effective factor of 7 (i.e., $r_{\text{total}}^* = 7 \times r_{\text{total}}$) yielded the best modelling results. The outcomes from APES_P-M are then compared with those from the P-M model to assess whether a more detailed calculations of resistance terms can enhance the P-M model's ability to capture fine-spatial variabilities in evaporation.

The second approach, designated as APES, models the evaporation of the BP columns (E_{BP_j} , $\text{g m}^{-2} \text{s}^{-1}$) as the sum of $E_{B\_BP_j}$ ($\text{g m}^{-2} \text{s}^{-1}$) and $E_{P\_BP_j}$ ($\text{g m}^{-2} \text{s}^{-1}$). This method is designed to evaluate whether a more detailed processes-based model performs better in capturing fine-spatial variabilities in evaporation. If the APES yields satisfactory results, the effects of microforms on the evaporation from both the bryophyte layer and the underlying peat can be further investigated separately.

The aerodynamic resistance, r_a , is given by (Allen et al., 1998), as:

$$r_a = \frac{\ln\left[\frac{z_u-d}{z_{om}}\right] \ln\left[\frac{z_u-d}{z_{oh}}\right]}{\kappa^2 u} \quad (27)$$

where z_u is the height of the measured wind speed (3 m), d is the zero plane displacement (0 m), κ is the von Karman constant (0.4), u is wind speed (m s^{-1}), z_{om} and z_{oh} are the roughness lengths of the surface for momentum transfer and heat transfer (0.1 and 0.01 m).

2.2.5 Statistical analysis

The impacts of ground cover and microform on ground surface evaporation were compared using repeated-measures split-plot ANOVA (mixed-effect models), with experimental round, ground cover and microform as fixed effects, and quadrat as the random effect. The mixed-effect models were constructed with different structures, either with a random intercept alone, or with both a random intercept and slope. To determine the best-fitting mixed-effect model, these various mixed-effect models were evaluated using maximum-likelihood estimation. Such estimation are generally preferred because it is more straightforward and flexible than the least-squares method when random effects are present in the model (LeMay and Robinson, 2004). In this study, the Akaike information criterion (AIC) and the Restricted Maximum Likelihood (REML), the most common likelihood-type criteria for mixed-effect models, were used to select the optimal model. The model with the lowest AIC and REML values was determined as the best model (Pinheiro and Bates, 2000) and was subsequently used in ANOVA to determine whether the fixed effect factors significantly influenced ground surface evaporation.

Before constructing the mixed-effect models, the measured evaporation data were log-transformed to satisfy the assumption of homogeneity of variance and normality for the analysis. Then, the mixed-effect models were constructed using the “lme4” package (Bates et al., 2015) in R programming language version 4.2.0 (R Core Team 2022). These models, along with their AIC and REML values, are presented in Table A2. Among them, the model with a random intercept and slope, which accounts for measurements over time and includes the random effect of the microform nested within the quadrat, demonstrates the best goodness of fit (the No.5 model in Table A2).

Additionally, the impacts of microform, depth and their interactions on soil temperature were analyzed by a two-way repeated-measures ANOVA, with soil temperature also being log-transformed. Paired t-tests were conducted to assess whether significant differences existed in variables such as soil temperatures at the same depth between hummocks and hollows. Spearman correlation analysis was performed to investigate the relationship between two variables. All data were checked to ensure they met the prerequisites for the statistical analyses.

2.3 Results

2.3.1 Evaporation

The ANOVA test result shows that the experiment round ($p < 0.001$), ground cover ($p = 0.002$) and interaction of ground cover and microform ($p = 0.087$) are significant factors on ground surface evaporation (Table A3). However, there is no significant difference between hummock and hollow for the same type of ground cover (Figure 2-2). The mean evaporation rates throughout the experiments were as follows: $E_{P\_Hummock}$ and E_{P_Hollow} at 14.16 and 11.76 g d⁻¹, respectively; $E_{BP\_Hummock}$ and E_{BP_Hollow} at 9.57 and 14.38 g d⁻¹, respectively; $E_{LBP\_Hummock}$ and E_{LBP_Hollow} at 9.44 and 9.91 g d⁻¹, respectively; and $E_{LP\_Hummock}$ and E_{LP_Hollow} at 5.68 and 7.64 g d⁻¹, respectively (Figure 2-2). Comparing across treatment groups, the only significant difference in evaporation was found between LBP-Hummock and P-Hummock ($p = 0.01$).

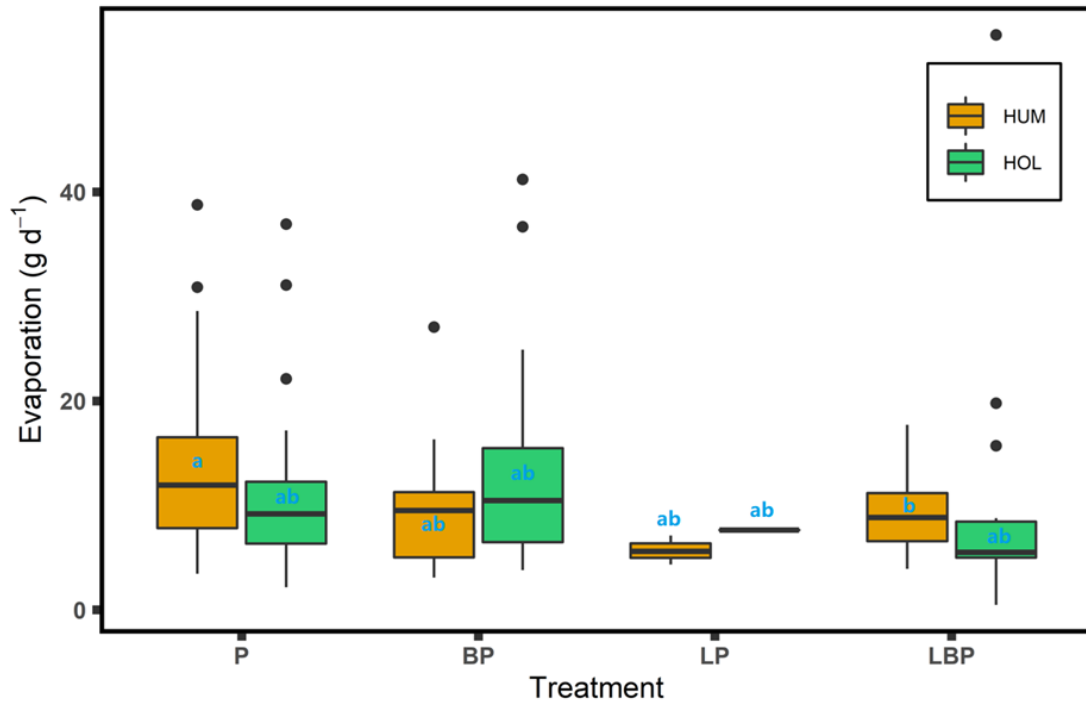


Figure 2-2. Evaporation rate of bare peat (P), bryophyte-peat (BP), litter-peat (LP) and litter-bryophyte-peat (LBP) between hummocks (HUM) and hollows (HOL) across 6 rounds of evaporation experiments. Different lower-case letters (in blue) represent significant differences between treatments ($p < 0.05$).

2.3.2 Soil temperature and biomass of bryophyte and litter between hummocks and hollows

Mean environmental variables during the study period are summarized in Table 2-1. Soil temperature was significantly influenced by depth and microform (both $p < 0.01$), but there was no significant interaction effect between depth and microform (Table A4). Deeper soil had lower temperature, and at the same depth, T_{soil} at hummocks was higher than at hollows (Figure 2-3). T_{soil} along depth between hummocks and hollows was only slightly different. At both hummocks and hollows, T_{soil} at the 5 cm depth was significantly higher than at 30 cm and 40 cm, and T_{soil} at 10 cm was significantly higher than at 40 cm (all $p < 0.01$). In addition, T_{soil} at

20 cm depth in hollows was significantly higher than at 40 cm ($p < 0.01$). However, there was no significant difference in T_{soil} at the same depth between hummocks and hollows, except at the 40 cm depth ($p = 0.008$).

Across the evaporation experiments, the mean bryophyte biomass was 0.74 g for hummocks compared to 0.49 g for hollows, and the mean litter biomass was 1.84 g for hummocks and 1.79 g for hollows (Figure 2-3). However, the differences in either bryophyte biomass or litter biomass between hummocks and hollows were not significant.

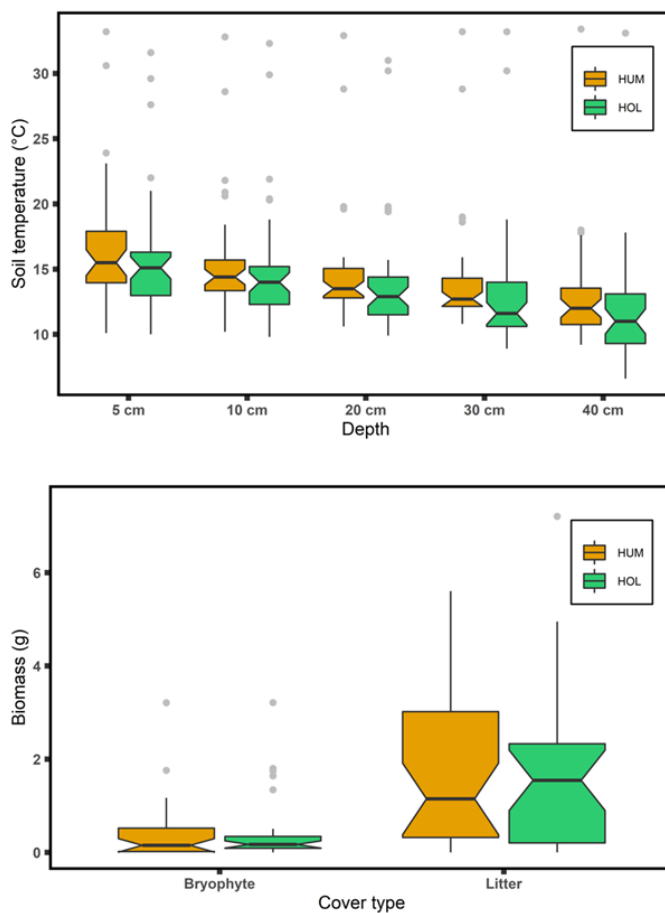


Figure 2-3. Soil temperature at multiple depths and the biomass of bryophyte and litter between hummocks (HUM) and hollows (HOL) across six rounds of the evaporation experiments.

Table 2-1. Mean environmental variants between hummocks and hollows during the study period.

Microform	Averaged environmental variants during the study period							Soil VWC at 15 cm	Soil VWC at 30 cm	Water table depth (m)	Maximum elevation difference (m)
	Soil temperature at 5 cm (°C)	Soil temperature at 10 cm (°C)	Soil temperature at 20 cm (°C)	Soil temperature at 30 cm (°C)	Soil temperature at 40 cm (°C)	Biomass of bryophyte (g)	Biomass of litter (g)				
Hummock	16.48±4.73a	15.54±4.42a	14.79±4.36a	14.23±4.47a	13.30±4.76a	0.74±1.80a	1.84±1.65a	0.50±0.08	0.67±0.03	0.70±0.24	~0.1
Hollow	16.00±4.86a	14.92±4.64a	13.98±4.60a	13.31±4.97a	11.82±4.46b	0.49±0.76a	1.79±1.83a				

Note: Water table depth refers to the distance between the water table and the peat surface. Maximum elevation difference is the estimated difference between the highest elevation of the hummock and the lowest elevation of the hollow within the same quadrat. Different letters indicate significant differences between hummocks and hollows ($P < 0.05$).

2.3.3 Environmental controls on evaporation

Evaporation was significantly positively correlated with RH_a ($\rho = 0.21$), R_n ($\rho = 0.46$), soil VWC at depths of 15 cm ($\rho = 0.5$) and 30 cm ($\rho = 0.44$). The correlations between evaporation and environmental variables differ slightly between hummocks and hollows. Hummock evaporation was significantly positively correlated with T_{soil} at 20 cm ($\rho = 0.37$), while hollow evaporation was significantly negatively correlated with T_{soil} at 40 cm ($\rho = -0.43$) and positively correlated with precipitation ($\rho = 0.3$). In addition, results from manual soil temperature measurements at the beginning (denoted by the subscript “begin”) and the end of the experiments (denoted by the subscript “end”) show that evaporation from hummocks was significantly positively correlated with T_{soil_begin} at 5 cm ($\rho = 0.26$) and negatively correlated with T_{soil_begin} at 40 cm ($\rho = -0.29$), while evaporation from hollows was negatively correlated with T_{soil_begin} at 5 cm ($\rho = -0.3$). Significant correlations were also found between evaporation from hummocks and T_{soil_end} at 5 cm ($\rho = 0.38$), 10 cm ($\rho = 0.41$), 30 cm ($\rho = -0.3$) and 40 cm ($\rho = -0.41$). However, no correlations were detected between T_{soil_end} at any measured depth and evaporation from hollows. Furthermore, no significant correlations were found between the biomass of bryophyte or litter and evaporation.

2.3.4 Modelling evaporation at hummocks and hollows

The models perform differently depending on the model type, ground cover, and microform (Figure 2-4). Specifically, the P-M model performed poorly for bare peat evaporation at both hummocks and hollows; it tended to overestimate the evaporation of the BP columns at hummocks and underestimate it at hollows. However, its predictions for the evaporation of the LBP columns at both hummocks and hollows were generally better than for the other two groups. Overall, the P-M model produced relatively satisfactory results, as its 95% confidence interval centered around the diagonal line.

In contrast, the APES_PM model predicted the evaporation of the BP columns at hummocks very well but did not perform well in modelling the evaporation of the BP columns at hollows, though its overall performance (based on the Average group) was acceptable. Meanwhile, the

APES model tended to overestimate the evaporation of the BP columns at both hummocks and hollows, except when the BP columns at hollows had high evaporation rates.

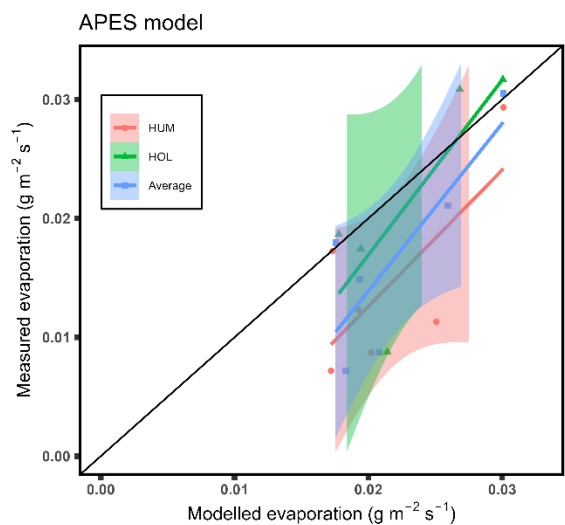
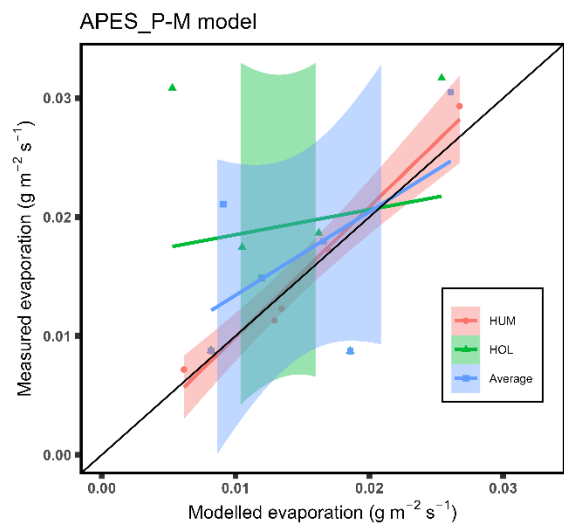
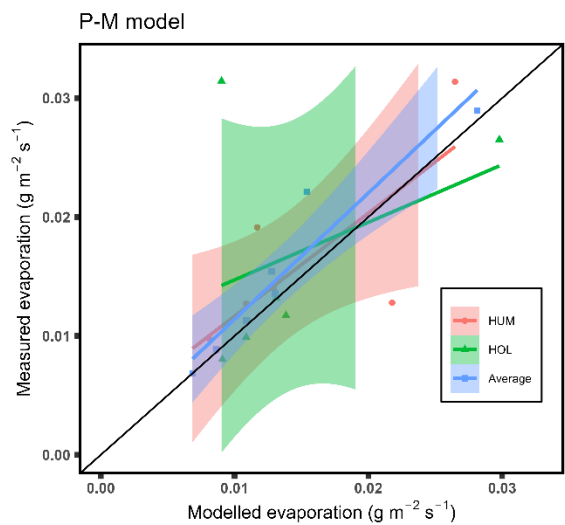
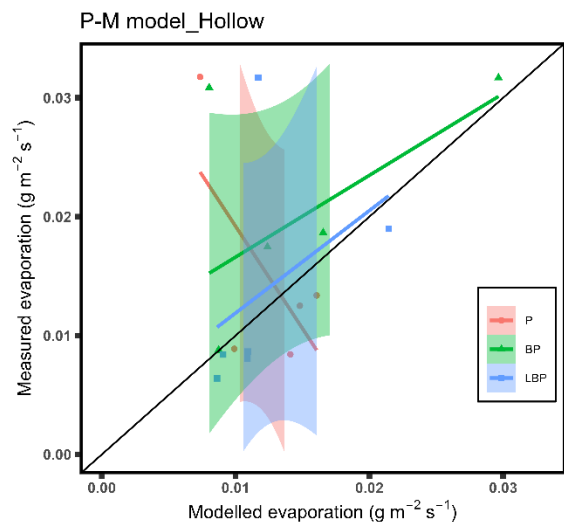
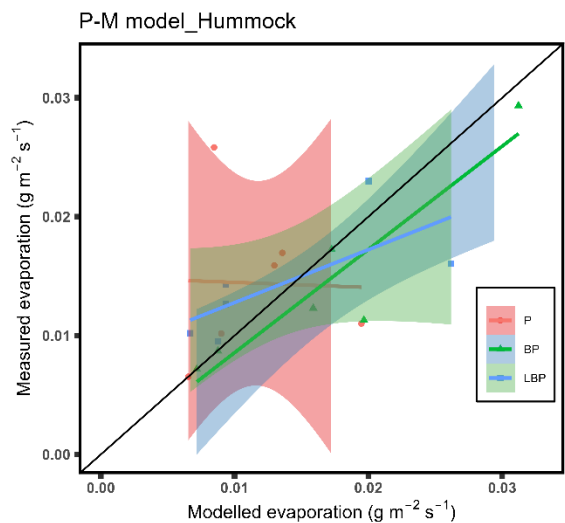


Figure 2-4. Performance of the P-M model on the evaporation of the P, BP and LBP columns, as well as the APES_P-M model and the APES model on the evaporation of the BP columns at hummocks (HUM) and hollows (HOL), and the average of hummocks and hollows (Average).

Each colored shading indicates the 95% confidence interval for each group.

2.4 Discussion

2.4.1 The combined effect of bryophyte, litter, and microform on peatland evaporation

Measured ground surface evaporation in this study fell within the reported range for peatland evaporation (up to around 29 g d^{-1}) (Nichols and Brown, 1980; Price et al., 1998). Direct studies on peatland evaporation are rarer compared to research on peatland ET. However, evidence shows that evaporation can exceed more than 50% of total peatland ET (Admiral and Lafleur, 2007b; Warren et al., 2018), making it an important component that should receive more research attention.

This study demonstrates that peatland ground surface evaporation is significantly influenced by the presence of bryophytes and litter. Bryophytes tend to have higher evaporation rates when water is not limited because their structure allows for more efficient capillary rise, while litter not only acts as a physical barrier for vapor transport (Farrick and Price, 2009), but also maintains moisture levels and keeps the temperature cooler underneath (Bristow, 1988). The counterbalancing effects between bryophytes and litter are evident when comparing the average evaporation of P, BP, LP and LBP across microforms. On average, LP evaporated 48.6% less than P, but with the presence of bryophyte layer, LBP evaporated 22.5% less than BP. Moreover, the most distinct difference in evaporation is observed between the LBP columns and the P columns at hummocks, with the P columns evaporating over 50% more than the LBP columns. This suggests that the combined bryophyte and litter layers creates a barrier effect on ground surface evaporation, as noted by Farrick and Price (2009). This barrier effect may be attributed to the very thin bryophyte layer ($\sim 0.5 \text{ cm}$) compared to the thicker litter layer ($\sim 5 \text{ cm}$) at the study site.

Surprisingly, microform did not directly affect the evaporation rate in this study, which can be partly explained by the observed pattern of soil temperature and the biomass of bryophytes and litter between hummocks and hollows. Since no significant differences were found in soil temperature at the same depth, or in the biomass of bryophytes and litter between hummocks and hollows, it is unsurprising that no significant differences in evaporation were observed between hummocks and hollows under the same ground cover type. Moreover, though soil VWC between hummocks and hollows was not measured, occasionally measurements of water table depths near the experimental quadrats showed that they were far below 0.5 m from the peat surface during the experimental period, indicating only modest variation in soil VWC between microforms from surface to the depth of 15 cm.

However, it needs clarification that microform is still an essential element influencing peatland ground surface evaporation. This study reveals that microform influences peatland evaporation through three indirect ways: interacting with ground cover type (Table A3), modifying the vertical profile of soil temperature (and probably soil moisture), and changing the key environmental drivers of evaporation. The potential explanations of the three indirect effects of microforms are provided below. Firstly, the interactions between microforms and ground covers can be explained by the previous studies which found that bryophyte species differ between hummocks and hollows (McCarter and Price, 2014; Robroek et al., 2006). Hummock species generally have higher water retention capacity, capitula densities and pore connectivity than hollow species (Hayward and Clymo, 1997; McCarter and Price, 2014). These characteristics enable hummock species to exchange vapor more efficiently under wet conditions and resist desiccation more efficiently under dry conditions. Similarly, the composition and thickness of litter may vary between microforms, which affects the exchange of heat and water vapor between peatland and atmosphere. But there is a paucity of evidence on this, and more research is needed. Secondly, microforms affect the vertical profile of soil temperature can be observed by the significant higher T_{soil} at 40 cm depth in hummocks than hollows, though no significant differences in temperature were detected in the shallower peat layers. This indicates potential influences of microforms on energy partitioning and ground

heat fluxes. Similar effects have been observed by Kettridge and Waddington (2014) and Thompson et al. (2015) in which they demonstrated differences in surface temperature and energy exchange in peat cores from hummocks and hollows under unburnt and burnt treatments. Thirdly, in contrast to the correlations between environmental factors and evaporation at hummocks, evaporation in hollows responded less sensitively to soil temperature at multiple depths, and was correlated with precipitation. This is probably due to the differences in energy fluxes caused by microforms as explained above, as well as the influence of peatland lateral flow paths on moisture available for evaporation, since hollows are often occupied by water pools (Whitfield et al., 2009).

Clearly, there is fine-spatial variations in peatland evaporation caused by bryophytes, litter, and microforms, but the key question is whether these variations matter. The most proper answer would be that it likely depends on the nature of the site. Based on this study, such small variations would not significantly bias the estimation of evaporation of the entire peatland. However, this may be due to the characteristics of the study site, which has a very thin bryophyte layer, an even distribution of bryophytes and litter among microforms, and relatively small microform features, with the maximum elevation difference between sampled hummocks and hollows within the same quadrat being only about 10 cm. Similar to litter, a thicker moss layer can exert strong control over water and heat fluxes beneath it (Blok et al., 2011; Park et al., 2018). For peatlands with larger microform features and uneven mosses, litter, and vegetation between hummocks and hollows, it is essential to account for spatial variation in evaporation.

2.4.2 Modelling peatland ground evaporation at the scale of the local microtopography

Accurately capturing variations in evaporation between hummocks and hollows relies on two important variables, surface temperature and resistance. The former is associated with the energy balance and the latter is determined by boundary layer conditions (Oke, 2002). For the P columns, resistance includes the aerodynamic resistance, which describes the friction from

air flowing over a rough surface, and surface resistance, which quantifies the resistance to water vapor movement through the peat surface (Allen et al., 1998). More specifically, the surface resistance of the P columns can be indicated by near-surface tension (Kettridge et al., 2021). For the BP columns, surface resistance is also determined by the size and structural properties of the bryophyte canopy (e.g., organ shape and diameter) (Rice and Schneider, 2004). The LBP columns' surface resistance further incorporates litter resistance, which can be modelled using parameters such as litter area index, litter layer depth, molecular diffusion through the litter layer and litter moisture level (Ogée and Brunet, 2002; Sakaguchi and Zeng, 2009). When surface temperature and the parameters for calculating resistance are accurately measured or quantified for various microforms, there is no doubt that evaporation models can capture the fine-spatial variations in evaporation caused by microforms.

However, there are no direct measurements for surface temperature and resistance, and the acquisition of field data like surface tension or certain parameters for ground covers and underlying soils can be challenging (Becker and Li, 1995; Kettridge et al., 2021). As a result, there is often insufficient field data to accurately parameterize or calibrate models (Dixon et al., 2017). Additionally, there is often a trade-off between remaining the simplicity of a model and improving its predictive capability by incorporating more detailed processes. Therefore, the key question is whether simple field measurements and simple models are able to provide satisfactory predictions of peatland ground surface evaporation that varies with ground covers and microforms. The results from this study show that both a simple model, like the P-M model, and a more complex model, such as the APES model, are able to provide satisfactory predictions of ground surface evaporation under various microforms or ground covers, based on easy field measurements of soil temperature and moisture. In general, the P-M model provided the best performance for modelling the evaporation of the LBP columns at both hummocks and hollows, while the P-M_APES model was most effective for the BP columns at hummocks, and the APES model was optimal for the BP columns at hollows. The larger error of the P-M model in predicting evaporations of the P and BP columns may be associated with the amount of soil in the MLs. As shown in Figure 2-1, the P and BP columns were not

filled to the top of the MLs, due to the consideration of the structure of the sample remaining undisturbed when applying the treatments. Adding more peat into the MLs would potentially alter the structure of the samples. As a result, surface resistance may have been affected by the PVC pipes, which was not reflected in the model. Further, it was assumed that peat properties, bryophytes, and litter were the same between hummocks and hollows, likely leading to large uncertainties in the modelling results. Additionally, the biases in the APES model are likely due to inaccuracies in estimating both the temperature and property parameters for the peat and bryophyte layers. Nevertheless, this study suggests that the fine-spatial variations in peatland ground surface evaporation resulting from bryophytes, litter and microforms can still be satisfactorily captured by evaporation models with simple field measurements on soil temperature and water content.

This work demonstrates the effects of bryophytes, litter and microforms on peatland ground surface evaporation and examines the performance of different models in capturing fine-spatial variations in evaporation, which can help to improve assessments of the impacts of disturbances on peatland ecosystems. Based on the IPCC 2019 special report, peatland disturbances including drainage for agriculture, peat extraction, burning, and overgrazing, etc., are the main drivers of accelerated peatland degradation (Jia et al., 2019). Since evaporation generally dominates the post-disturbance ET in peatlands, accurately modelling evaporation is essential for evaluating the hydrological state of post-disturbance peatland ecosystems and predicting future carbon budgets.

2.5 Conclusions

This study examined the effects of microforms on the evaporation of peat, peat-bryophyte, peat-litter, and peat-bryophyte-litter columns in a montane fen in the Canadian Rocky Mountain by conducting six rounds of on-site micro-lysimeter experiments during the growing season of 2021. The results demonstrate that evaporation is significantly influenced by ground cover type and the interaction effect between ground cover and microform. While differences between hummocks and hollows in terms of the evaporation of peat, peat-bryophyte, peat-litter,

and peat-bryophyte-litter columns, as well as soil temperature at the same depth and the biomass of bryophytes and litter, were not significant, fine-scale spatial variation remains an important factor that should not be neglected when estimating peatland water fluxes at the scale of the local microtopography. Although microform did not directly impact ground surface evaporation in this study, it indirectly affected evaporation by interacting with ground cover type, modifying the vertical profile of soil temperature, and changing key environmental drivers of evaporation. Both the simple P-M model and the more complex APES model captured this fine-scale variation using field measurements of soil temperature and moisture. The findings from this study help improve the accuracy of evapotranspiration estimates for assessing the hydrological conditions of peatlands.

2.6 Acknowledgements

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Chapter 3

The dependence of evaporative efficiency of vegetated surfaces on ground cover mass fractions in vegetated soils in mesic ecosystems

3.1 Introduction

Evapotranspiration (ET) is defined as the total water flux to the atmosphere from terrestrial ecosystems, including transpiration (T) from plants and direct evaporation (E) from surfaces of bare soil, open water, ground cover (e.g., moss and litter), and canopy. Notably, ET is a key component of the global water cycle, yet it is difficult to estimate due to limited site observations, measurement errors and uncertainties in upscaling approaches (Pascolini-Campbell et al., 2021). Consequently, poor parameterization of ET reduces the effectiveness of land surface models (LSMs) in supporting water resources management and predicting climate change impacts from local to global scales. In response to these challenges, efforts to better constrain ET in these models—such as quantifying the relative contributions of E and T to ET through various partitioning methods (Stoy et al., 2019)—have been made. However, these efforts have had limited success, with high uncertainties in the global T/ET ratio ranging from 0.35 to 0.90 (Coenders-Gerrits et al., 2014; Fatichi and Pappas, 2017; Jasechko et al., 2013; Schlesinger and Jasechko, 2014; Wei et al., 2017). This suggests that further efforts are needed to better understand the pathways and mechanisms that control T and E fluxes.

High uncertainties in ET estimates partly stem from biases in modelling evaporation. For example, Sakaguchi and Zeng (2009) concluded that unrealistic ET partitioning in the National Center for Atmospheric Research (NCAR) Community Land Model Version 3.0 (CLM 3) was due to overestimated evaporation from soil and canopy surfaces. Such overestimation was attributed to problematic representations of soil resistance over litter-covered soils and below canopy wet soils (Sakaguchi and Zeng, 2009). Similarly, these issues persisted in CLM 4 (Tang and Riley, 2013), highlighting the need for further improvements in these formulations. In contrast to the extensive research on bare soil evaporation (An et al., 2018; Flumignan et al.,

2012; Lehmann et al., 2018; Merlin et al., 2011; Shimojima et al., 1996; Wilson et al., 1994; Yang and Yanful, 2002), the understanding of non-bare soil evaporation remains limited, particularly regarding soil evaporation under various ground covers (e.g., moss and litter) and below canopies with altered microclimates (Kool et al., 2014). Given that surface evaporation contributes around 19% of global ET (Zheng et al., 2022), with approximately 7% coming from bare soil evaporation (Miralles et al., 2011), it is estimated that roughly 12% is contributed by non-bare soil evaporation. The high contribution of evaporation from non-bare soils underscores the need for a better representation of non-bare soil evaporation in models to improve the accuracy of ET estimates.

Evaporation from vegetated surfaces describes the transfer of water vapor across multi-layer soil-atmosphere interface, generally including layers like soil, bryophyte, litter, and canopy of vascular or woody plants. To begin with, soil (e.g., mineral soil or peat), as the substrate of the soil-atmosphere column, influences vertical thermal and pressure gradients, as well as the amount of moisture available for evaporation, through its thermal-hydro-mechanical characteristics (An et al., 2018; Flumignan et al., 2012; Shimojima et al., 1996; Wilson et al., 1994; Yang and Yanful, 2002). Above the soil, bryophytes, often consist of an assemblage of *Sphagnum*, mosses, liverworts, hornworts and other shade-tolerant terrestrial species (Thielen et al., 2021; Vitt and House, 2021), occupy the next layer. Unlike vascular plants, *Sphagnum* and some other mosses cannot actively regulate their water content; instead, they rely on their structure and physiological traits to transport water to their capitula (where photosynthesis occurs). This vertical water transport occurs primarily through capillary action (Goetz and Price, 2015; Hayward and Clymo, 1982; McCarter and Price, 2014; Rice and Schneider, 2004; Thielen et al., 2021). Further up, litter and the plant canopy above the bryophyte layer generally serve as barriers, intercepting precipitation and solar radiation, and decoupling the moisture content and energy balance of the underlying layers from the atmosphere (Campbell and Williamson, 1997; Farrick and Price, 2009; Kettridge et al., 2013b; Petrone et al., 2001; Putuhena and Cordery, 1996; Rouse, 2000; Thompson et al., 1999). Nevertheless, these layers

have not been well-incorporated into LSMs (Sakaguchi and Zeng, 2009), and there is a paucity of direct field measurements to support model validation.

To date, a few LSMs have developed modules to account for the effects of bryophytes (e.g., Atmosphere-Plant Exchange Simulator (APES) and Canadian Land Surface Scheme Canadian Land model (CLASS)), litter (e.g., Soil-Vegetation-Atmosphere Transfer (SVAT) and CLM), and overstory canopy (e.g., CLM and Boreal Ecohydrology Tree Algorithm (BETA)) (Enrique et al., 1999; Kettridge et al., 2013b; Launiainen et al., 2015; Sakaguchi and Zeng, 2009; Wu et al., 2016). However, these modules require site-specific parameters such as the hydrophysical and thermal properties of the soil layers (Enrique et al., 1999; Launiainen et al., 2015; Ogée and Brunet, 2002; Souza et al., 2022); micrometeorological conditions to lump the entire soil and canopy layers together to determine bulk resistance to vapor transfer, or treating the bryophyte layer as a porous medium for water flow (Kettridge et al., 2013b; McCarter and Price, 2014; Price et al., 2009; Sakaguchi and Zeng, 2009; Weber et al., 2017).

A meta-study on modelling efforts of bare soil evaporative efficiency (SEE, the ratio of actual evaporation (E_a) to the potential evaporation (E_0)) by Merlin et al. (2016) showed a significant correlation between the critical soil moisture $\theta_{1/2}$ (i.e., the soil water content when SEE is 0.5) and soil texture (i.e., sand and clay fractions) across the world. Building on this finding, they incorporated this relationship into a new model that significantly outperformed the evaporation modules of major LSMs (Merlin et al., 2016). Additionally, they suggested that the model could be applied to soils partially covered by mulch, crop residue, or sparse vegetation (Merlin et al., 2016). The underlying explanation for this correlation lies in the dominance of capillary flow resistance in surface resistance in the Stage I evaporation (i.e., the plane of phase change is mostly at the ground surface, including the transition between Stage I and II), with capillary flow resistance being determined by soil textures (Lehmann et al., 2018). Similarly, since water absorption by mosses mainly takes place through external capillaries (i.e., the gaps between neighboring shoots, leaves, leaves and stems, leaves and rhizoids), as well as internal conduction systems (Giordano et al., 1993; Goetz and Price, 2015; McCarter and Price, 2014; Rice and Schneider, 2004; Thielen et al., 2021), it is hypothesized

that a similar relationship exists between $\theta_{1/2}$ and moss mass fraction (i.e., the proportion of the dry weight of mosses relative to the total weight of vegetated soil column) across moss-covered sites. This is because mosses form a unique layer in vegetated surfaces, and their mass fraction can thus be regarded as a parameter indicating the texture of the vegetated soil evaporative column. In contrast, litter may not effectively control water movement through capillary action depending on the material, as wider gaps can exist among different litter materials (Guevara-Escobar et al., 2007). However, Sato et al. (2004) found that the litter layer's maximum water storage capacity was directly proportional to its mass. Moreover, the litter layer resistance has been modelled using the litter effective leaf area index (Sakaguchi and Zeng, 2009), a parameter closely correlated with biomass. This evidence further indicates that a similar relationship may exist between $\theta_{1/2}$ and litter mass fraction as well. As for the canopy, it not only alters the microclimate and water input (through interception), but also influences the stability of the thermal structure under the canopy, depending on the thickness of the canopy layer (Niu and Yang, 2004; Sakaguchi and Zeng, 2009). As a result, the relative magnitudes of aerodynamic resistance and surface resistance may be altered. Given this context, the paper aims to test whether the correlation between $\theta_{1/2}$ and texture parameters could be adapted to vegetated surface conditions across a range of soil types and ground cover types, with and without the presence of an overstory canopy. Specifically, this study will: (1) examine if a correlation exists between $\theta_{1/2}$ and vegetated soil texture parameters (i.e., ground cover mass fractions) under open and closed canopy conditions; and if so, (2) develop a SEE model for vegetated surfaces by incorporating this relationship.

3.2 Study sites and methods

3.2.1 The evaporative efficiency theory and models

Soil evaporation efficiency (SEE or β) is the ratio of actual soil evaporation (E_a) to potential evaporation (E_0). While SEE typically refers to the evaporation efficiency of bare soil, in this study, SEE is applied to denote the evaporation efficiency of ground surfaces covered by bryophytes and litter as well. Early research established that SEE can be represented by

analytical functions of surface soil moisture over a range of soil textures, with the shape of the functions affected by soil textures, thickness and atmosphere conditions (Chanzy and Bruckler, 1993; Komatsu, 2003; Kondo et al., 1990; Merlin et al., 2011; Philip, 1957). The general form of the SEE functions that accounts for soil thickness, texture and evaporation demand is provided in Merlin et al. (2011).

Table 3-1 lists the SEE models that will be used in this study along with their major formulations. Models like S92, S & M 92, K03 and M11 are applicable under both moisture-driven and energy-driven conditions. In moisture-driven conditions (also referred to as moisture-limited conditions), soil moisture, rather than evaporative demand, is the limiting factor for evaporation. In contrast, in energy-driven conditions (also referred to as energy-limited conditions), evaporation is limited by evaporative demand, such as when the available energy for evaporation is low. According to M11, moisture-driven conditions are defined when the parameter P in Eq. T4 exceeds 0.5, while energy-driven conditions occur when P is below 0.5 (Merlin et al., 2011).

Table 3-1. A list of the bare soil evaporative efficiency (SEE) models and their formulations.

Model	Key Formulations	References
S92	$r_s = \exp[A - (B\theta/\theta_{sat})] \quad (\text{Eq. T1})$ $SEE = \frac{r_{ah}}{r_{ah} + r_s} \quad (\text{Eq. T2})$ with r_s, being the surface resistance ($s\ m^{-1}$), θ being the soil water content at the measured depth (-), θ_{sat} being the saturated soil water content (-), r_{ah} being the aerodynamic resistance that accounts for natural convection ($s\ m^{-1}$), and A and B being the best-fit parameters (-). S92 used the default value as $A=8.206$, and $B=4.255$.	Sellers et al. (1992)
S & M 92	Same formulations with S92.	Sellers et al. (1992) and Merlin et al. (2011)

	Parameter A and B are calibrated for each treatment at each site, following the procedure in Merlin et al. (2011).	
K03	$SEE = 1 - \exp\left(\frac{-\theta}{\theta_c}\right) \quad (\text{Eq. T3})$ with θ_c being a semiempirical parameter that depends on site conditions (-). θ_c was calibrated by substituting θ with $\theta_{1/2}$ at $SEE=0.5$ in Eq. 3 for each treatment at each site.	Komatsu (2003)
M11	$SEE = \left[\frac{1}{2} - \frac{1}{2} \cos\left(\pi \frac{\theta}{\theta_{sat}}\right)\right]^P \quad (\text{Eq. T4})$ with P being a parameter accounting for the soil thickness and evaporative demand (-). The equation was used when $\theta < \theta_{sat}$. P was calibrated by actual SEE for each treatment at each site following Merlin et al. (2011).	Merlin et al. (2011)
M16	$SEE = \frac{e_s(T_s) - e_a}{e_s(T_{s,wet}) - e_a} \times \frac{r_{ah,wet}}{r_s + r_{ah}} \quad (\text{Eq. T5})$ $r_s = r_{s,ref} \exp\left(-\frac{\theta}{\theta_{efolding}}\right) \quad (\text{Eq. T6})$ where T_s is the soil surface temperature (K); $e_s(T_s)$ is the saturated vapor pressure at the soil surface (Pa); e_a is the vapor pressure of air (Pa); $T_{s,wet}$ and $e_s(T_{s,wet})$ is the soil temperature (K) and saturated vapor pressure (Pa) at water-saturated soil surface (corresponding to $r_s=0$), respectively; $r_{ah,wet}$ is the associated aerodynamic resistance at T_s, wet ($s\ m^{-1}$); $r_{s,ref}$ ($s\ m^{-1}$) is the reference surface resistance (the asymptotic value of r_s for soil water content θ (%) around 0, and $\theta_{efolding}$ is the soil water content (%) at which $r_s=r_{s,ref}/e$. $r_{s,ref}$ and $\theta_{efolding}$ were determined based on $\theta_{1/2}$ and the slope of SEE at $\theta_{1/2}$ (denoted as $slope_{1/2}$). And the rest of parameters were determined by meteorological measurements at each site and by running a soil energy balance model as demonstrated in Merlin et al. (2016).	Merlin et al. (2016)

However, M16 is restricted to moisture-driven conditions. The reason this model is restricted to moisture-driven conditions can be explained as follows. According to the general form of the SEE function (i.e., M11), a sharp change in slope occurs at $SEE=0.5$ (Lehmann et al., 2018; Merlin et al., 2016). The soil water content when SEE is 0.5 is thus called the cut-off soil water content ($\theta_{1/2}$). Under moisture-driven conditions, though SEE, as a function of soil moisture, is nonlinear, it approaches linearity around its mid-value. Therefore, both $\theta_{1/2}$ and the slope at $\theta_{1/2}$ (denoted as $slope_{1/2}$) can be linearly approximated based on measured SEE and soil moisture near this midpoint (Merlin et al., 2016). Once $\theta_{1/2}$ and $slope_{1/2}$ are determined, they can be used to estimate SEE as soil moisture changes. This is how M16 predicts SEE (Merlin et al., 2016). The linear approximation of $\theta_{1/2}$ and the slope at $\theta_{1/2}$ is more accurate when soil moisture is the primary limiting factor for evaporation. That is, M16's performance improves as the parameter P increases (Merlin et al., 2011; Merlin et al., 2016).

Recently, Merlin et al. (2016) examined data from more than 30 bare soil sites worldwide and discovered a significant linear correlation between $\theta_{1/2}$ and the fractions of sand and clay in soil. Such relationship is explained by the effects of soil texture on capillary flow resistance, a dominant factor in surface resistance during Stage I evaporation and the transition between Stage I and II (Lehmann et al., 2018). Merlin et al. (2016) further found that in M16, using $\theta_{1/2}$ derived from the clay and sand fractions to model evaporation yielded better results than the evaporation modules of the major LSMs, such as ISBA (Interaction Sol-Biosphère-Atmosphère), H-TESSEL (Hydrology-Tiled ECMWF Scheme for Surface Exchange over Land), and CLM (Community Land Model). Considering $\theta_{1/2}$'s strong correlation with soil texture parameters and its important role in estimating evaporation, $\theta_{1/2}$ is referred to as the critical soil water content (Lehmann et al., 2018).

Despite the different forms of analytical functions and the specific conditions under which they should be applied, SEE models effectively predict SEE in response to changes in soil moisture. This makes them particularly valuable for estimating actual evaporation, as potential evaporation can be calculated from meteorological data.

3.2.2 Study sites

The three study sites represent common mesic ecosystems in the Canadian Rocky Mountains (Figure 3-1). Specifically, these sites include a montane fen (Sibbald), a sub-alpine marsh (Burstall), and a sub-alpine wet meadow (Bonsai). The sites are classified based on the Alberta Wetland Classification System (Alberta Environment and Sustainable Resource Development (ESRD), 2015).

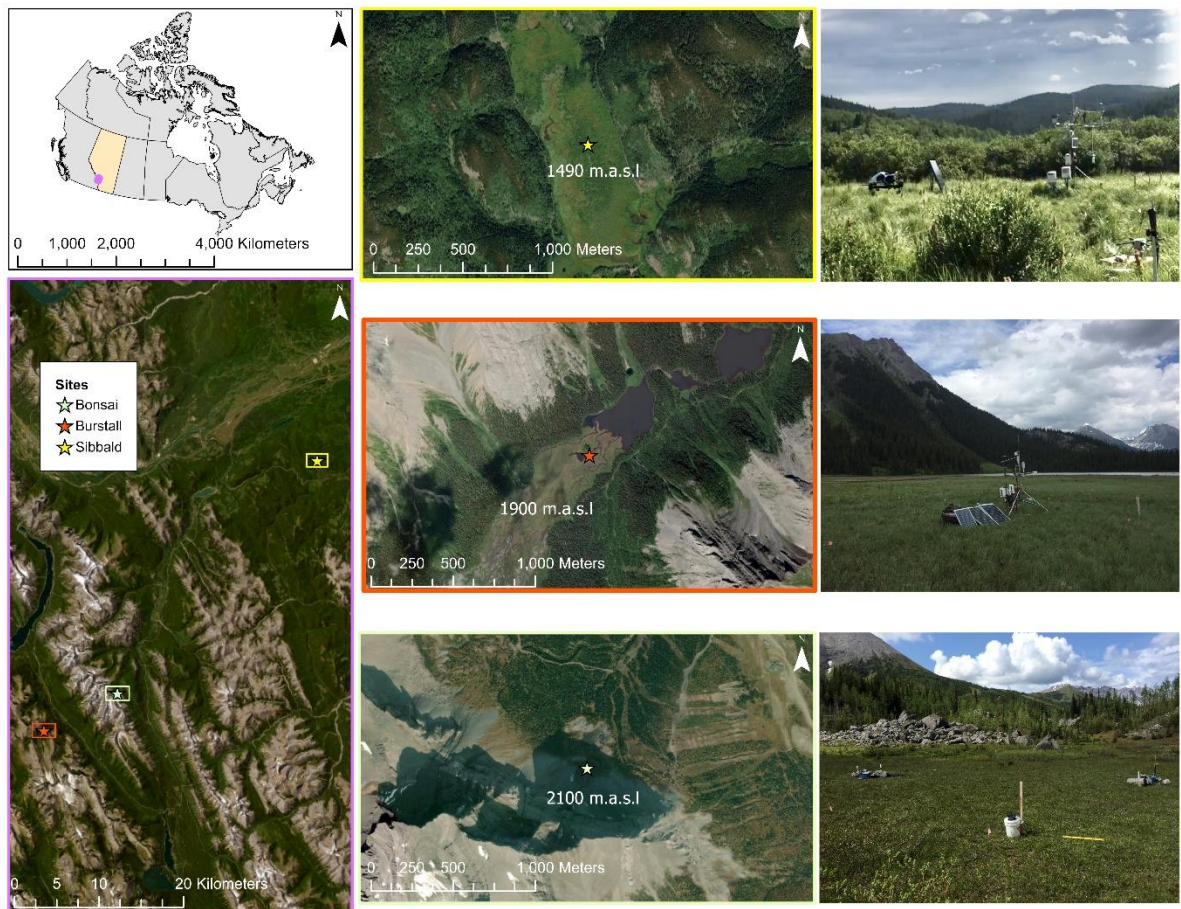


Figure 3-1. Map of the three study sites in Canadian Rocky Mountains. Top Left: Inset showing location within Alberta, Bottom Left: Site locations within the Rocky Mountains. Middle Top: Sibbald Fen, Middle Middle: Burstall Wetland. Middle Bottom: Bonsai Meadow. Right Top, ground cover at Sibbald, Right Middle: ground cover at Burstall. Right Bottom: ground cover at Bonsai.

Sibbald Fen (51.06°N, 114.87°W), with a mean elevation of 1490 m a.s.l. and a surface area of 9.3 km², is located in the foothills of the Canadian Rocky Mountains in Kananaskis country. The fen is south facing and features distinct hummocks and hollows. According to data from the nearest climate station (Environment Canada ID: 3053600; ~1,391 m a.s.l.), approximately 10 km west from the site, the mean air temperature from 1981 to 2010 is 3.6 °C, with a mean annual precipitation of 639.4 mm. Approximately one-third of the precipitation occurs during the growing season (June to August). In terms of vegetation, the dominant species consists of sedges (*Carex. spp.*) and willows (*Salix spp.*), with a very thick layer of sedge litter present above ground. Below this litter layer, the moss layer is thin, and contains diverse species including *Aulacomnium palustre* (Hedw.) Schwaegr., *Bryum pseudotriquetrum* (Hedw.) Gaertn. et. al., *Calliergon giganteum* (Schimp.) Kindb., *Calliergon richardsonii* (Mitt.) Kindb. in Warnst., *Campylium stellatum* (Hedw.) C. Jens., *Hypnum lindbergii* (Mitt.), *Plagiomnium ellipticum* (Brid.) T. Kop., *Pohlia nutans* (Hedw.) Lindb., and *Warnstorfia fluitans* (Hedw.) Loeske (Lei, 2021). Specifically, the average bryophyte layer measures around 5 mm, while the litter layer is around 5 cm thick. Additionally, the upper 0.5 m of peat is primarily composed of decomposing sedge (Wang et al., 2016). Beneath the peat layer, the soil is characterized as alluvium (sandy gravel and boulders) and black shale of marine origin, as shown in the 1971 Alberta water well drilling report (GIC Well ID 404614)). For further details, more site information can be found in Wang and Petrone (2022).

Burstall Marsh (50.78°N, 115.34°W), with a mean elevation of 1900 m a.s.l. and a surface area of 0.4 km², is situated at mid-elevations in the Spray River valley in Kananaskis country. According to the data from the nearest long-term climate station (ID: 3053604, ~1,610 m a.s.l., 1981-2010, 19 km away), the mean annual temperature is 1.1°C, with a mean annual precipitation of 568 mm. Notably, approximately one third of precipitation occurs in the growing season (June to August). In terms of vegetation, the dominant plants are sedges (*Carex. spp.*) and willows (*Salix spp.*), with relatively thick sedge litter present above ground. Moreover, the wetland is quite flat, featuring a living moss layer composed of peat moss (*Sphagnum spp.*) and feather moss (*Eurhynchium spp.*) above the soil surface. The average

thickness of the bryophyte layer and the litter layer is around 1 cm and 5 cm, respectively. Additionally, the upper 0.2 m of soil consists of *Sphagnum*-decomposed peat. Beneath the peat layer, soil is characterized as grey luvisols (Natural Regions and Subregions of Alberta, 1994, Alberta Environmental Protection). For further details, more site information can be found in Hathaway et al. (2022).

Bonsai Meadow (50.82°N, 115.21°W) is located beneath the headwall of Fortress Mountain in Kananaskis country, where its mean elevation is 2,100 m a.s.l., and surface area is 0.01 km². The wetland is mostly flat, with only a 3 m change in elevation. According to data from the nearest long-term climate station (ID: 305MGFF, ~2,543 m), at a distance of 13.7 km, the mean temperature from 2011 to 2021 is -1.2 °C. Although no long-term precipitation record was found, the mean temperature and rainfall measured during June to August in 2018 at the site were 9 °C and 339 mm, respectively (Hrach et al., 2021a). In terms of vegetation, there are two distinct groups: sparsely distributed overstory species (e.g, *Salix* spp., *Larix* spp., and *Abies* spp.) and abundant understory species, including *Erigeron* spp., *parnassia* spp., and *Equisetum* spp. (Chau, 2023; Hrach et al., 2021a). The average height is around 0.8 m for the overstory canopy and 0.1 m for the understory canopy. Below the understory canopy, litter composed of decomposed leaves and branches from the above-mentioned vegetation is highly mixed with the top layer of the soil (~2 cm). Furthermore, brown moss (*Tetradontium* spp.) can sometimes be found near the headwall or at the center of the meadow, but is very thick (~ 5 mm) in the riparian area where streams flow through the meadow into a seasonal ephemeral tarn. Near the stream, there is a thin layer of sand above a semi-pervious layer of very fine silt, while at the center of the meadow, soils are primarily defined by silt and clay (Christensen, 2017). For further details, more site information can be found in Hrach et al. (2021a).

3.2.3 Experimental design

The evaporation experiment was conducted in July and August of 2021, during which time each site underwent six rounds of measurements (Table B1). As illustrated in Figure 3-2. In each experiment, the experimental design included six quadrats that were randomly distributed

at each study site. Specifically, three quadrats were located under the canopy of willow trees while the other three were directly exposed to sun.

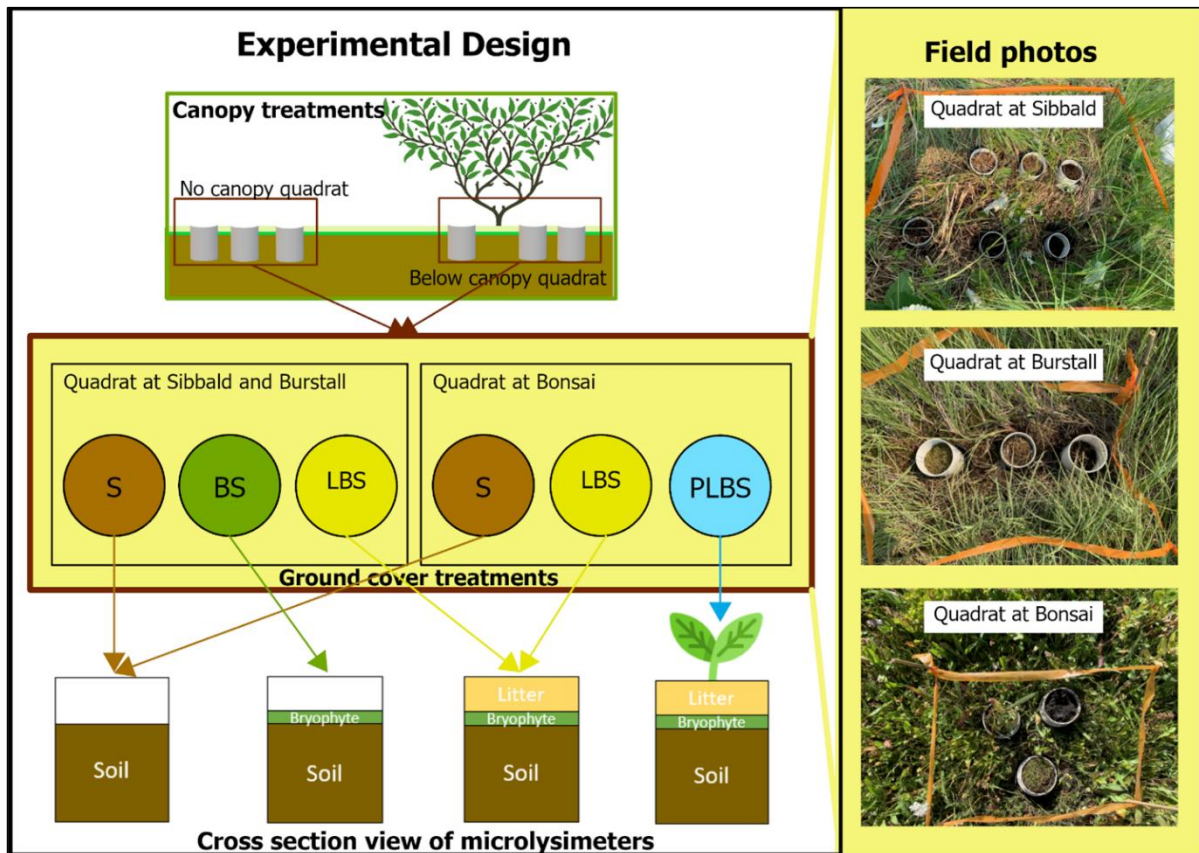


Figure 3-2. Illustration of experimental design. At each site, there were two levels of canopy treatments: no canopy (NC) and below canopy (BC). Each canopy treatment contained three quadrats, and each quadrat included three micro-lysimeters (MLs) in Burstall and Bonsai, while Sibbald had six MLs. Different ground cover treatments: bare soil (S), soil covered by bryophytes (BS), soil covered by both bryophytes and litter (LBS), and soil covered by bryophytes, litter and ground vascular vegetation (PLBS) were randomly assigned to each ML at each quadrat, varying by study site.

The ground cover treatments differed at each site (Figure 3-2). Micro-lysimeters (MLs) were installed at all three sites. The MLs at Sibbald and Burstall were 10 cm in diameter and 15 cm in depth, while the Bonsai MLs were 10 cm in diameter and 7.5 cm in depth due to the very

thin soil layer. All MLs were constructed from 4-inch $\times$ 10-ft PVC pipes (IPEX model # 003245), following the procedure described by Flumignan et al. (2012). At Sibbald, six MLs were installed, three in hummocks and three in hollows within each quadrat. In terms of treatments, two levels were applied: soil (S) and soil-bryophyte (BS), along with one control (i.e., soil-bryophytes-litter (LBS)). These were randomly assigned to three MLs in hummocks and the other three MLs in hollows within each quadrat. Notably, measured soil temperature and evaporation from the hummock and hollow of the same treatment in the same quadrat were averaged at Sibbald to avoid unnecessary complexity of the impacts of microforms on evaporation. In addition, the effects of microforms on evaporation processes at Sibbald were examined and presented in the previous Chapter (Wang and Petrone, 2022). In contrast, Burstall and Bonsai have no apparent microform features, so only three MLs were installed in each quadrat. Burstall had the same ground cover treatments as Sibbald (i.e., S, BS and LBS). Bonsai had a third treatment added due to the highly mixed bryophytes and litter at the surface, along with dense ground vascular vegetation. To account for this complexity, the soil-bryophytes-litter-ground vascular vegetation (PLBS) was added in addition to the S and LBS treatments.

Ground vascular vegetation (i.e., understory vascular vegetation) was included in the evaporation experiment at Bonsai because it is abundant and forms a distinct layer in the soil-atmosphere evaporative column. More importantly, most of the vascular plants in the MLs were found dead during the experimental period, so the contribution of transpiration from these plants to the overall water loss in the MLs was assumed to be negligible. However, it should be clarified that the total water loss from the PLBS group is likely to be ET rather than E. Nevertheless, for the sake of consistency, E is still used to denote ET from this group.

3.2.4 Measuring non-canopy and below-canopy microclimate conditions

Meteorological variables measured at each site included net radiation (R_n , $W\ m^{-2}$), air temperature (T_a , $^{\circ}C$), air relative humidity (RH_a , %), wind speed (u , $m\ s^{-1}$) and precipitation. The measurement heights for R_n , T_a , RH_a and u were 3 m at both Sibbald and Bonsai, and 2 m

at Burstall. Specifically, R_n was measured using an NR-Lite2 (Kipp Zonen: Delft, Netherlands), T_a and RH_a were measured using an HMP-155 T/RH probe (Vaisala: Helsinki, Finland), and u was measured using an R.M. Young 05103 propeller anemometer (R.M. Young: Traverse City, Michigan, USA). Precipitation was measured at 3 m at Sibbald using a TR-525I tipping bucket rain gauge (Texas Electronics: Dallas, USA), at 2 m at Burstall using a RG3-M HOBO rain gauge with a M-RSA solar radiation shield (Onset Computer Corp.: Massachusetts, USA), and 2.5 m at Bonsai using an OTT Pluvio² precipitation gauge with an alter shield (OTT HydroMet: Kempen, Germany). In addition to these meteorological variables, other environmental variables were continuously monitored, including soil heat flux ($W\ m^{-2}$), soil temperature (T_{soil} , °C) and soil volumetric water content (Soil VWC). Soil heat flux was measured at each site using HFP01 soil heat flux plates (HukseFlux: Delft, Netherlands) placed 6 cm below the surface. T_{soil} was measured using Type E Thermocouples (Omega Engineering: Connecticut, USA) at depths of 15 cm and 30 cm at Sibbald, at 5 cm, 10 cm, and 15 cm at Burstall, and at 5 cm and 10 cm at Bonsai. Soil VWC was measured using ECH2O EC-5 sensors (Meter Group, Hopkins, Washington, USA). At both Sibbald and Burstall, soil VWC sensors were inserted horizontally at 15 and 30 cm depths. In contrast, at Bonsai, two sensors were inserted vertically, covering the top 30 cm of soil depth. All variables were continuously monitored, with measurements taken every 30 seconds and averaged or summed into 30-minute intervals, recorded by a CR1000 datalogger (Campbell Scientific: Logan, Utah, USA).

In addition to the above measurements, T_a and RH_a were also logged every half hour using HOBO U23 Pro V2 temperature/relative humidity probes with plastic radiation shields (Onset: Bourne Massachusetts, USA) attached at each climate station at a height of around 1 m at each site. T_{soil} was also manually measured at depths of 5, 10, 20, 30 and 40 cm in each quadrat at Sibbald and Burstall, and at depths of 5 cm, 10 cm and 20 cm depths in each quadrat at Bonsai, using a handheld soil temperature sensor (Type K thermocouple, Omega Engineering: Connecticut, USA). Similarly, Soil VWC was manually measured in each quadrat for the S and PLBS groups at Bonsai, with probes inserted vertically to cover the top 30 cm-depth using a handheld CS-650 volumetric water content probe (Campbell Scientific: Utah, USA). These

measurements of T_{soil} and Soil VWC were recorded at both the beginning and the end of each round of the evaporation experiment (Table B1).

In order to account for the effect of the canopy on below-canopy microclimates, four to five HOBO U23 Pro V2 temperature/relative humidity probes with homemade plastic radiation shields (Onset: Bourne Massachusetts, USA) were attached to the branches of randomly selected willow trees. These probes were positioned just below the main willow canopy (approximately 0.5 m) at each site and measured below-canopy air temperature (T_{a_BC} , °C) and relative humidity (RH_{a_BC} , %) every 30 minutes throughout the study period. Additionally, photosynthetically active radiation (PAR, $\mu\text{mol of photons m}^{-2} \text{ s}^{-1}$) at ground level under NC and BC conditions in each quadrat was measured once or twice during each round at each site using a LI-COR Biosciences Quantum sensor (LI-190R) attached to the console of the LAI-2200C plant canopy analyzer (LiCor BioSciences, Lincoln, USA). Furthermore, leaf area index (LAI) was measured monthly at each site during the growing season of 2021 using the LAI-2200C plant canopy analyzer (LiCor BioSciences, Lincoln, USA).

All aforementioned devices and their measurement uncertainties are listed in Table B2.

3.2.5 Measurement of actual evaporation using micro-lysimeters (MLs)

The MLs have been tested and proven reliable for soil evaporation measurements under variable evaporative demands and precipitation conditions for up to four consecutive days without requiring reinstallation (Flumignan et al., 2012). It should be noted that the duration of the evaporation experiment for round #2 at Sibbald and round #4 at Bonsai was extended to 5 days (Table B1) due to a bear encounter that restricted access to the site. It is assumed that this impact was minimal because light rainfall during the period prevented the complete drying of the samples in the MLs.

Before installing the MLs at Sibbald and Burstall, vascular vegetation in each quadrat was removed by clipping the above-ground biomass. At all sites, the MLs, without caps, were inserted into the ground using light strokes with a mallet until the upper edge of the MLs was

level with the ground surface. After that, the MLs containing the sample columns were carefully extracted to avoid disturbing the structure of the samples and the remaining pits. The extracted MLs were sealed at the bottom with corresponding PVC pipe caps (IPEX model # 650580) with an inner diameter of 10 cm, ensuring no water could drain from the bottom. For MLs under S treatments, bryophytes, litter and plants were carefully removed, while for MLs under BS treatments, only litter or vascular plants were removed. The exterior of the MLs was cleaned with a dry cloth, and weighed using an electric laboratory balance (CGOLDENWALL; Max: 3,000 g; resolution: 0.01g) on-site. The balance was placed inside a 13 L transparent storage container to prevent turbulent air from affecting the weighing process. Before each measurement, the scale was leveled. After recording the initial weights (W_{before}), the MLs were placed back into where the column samples were extracted.

At each site, one round of measurements involved recording the weight of the MLs two days after installation, after which they were returned to the field for the remaining days until the soil columns were taken back to the lab (Table B1). For the other five rounds, the weights of MLs were measured only at the beginning and end of each round. The final weight of each ML was denoted as W_{after} . The evaporation (E_a , g d⁻¹) from the MLs was calculated as (Flumignan et al., 2012):

$$E_a = \frac{W_{\text{before}} - W_{\text{after}} + (\text{Precip} \times A_{\text{MLs}})}{\text{Time}} \quad (1)$$

where W_{before} and W_{after} are the weight of the ML samples at the beginning and end of each evaporation experiment (g), respectively; Precip is the precipitation input (cm); A_{MLs} is the cross-sectional area of the PVC pipes (cm²); and Time is the duration of each evaporation experiment (days).

Precipitation used in Eq. 1 for the below-canopy treatment was calculated by subtracting the rainfall interception from the total rainfall. The rainfall interception rate (%) was estimated using an empirical relationship with the leaf area index (LAI), which has been previously applied to estimate wetland vegetation (*Salix* spp.) (see Fr  dette et al. (2019)). This relationship

was originally developed by Martin and Stephens (2006) based on *Salix viminalis* L. trees. The precipitation for the below-canopy treatment was calculated as:

$$\text{Precip} = \text{Rainfall}(1 - (3.01\text{LAI} + 1.12)/100) \quad (2)$$

where Precip is the precipitation input (cm), rainfall is the total rainfall during each round of the evaporation experiment (cm), and LAI is the leaf area index, which was measured monthly throughout the growing season at each study site. It should be noted that Eq. 2 has not been tested at the study sites for this research, which introduces uncertainty into the below-canopy modelling results.

3.2.6 Quantification of ground cover mass fractions

After each evaporation experiment, samples under BS, LBS and PLBS categories were taken back to the lab at the University of Calgary Biogeoscience Institute to measure the dry weight of soil, bryophytes, litter, and living plant biomass. For the samples from Sibbald and Burstall, fresh leaves and roots were removed. Bryophytes, litter and plants were manually identified, sorted, and placed in 3-inch and 9-inch foil plates, respectively. These plates were then oven dried at 70 °C (Fisher SCI, Isotemp incubator 200 series) until their weights were constant (W_{constant}), a process that took approximately 72 hours. The weights were measured using an electric scale (Sartorius ENTRIS3231-ISUS; Max: 320 g; resolution:0.001 g). The dry weight of the biomass of bryophytes (W_B), litter (W_L) or ground vascular vegetation (W_P) was calculated as the difference between W_{constant} and the corresponding weight of the foil plate (W_{plate}), as follows:

$$W_k = W_{\text{constant}} - W_{\text{plate}} \quad (3)$$

where W_k is the dry weight of the ground cover biomass (g), with subscript k representing B for bryophyte, L for litter, and P for ground vascular vegetation, respectively. W_{constant} is the constant dry weight of the sample (g), and W_{plate} is the weight of the foil plate for each sample (g).

The mass fraction (f_k) of bryophyte, litter or ground vascular vegetation was calculated as follows:

$$f_k = \frac{W_k}{W_s + W_B + W_L + W_P} \quad (4)$$

where W_s is the dry weight of the soil, and subscript k corresponds to B, L and P for bryophytes, litter and ground vascular vegetation, respectively.

In the LBS category, some samples had no apparent bryophytes; therefore, these samples were reclassified as soil-litter (LS). However, LS was excluded from further analysis due to its very limited sample size (only 3), which was heavily influenced by the meteorological conditions of the sampling rounds. Additionally, measurements from hummocks and hollows within the same quadrat at Sibbald were averaged, to mitigate the impact of microtopography. This approach was essential, as previous research has demonstrated a significant interaction between ground cover and microform on both evaporation rates and the vertical temperature profile of the soil (Wang and Petrone, 2022). By averaging the measurements, the influence of microforms was effectively cancelled out, thereby allowing for a more accurate characterization of ground cover effects on soil properties. Consequently, across the three site sites, there were a total of four levels of ground cover type treatment (i =S, BS, LBS, PLBS), and two levels of canopy treatment (j =no canopy (NC) and below canopy of the willow trees (BC)), with three replicates for each treatment in each round of the experiment.

3.2.7 Deriving $\theta_{1/2}$ and $\text{slope}_{1/2}$ from linear regression

Assuming water evaporates freely from the surface (i.e., $r_s = 0$), E_0 (W m^{-2}) was calculated from the Penman–Monteith equation as (Monteith, 1965):

$$E_0 = \frac{\Delta(R_n - G) + \frac{\rho c_p \text{VPD}}{r_{ah}}}{\Delta + \gamma} \quad (5)$$

where ρ is the density of air (kg m^{-3}), c_p is the specific heat of air at constant pressure ($1,010 \text{ J kg}^{-1} \text{ } ^\circ\text{C}^{-1}$), r_{ah} is atmospheric resistance to water vapor transport (s m^{-1}), VPD is atmospheric

vapor pressure deficit (kPa), γ is the psychrometric constant (kPa °C⁻¹), and Δ is the slope of the relationship between saturation vapor pressure and temperature (kPa °C⁻¹).

The formulation of r_a (s m⁻¹) under the neutral condition is given by Allen et al. (1998), as:

$$r_a = \frac{\ln\left(\frac{z_u - d}{z_{om}}\right) \ln\left(\frac{z_u - d}{z_{oh}}\right)}{k^2 u} \quad (6)$$

where d is the zero-plane displacement height (m) which is 0 for bare soil, and 2/3 of the total ground cover thickness; z_{om} is the roughness length governing momentum transfer, being 0.005 m for bare soil (Merlin et al., 2011), and 0.123 of the total ground cover (Allen et al., 1998); and the roughness length governing transfer of heat and vapor, z_{oh} (m), is approximated by 0.1 z_{om} (Allen et al., 1998). A list of d , z_u , z_{om} and z_{oh} with respect to each ground cover treatment at each site was provided in Table B3.

To account for natural convection, the aerodynamic resistance r_{ah} (s m⁻¹) is calculated following Merlin et al. (2016), as:

$$r_{ah} = \frac{r_a}{(1 + R_i)^\eta} \quad (7)$$

$$R_i = \frac{\beta_{thermal} \times g z_u (T_s - T_a)}{T_a u^2} \quad (8)$$

where $\beta_{thermal}$ is the thermal expansion coefficient, set to 5 as used by Choudhury et al. (1986) and Merlin et al. (2011); g is the gravitational constant (9.8 m s⁻²), T_s is the surface soil temperature at 5 mm (K), which was linearly extrapolated by T_{soil} at various measuring depths at each site; T_a is the air temperature (K). In Eq. 7, the coefficient η is set to 0.75 under unstable conditions ($T_s > T_a$) and to 2 under stable conditions ($T_s < T_a$); u is the wind speed (m s⁻¹) and z_u is the height (m) at which the wind speed was measured.

Actual evaporation E_a (g d⁻¹) is then converted into the same unit with E_0 (W m⁻²), so that the SEE can be calculated as:

$$SEE_{i,j} = \frac{E_{a,i,j}}{E_{o,i,j}} \quad (9)$$

where the subscript i corresponds to ground cover treatments and the subscript j corresponds to canopy treatments.

It is worth mentioning that E_0 and r_{ah} exhibited variations between NC and BC conditions. Specifically, E_{0_NC} and r_{ah_NC} were determined using environmental variables measured in NC, whereas E_{0_BC} and r_{ah_BC} were calculated using environmental variables collected in BC or adjusted for BC based on the significant correlations observed between measurements in NC and BC. Furthermore, the microclimates, including T_{soil} at multiple depths, T_a , RH_a and PAR between NC and BC, are described in Appendix B (Section B). In addition, G was determined by the thermal conductivity of the soils at the respective site and the temperature differences between T_{soil} at the depth matching that of the MLs at the respective site. Exceptionally, R_{n_BC} was fixed to 33%, 54%, and 40% of R_{n_NC} for Sibbald, Burstall and Bonsai, respectively. This determination was based on PAR measurements between NC and BC (Appendix B (Section B)). However, a clear correlation between PAR readings under NC and BC at each site was not observed, and PAR interception displayed significant variation across measurement days. This variability can be attributed to differences in canopy structures, leaf orientations, willow tree angles, and solar radiation intensity. Due to the lack of additional information to establish a more precise relationship of R_n between NC and BC, the average PAR interception across all measurements was calculated as the R_n interception, assuming a linear correlation between R_n and PAR, as presented in Singh et al. (2012). It is acknowledged that calculating R_{n_BC} in this manner may introduce uncertainty.

The slope $_{1/2\_i,j}$ was derived from the linear regressions using the observed $\theta_{i,j}$ and $SEE_{i,j}$. Additionally, $\theta_{1/2\_i,j}$ was calculated from the linear regression at the point where $SEE_{i,j}$ equals 0.5. Further details regarding the evaporation experiments and the data processing procedures are provided in Appendix B.

3.3 Results and Discussions

3.3.1 Correlation between critical soil water content and ground cover mass fractions

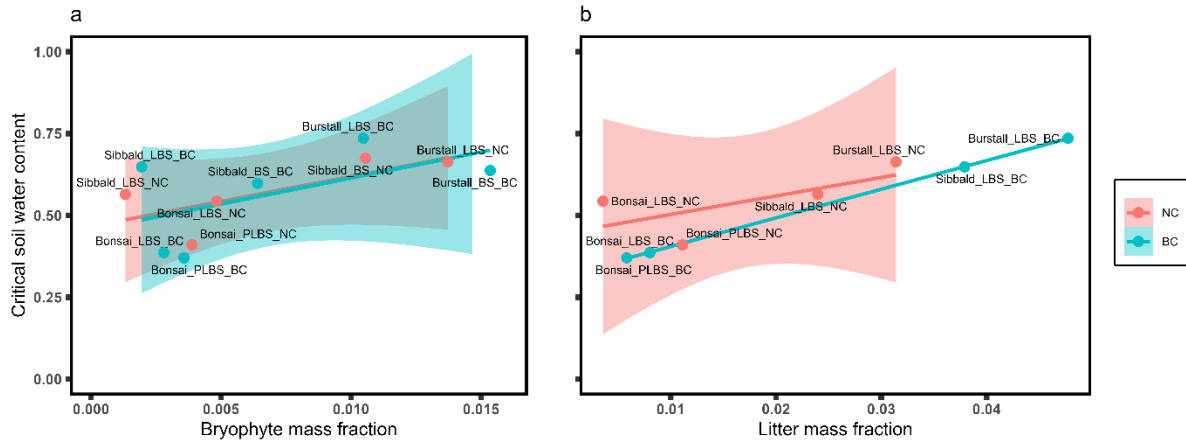


Figure 3-3. The relationship between critical soil water content and bryophyte mass fraction (a) and litter mass fraction (b). The shading represents the 95% confidence interval for the no canopy (NC) and below canopy (BC) treatments, respectively.

As hypothesized, significant linkages exist between $\theta_{1/2}$ and ground cover mass fractions (Figure 3-3). Higher $\theta_{1/2}$ values are associated with higher ground cover mass fractions for both bryophytes and litter. Surprisingly, the presence of an overstory canopy did not affect these relationships, although there was a slight difference between the NC and BC treatments in the correlation between $\theta_{1/2}$ and litter mass fractions. Moreover, a perfect fit was observed between $\theta_{1/2}$ and litter mass fractions under BC, with $R^2 > 0.99$. It is important to note that the four data points originate from three distinct sites, each with its own separate data collection and calculation process; therefore, this perfect fit is considered entirely coincidental. Nevertheless, it suggests a very strong correlation between the fraction of litter mass and critical soil moisture. Due to insufficient data to investigate the linkage between $\theta_{1/2}$ and ground vascular vegetation in detail, any statement regarding ground vascular vegetation is subject to uncertainty. Thus, the following discussions will focus solely on bryophytes and litter.

Across all treatments and sites, the bryophyte mass fraction-based $\theta_{1/2}$ is fitted as follows:

$$\theta_{1/2} = 15.62f_B + 0.46 \quad (R^2: 0.4) \quad (10)$$

And the litter mass fraction-based $\theta_{1/2}$ is fitted as follows:

$$\theta_{1/2} = 7.42f_L + 0.38 \quad (R^2: 0.8) \quad (11)$$

Stepwise regression showed that both f_B and f_L are necessary for the multilinear model for predicting $\theta_{1/2}$, as no significant correlation was found between f_B and f_L (Pearson correlation coefficient: -0.017, p-value: 0.96; Spearman coefficient: -0.36, p-value: 0.28). The multilinear model is expressed as follows:

$$\theta_{1/2} = 15.82f_B + 3.45f_L + 0.40 \quad (R^2=0.6) \quad (12)$$

The linear relationship between $\theta_{1/2}$ and ground cover mass fractions is likely prevalent in mesic but non-flooded ecosystems. As Lehmann et al. (2018) demonstrated, the physical basis for soil texture-dependent $\theta_{1/2}$ lies in the effect of soil texture on capillary flow resistance during Stage I evaporation and the transition between Stage I and II. Similarly, many bryophytes (e.g., mosses in this study) have a comparable effect, as they moderate evaporation primarily through capillary action (Goetz and Price, 2015; McCarter and Price, 2014). Additionally, these plants have a large water storage capacity (Rouse, 2000), which allows them to maintain the vaporization plane (i.e. the evaporating surface) of the soil-atmosphere evaporation column. Therefore, their presence supports the persistence of Stage I evaporation even under conditions where the soil would otherwise dry out more rapidly. Moreover, their mass fraction, a texture parameter indicating the influence of bryophytes on capillary flow resistance in a layered soil column, likely plays a key role in shaping evaporation patterns in moss-covered ecosystems. On the other hand, litter modifies the evaporative gradient (e.g., VPD) between the vaporization plane and the atmosphere, increasing the resistance of molecular transport from the bryophyte layer to the litter surface. This resistance is closely related to the thickness of the litter layer (Fuchs and Hadas, 2011). In this case, the mass

fraction of litter likely serves as an indicator of the litter thickness in the layered soil column. Consequently, the ground cover mass fractions, as indicators of resistance to water vapor transport in the layered soil column, play a critical role in influencing soil moisture dynamics.

Although the significant linear relationship between $\theta_{1/2}$ and ground cover mass fractions is likely prevalent in mesic ecosystems, the coefficients of this relationship are expected to vary slightly across different ecosystems due to variations in bryophyte species and litter materials (Goetz and Price, 2015; Sato et al., 2004) as well as measurement biases. Moreover, while water uptake in mosses predominantly occurs via external capillaries (i.e., ectohydric mosses), some species also rely on internal water movement (i.e., endohydric mosses) (Giordano et al., 1993). Therefore, grouping all mosses together may introduce uncertainties into this study. Nevertheless, since mass fractions are relatively easy to acquire, utilizing them as parameters could offer a practical and valuable method for estimating evaporation from bryophytes and litter-covered soils.

Another interesting finding is the significant correlation of $\theta_{1/2}$ between NC and BC conditions under the same ground cover treatment at the same site. Since the canopy influences evaporation by modifying energy and moisture inputs, and the formulation of SEE uses potential evaporation as its denominator, this minimizing the effect of evaporative demand on actual evaporation, likely making moisture input the dominant factor. To test this hypothesis, below-canopy $\theta_{1/2}$ was calculated from non-canopy $\theta_{1/2}$ using the empirical precipitation interception equation as shown in Eq. 2. Surprisingly, the modelled below-canopy $\theta_{1/2}$ agrees well with the measured below-canopy $\theta_{1/2}$ (Figure 3-4). The relationship of $\theta_{1/2}$ between NC and BC is determined as follows:

$$\theta_{1/2,i\_BC} = \theta_{1/2,i\_NC}(1 - (3.01LAI + 1.12)/100) \quad (13)$$

with i being S, BS, LBS and PLBS, respectively.

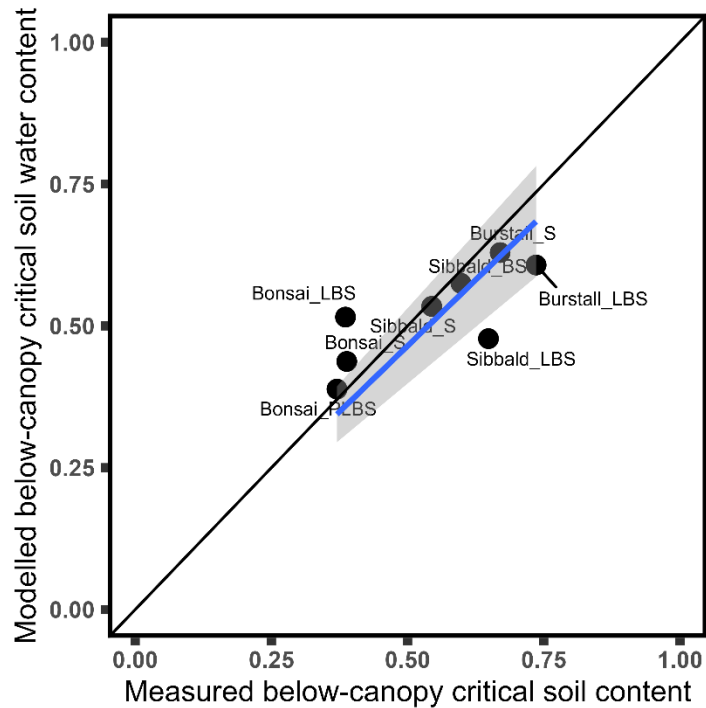


Figure 3-4. Comparison of modelled below-canopy critical soil water content from Eq. 13 with measured below-canopy critical soil water content for each ground cover treatment across all sites.

3.3.2 Performance of current SEE models for vegetated surfaces

The SEE models (Table 3-1) are applied in the condition of the vegetated surfaces under NC and BC treatments, and the results are presented in Figure 3-5. Three distinctive patterns can be observed from Figure 3-5: (1) the models generally perform better under NC conditions compared to BC conditions; (2) the models with parameters calibrated for each site (e.g., S & M 92 and M11) outperform the model using default parameters (e.g., S92); and (3) the distribution of points representing modelled SEE versus measured SEE from peat-substrate sites (e.g., Sibbald and Burstall) is more scattered around the fitted lines compared to those from the mineral soil-substrate site (i.e., Bonsai).

Among the four site-calibrated models, S & M 92, M11 and M16 provide a closer match to the measured SEE than K03. The better performance of S & M 92, M11 and M16 is possibly due to their formulations, which account for the coupled effect of changes in soil moisture on surface resistance, aerodynamic resistance and evaporative demand within a soil-atmospheric continuum, while K03 does not consider this effect. For S & M 92 and M16, this coupled effect is evident in Eq. T1, Eq. T2, Eq. T5 and Eq. T6, whereas for M11, it is reflected in the calibration of parameter P in Eq. T4. However, under BC conditions, the canopy alters microclimates and evaporative demand (as detailed in Appendix B, Section B), and likely affects the relationship between soil moisture, surface resistance, aerodynamic resistance, and evaporative demand. Given that this altered relationship was not accounted for in the SEE models under BC conditions, the failure of these SEE models under BC conditions is unsurprising. Additionally, K03 was developed based on SEE and soil moisture in the top 1-3 mm of the surface (Komatsu, 2003), whereas the soil moisture in this study was measured at a much deeper depth. This further explains K03's poor performance.

Interestingly, M16 shows a consistent underestimation of non-canopy SEE while demonstrating higher accuracy in estimating below-canopy SEE (except for Sibbald_LBS_BC). The systematic bias of M16 may arise from the energy storage within the litter and bryophyte layers not being included in the soil energy balance model. However, energy storage in ground covers may be smaller under BC conditions due to reduced solar radiation, and as a result, the omission of energy storage has less impact on modelling accuracy in BC conditions compared to NC conditions. Nevertheless, M16's ability to model SEE of vegetated surfaces, based on $\theta_{1/2}$ and $\text{slope}_{1/2}$, supports the assumption that ground covers can be treated as hypothetical soils.

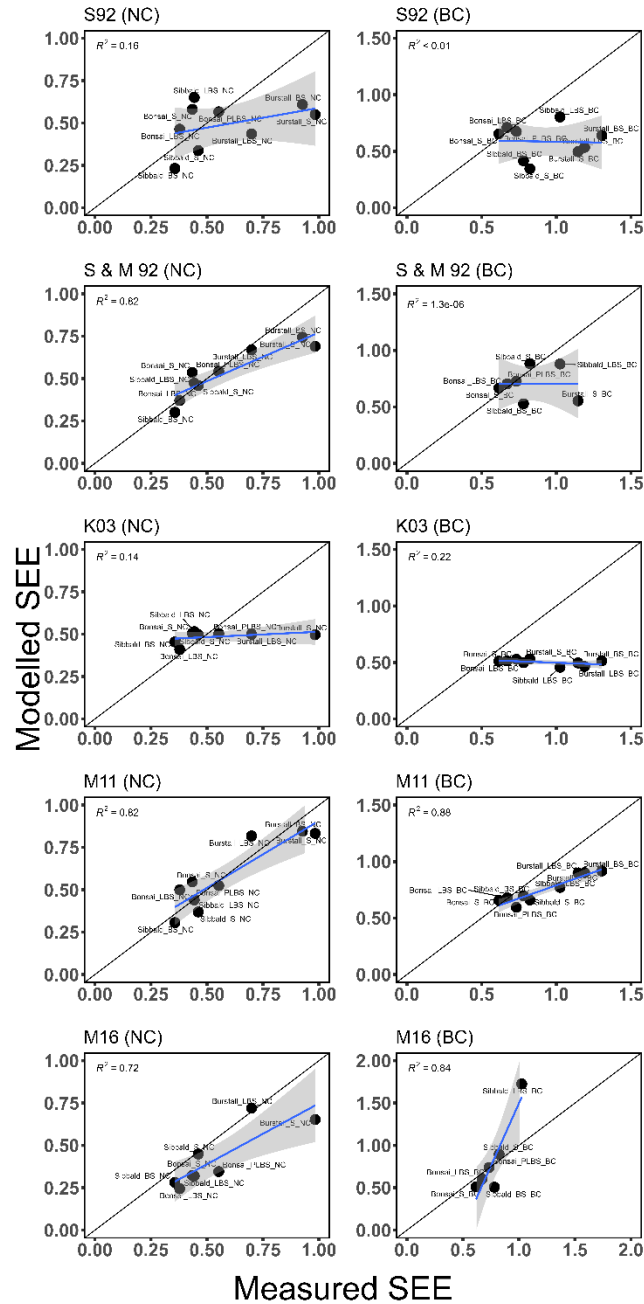


Figure 3-5. The simulated SEE versus the measured SEE for each ground cover treatment at each site under NC and BC conditions by the SEE models listed in Table 3-1. Blue lines denote the fitted regression between modelled SEE and measured SEE, and the gray shadows denote 95% confidence interval. Some simulated SEE that are unrealistic (i.e., SEE >5) have been removed from the results.

While S & M 92, M11 and M16 demonstrated their applicability in vegetated soils under NC conditions, their performances varied due to the different mathematical expressions they use to approximate the non-linear relationship between soil moisture and SEE. It remains unclear whether these mathematical expressions are better suited to specific site types, as no model performance comparison was done by site. This was due to the poor performance of these SEE models at individual sites, which had limited data points (only three per site) and large evaporation variability (even with similar soil, bryophyte, and litter content, and under comparable meteorological conditions). Consequently, a good fit between modelled and measured SEE only appeared when the sample size increased (i.e., when sites were combined).

It is important to note that the large variations in evaporation data are expected due to difficulties in installing MLs without disturbing the soil structure and accurately measuring the weights of the MLs on-site. These difficulties are particularly pronounced in peatlands, where the sponge-like nature of peat make it highly susceptible to losing its structure under mechanical stress. Since changes in soil structure can influence evaporation processes (Or et al., 2013), this increased susceptibility to soil structural change in peatlands likely contributes to greater variations in evaporation. This variability is reflected in the more scattered distribution of modelled SEE values around the fitted lines at Sibbald and Burstall, compared to the tighter distribution seen at Bonsai.

Additionally, while pooling the sites together improves the performance of the SEE models, their fitted lines still show notable deviations from the 1:1 diagonal line (Figure 3-5). Notably, most models tend to overestimate SEE when SEE is small while underestimate SEE when it is large. This systematic bias, which has been discussed in previous SEE modelling studies (e.g., Merlin et al. (2011) and Merlin et al. (2016)), mainly arises from two factors: (1) the non-stationary geometry of the soil moisture profile during simultaneous drying and draining, while the mathematical expressions for SEE and θ assume stationarity; and (2) the determination of $\theta_{1/2}$ from pairs of SEE and θ observations relies on a linear approximation based on the assumption of moisture-driven conditions, despite the relationship between SEE and θ being non-linear and asymmetrical (Merlin et al., 2011; Merlin et al., 2016). In S & M 92 and M11,

this bias can be reduced by dynamically calibrating parameter A, B and P rather than using constants specific to site or ground cover type (Merlin et al., 2011). In M16, the bias can be minimized by excluding energy-limited conditions (i.e., applying the model under conditions where $R_n - G > 100 \text{ W m}^{-2}$ and $E_0 > 100 \text{ W m}^{-2}$ (Merlin et al., 2016). This is because as the conditions become more moisture-driven (i.e., as the parameter P increases), the relationship between SEE and θ becomes more linear at the mid-range of SEE values, as illustrated in Figure 5 in Merlin et al. (2011). Nonetheless, the systematic bias should not be interpreted as a lack of applicability of SEE models in vegetated soils. The success of S & M 92, M11, and M16 across various sites, along with the significant correlation between $\theta_{1/2}$ and ground cover mass fractions, demonstrates that the SEE theory and some of the SEE models can be effectively applied to vegetated soils.

3.3.3 Towards a ground cover mass fraction-based SEE approach for vegetated surfaces

The previous sections suggest that developing a ground cover mass fraction-based SEE for vegetated soils is feasible. For example, the relationship between $\theta_{1/2}$ and the ground cover mass fractions (i.e., Eq. 12) can be integrated into M16, a model which relies on $\theta_{1/2}$ and $\text{slope}_{1/2}$ to predict SEE (Merlin et al., 2016). However, while soil texture-based $\theta_{1/2}$ can be directly incorporated into M16 for mineral, bare soil conditions (since $\text{slope}_{1/2}$ is treated as a constant), M16 cannot be applied to vegetated soil sites, because $\text{slope}_{1/2}$ is not a constant for vegetated soils and can only be determined from measured SEE and θ . Similarly, S & M 92 and M11 are also inapplicable without SEE and θ measurements to determine the parameters A, B and P. Given that many ecosystems have not yet had evaporation measurements taken, there is a clear need for a SEE approach that does not require evaporation data.

As mentioned, SEE models are useful for estimating actual evaporation since potential evaporation can be derived from meteorological data. Thus, this section focuses on developing a ground cover mass fraction-based SEE approach for vegetated surfaces that does not require evaporation data for model parameterization. This new method will be particularly useful in

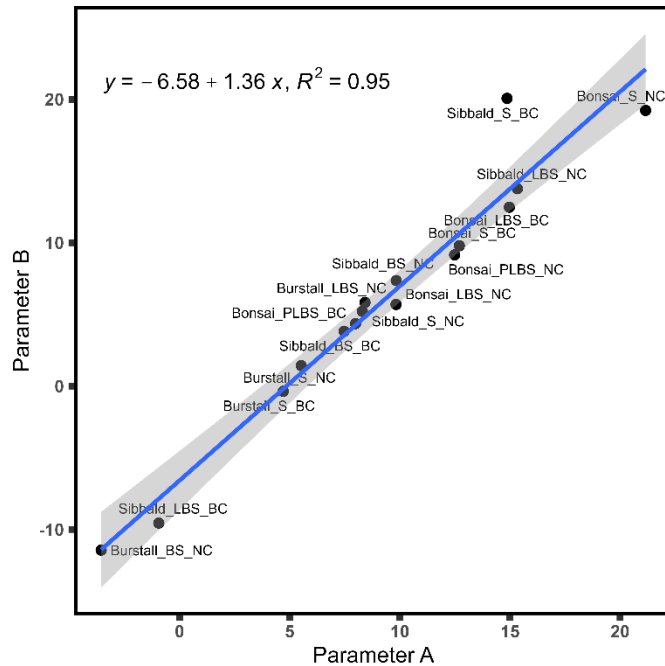
estimating actual evaporation in ecosystems covered with bryophytes and litter, where directly parameterizing their surface resistance is challenging.

3.3.3.1 Simplifying surface resistance expression

A closer examination of S & M 92 and M11, which yield satisfactory simulations with relatively simpler formulations than M16, provides valuable insights for modelling SEE in vegetated surfaces. The good performance of S & M 92 and M11 underscores the necessity of calibrating site-specific parameters, such as A, B and P in Eq. T1 and Eq. T4. Additionally, S & M 92 provides a formula for calculating surface resistance for vegetated surfaces—a key challenge in evaporation modelling—making it more versatile than M11. Therefore, the proposed method will aim to modify S & M 92, focusing on calibrating parameters A and B in its surface resistance expression using ground cover mass fractions.

It was found that the two site-specific parameters A and B in the surface resistance expression in S & M 92, are linearly correlated with each other (Figure 3-6). More interestingly, parameters A and B are found to be close to 8 and 5 for many studies (Crow et al., 2008; Kustas et al., 1998; Sellers et al., 1992), and the linear relationship between A and B established in this study can yield very close values (e.g., when A=8, B is 4.3). Moreover, the relationship here can also generate values of A and B that are found to deviate from 8 and 5 (e.g., Auradé and Lamasquère in Merlin et al. (2011)). The evidence suggests that such an empirical relationship is common across ecosystems. A table of the published A and B values, along with the estimated B values based on the relationship found in this study, is provided in Table B4. The small differences between the published B values and the B values estimated using the A-B relationship determined in this study are likely attributed to measurement biases, site heterogeneity, and the size of the study site (Table B4). Larger sites tend to exhibit greater heterogeneity in soil composition, ground cover and vegetation, which increases the deviation between the estimated and published B values. Based on the linear correlation between A and B, the surface resistance expression in S & M 92 can be simplified as:

$$r_s = \exp[A - (1.36A - 6.58)\theta/\theta_{sat}] \quad (14)$$



Eq. 14 describes the relationship between surface resistance and soil moisture, with only the parameter A needing calibration. This parameter can be determined by combining Eq. T2 and Eq. 14 when SEE equals 0.5 and θ is equal to $\theta_{1/2}$. Moreover, $\theta_{1/2}$ can be estimated from ground cover mass fractions using Eq. 12, an equation that is considered prevalent across mesic ecosystems. Once parameter A is calculated, the surface resistance of a vegetated ground surface in response to changes in soil moisture is also determined.

Figure 3-7 demonstrates the proposed modelling procedure. As mentioned, the parameter A can be determined by combining Eq. 14 and Eq. T2. This involves substituting $\theta_{1/2}$, r_{ah} (which is determined through the meteorological measurements as per Eq. (6) to Eq. 8), and prior knowledge of the site's θ_{sat} , into Eq. 14 and Eq. T2. Additionally, $\theta_{1/2}$ can be estimated by the ground cover mass fractions through Eq. 12. Therefore, by combining Eq. T2, Eq. 12 and Eq. 14, a simple approach for modelling SEE for vegetated surfaces is achieved. The model only

requires meteorological data, θ_{sat} , and ground cover mass fractions, and the formulations are simple and easy to use.

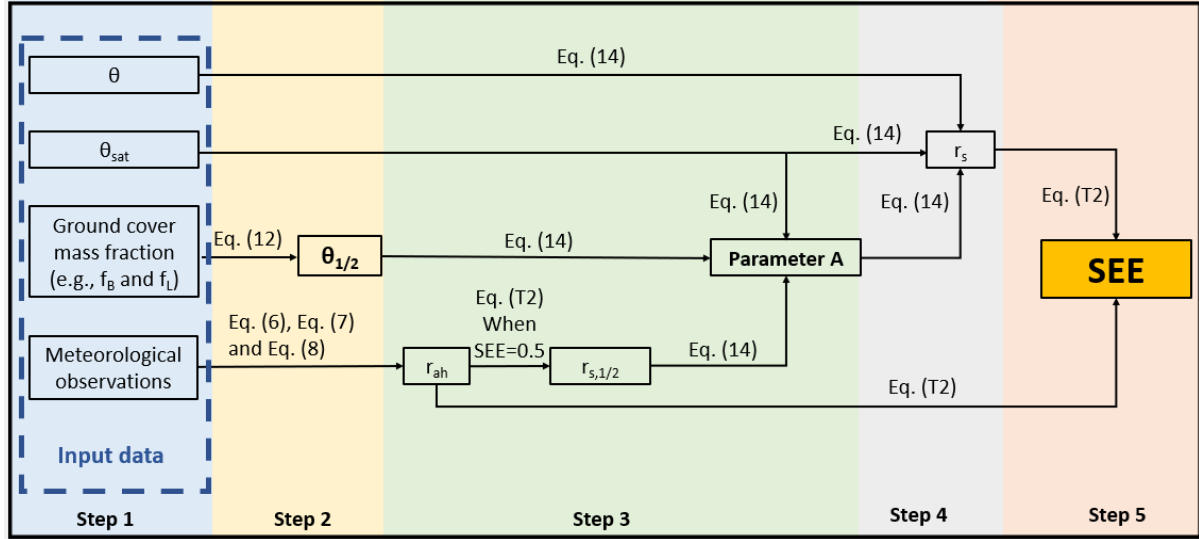


Figure 3-7. Overview of the modelling approaches including input/output data sets and key equations.

Figure 3-8 presents the performance of the proposed model under NC and BC conditions. Clearly, the proposed model produces SEE values that closely align with the measured SEE values under NC conditions for most site and ground cover combinations. However, the proposed model underestimates SEE under BC conditions, which will be investigated in the next section.

Under NC conditions, the modelled SEE for Sibbald_LBS_NC showed a significant discrepancy from the measured value. This deviation was due to some high soil temperature records in three experiment rounds, which led to a very large value of r_{ah} . This, in turn, introduced a substantial bias in determining the parameter A, as outlined in step 3 of Figure 3-7. If Sibbald_LBS_NC is excluded, the R^2 of the proposed approach under the NC conditions would increase from 0.47 to 0.93. Notably, the modelled SEE for Sibbald_LBS_NC did not differ significantly from the measured SEE values in S & M 92, M11 and M16, as presented in Figure 3-5. This is attributed to the fact that S & M 92, M11 and M16 were calibrated using SEE and

θ measurements, making them less sensitive to a few sporadic high temperature recordings. In contrast, the proposed method, while reducing the need for evaporation data, is more prone to bad performance when the quality of the input data is compromised.

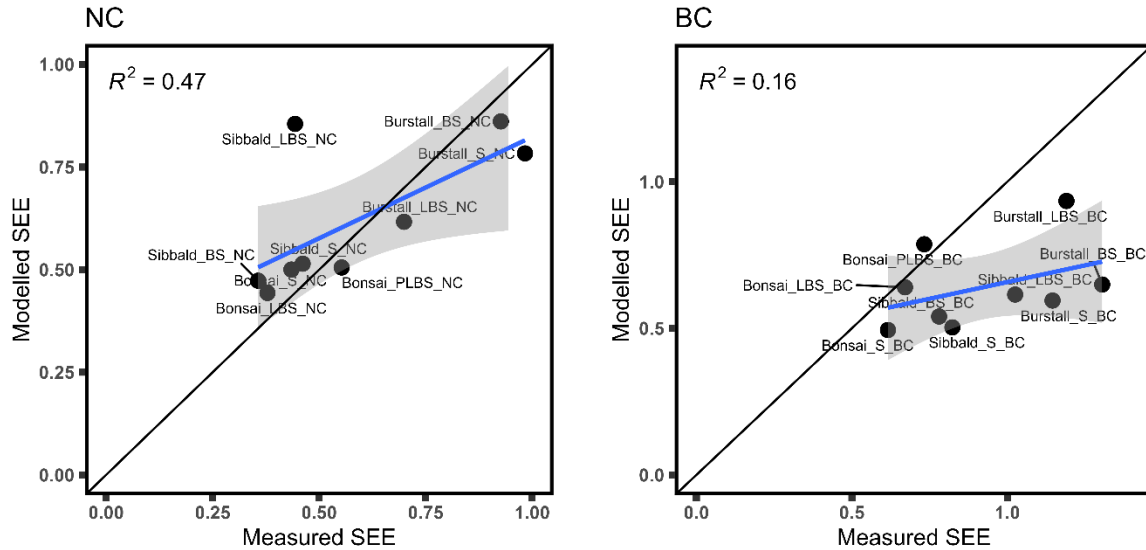


Figure 3-8. The simulated SEE from the proposed model versus the measured SEE for each ground cover treatment at various sites under NC and BC conditions. Blue lines denote the fitted regression between the modelled SEE and the measured SEE, and the gray shadows indicate the 95% confidence intervals.

By comparing the R^2 values in Figure 3-5 and Figure 3-8, it become apparent that the proposed approach does not outperform S & M 92 for the NC group, although it shows a slight advantage for the BC group. Furthermore, this method demonstrates inferior performance compared to both M11 and M16 for both NC and BC groups. Like the other SEE models, the proposed approach exhibits the same systematic bias of overestimating SEE when SEE is small and underestimating it when it is large. However, it is worth emphasizing that the proposed approach requires minimal data input and model parameterization, and it does not need evaporation measurements. This feature renders it valuable for estimating SEE for data-limited ecosystems with vegetated soils.

3.3.3.3 Correction for modelling below-canopy SEE

Figure 3-5 and Figure 3-8 reveal that SEE models are more suitable for the NC conditions, while they tend to underestimate the below-canopy SEE. This underestimation is attributed to the reduced moisture input and evaporation demand caused by the overstory canopy. To account for this effect in the proposed SEE model, an initial strategy was to adjust for soil water availability under below-canopy conditions. Given the significant linear relationship was found between below-canopy $\theta_{1/2}$ and non-canopy $\theta_{1/2}$ (as shown in Eq. 13), it is reasonable to question whether a similar linear relationship exists between the actual below-canopy SEE and modelled below-canopy SEE. Noticing the actual below-canopy SEE was greater than the modelled below-canopy SEE (Figure 3-8), a correction for the below-canopy SEE was attempted by adjusting the uncorrected SEE using the coefficient relating below-canopy $\theta_{1/2}$ to non-canopy $\theta_{1/2}$ (i.e., $SEE_{BC\_corrected} = SEE_{BC\_uncorrected} / [1 - (3.01LAI + 1.12)/100]$). However, this adjustment did not significantly improve the model's performance (Figure 3-9a). Instead, a more effective correction could be achieved by incorporating a factor based on the reduction in below-canopy E_0 relative to non-canopy E_0 (Figure 3-9b), as:

$$SEE_{BC\_corrected\_i} = \frac{SEE_{BC\_i}}{(1 - \frac{E_{0BC\_i}}{E_{0NC\_i}})} \quad (15)$$

where the subscript i represents S, BS, LBS and PLBS, respectively.

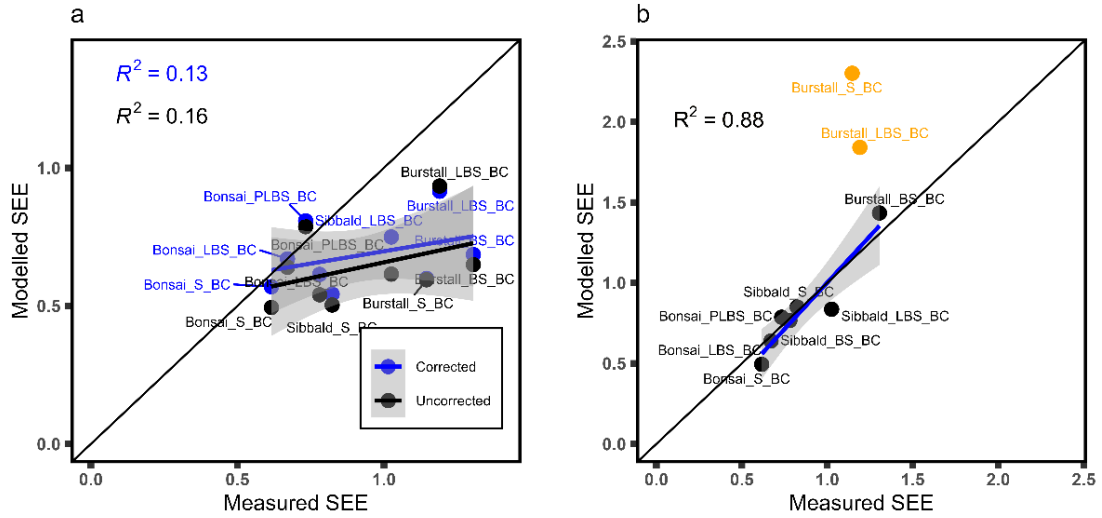


Figure 3-9. Modelled below-canopy SEE versus measured SEE with moisture input correction (a) and energy demand correction (b). Gray shadows denote the 95% confidence intervals.

The correction for below-canopy conditions in Eq. 15 can be interpreted using M11's parameter P . But before interpreting the correction, it is necessary to recall that the parameter P reflects whether evaporation is primarily limited by energy ($P < 0.5$, when SEE is not sensitive to soil moisture), or by soil moisture ($P > 0.5$) (Merlin et al., 2011). When evaporation is more constrained by soil moisture (i.e., the larger the value of the parameter P), the linear approximation of $\theta_{1/2}$ when SEE is 0.5 in M16 becomes more accurate. Similar to M16, the proposed method also depends on linear approximation, as the determination of the parameter A in Eq. 14 is based on the relationship between $\theta_{1/2}$ and $SEE = 0.5$. Consequently, better model predictions from the proposed method are generally associated with higher values of the parameter P . With this in mind, the connection between the model performance for each treatment at the three sites (Figure 3-8) and the variability of the corresponding parameter P (Figure 3-10) becomes evident. As expected, NC conditions show higher values of the parameter P compared to BC conditions (Figure 3-10), which explains the better modelling results under the NC conditions. Lower values of the parameter P under BC conditions suggest

that below-canopy evaporation is more energy-limited, which indicates the need for correcting evaporative energy for below-canopy SEE, as seen in Eq. 15.

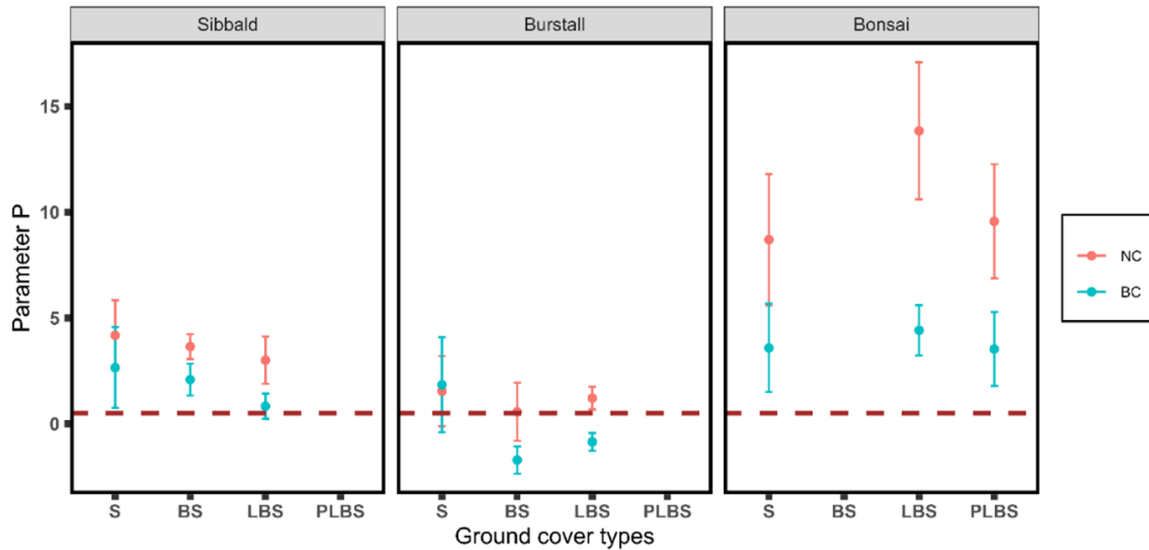


Figure 3-10. The error bars represent site-calibrated parameter P from M11 for each treatment at each site. The length of the bar indicates the 95% confidence interval of P for each group, and the dots denote the average value for each group. The horizontal dashed line indicates $P=0.5$.

However, it should be noted that in Figure 3-9 (b), only the below-canopy SEE at Sibbald and Burstall was corrected, as the uncorrected modelled below-canopy SEE at Bonsai already closely matched the measurements (Figure 3-8). These good modelling results at Bonsai is expected, given the consistently high values of P for all treatment groups, even under BC conditions (Figure 3-10). In contrast, a large amount of P values from Burstall was below 0.5 even under the NC condition, which explains the poorer model performance at Burstall compared to the other two sites. Interestingly, based on the criteria of P set by Merlin et al. (2011), evaporation at Sibbald is primarily driven by moisture and thus, the correction for below-canopy SEE at Sibbald is not required. However, the modelled below-canopy SEE at Sibbald were not satisfactory without the correction. Based on the findings from this study, a correction is required for any below-canopy P value less than 3.5. This threshold helps in

distinguishing when corrections are needed to account for energy constraints in below-canopy conditions. This criterion is derived solely from the analysis of this dataset; its applicability to other datasets needs further investigation.

Additionally, the values of below-canopy SEE from Burstall site are over-corrected (Figure 3-9b). It is probably because the correction assumes that overstory canopy is the cause for energy-driven condition, and if without canopy, the evaporation would become moisture-driven. Therefore, the correction uses the non-canopy evaporative demand as a basis to correct the below-canopy evaporative demand (quantified by relative reduction in the evaporative demand below canopy than non-canopy). However, many P values from Burstall were below 0.5 even under the NC condition (Figure 3-10), resulting in bad modelling results even under NC conditions. As a result, using the NC condition to correct BC condition does not work well for Burstall.

Overall, SEE models are evidently more suitable for the moisture-driven conditions. The correction method proposed here is based solely on data collected from three study sites, and the physical mechanisms underlying this correction remain unclear, warranting further research. In addition, how to accurately model below-canopy evaporation under less moisture-driven conditions is not within the scope of this study. It is worth noting that Allen et al. (2017) found that below-canopy evaporation in a flooded forest was linked to the available energy below the canopy. This finding provides a basis for modelling below-canopy SEE in energy-driven conditions in future research.

3.4 Model application perspectives

In the vein of Sellers et al. (1992), Merlin et al. (2011) and Merlin et al. (2016), this study explores the linkage between critical soil water content and ground cover mass fractions, as well as the application of SEE models in vegetated soil conditions. A simple approach to modelling SEE was applied across various soil-substrates, ground covers and canopy cover, yielding satisfactory results. The approach is expected to be widely applicable, given that its parameters are easily acquired and its formulation is simple and straightforward. However, it

should be pointed out that no claims are made to describe the full intricacies of the evaporation processes through the multi-layered soil-atmosphere interface. Rather, the approach here is to provide the best estimates with limited field information and easily acquired parameters for vegetated soil evaporation.

One might be concerned that the proposed approach was developed and tested on the same dataset, raising potential overfitting issues and suggesting it may not generalize well to other sites. While further investigation is needed to confirm its broader applicability, there are two strong pieces of evidence that support the idea that this approach is not limited to the three study sites used in this research. First, the significant linear correlation between critical soil moisture and the soil texture parameters—such as sand and clay fractions in bare soil and the mass fractions of litter and bryophytes in vegetated soils—has strong physical basis (Lehmann et al., 2018), even though the specific coefficients in this correlation may vary and require additional study. Second, the observed correlation between the parameters A and B appears to extend beyond these three sites (Table B4), suggesting broader applicability.

The model presented here is suitable for mesic ecosystems where evaporation is sensitive to soil moisture. The physical mechanisms underlying SEE suggest that this approach may also be applicable for drier ecosystems, as M16 was developed based on arid sites. However, different ground covers may regulate evaporation differently depending on the stages of the evaporation process. Therefore, future studies are required to examine the performance of this approach with respect to the three stages of the evaporation. Moreover, Merlin et al. (2016) confined their data to conditions where $R_n - G > 100 \text{ W/m}^2$ and $E_0 > 100 \text{ W/m}^2$, and Lehmann et al. (2018) excluded any E_0 less than 2 mm d^{-1} to avoid energy-limited conditions. In contrast, this study made no such constraints. In fact, the majority of the data here fell below the lower limit of their criteria, indicating that the parameter P from M11 (Merlin et al., 2011) is a better indicator for defining the moisture-driven condition. Here, $P = 3.5$ is defined as a threshold, but more research is needed to refine this value further.

In addition, another way of modelling SEE was explored by applying Eq. 12 into the SEE formulation of M11. However, the modelling outcomes were less satisfactory compared to the approach suggested in this study. Moreover, calibrating P using observed pairs of SEE and θ as described by Merlin et al. (2011) is a better procedure than merely substituting $\theta_{1/2}$ to calibrate P . Using Merlin et al.'s procedure to calibrate P yielded very good modelling results (Figure 3-5), but this procedure requires evaporation data. Another reason for favoring the proposed method over M11 is that the similar form of the expression for surface resistance (e.g., Eq. T1) has been widely used in LSMs (Oleson et al., 2008; Sellers et al., 1996). This allows the proposed approach from this study to be easily incorporated in LSMs.

Some recommendations for future studies are provided. Firstly, the overstory canopy in these study sites is formed by short willow trees, thus it is uncertain how the correction will work for taller and more complex canopies formed by various or mixed species. Further, the ground cover layers are relatively homogenous, but as Whitfield et al. (2009) mention, ground cover layers (e.g., moss) engaged in the water cycle might be different between forest and wetland ecosystems. Therefore, a global meta-analysis across contrasting climates, biomes, and ecosystem structures is warranted to examine the applicability of this approach. However, it is acknowledged that obtaining precise mass fractions in large-scale investigations can indeed be challenging. Nonetheless, collaborative interdisciplinary research can facilitate the estimation of mass fractions. For example, litter biomass could be extrapolated by combining remote-sensed aboveground biomass data (e.g., Kumar and Mutanga (2017)), vegetation allometric equations, soil respiration and decomposition models (e.g., Matthews (1997)), and modern machine learning methods (e.g., He et al. (2021)). Furthermore, bryophyte biomass can be acquired from integrating biogeochemical models that include nitrogen and phosphorus fixation rates (e.g., Porada et al. (2014)). Estimating soil mass is also feasible, considering parameters like soil type, depth, moisture, and bulk density (e.g., Shangguan et al. (2014)).

On the other hand, since collecting mass fraction data through field investigations is quite straightforward, future researchers are encouraged to not only gather mass fraction data but also to evaluate the method across multiple sites. As mass fraction data for ground covers

gradually accumulates across different locations, the potential for expanding this method to regional or even global scales will become more evident. Through these advancements, the accuracy of these results can be further validated, and the practical applications of this method can be realized on a broader scale.

Secondly, more scattered data are observed from peat-substrate evaporative columns, which is attributed primarily to measuring errors, although a detailed examination of peat is needed. In fact, modelling peat evaporation is still very challenging, not only due to the difficulty in collecting field data (e.g., soil tension, moss resistance) (Kettridge et al., 2021), but also because the hydrological properties of peat are highly influenced by its decomposition level, forming materials, shrink-and-swell patterns and their interactions with microbial communities (Rezanezhad et al., 2016). As for now, a texture-based pedotransfer function is used for mineral soils (Lehmann et al., 2018; Merlin et al., 2016), which has proven to work well for bare soils across the world. However, for peat, developing the pedotransfer function is still in progress (Chapman et al., 2017; Van Looy et al., 2017). A recent meta-analysis on 2,507 northern peat samples provided several empirical equations for predicting saturated hydraulic conductivity based on site information (Morris et al., 2022), which may serve as a foundation for developing a similar texture-based pedotransfer function for peats.

3.5 Conclusions

Bare soil evaporation has been extensively studied, but less is known regarding how site-specific features, particularly ground covers (i.e., bryophytes and litter) and overstory tree canopies, influence evaporation processes. Inspired by recent advances in modelling bare soil evaporative efficiency (SEE), this study explored SEE over a range of soil substrates and ground cover types, both with and without the presence of an overstory canopy, in three mesic ecosystems in the Canadian Rocky Mountains. A significant relationship was found between the critical soil water content and ground cover mass fractions across various ground cover types, in both the presence and absence of an overstory canopy. This relationship is expected to be prevalent across different ecosystems. Moreover, a simple approach for modelling SEE

of vegetated surfaces, along with a correction method for below-canopy SEE, is proposed. The new model yields satisfactory simulations and is expected to be widely applicable, given the strength that its parameters are easily acquired, and its formulation is simple and straightforward. While this model may be particularly suited to mesic ecosystems, the underlying mechanisms of SEE suggest that it could also be applicable in drier conditions. The proposed model will be useful in better parameterizing ET in LSMs and can be a powerful tool for evaluating how the water cycle, especially ET, is affected by climate change or by disturbances that alter the density, structure, and spatial arrangement of vegetation in ecosystems.

3.6 Acknowledgements

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Chapter 4

Evapotranspiration partitioning in bryophytes and litter covered wetlands

4.1 Introduction

Evapotranspiration (ET), the combined water loss from transpiration (T) and evaporation (E), regulates the water balance, energy exchange, and carbon fluxes within terrestrial ecosystems. Partitioning ET into E and T, provides crucial insights into hydrological processes and ecological functions. These insights are instrumental in designing sustainable land management strategies and assessing ecosystem responses to changing climate. Despite the fundamental role of ET partitioning, direct measurements of E and T are scarce and the underlying mechanisms governing ET partitioning remain poorly understood (Cao et al., 2022). Particularly, the global estimates of the ratio of transpiration to evapotranspiration (T/ET), derived either from ecosystem-scale observations or ET partitioning models, vary widely, with reported values ranging from 0.35 to 0.90 (Coenders-Gerrits et al., 2014; Fatichi and Pappas, 2017; Jasechko et al., 2013; Schlesinger and Jasechko, 2014; Wei et al., 2017). This significant variation highlights the need for more ecosystem-scale observations to provide ground validation and for the development of better partitioning approach to improve the accuracy of estimated T/ET ratios from site to global scales (Cao et al., 2022; Chen et al., 2022b).

Presently, there is a significant lack of research focused on ET partitioning for wetland ecosystems, despite an extensive body of literature related to wetland ET. To the authors' knowledge, no more than twenty field investigations have been conducted on wetland ET partitioning, with the majority concentrating on hydroperiods in which E mostly comes from standing water or saturated soils (Allen et al., 2017; Bijoor et al., 2011; Burba et al., 1999; Goulden et al., 2007; Hussey and Odum, 1992; Kiniry et al., 2023; Xu et al., 2011a; Zhang et al., 2018b). These studies have produced varying results regarding the dominance of T or E in ET and the environmental factors that control them, suggesting that T/ET in wetland ecosystems is regulated by both structural properties, such as vegetation composition, density,

and areas of open water, and environmental conditions, including climatic variables and water table depth (Admiral and Lafleur, 2007b; Allen et al., 2017; Eichelmann et al., 2022; Goulden et al., 2007; Kiniry et al., 2023; Warren et al., 2018). However, a comprehensive understanding of the temporal variability in T/ET and the factors influencing it is still lacking (Cao et al., 2022). Moreover, many wetlands do not remain consistently waterlogged, which prompts the following questions. What discrepancies arise in the way ET partitioning responds to environmental factors under different water availability conditions? Specifically, how does ET partitioning differ between non-flooded conditions, where the water table is below the land surface and the ground surface is not saturated, and flooded conditions, where the water table is at or above the land surface? Furthermore, can current modelling approaches accurately capture the temporal variability of wetland ET partitioning under changing meteorological conditions and water availability? Answering these questions is crucial for gaining a deeper understanding of water-energy-carbon interactions within wetland ecosystems.

As mentioned, the mechanisms that regulate ET partitioning are not thoroughly understood, and the limitations of ET partitioning methods introduce further difficulties to monitoring ET partitioning in wetland ecosystems. Estimating ET partitioning typically involves multiple field-based techniques, such as stable isotope analysis, lysimeters, porometers, sap flow measurements, and eddy covariance systems (Kool et al., 2014). However, these methods are often time-consuming, context-specific, and unsuitable for investigating the temporal variability in T/ET and its environmental controls. On the other hand, modelling approaches can be more convenient and enable the exploration of temporal variability, yet they necessitate accurate parameterization, and model validation is not always available (Eichelmann et al., 2022). Moreover, certain modelling methods rely on assumptions that are ecosystem- or region-specific. For example, the underlying water-use efficiency (uWUE)-based model assumes that ET is primarily dominated by T (Zhou et al., 2016), a condition that might not hold true in wetland ecosystems (Eichelmann et al., 2022). To date, the prevailing models for partitioning wetland ET into E and T are based on the Shuttleworth–Wallace model (Shuttleworth and Wallace, 1985), with variations like the Massman method (Massman, 1992),

the Wang–Yamanaka method (Wang and Yamanaka, 2014), and the Kim–Verma method (Kim and Verma, 1996; Moore et al., 2022). These models calculate the latent heat flux from the vascular plant canopy and the ground surface according to environmental specifics and research goals (Burba et al., 1999; Chen et al., 2022c; Moore et al., 2022). The effectiveness of these models depends on accurate parameterization of bulk canopy resistance and ground surface resistance. However, these models do not explicitly accommodate the impacts of bryophytes and litter in mediating the exchange of water and energy between soil and atmosphere (Fatichi and Pappas, 2017), despite substantial evidence demonstrating the significant influence of these ground covers on evaporation processes (Farrick and Price, 2009; Goetz and Price, 2015; McCarter and Price, 2014; Wang and Petrone, 2022).

Prior investigations into evaporation from soil columns covered with bryophytes and litter (referred to as ground surface evaporation hereafter) in three types of wetlands in the Canadian Rocky Mountain revealed that ground surface evaporation was significantly affected by the interaction effects of ground covers, microforms and overstory canopy (Wang and Petrone, 2022; Wang et al., 2023). Ground surface evaporation can be estimated using soil evaporative efficiency (SEE), defined as the ratio of actual evaporation to potential evaporation (Merlin et al., 2011; Wang et al., 2023). For bare soils, SEE can be modelled based on weather data and soil volumetric content (Chanzy and Bruckler, 1993; Komatsu, 2003; Kondo et al., 1990; Merlin et al., 2011; Philip, 1957), and Wang et al. (2023) found that these SEE models could be adapted for bryophyte and litter covered soils by incorporating the mass fractions of bryophytes and litter in the soil columns. However, Wang et al. (2023) focused on testing and adapting the SEE models for bryophytes and litter covered soils. Despite the effectiveness of the SEE models demonstrated in that study, Wang et al. (2023) did not comprehensively examine how, and to what extent, ground covers and overstory canopy influence ground surface evaporation across multiple study sites, while this knowledge is crucial for characterizing wetland water use patterns.

Building on the work of Wang and Petrone (2022) and Wang et al. (2023), this study will examine the impacts of bryophytes and litter on ground surface evaporation in three wetland

sites. Given the previously noted lack of methodology for quantifying ground surface resistance in bryophytes and litter covered wetland surface, and considering the effectiveness of the new SEE approach demonstrated in Wang et al. (2023), this study also tests the feasibility of integrating the new SEE approach into the widely used Shuttleworth–Wallace model to partition ET into vascular plant transpiration and ground surface evaporation on a daily basis. If the partitioning results align well with field measurements, the study will further investigate the effects of bryophytes and litter on ET partitioning and examine the effects of environmental variables on ET partitioning in wetland ecosystems.

4.2 Study sites and Methods

4.2.1 Study sites

The three study sites represent the typical wetland ecosystems found within the Canadian Rocky Mountains (Figure 4-1). These sites encompass a montane fen known as Sibbald, a sub-alpine marsh called Burstall, and a sub-alpine wet meadow named Bonsai. The sites are classified based on the Alberta Wetland Classification System (Alberta Environment and Sustainable Resource Development (ESRD), 2015). The characteristics of the sites, including geographical setting, soil, vegetation, climate, and hydrological conditions are briefly provided below.

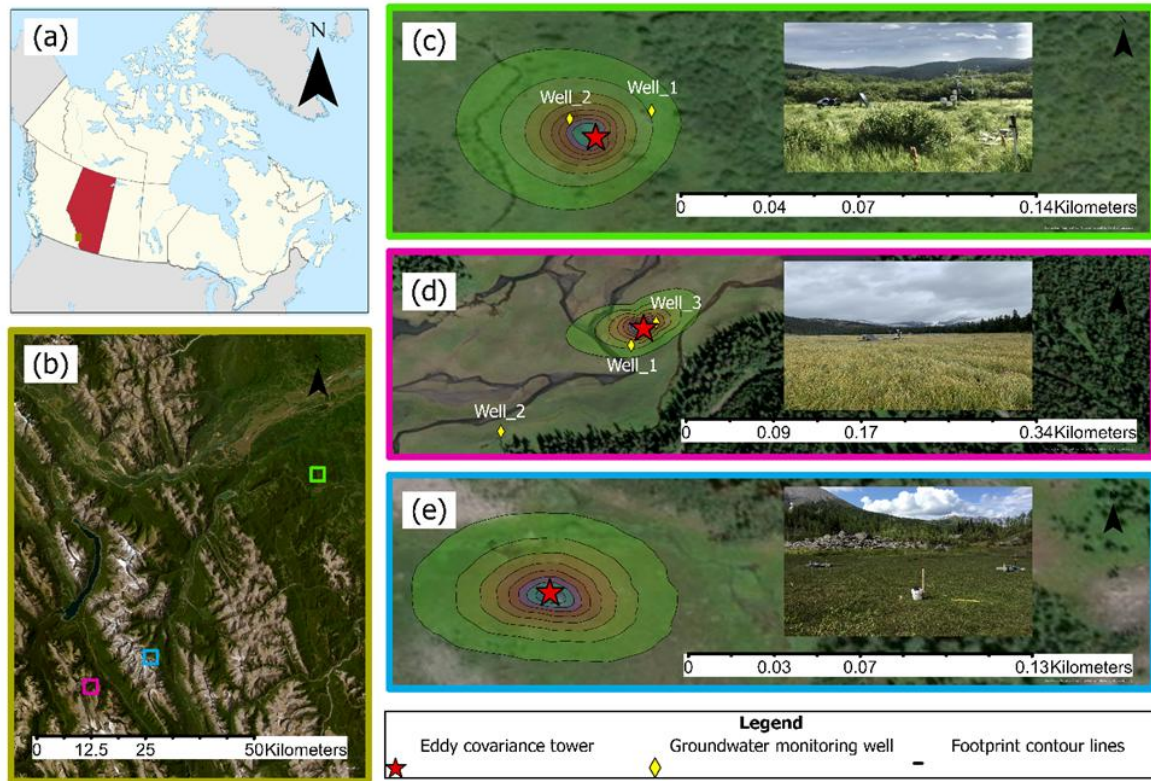


Figure 4-1. Locations of the three study sites in Canadian Rocky Mountains. Panel (a) shows the site locations within Alberta, Canada. Panel (b) shows the site locations within Canadian Rocky Mountains. Panel (c), (d) and (e) display Sibbald, Burstall and Bonsai wetlands, respectively, along with the locations of eddy covariance systems, groundwater monitoring wells, the footprints during the study period, and a site photo for each wetland. The footprint contour lines in panel (c), (d) and (e) are shown in steps of 10 %, from 10 to 80 %.

Sibbald Fen (51.06°N, 114.87°W) is a valley confined peatland situated in the foothills of the Canadian Rocky Mountains. It spans approximately 2.1 km in length and 0.4 km in width, with an average elevation of 1,490 m above sea level. Five upland streams flow into Sibbald Fen, with a single creek serving as its drainage outlet (Streich and Westbrook, 2020). The dominant vascular plants are sedges (*Carex* spp.) and willows (*Salix* spp.). The climate normal from 1981 to 2010, recorded at a long-term climate station (Environment Canada station ID: 3053600; ~1,391 m a.s.l.), situated within 10 km from the study site, shows an average air

temperature of 3.6 °C and annual precipitation of 639.4 mm. During the study period (July and August 2021), the site recorded a mean temperature of 14.0 °C, and precipitation of 137.7 mm, which are 0.2 °C lower and 2 mm less than the long-term climate normal for the same months. While long-term water balance measurements were unavailable, a previous water balance study conducted between June and August 2017—during a period with temperature 9.1 °C higher and 136.2 mm less precipitation than the climate normal for the same period—revealed a substantial decline in the water table depth, up to 1.0 m below the ground surface (Streich and Westbrook, 2020). In total, outflowing streamflow and ET collectively accounted for 51% and 49% of the total water loss of the site, respectively (Streich and Westbrook, 2020).

Burstall Marsh (50.78°N, 115.34°W) is situated at mid-elevations (1,900 m) in the Spray River valley in Kananaskis, Alberta. The wetland is around 1.2 km in length and 0.35 km in width. The soil consists of a thin peat layer of about 20 cm deep, overlying grey luvisols. Dominant plants are sedges (*Carex* spp.) and willows (*Salix* spp.). The wetland comprises two main streams: one characterized by cloudy, glacier-fed water, and the other by reddish-brown, likely sourced from groundwater (Hathaway et al., 2022). Both streams maintain surface flow throughout the entire season. The mean annual temperature, according to the 1981-2010 climate normal from the nearest long-term climate station, 19.38 km away (Environment Canada station ID: 3053604, ~1,610 m a.s.l.), is 1.1 °C, with an annual precipitation of 568.1 mm. During the study period, the average air temperature was 11.6 °C, and the total precipitation was 32.2 mm, which is 0.3 °C lower and 81.1 mm less than the climate normal for the same period. Although long-term water balance data were not available, water table depths measured during the study period consistently remained close to the ground surface, fluctuating between 0.1 m below to 0.1 m above the ground.

Bonsai Meadow (50.82°N, 115.21°W) is situated at an elevation of approximately 2,100 m a.s.l., located beneath the headwall of Fortress Mountain, Alberta. The headwall at the southern edge of Bonsai rises about 500 m, while talus slopes descend approximately 200 m into the meadow (Christensen et al., 2020). Two creeks flow through the meadow and converge at a confluence located in the north-central region of the wetland, ultimately draining into a

seasonal ephemeral tarn (Christensen, 2017; Hrach et al., 2021a). The area of Bonsai meadow is roughly 0.01 km². The soil mainly consists of silt and clay within the 80% footprint of the eddy covariance measurements. Vegetation in the area is characterized by sparsely distributed overstory species (e.g, *Salix* spp., *Larix* spp., and *Abies* spp.) and abundant understory species including *Erigeron* spp., *parnassia* spp., and *Equisetum* spp. The nearest long-term climate station (Environment Canada station ID: 305MGFF, ~2,543 m), at a distance of 13.7 km, shows that the mean annual temperature in July and August from 1994 to 2021 was 9.5 °C. However, precipitation records were not available from this climate station. During the study period of 2021, the mean temperature at the site was recorded as 11.7 °C, with total precipitation of 128.3 mm from July to August. Long-term water balance data were also not available. A previous hydrogeological survey indicates that the water table depth is generally at least 2 m below the ground surface during the growing season (Christensen, 2017; Christensen et al., 2020).

The three wetlands were abundantly covered by bryophytes and litter. At Sibbald, the bryophyte layer was approximately 5 mm thick, including *Aulacomnium palustre* (Hedw.) Schwaegr., *Bryum pseudotriquetrum* (Hedw.) Gaertn. et. al., *Calliergon giganteum* (Schimp.) Kindb., *Calliergon richardsonii* (Mitt.) Kindb. in Warnst., *Campylium stellatum* (Hedw.) C. Jens., *Hypnum lindbergii* (Mitt.), *Plagiomnium ellipticum* (Brid.) T. Kop., *Pohlia nutans* (Hedw.) Lindb., and *Warnstorfia fluitans* (Hedw.) Loeske (Lei, 2021). The average thickness of the litter layer was 5 cm, comprising of undecomposed sedges. At Burstall, a bryophyte layer of 1 cm thickness was dominated by peat moss (*Sphagnum* spp.) and feather moss (*Eurhynchium* spp.). Above this layer, there was a sedge litter layer measuring about 5 cm in thickness. At Bonsai, the bryophyte covering consists primarily of Brown moss (*Tetradontium* spp.), and its distribution is not uniform. It is scarce around the headwall and central parts of the meadow, but it becomes notably dense (about 5 mm thick) near the steam bank. Litter of decomposed leaves and branches of the ground vascular vegetation is highly mixed with the top layer of the soil (~2 cm). More descriptions of the sites can be found in previous studies

(Hathaway et al., 2022; Hrach et al., 2021a; Hrach et al., 2021b; Streich and Westbrook, 2020; Wang and Petrone, 2022; Wang et al., 2023).

4.2.2 Measurements of environmental variables

At all sites, net radiation (R_n , $W\ m^{-2}$) was measured using NR-Lite2 radiometers (Kipp Zonen: Delft, Netherlands), air temperature (T_a , $^{\circ}C$) and relative humidity (RH_a) were measured with HMP-155 T/RH probes (Vaisala; Helsinki, Finland) and wind speed (u , $m\ s^{-1}$) and direction were measured using an R.M. Young 05103 propeller anemometer (R.M. Young: Traverse City, Michigan, USA). The measurement height for R_n , T_a , RH_a and u was 3 m at both Sibbald and Bonsai, and 2 m at Burstall. Precipitation was measured at 3 m at Sibbald using a TR-525I tipping bucket rain gauge (Texas Electronics: Dallas, USA), and 2 m at Burstall using a RG3-M HOBO rain gauge with a M-RSA solar radiation shield (Onset Computer Corp.: Massachusetts, USA). At Bonsai, precipitation was measured at 2.5 m using an OTT Pluvio² precipitation gauge with an alter shield (OTT HydroMet: Kempten, Germany).

In addition to these meteorological variables, other environmental variables were also continuously monitored, including soil heat flux ($W\ m^{-2}$), soil temperature (T_{soil} , $^{\circ}C$) and soil volumetric water content (Soil VWC). Soil heat flux was measured at each site using HFP01 soil heat flux plates (HuskeFlux: Delft, Netherlands) placed 6 cm below the surface. T_{soil} was measured using Type E Thermocouples (Omega Engineering: Connecticut, USA) at depths of 15 cm and 30 cm at Sibbald, at 5 cm, 10 cm, and 15 cm at Burstall, and at 5 cm and 10 cm at Bonsai. Soil VWC was measured using ECH2O EC-5 sensors (Meter Group, Hopkins, Washington, USA). At both Sibbald and Burstall, soil VWC sensors were inserted horizontally at 15 and 30 cm depths. In contrast, at Bonsai, two sensors were inserted vertically, covering the top 30 cm of soil depth. All variables were continuously monitored, with measurements taken every 30 seconds and averaged or summed into 30-minute intervals, recorded by a CR1000 datalogger (Campbell Scientific: Logan, Utah, USA).

Manual measurements included water table depth at Sibbald and Burstall, which was measured at two to three groundwater monitoring wells (Figure 4-1), using a water level tape

(model: 101M, Solinst, Georgetown, Canada). However, unlike Sibbald, the water table depth at Burstall was manually measured until August 10, at which point new water level loggers and one barometer (Levellogger 5, Solinst, Georgetown, Canada) were installed to continuously monitor the water table depth. Additionally, leaf area index (LAI) was measured monthly at each site during the growing season of 2021 using the LAI-2200C plant canopy analyzer (LiCor BioSciences, Lincoln, USA). There are other environmental measurements, which are not used in this chapter, are detailed in the previous two chapters.

4.2.3 Eddy covariance measurements and data processing

At every site, there was an eddy-covariance (EC) tower in continuous operation throughout the growing season of 2021 (Figure 4-1). LI-7200 closed path infrared gas analyzers (LI-COR: Lincoln, Nebraska, USA) were employed at both Sibbald and Burstall, and an LI-7500 open-path system (LI-COR: Lincoln, Nebraska, USA) was used at Bonsai, for measuring H₂O and CO₂ fluxes. At Sibbald and Burstall, the EC systems were equipped with Gill Windmaster Pro anemometers (Gill Instruments Limited, UK) and at Bonsai, the EC tower was equipped with a CSAT3 3-D sonic anemometer (Campbell Scientific, Logan, Utah, USA), for measuring wind components, sonic temperature and speed of sound. The sensors were set at a measurement height of 3 m, 2 m, and 3 m for Sibbald, Burstall, and Bonsai, respectively. Raw fluxes were sampled at a frequency of 20 Hz, processed into 30-min average fluxes, and the half-hour data were saved on a CR1000 datalogger (Campbell Scientific, Logan, Utah, USA). All flux data were then corrected for density, sensor separation, time lag and coordinate rotation (double coordinate rotation is used) following common FLUXNET protocols (Aubinet et al., 2012; Burba et al., 2012; Foken and Leclerc, 2004; Kaimal and Finnigan, 1994; Leuning and Judd, 1996; Webb et al., 1980). The resulting half-hour fluxes were then processed in a custom R script in R programming language version 4.3.0 (R Core Team 2023) to ensure that they had at least 80% of the high-frequency records and the periods of potential dew formation on the IRGA lenses were removed. Spikes (i.e., data points that exceed ± 3 standard deviations of a moving average consisting of 10 half-hour neighbouring values) and physically improbable values were also removed. Footprints were modelled to ensure that at least 80% of

the flux originated from within the area of interest, using their FFP R-functions (Kljun et al., 2004). All flux data were also filtered for periods of low atmospheric turbulence using the 50% friction velocity threshold by the “REddyProc” R package, according to the method described in Papale et al. (2006) and Pastorello et al. (2020). This friction velocity (u^*) filtering procedure is necessary for determining the validity of the night-time fluxes, as used by Novick et al. (2009) to examine the nocturnal ET fluxes from eddy covariance records.

The gaps in half-hour fluxes were filled by the marginal distribution sampling (MDS) method outlined in Reichstein et al. (2005), where R_n , vapor pressure deficit (VPD), and u^* were used as the gap-filling conditions. However, when this was not possible, the seasonal mean ratio between ET and potential evapotranspiration (PET) was used. The choice of the MDS method was based on the study by Novick et al. (2009) where they found that this method generally performed well, with a site average bias error of less than 10% and a mean absolute error close to the random measurement error of the dataset. The half-hourly fluxes were then aggregated into the daily scale.

Ground heat flux (G , $W m^{-2}$) at Sibbald calculated from the soil heat flux measurements, while at Burstall and Bonsai, due to intermittent malfunctions of the soil heat flux plates, G was calculated calorimetrically using profiles of soil temperatures and soil heat capacity (Gao et al., 2017; Sauer and Horton, 2005).

The lack of energy balance closure is common among flux sites, and the energy balance ratio (EBR), which is the ratio of the sum of the sensible heat and the latent heat to the difference between R_n and G , is around 0.76 for wetland ecosystems (Stoy et al., 2013). In this study, the averaged EBR calculated from the daily, MDS gap-filled fluxes during the study period is 0.77 for Sibbald, 1.21 for Burstall, and 0.83 for Bonsai, respectively. The average EBR at Burstall indicates that the site may experience advection fluxes. To provide a sufficient evaluation of the SEE-incorporated Shuttleworth–Wallace model, the modelled latent heat fluxes were compared to both energy balance uncorrected and energy balance corrected latent heat fluxes from the eddy covariance measurements. The energy balance correction was performed

following the FLUXNET data processing procedure based on the assumption that the Bowen ratio is correct (Pastorello et al., 2020).

4.2.4 The controlled evaporation experiments

To quantify the effects of ground covers and the overstory canopy on ground surface evaporation, micro-lysimeters (MLs) were utilized to measure the evaporation rate from soil columns under various ground covers, both with and without the presence of an overstory canopy. The MLs had dimensions of 10 cm in diameter and 15 cm in depth at Sibbald and Burstall. At Bonsai, the MLs were also 10 cm in diameter but had a shallower depth of 7.5 cm due to the presence of a thin soil layer.

A detailed description of the design of the controlled evaporation experiments and supplementary microclimatic measurements has been provided elsewhere (Wang et al., 2023). Briefly, the controlled evaporation experiments involved various ground cover combinations, such as bare soil (S), bryophyte-covered soil (BS), litter and bryophytes covered soil (LBS), and soil covered by ground vascular vegetation, litter, and bryophytes (PLBS). The PLBS treatment was applied only at Bonsai, where the ground vascular vegetation was the understory short vascular plants. Additionally, two levels of canopy treatment were applied: no canopy (NC) and below the canopy of willow trees (BC). The experiments were carried out during July and August of 2021, during which each site underwent 6 measurement rounds, with each round lasting 2 to 4 days (Table C1). Within each round, there were three replicates for every treatment level.

At each site, one of the six rounds is unique because ground surface evaporation was measured both in the middle and at the end of that round. As a result, this round contains two evaporation measurements. Specifically, these measurements are labeled as round 1.1 and 1.2 at Sibbald, and round 3.1 and 3.2 at both Burstall and Bonsai.

The quantification of the actual evaporation rate (E_a , mm d⁻¹) involved measuring the change in weight of the MLs before and after each experimental round, excluding any rainfall recorded during the same period, as:

$$E_a = \frac{10 \times [W_{\text{before}} - W_{\text{after}} + (\text{Precip} \times A_{\text{MLs}})]}{\text{Day} \times A_{\text{MLs}}} \quad (1)$$

where W_{before} and W_{after} are the weight of MLs at the beginning and the end of each evaporation experiment (g), respectively; Precip is the precipitation input to MLs (cm) calculated based on the relationship between rainfall interception and LAI of the willow trees (Wang et al., 2023); A_{MLs} is the cross-sectional area of the PVC pipes (cm²); Day is the duration of each evaporation experiment (d); and 10 is the conversion coefficient to convert the unit from centimeters to millimeters. In some cases, ground surface evaporation was very low, and due to the measurement errors, some MLs exhibited negative evaporation rates. These data were excluded from the analysis.

Following each round of evaporation experiments, the dry weights of soil, bryophytes, litter, and ground vascular plants were determined by oven-drying the samples at 70 °C (using the Fisher SCI, Isotemp incubator 200 series) until their weights became constant. The mass fraction (f_k) of soil, bryophytes, litter or ground vascular vegetation was calculated as:

$$f_k = \frac{W_k}{W_s + W_B + W_L + W_P} \quad (2)$$

where W_k is the dry weight of the sample (g); and subscript k corresponds to S, B, L and P for soil, bryophytes, litter, and ground vascular vegetation, respectively. The biomass of bryophytes, litter and ground vascular vegetation between NC and BC conditions were presented in Appendix B (Section B). At any site, no significant difference in dry biomass was detected between NC and BC conditions for any of the ground cover types.

4.2.5 Porometry measurements

Leaf porometer (Model SC-1, Decagon: Pullman, WA) was employed to measure stomatal conductance (g_s , m s^{-1}) of the dominant vascular vegetation, similar to the measurement described in Lafleur (1988) and Moore et al. (2022). At Sibbald, g_s was measured for willows (*Salix lasiandra*) and sedges (*Carex* spp.), which constituted 23% and 65% of the land cover of the site, respectively (Streich, 2019). At Burstall, the dominant species were also willows (*Salix bebbiana*, *Salix planifolia*) and sedges (*Carex* spp.), which took up around 10% and 35% of the land cover, respectively (Hathaway, 2022). At Bonsai, the measured plants were *Salix bebbiana*, *Salix planifolia*, *Erigeron caespitosus* and *parnassia*. Collectively, the willows and ground vascular vegetation at Bonsai contributed to approximately 20% and 50% of the land cover, based on unpublished data from Hrach (2020).

The preliminary porometry measurements on the adaxial and abaxial sides of leaves of the dominant species indicate the porometer response on the abaxial surface is extremely low, probably due to low light availability. Therefore, only the adaxial surfaces of these species were sampled. It is important to note that willows (*Salix* spp.) can be either amphistomatous (i.e., leaves with stomata on both adaxial and abaxial surfaces), hemiamphistomatous (i.e., leaves with stomata on only the adaxial surface), or hypostomatous (i.e., leaves with stomata only on the abaxial surface), while *Carex* and *parnassia* are known as hypostomatous with few exceptions (Argus, 1986; Ghahremaninejad et al., 2012; Lafleur, 1988; Standley, 1986; Wu et al., 2005). No information is available for *Erigeron caespitosus*, but evidence shows that some species from the *Erigeron* genus, like *Erigeron Canadensis* and *Erigeron bonariensis*, are amphistomatous (Shahzad et al., 2022). Measuring stomatal conductance solely on the adaxial side can introduce uncertainty, but based on the results of the preliminary measurements, this uncertainty was assumed negligible.

For willows, four leaves at the canopy height, orienting north, south, west, and east per individual tree, were randomly selected. For sedges, two specific points along the leaf were chosen, starting from the tip and moving towards the leaf stalk. The first point was where the

width of the leaf could completely cover the measurement hole of the sensor head, while the second point was at the bottom of the leaf where it attached to the ligules. The g_s of the sedges was compared at the two measuring points and no statistically significant difference was found, which is in accordance with the findings of Lafleur (1988). Measurements were then averaged for each individual plant, and the mean g_s for each plant was assigned to the time corresponding to the midpoint of the measurement session.

All measurements were conducted two to three times per week, excluding days with rainfall (Lafleur, 1988), between July 19th and August 31st in 2021. Measurements were carried out between 11:00 AM to 5:00 PM, with three successive readings taken per leaf and three to nine individuals per species as replicates. Calibration was made prior to the measurements per measurement day. And recalibration within the same day was performed sporadically in response to significant shifts in ambient temperature or relative humidity (Moore et al., 2022).

4.3 Evapotranspiration partitioning using the modified Shuttleworth–Wallace model

4.3.1 The model structure and the formulation

The Shuttleworth–Wallace (S-W) model was utilized to partition latent heat flux (λET , the amount of energy used for evapotranspiration, expressed in $W\ m^{-2}$) into vascular plant transpiration (λT , defined as the amount of energy used for transpiration from vascular vegetation, expressed in $W\ m^{-2}$) and ground surface evaporation (λE , defined as the amount of energy used for evaporation from soil, bryophytes and litter) in this study. The model was developed by Shuttleworth and Wallace (1985), and has been widely used for ET partitioning across various ecosystems, ranging from humid to arid (Chen et al., 2022a; Hu et al., 2009).

The S-W model likens the movement of water vapor from the soil to the atmosphere to the flow of electric current. A schematic illustration of the S-W model for bryophytes and litter covered wetlands is presented in Figure 4-2, where the ground surface level is positioned at the top surface of the litter layer, and the canopy is a conceptual single layer representing all

vascular plants including sedges, willows and others mentioned in the site descriptions. The canopy height shown in Figure 4-2 resembles a cloth draped over the site as illustrated in Ameriflux ancillary data (<https://ameriflux.lbl.gov/>). The average height of the hypothetical canopy at each site, referred to as the mean aerodynamic canopy height, was determined based on its effect on the logarithmic wind profile and was set to 1.6 m, 1.6 m and 0.8 m for Sibbald, Burstall and Bonsai, respectively, to match the roughness length and the displacement height used for processing EC fluxes at each site. The resistance to water vapor flow includes the aerodynamic resistance between the canopy and the eddy covariance measurement level, denoted as r_{aa} ; the aerodynamic resistance between the ground and the canopy, denoted as r_{as} ; the bulk boundary layer resistance of the vegetative elements in the canopy, denoted as r_{ac} ; the bulk stomatal resistance of the canopy, denoted as r_{sc} ; and the ground surface resistance, denoted as r_s . All resistance terms are measured in $s\ m^{-1}$. The details of the model's structure and parameterization are provided in Shuttleworth and Wallace (1985).

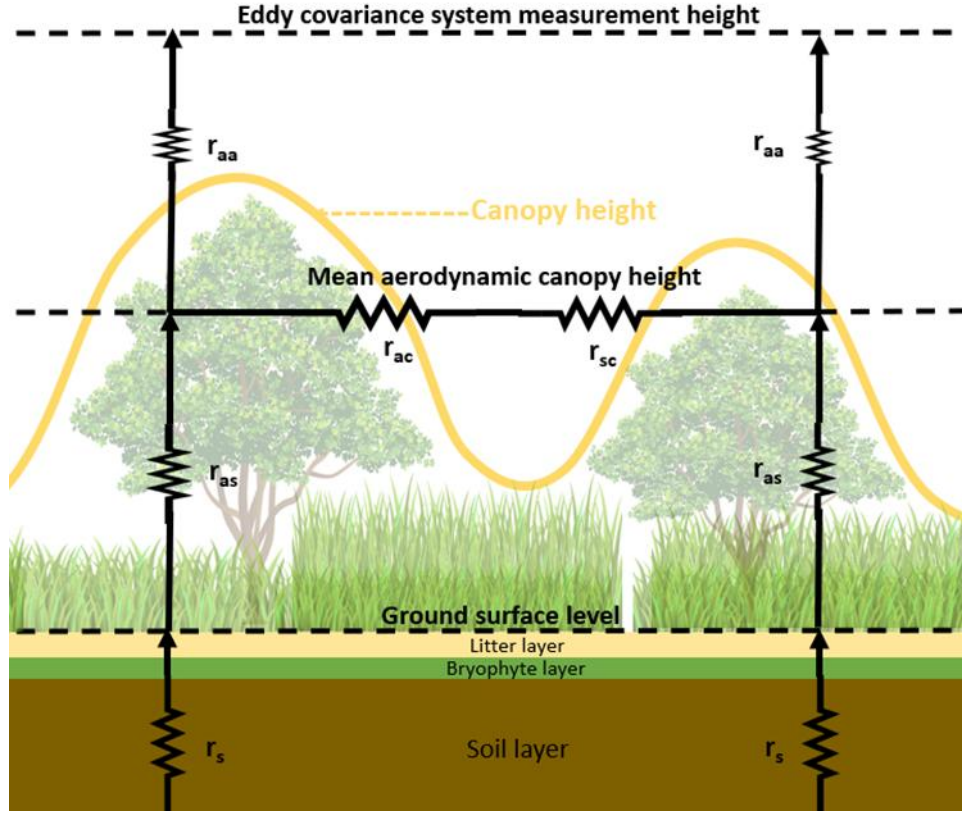


Figure 4-2. Schematic illustration of the latent heat partitioning for bryophytes and litter covered wetlands with the Shuttleworth–Wallace model. This graph was adapted from Shuttleworth and Wallace (1985). The resistance terms, r_{aa} , r_{as} , r_{ac} , r_{sc} , and r_s are explained in the main text.

Based on the S-W model, the wetland λET , which is the sum of λT from vascular vegetation and λE from soil, bryophytes, and litter, was calculated as follows:

$$\lambda ET = C_c PM_c + C_s PM_s \quad (3)$$

$$PM_c = \frac{\Delta(R_n - G) + \left[\frac{\rho c_p VPD - \Delta r_{ac}(R_{ns} - G)}{r_{aa} + r_{ac}} \right]}{\Delta + \gamma \left(1 + \frac{r_{sc}}{r_{aa} + r_{ac}} \right)} \quad (4)$$

$$PM_s = \frac{\Delta(R_n - G) + \frac{\rho c_p VPD - \Delta r_{as}[(R_n - G) - (R_{ns} - G)]}{r_{aa} + r_{as}}}{\Delta + \gamma \left(1 + \frac{r_s}{r_{aa} + r_{as}} \right)} \quad (5)$$

where C_c and C_s are coefficients that depend on Δ , γ , r_{aa} , r_{ac} , r_{as} , r_{sc} , and r_s (Shuttleworth and Wallace, 1985), R_n is the net radiation (W m^{-2}), VPD is the atmospheric vapor pressure deficit (kPa), R_{ns} is the net radiation at the ground surface (W m^{-2}), G is the ground heat flux (W m^{-2}), ρ is the density of air (kg m^{-3}), c_p is the specific heat of air at constant pressure ($1,010 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$), Δ is the slope of the relationship between saturation vapor pressure and temperature ($\text{kPa } ^\circ\text{C}^{-1}$), and γ is the psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$). The expressions of C_c and C_s can be found in Shuttleworth and Wallace (1985) and thus not presented in this study. The calculations of the resistance terms r_{aa} , r_{ac} , r_{as} , r_{sc} , and r_s are introduced later.

R_{ns} was calculated based on Beer's law relationship, following Shuttleworth and Wallace (1985):

$$R_{ns} = R_n \exp(-k \cdot \text{LAI}) \quad (6)$$

where k is the bulk canopy extinction coefficient (-) and LAI is the leaf area index (-). The extinction coefficients for sedges and willows were reported to be both 0.6 (Cannell et al., 1987; Körner, 1982). Therefore, this value was chosen for calculating R_{ns} for our study sites, as the canopies of the study sites mainly consists of sedges and willows.

Following Shuttleworth and Wallace (1985), λT and λE were calculated based on Eq. 7 and Eq. 8, which were derived by combining the flux gradient equation of the latent heat between the canopy level and the eddy covariance measurement height, the Penmen-Monteith equation, and the law of conservation of mass. Consequently, Eq. 7 and Eq. 8 were restructured into Penmen-Monteith type equations containing the vapor pressure deficit at the canopy height (VPD_c , kPa), as (Shuttleworth and Wallace, 1985):

$$\lambda T = \frac{\Delta[(R_n - G) - (R_{ns} - G)] + \frac{\rho c_p \text{VPD}_c}{r_{ac}}}{\Delta + \gamma(1 + \frac{r_{sc}}{r_{ac}})} \quad (7)$$

$$\lambda E = \frac{\Delta(R_{ns} - G) + \frac{\rho c_p \text{VPD}_c}{r_{as}}}{\Delta + \gamma(1 + \frac{r_s}{r_{as}})} \quad (8)$$

The derivation of the expression for VPD_c is provided in Shuttleworth and Wallace (1985), as:

$$VPD_c = VPD + \frac{[\Delta(R_n - G) - (\Delta + \gamma)\lambda ET]r_{aa}}{\rho c_p} \quad (9)$$

where λET was calculated based on Eq. 3, Eq. 4 and Eq. 5, and was equal to the sum of λT and λE calculated from Eq. 7 and Eq. 8.

The formulation presented in this section strictly adhere to the original Shuttleworth–Wallace model. Additionally, the two aerodynamic resistance terms, r_{aa} and r_{as} , were also calculated following the same approach as Shuttleworth and Wallace (1985), and thus were not presented in this study. The deviations from the original S-W model pertain to the calculations of the resistance terms associated with the canopy and the ground surface, and these are demonstrated in Section 4.3.2 and Section 4.3.3.

4.3.2 Parametrization of resistance terms associated with vegetation canopy

The bulk stomatal resistance of the canopy, r_{sc} , was estimated based on the big-leaf model of canopy stomatal conductance, which is the sum of the porometry-based leaf stomatal resistances of the dominant vascular vegetation species weighted by the effective LAI of the study sites (Ding et al., 2014):

$$r_{sc} = \frac{1}{g_{sc}} \quad (10)$$

$$g_{sc} = (\sum_i g_{sl_i} \cdot F_i) \cdot LAI_e \quad (11)$$

where g_{sl} is the half-hourly leaf stomatal conductance ($s\ m^{-1}$) reconstructed from the best fitted relationships (i.e., parabolic) between porometry-based leaf stomatal conductance (g_s , $m\ s^{-1}$) and half-hourly VPD (Table C2), as VPD is likely the main driver of the canopy conductance rather than soil moisture or photosynthetic photon flux density (PPFD) (Flo et al., 2022). The subscript i corresponds to each measured species, F_i is the land cover proportion of

each species, and LAI_e is the effective LAI. For $LAI \leq 2$, $LAI_e = LAI$; for $LAI > 4$, $LAI_e = LAI/2$; and $LAI_e = 2$ for others (Ding et al., 2014).

Typically, there are two approaches for scaling g_{sl} to g_{sc} . The first, known as the big-leaf model, scales up g_{sl} weighted by LAI_e , as used in this study. The second approach, the dual-leaf model, requires differentiating the mean leaf stomatal conductance and their respective fractions of LAI for sunlit and shaded leaves (Ding et al., 2014). The dual-leaf model could not be employed due to the lack of measurements of sunlit and shaded leaves. Instead, the big-leaf model, which treats the canopy as a single big-leaf (which is consistent with the assumption made by the S-W model), was used, though in reality, the canopy comprises multiple and potentially overlapped layers of vascular plants. Additionally, the justification of using LAI_e instead of LAI is that the contribution of different leaves to g_{sc} might vary due to differences in their positions, orientations, light availability, etc. Without using LAI_e , g_{sc} would be overestimated. It should be pointed out that the empirical relationship between LAI and LAI_e used in this study, which has been previously applied for croplands (Ding et al., 2014; Zhang et al., 2008), may be ecosystem-specific. More complex methods for calculating LAI_e do exist (e.g., Kompanizare et al. (2022)). However, this relationship is probably the simplest way to calculate LAI_e from available site measurements and it proved effective in this study (presented in Section 4.5.3).

The bulk boundary layer resistance of the canopy (r_{ac} , $m\ s^{-1}$) is calculated following Shuttleworth and Wallace (1985), as:

$$r_{ac} = \frac{r_b}{2LAI} \quad (12)$$

where r_b is the leaf boundary layer resistance ($s\ m^{-1}$).

Instead of assigning an arbitrary value of r_b as Shuttleworth and Wallace (1985), r_b was calculated according to the empirical formula of Kellner (2001):

$$r_b = \frac{a(u^* z_0/v)^{0.25} - b}{\kappa u_*} \quad (13)$$

where z_0 is the roughness length (m) (Table C3), u^* is the friction velocity determined from eddy covariance measurements (m s^{-1}), κ is the von Karman constant (0.4), a and b are empirical parameters, 1.58 and 3.4, respectively, and ν is the kinematic viscosity of air ($\text{m}^2 \text{s}^{-1}$), which was calculated following Sutherland (1893):

$$\nu = \frac{\mu}{\rho} \quad (14)$$

$$\mu = \frac{1.458 \times 10^{-6} (T_a + 273.15)^{3/2}}{(T_a + 273.15) + 110.4} \quad (15)$$

where μ is the dynamic viscosity ($\text{kg m}^{-1} \text{s}^{-1}$) and ρ is the density of the air (kg m^{-3}).

4.3.3 Using the SEE model to parameterize wetland ground surface resistance

To account for the effects of bryophytes and litter on ground surface resistance (r_s , s m^{-1}), part of the formulation used to model the evaporative efficiency (SEE) of vegetated surfaces was integrated into the S-W model, building upon the approach developed in earlier research conducted on the same wetlands (Wang et al., 2023). As mentioned, SEE is the ratio of the actual evaporation to potential evaporation. By using the flux gradient equation for evaporation (i.e., $\lambda E = \frac{\rho c_p}{\gamma} \times \frac{e^*(T) - e_a}{r_{ah} + r_s}$) to express actual evaporation (with r_{ah} and r_s) and potential evaporation ($r_s = 0$) (Merlin et al., 2011; Merlin et al., 2016; Sellers et al., 1992), SEE can be expressed as:

$$\text{SEE} = \frac{r_{ah}}{r_{ah} + r_s} \quad (16)$$

$$r_s = \exp[A - (B\theta/\theta_{\text{sat}})] \quad (17)$$

where r_s is the ground surface resistance (s m^{-1}), θ is the soil volumetric water content at the measured depth, θ_{sat} is the saturated soil volumetric water content, r_{ah} is the aerodynamic resistance that accounts for atmospheric stability conditions (s m^{-1}) (Choudhury et al., 1986; Merlin et al., 2016), and A and B are the site-specific parameters. The variables in the flux gradient equation for evaporation are explained in Merlin et al. (2016).

The soil volumetric water content when SEE is 0.5 is termed the critical soil water content ($\theta_{1/2}$) and it has been found to be linearly correlated with soil texture parameters (e.g., sand and clay fractions of the soils) for bare soil conditions (Merlin et al., 2016). In Wang et al. (2023), a significant linear relationship was found between $\theta_{1/2}$ and bryophytes and litter mass fractions, as:

$$\theta_{1/2} = 15.82f_B + 3.45f_L + 0.40 \quad (18)$$

where f_B and f_L is the mass fractions of bryophytes and litter of the soil columns, respectively.

Wang et al. (2023) also presented evidence showing that the previously considered site-specific parameters A and B in Eq. 17 were influenced by both micrometeorological conditions and ground cover conditions, and there was a significant linear relationship between A and B, as:

$$B = 1.36A - 6.58 \quad (19)$$

Wang et al. (2023) further suggested that Eq. 18 and Eq. 19 might be broadly applicable across mesic ecosystems, given their physical basis in terms of the influence of soil texture on ground surface resistance (Lehmann et al., 2018) and the reported A and B values from other studies (e.g., Crow et al. (2008), Sellers et al. (1992), Kustas et al. (1998) and Merlin et al. (2011)). Therefore, the method used here for parameterizing r_s may be applicable beyond the three sites in this study.

The procedure for determining r_s involves three steps. Firstly, the ground surface resistance at which SEE was 0.5 (denoted as the critical ground surface resistance, $r_{s, \frac{1}{2}}$) for each day, was determined using Eq. 16. In this equation, r_{ah} was substituted with r_{as} to represent the aerodynamic resistance below the hypothetical vascular vegetation canopy. Secondly, by substituting $r_{s, \frac{1}{2}}$ and $\theta_{1/2}$ into Eq. 17, using site-specific characteristics of f_B , f_L , and θ_{sat} , and subsequently combining Eq. 17 with Eq. 19, the parameters A and B were determined for each day. It is crucial to emphasize that the parameters A and B were treated as constant as long as

the ground cover and meteorological conditions remained unchanged, irrespective of changes in θ . This assumption is supported by the evidence demonstrated in Wang et al. (2023). Consequently, given the day-to-day variations in meteorological conditions, the parameters A and B were treated as constant coefficients for each day and site. Finally, the daily r_s at each site was calculated using the respective daily values of A and B, along with the daily average θ , according to Eq. 17.

The S-W model for partitioning ET was run at the daily scale, and additional parameters in the S-W model were provided in Table C3.

4.4 Evaluating the impacts of bryophytes and litter on wetland ground surface evaporation

The impacts of bryophytes and litter, along with their interactions with the presence of the willow tree canopy, on ground surface evaporation, were examined by mixed-effect models. The mixed-effect models were chosen due to the split-plot design of the evaporation experiments, where various ground cover treatments were assigned to each quadrat under two levels of the canopy condition. In other words, ground cover treatments were nested within the quadrats, and the quadrats were nested within the canopy conditions.

In mixed-effects models, fixed effects were the experimental factors that are of primary interest, like ground covers and canopy conditions in this study, and random effects were the uncontrollable variability associated with certain levels of the groups (e.g., quadrats) (Pinheiro and Bates, 2000). Additionally, the experiments were conducted over six rounds per site and the environmental conditions varied across each round, the round itself should be regarded as a fixed effect to account for the impacts of environmental conditions on ground surface evaporation. However, including the round in the mixed-effects models may not provide an intuitive understanding of the impacts of environmental conditions on ground surface evaporation. Therefore, the round was further divided into two factors, the atmospheric evaporative demand and the water availability, because they have long been recognized as the two dominant controls on the evaporation process (Allen et al., 1998; Budyko, 1961; Fu, 1981;

Monteith, 1981). The atmospheric evaporative demand was quantified by the average daily potential evapotranspiration (PET) for each round, computed using the Penman–Monteith equation, assuming water evaporates freely from the surface (i.e., $r_s = 0$) (Allen et al., 1998). The water availability was indicated by both the soil volumetric water content (θ) and the water table depth. Based on the meteorological and soil water conditions during the study period (presented in Section 5.1), the atmospheric evaporative demand of each round at each site was then categorized into high, moderate, and low levels and the water availability was classified as high or moderate. Additionally, site was considered as a fixed-effect factor to account for the unique biological elements (e.g., bryophytes and vegetation community) and geographical setting of each site. Overall, the fixed-effect factors for constructing the mixed-effects models include Site (categorical), Evaporative Demand (categorical), Water Availability (categorical), Canopy (categorical) and Ground Cover (categorical), while the Quadrat (categorical) was treated as the random effect factor. Since all the explanatory variables were categorical with a maximum of three levels, non-linear relationships between them and ground surface evaporation were not considered when constructing the mixed-effect models.

There are two types of mixed-effects models, the linear mixed models (LMMs) and the generalized linear mixed models (GLMMs). Compared to LMMs, GLMMs are able to deal with the non-Gaussian distributed responsive variable, like Poisson-distributed, binomial-distributed or Bernoulli-distributed data, by specifying the appropriate error distribution and the link function (Harrison et al., 2018). Both type of models have been widely used in analyzing the impacts of environmental variables on ground surface evaporation, ET, or ET-related variables like canopy conductance and tree sap flow (André-Alphonse et al., 2023; Irmak and Mutiibwa, 2010; Simpson et al., 2022; Wang and Petrone, 2022). Given that the responsive variable in this study, ground surface evaporation, approximates a Gaussian distribution after being log-transformed, only LMMs were employed. In fact, applying log-transformation on the response variable in LMMs is equivalent to employing the 'Gaussian' family with the log link function in GLMMs. The general form of LMMs used in this study is given as Eq. 20:

$$\lg(\text{Ground surface evaporation}) = \sum \beta X + \sum \gamma Z + \varepsilon \quad (20)$$

where **Ground surface evaporation** is the vector of the responsive variable, ground surface evaporation (mm d⁻¹), $\lg(\dots)$ is the logarithmic function with a base of 10, $\sum \beta X$ represents all the fixed-effects terms where β is the vector of coefficients for fixed-effect factors matrix **X**, $\sum \gamma Z$ represents the random-effect terms where γ is the vector of coefficients for random effect factors matrix **Z**, and ε represents the errors. Unless stated otherwise, vectors are denoted by bold lowercase letters, while matrices are denoted by bold uppercase letters.

LMMs offer multiple ways to incorporate the random effect factor into model structures, including structures with random intercepts or with both random slopes and intercepts (Harrison et al., 2018). Thus, LMMs in this study were constructed into models with various structures and the goodness of fit of these models was evaluated by the Akaike's Information Criterion (AIC), the Restricted Maximum Likelihood (REML), root mean square error (RMSE) and mean square error (MSE). The model with the optimal structure is the one with the lowest AIC, REML, RMSE and MSE values, and if two models with different structures exhibit the same goodness of fit, the model with a simpler structure is preferred. The LMMs in this study were constructed by the “lme4” package (Bates et al., 2015) in R programming language version 4.3.0 (R Core Team 2023). RMSE and MSE were calculated by the “rmse” and “mse” functions from the “sjstats” package (Lüdtke, 2019).

Furthermore, not all the fixed-effect variables and their interactions have significant impacts on ground surface evaporation. To identify all the significant variables, the backward selection was employed. This process began with the model having all candidate terms. Each term was tested for removal until no further terms could be deleted without causing a statistically significant loss of fit. Any term is considered significant only if the model containing it demonstrates better goodness of fit compared to the other models and if the p-value from the analysis of variance test (ANOVA) type III test for this term falls below 0.05. The process for determining the optimal structure of the LMMs is detailed in Table C4. Interestingly, based on the goodness of fit, the optimal model structure is the fixed-effect model (Model No.1 in Table

C4). However, since the experimental design of the evaporation experiments reflects a hierarchical structure, and there are still debates about whether or not to exclude the random effect term from the LMMs in this situation, both the optimal fixed-effect model and the optimal linear mixed model (i.e., Model No. 2 in Table C4) were retained for further analysis. The backward selection was performed by the “step” function in the “lmerTest” package (Kuznetsova et al., 2017), and the ANOVA type III test was performed by the “Anova” function in the “car” package (Fox and Weisberg, 2018). The assumptions of the linear models, including equal variance of errors and normality of errors, were checked for both optimal models, and the two models generally met these criteria. The results of the backward selection and the ANOVA table for the optimal fixed-effect model and the optimal linear mixed model are presented in Table C5 and Table C6, respectively.

The LMMs and the ANOVA test identified the factors that significantly affected ground surface evaporation. To further understand the impact of each type of the ground cover on ground surface evaporation, the Wilcoxon rank-sum test was also used to compare whether the median ground surface evaporation under one treatment level was statistically different from that under another treatment level. Before conducting the Wilcoxon rank-sum test, the ground surface evaporation was averaged for each round under the same treatment level of canopy and ground cover to eliminate uncontrolled variabilities from the quadrats. A two-sided p -value ≤ 0.05 was considered statistically significant. However, the Wilcoxon rank-sum test was only applied to pairs of groups with two or more data points, and the results should be interpreted with caution, as the small sample size in this study may have led to insignificant p -values.

4.5 Results

4.5.1 The environmental conditions

Throughout the study period, various meteorological and soil water conditions were observed at the three sites. In Sibbald (Figure 4-3), the daily weather conditions remained relatively stable from early July to mid-August, with daily T_a around 15 °C, daily R_n between 150 to 200 W m⁻², daily VPD between 0.5 to 1 kPa, and daily T_{soil} ranging from 12 to 20 °C.

Meanwhile, soil water content and water table depth steadily decreased. Beginning August 9th, the water table depth at the well #2 dropped to the well's bottom which was approximately 1.4 m below the ground surface. From mid-August, the region experienced several days of cloudy, rainy weather, which led to a noticeable decrease in R_n , T_a , VPD and T_{soil} , and soil water content showed a slight increase. During this period, the water table depth in the well #1 showed a slight response to the precipitation, while the well #2 remained dry.

The ground surface evaporation under various treatments at Sibbald typically mirrors the dynamics of PET. Based on Figure 4-3, the six rounds of the experiments are divided into three conditions. Condition 1, consisting of rounds 1.1 and 1.2, is marked by high atmospheric evaporative demand and high water availability. Condition 2, which includes rounds 2, 3, 4, and 6, is characterized by moderate evaporative demand and moderate water availability. Condition 3, represented by round 5, is characterized by low evaporative demand and moderate water availability.

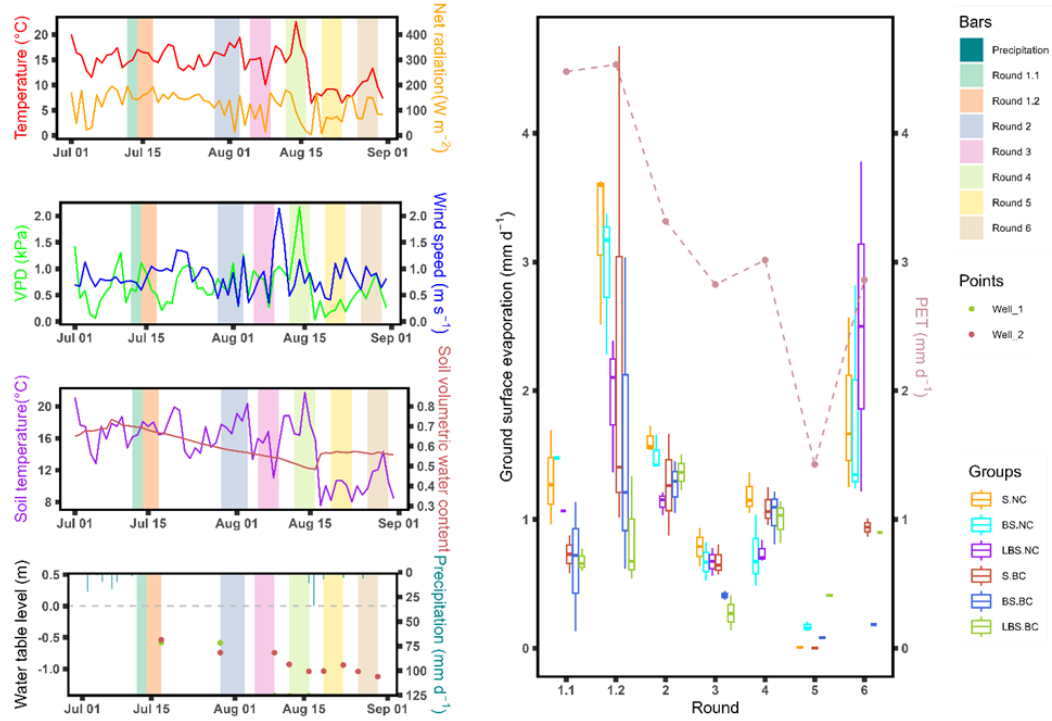


Figure 4-3. Environmental conditions (left panel), measured ground surface evaporation (boxplots at the right panel) and corresponding potential evapotranspiration (PET, dashed line in the right panel) at Sibbald during the study period. Each round of the evaporation experiments is indicated by different colored shades in the left panel.

The meteorological measurements at Burstall began on July 8th. During the measurement period, the meteorological conditions observed at Burstall closely resembled those at Sibbald (Figure 4-4). However, Burstall consistently maintained saturated conditions throughout the study period, with its soil water content around 0.7 and its water table remaining within 0.1 m of the ground surface. The ground surface evaporation at Burstall also followed the dynamics of PET. Based on Figure 4-4, rounds 1, 2, 3.1 and 3.2 are classified under Condition 1, which is characterized by high evaporative demand and high water availability. Rounds 5 and 6 fall under Condition 2 marked by moderate evaporative demand and high water availability, and round 4 represents Condition 3, which has low evaporative demand and high water availability.

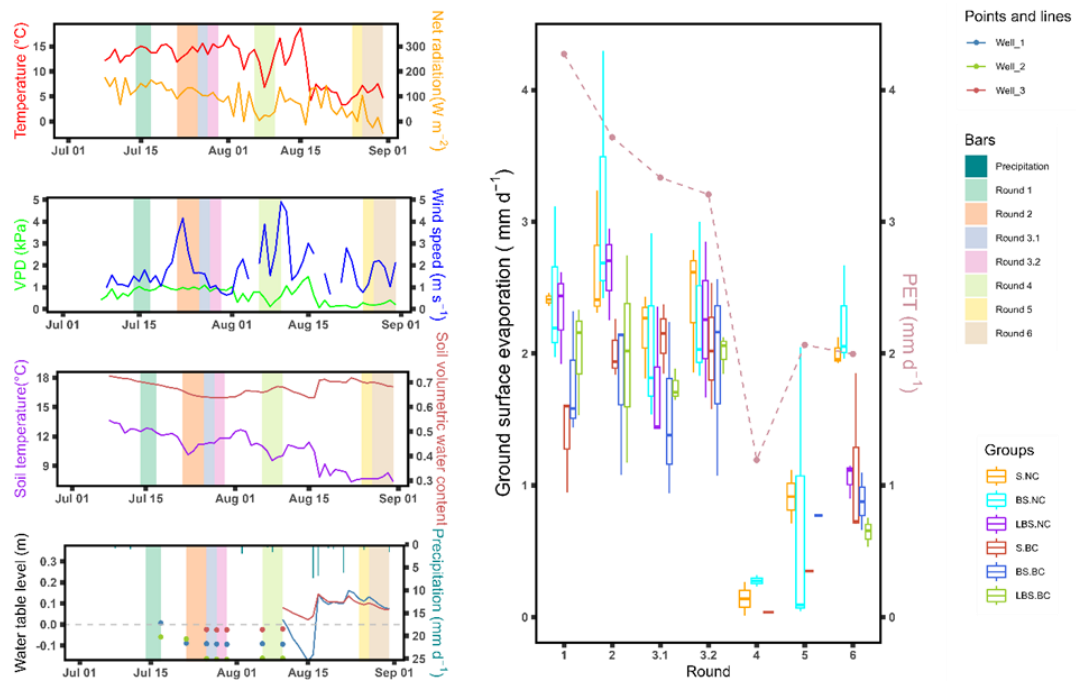


Figure 4-4. Environmental conditions (left panel), measured ground surface evaporation (boxplots at the right panel) and corresponding potential evapotranspiration (PET, dashed line in the right panel) at Burstall during the study period. Each round of the evaporation experiments is indicated by different colored shades in the left panel.

At Bonsai (Figure 4-5), the collection of meteorological data began on July 6th. From early July to mid-August, the daily weather conditions remained relatively stable, with both daily T_a and T_{soil} above 10 °C, daily R_n around 100 W m⁻², and daily VPD between 0.5 to 1 kPa. During this period, soil water content steadily decreased. In late August, frequent precipitation led to a sudden increase in soil water content, while R_n , T_a , VPD and T_{soil} were all relatively low. Ground surface evaporation also mirrored PET. However, PET from round 1 to round 3.2 was not calculated due to the lack of ground heat fluxes data for that period. Based on the environmental conditions presented in Figure 4-5, round 1 is classified under Condition 1, characterized by high evaporative demand and moderate water availability. Rounds 2, 3.1 and 3.2 are grouped into Condition 2, marked by both moderate evaporative demand and water availability. Rounds 4, 5 and 6 are grouped into Condition 3, featuring low evaporative demand and moderate water availability.

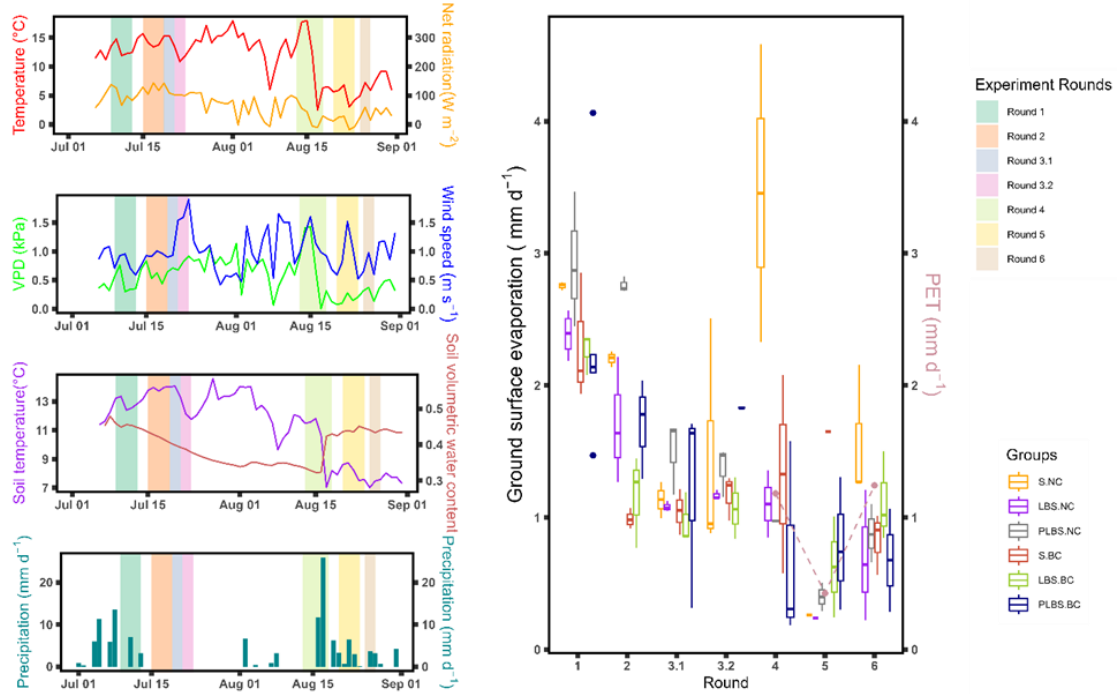


Figure 4-5. Environmental conditions (left panel), measured ground surface evaporation (boxplots at the right panel) and corresponding potential evapotranspiration (PET, dashed line in the right panel) at Bonsai during the study period. Each round of the evaporation experiments is indicated by different colored shades in the left panel.

4.5.2 Ground surface evaporation in bryophytes and litter covered wetlands

The backward selection and the ANOVA test for both the optimal fixed-effect model and the optimal linear mixed model show that ground cover, along with its interaction effects with site, evaporative demand, and water availability, significantly impacts ground surface evaporation (Table C5 and Table C6).

Figure 4-6 presents ground surface evaporation across various conditions of evaporative demand, water availability, canopy, and ground cover types, using grouped box-violin plots. In this figure, the violin plots show the distribution of ground surface evaporation data (only created for groups with two or more data points), while the boxplots display the lower quartile,

median, and upper quartile values of the ground surface evaporation. Additionally, the mean value for each group is marked by gray dots.

As shown in Figure 4-6, when evaporative demand was high or moderate, ground surface evaporation under bryophytes and litter covers (e.g., BS and LBS groups) was generally lower than that of bare soils for all the sites, regardless of water availability conditions. When evaporative demand was low and water availability was high or moderate, ground surface evaporation under bryophytes and litter covers appeared higher than that of bare soils at sites with peats soil substrates, such as Sibbald and Burstall. However, at the site with mineral soil substrate, Bonsai, ground surface evaporation under bryophytes and litter covers was generally lower than that of bare soils, irrespective of evaporative demand conditions. Using the Wilcoxon rank-sum test to compare ground surface evaporation across different ground cover treatments under the same canopy, evaporative demand and water availability conditions, significant differences were only detected in two cases: (1) at Burstall between S and LBS under BC conditions, when both evaporative demand and water availability were high, and (2) at Bonsai between S and PLBS under BC conditions, when the evaporative demand was moderate or low.

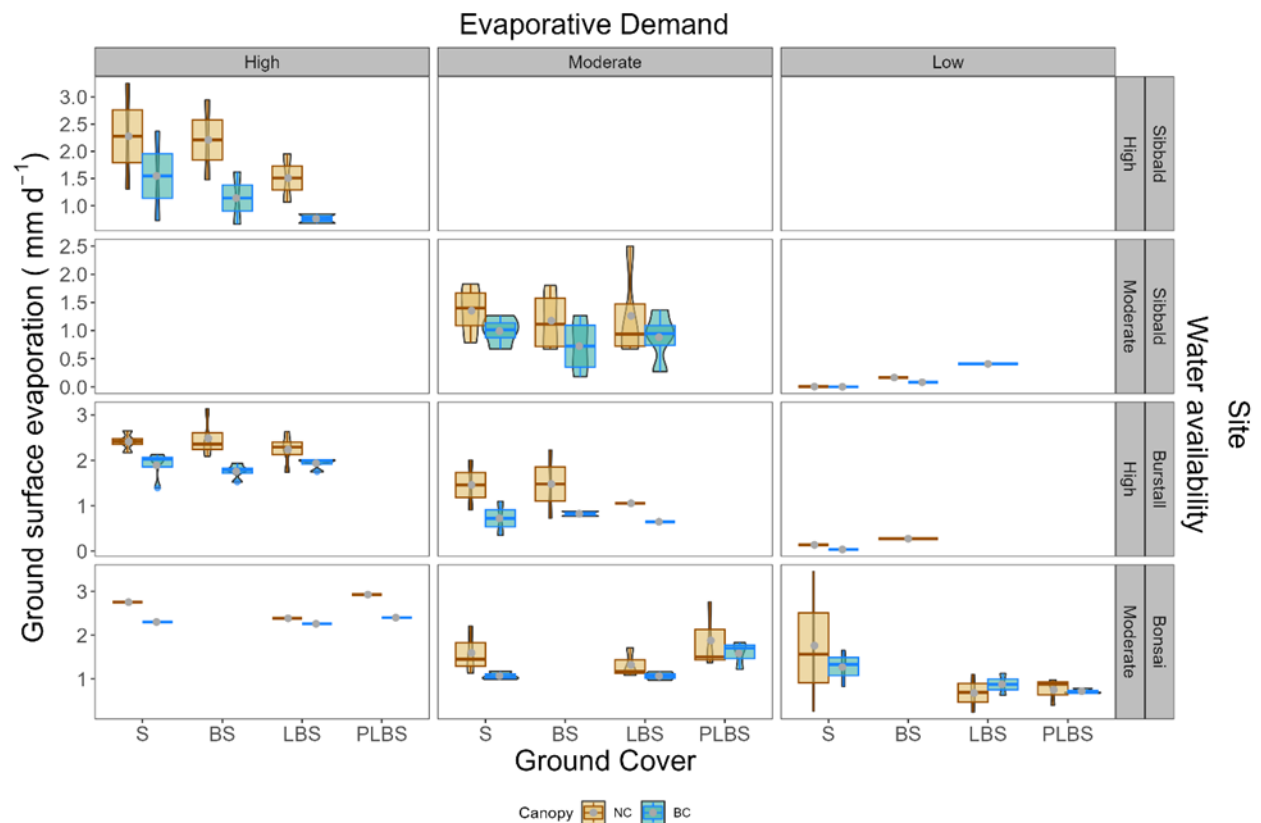


Figure 4-6. The grouped box-violin plot of ground surface evaporation for various ground cover types: bare soil (S), soil-bryophyte (BS) and soil-bryophyte-litter (LBS) at Sibbald and Burstall, and S, LBS and soil-bryophyte-litter-ground vascular vegetation (PLBS) at Bonsai. Data are shown for both open area (NC) and areas below willow tree canopy (BC), across conditions of high, moderate, and low evaporative demand, and high and moderate water availability.

It can also be observed from Figure 4-6 that, in most cases, ground surface evaporation was lower under BC compared to its counterparts under NC. However, the impacts of canopy and its interaction effects with site, evaporative demand, water availability, and ground covers on ground surface evaporation are not consistent across different statistical analysis. On one hand, the backward selection for both models indicates that canopy and its interaction effects with other fixed-effect factors are necessary variables affecting ground surface evaporation; on the other hand, the ANOVA test for the optimal fixed-effects model and the optimal mixed effect models shows that canopy itself is not a significant factor. Additionally, the significance of the

interaction effects of canopy with site, evaporative demand, water availability, and ground covers from the ANOVA tests for both models are not consistent (Table C5 and Table C6). Furthermore, the Wilcoxon rank-sum test comparing ground surface evaporation across different canopy treatments, while under the same ground cover, evaporative demand and water availability conditions, reveals a significance only at Burstall. This difference occurred between the NC and BC treatments for the S and BS groups, under conditions where both the evaporative demand and the water availability were high.

Overall, the controlled evaporation experiments show that the effects of site, evaporative demand, water availability, canopy and ground cover on ground surface evaporation are interactive and site-specific. More importantly, the backward selection, the ANOVA test and the Wilcoxon rank-sum test all identified ground cover as a significant variable affecting ground surface evaporation. These results highlight the need to incorporate ground cover into evaporation models for estimating wetland ground surface evaporation.

4.5.3 Evapotranspiration partitioning in bryophytes and litter covered wetlands

Over the study period, Sibbald recorded a total ET of 196 mm, averaging 3.2 mm per day. Burstall recorded a total of 159 mm, or 2.9 mm d⁻¹, while Bonsai had a total ET of 49 mm, which corresponds to 1.4 mm per day.

Daily partitioning of λE into λT and λE , using the modified S-W model, during the study period is presented in Figure 4-7. In this figure, the ET partitioning at Burstall began on July 8th when the field measurement started, while at Bonsai, it began on July 27th when ground heat flux data became available. Throughout the partitioning period, the average daily T/ET ratios for Sibbald, Burstall, and Bonsai were 0.86, 0.46, and 0.61, respectively. Days with negative T/ET values were excluded from the daily average calculations. The negative T/ET is a result of the S-W model's parameterization not effectively partitioning ET under low R_n conditions, causing small λT values to appear as negative. However, based on the eddy covariance-based, energy balance corrected λET and the lysimeter-based ground surface evaporation, ET under low R_n conditions (i.e., rounds 5 and 6) was dominated by E. Despite

the poor performance of the S-W model under low R_n conditions, the overall results show that ET at Sibbald and Bonsai during the study period was more T-dominated, while Burstall was more E-dominated. When excluding rainy days, the daily average T/ET ratios were 0.86 for Sibbald, 0.50 for Burstall, and 0.60 for Bonsai. The model did not produce negative T/ET values on rain-free days.

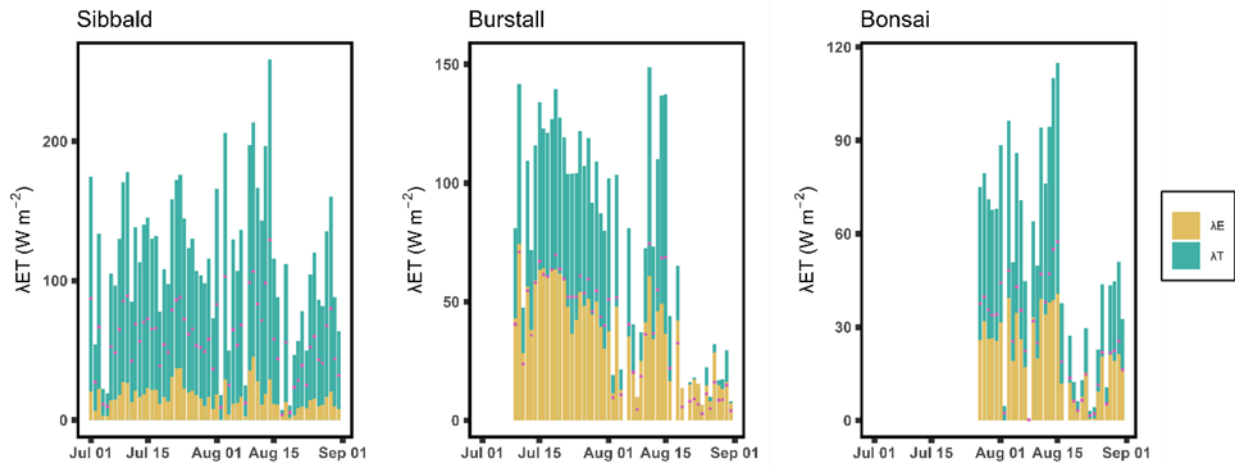


Figure 4-7. The stacked bar plot of the daily latent heat (λET , $W m^{-2}$) partitioned into evaporation (λE , $W m^{-2}$) and transpiration (λT , $W m^{-2}$) components based on the modified Shuttleworth–Wallace model over the study period for three sites. The magenta segment on each bar represents 50% of daily λET .

Partitioning results were validated by comparing λET from the modified S-W model with eddy covariance measurements at the daily scale and by comparing modelled λE with microlysimeter measurements across all 6 rounds of evaporation experiments. As shown in Figure 4-8, the modelled λET agrees well with the measured λET , especially with the energy balance-corrected λET , as the slopes of fitted linear regressions range from 0.87 to 1.16, intercepts range from -18.50 to 3.78 $W m^{-2}$, and R^2 values are all greater than 0.78. Better agreement with the energy balance corrected fluxes is anticipated, as the S-W model is based on the energy balance closure.

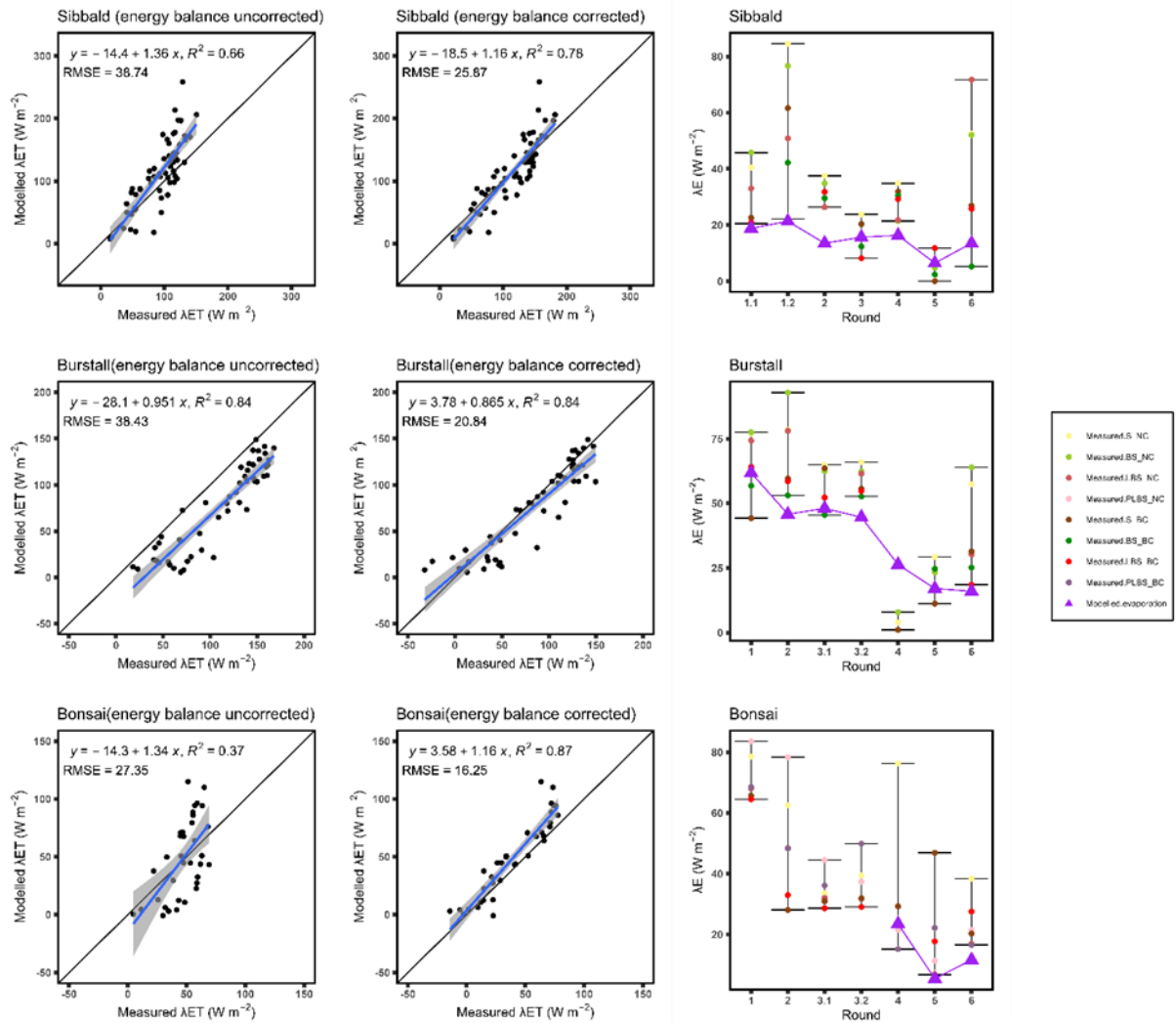


Figure 4-8. Comparisons between the modelled and measured latent heat (λET) during the study period (left and middle panels), and between the modelled and measured ground evaporation (λE) across all 6 rounds of evaporation experiments (right panel).

In Figure 4-8, the purple lines linking modelled ground surface evaporation (purple triangles) in the right panel illustrate the temporal variation of the modelled evaporation across 6 rounds of experiments. In these plots, the range and the magnitude of measured evaporation under various ground covers and overstory canopy conditions for each round of evaporation experiment are represented by the black range bars and the colorful dots. Clearly, the modelled ground surface evaporation at the three sites is slightly lower than the lysimeter-based

measurements but it is considered a reasonable representation of actual ground surface evaporation. This is because the three wetlands had sedges and other tall vascular plants present, which might exert shading effects that led to lower ground surface evaporation. However, these plants were removed in the controlled evaporation experiments; therefore, the lysimeter-based ground surface evaporation would have been greater than the actual ground surface evaporation. Notably, Sibbald has noticeably denser growth of sedges, as shown in the field photo (Figure 4-1). This could explain the larger intercept of the fitted linear regression between modelled and measured λET , as the actual light availability below the hypothetical canopy at Sibbald may be less than that in the S-W model's parameterization.

Overall, the modelled results show satisfactory consistency with the measurements in terms of both magnitude and temporal dynamics, which substantiates the appropriateness of the modified S-W model for accounting for the impact of bryophytes and litter on ground surface evaporation and evapotranspiration partitioning.

4.5.4 The environmental controls on evapotranspiration partitioning

If the modified S-W model accurately represents the fundamental mechanisms driving wetland ET partitioning, then the environmental controls of daily ET partitioning are the input variables of the modified S-W model, such as R_n , G , T_a , u , VPD , and LAI , as introduced in the method section. Their influences on ET partitioning has been well examined in Shuttleworth and Wallace (1985) and are therefore not repeated here. However, since the S-W model in this study was modified with a novel method for parameterizing the ground surface resistance using the mass fractions of bryophytes and litter, the question remains: how and to what extent do the mass fractions of these ground covers affect wetland ET partitioning?

Figure 4-9 illustrates the daily T/ET derived from the modified S-W model across varying mass fractions of bryophytes, with all other variables remaining unchanged. For sites where ET is dominated by T , such as Sibbald and Bonsai, the average T/ET changes during the study period were less than 1%, when the bryophyte layer ranges from completely removed ($f_B=0$) to its maximum possible extent (i.e., $f_{Bmax} = 1 - f_L$). In contrast, at Burstall, where ET is more

E-dominated, the changes in T/ET are more pronounced, reaching up to 10%. An increase in the mass fraction of bryophytes results in a decrease in the average daily T/ET for the study period, which is due to a large increase in E, a slight decrease in T, and a marginal increase in ET (Figure C1). However, for $f_B \geq 0.5$, a further increase in f_B does not lead to significant changes in E, T, ET, or T/ET.

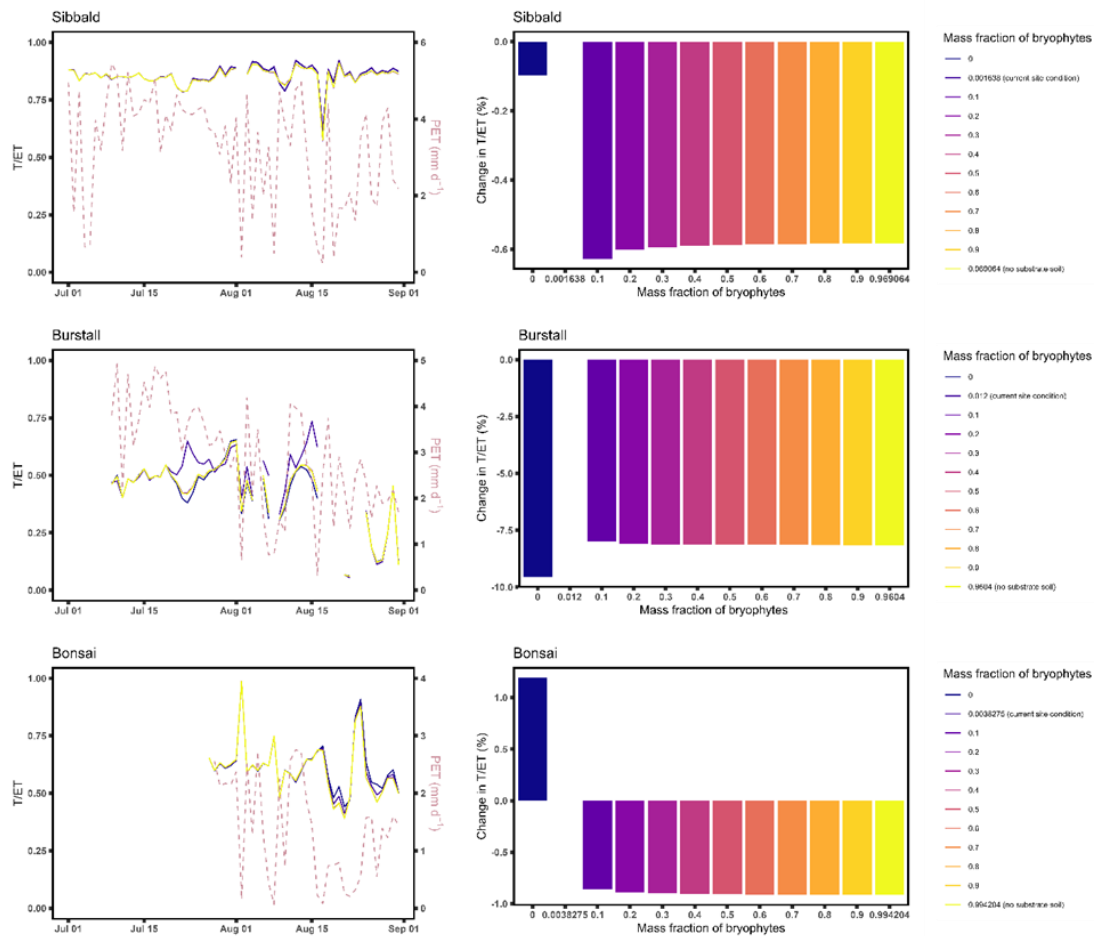


Figure 4-9. The dynamics of the modelled daily T/ET corresponding to different mass fractions of bryophytes and daily PET (pink) during the study period at the three sites (left panel), and the percentage change in modelled T/ET compared to the actual site conditions for each mass fractions of bryophytes (right panel). Negative T/ET values are excluded in the left panel.

Figure 4-10 presents the simulated daily T/ET for various mass fractions of litter. The effect of litter mass fraction on E, T, ET and T/ET is very similar to that of bryophytes, as shown in Figure 4-10 and Figure C2, though litter results in slightly larger changes in T/ET. This similarity is expected due to the SEE method of parameterizing the ground surface resistance, where both bryophytes and litter mass fractions are linearly related to critical soil water content (Eq. 18). Additionally, a comparison of the modelled daily T/ET dynamics (shown in Figure 4-9 and 4-10) with conditions of evaporative demand (indicated by PET) and water availability (Figure 4-3) reveals that the discrepancies in the modelled T/ET across varying mass fractions of bryophytes or litter are most evident under condition of high water availability and large fluctuations in evaporative demand between moderate and low levels.

Despite the influences of evaporative demand and water availability on changes in T/ET, Figure 4-9 and Figure 4-10 suggest that bryophytes and litter covers do not substantially impact the magnitude of T/ET in wetland ecosystems, with maximum changes in T/ET around 10%, despite their significant effects on ground surface evaporation. The influence of bryophytes and litter appears more pronounced in wetlands where ET is dominated by E, as seen in Burstall.

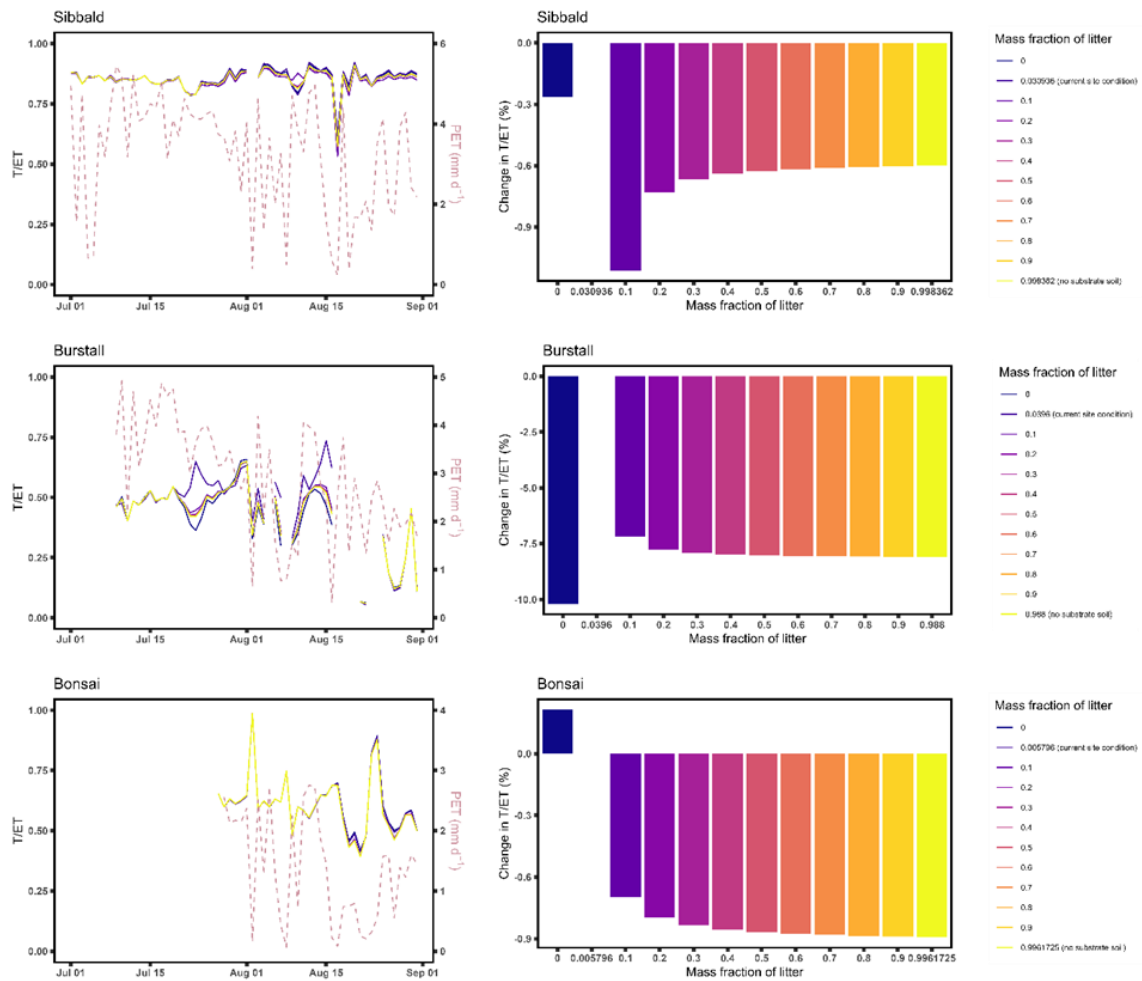


Figure 4-10. The dynamics of the modelled daily T/ET corresponding to different mass fractions of litter and daily PET (pink) during the study period at the three sites (left panel), and the percentage change in modelled T/ET compared to the actual site conditions for each litter mass fraction of (right panel). Negative T/ET values are excluded in the left panel.

In addition to the findings presented earlier, which are based on three study sites, a review of the existing literature on wetland ET partitioning highlights LAI as a key factor influencing this process in wetland ecosystems globally. The relationship between LAI and the ratio T/ET is quantified using a methodology similar to that used by Wang et al. (2014), which fitted an exponential relationship between LAI and T/ET across various ecosystems worldwide. By synthesizing the available LAI and T/ET data, significant exponential relationships are

observed between T/ET and both the average and maximum LAI during the growing season in flooded and non-flooded wetlands (Figure 4-11). Furthermore, the average T/ET values from the three sites during the study period generally align with the predicted range of the exponential relationships for flooded and non-flooded wetlands, corroborating the validity of the partitioning results presented in section 4.5.3.

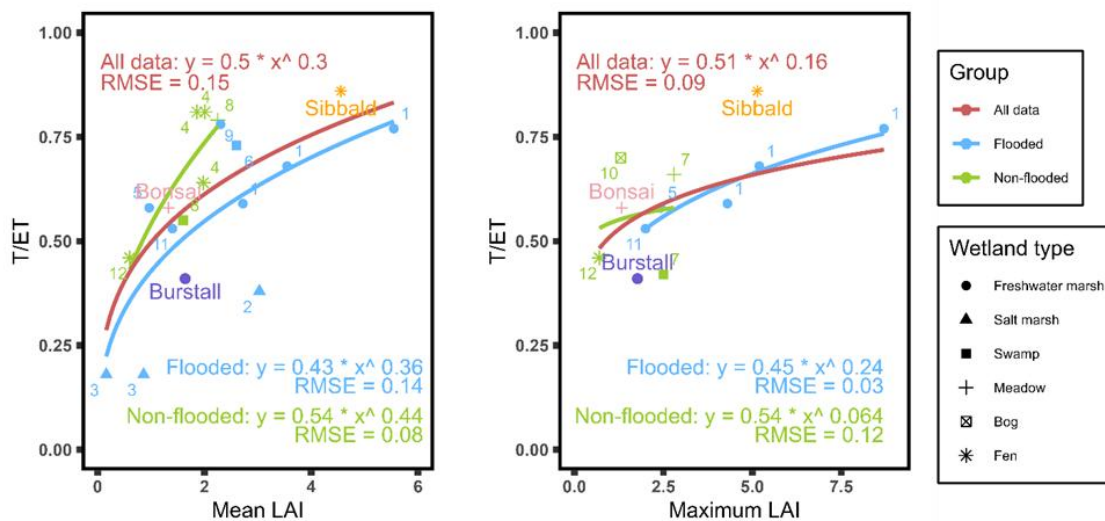


Figure 4-11. The relationship between mean growing season T/ET and mean growing season LAI (left) and maximum growing season LAI for the overall dataset (red), flooded wetlands (blue) and non-flooded wetlands (green). T/ET values from Sibbald (orange), Burstall (purple) and Bonsai (pink) were not included when fitting the exponential relationships. Numbers indicate the sources of data (Table C7).

4.6 Discussions

4.6.1 The effects of bryophytes and litter covers on wetland ground surface evaporation

The results of the controlled evaporation experiments demonstrate that wetland ground surface evaporation is constrained by a combination of ground covers and overstory canopy, consistent with previous research (Campbell and Williamson, 1997; Farrick and Price, 2009;

Kettridge et al., 2013b; Petrone et al., 2001; Price et al., 1998; Putuhena and Cordery, 1996; Rouse, 2000; Thompson et al., 1999). More importantly, this study evidently shows that these impacts interact with evaporative demand and water availability, and are site-specific.

As reported, bryophytes are a group of non-vascular plants that typically grow above soils in moist environments. In northern peatlands, the most common bryophytes are mosses, like *Sphagnum* species (i.e., peat mosses) and brown mosses (Vitt and House, 2021). These species are also the dominant ones in this study. Research shows that mosses can absorb water from their surroundings through their leaves and stems, and store water between 300% and 500% of their dry weight (Bayfield, 1973; Rouse, 2000), but most of them do not have mechanisms for active water regulation. Instead, they rely on their structural and physiological properties to transport water up to their capitula where photosynthesis takes place (Goetz and Price, 2015; McCarter and Price, 2014; Rice and Schneider, 2004; Thielen et al., 2021). This water movement, which is mainly through capillary action, is also regulated by the strength of water binding to mosses and soil substrates, as well as by soil-water potential between soil substrates and atmosphere (Admiral and Lafleur, 2007b; Goetz and Price, 2015; Hayward and Clymo, 1982). Despite site-specific variations in species composition, life traits, biomass, and water use strategies of mosses, when soil-water potential is high, mosses actively evaporate water (Rouse, 2000), but when the surroundings become dry, mosses can quickly equilibrate their water potential with the surrounding air to reduce evaporation loss (Goetz and Price, 2015).

Litter refers to dead plant material that accumulates on the ground and decomposes over time to replenish soils with nutrients. Dense litter, due to its lighter color, has a higher albedo than vegetation, and thus reflects more radiation back to the atmosphere and contributes to a cooling effect on the underlying surface (Eichelmann et al., 2018). Although the effects of litter on energy and water fluxes in natural wetland ecosystems have not been extensively examined, limited research suggests that litter in wetlands acts similar to mulch (Eichelmann et al., 2018; Goulden et al., 2007). Mulch, typically used in gardening and agriculture, consists of organic materials like leaves, straw, and bark chips, or synthetic materials such as plastics or rubber, is applied over soil surfaces for soil and water conservation purposes. In reclaimed wetlands,

mulch helps reduce ground surface evaporation by intercepting net radiation (Price et al., 1998), maintaining lower daytime soil temperatures (Bristow, 1988; Wang and Petrone, 2022), keep consistent or slightly higher soil moisture levels ((Petrone et al., 2001; Price et al., 1998), and reducing atmospheric mixing within the litter layer (Hares and Novak, 1992). Most research on litter focuses on forest ecosystems, where it has been found to intercept annual rainfall by varying degrees, ranging from marginal (~2%) to substantial (~40%) (Helvey and Patric, 1965; Walsh and Voigt, 1977). The water storage capacity of litter also depends on rainfall intensity and the type of litter material (Guevara-Escobar et al., 2007; Putuhen and Cordery, 1996).

The combined bryophytes and litter layers have been found to reduce soil evaporation rates (Farrick and Price, 2009; Wang and Petrone, 2022). This study supports that finding and further suggests that the “barrier” effect of bryophytes and litter on wetland ground surface evaporation occurs when evaporative demand is moderate to high. This can be explained by litter’s ability to limit ground surface evaporation and mosses’ ability to equilibrate their water potential with the surrounding air to reduce evaporation loss as mentioned earlier, since a higher evaporative demand indicates a drier atmosphere. Conversely, when the evaporative demand is low, the amount of water evaporated from the ground surface may depend on the ground surface moisture level. In this case, bryophytes and litter covers would retain more moisture than bare soils, resulting in higher evaporation rates.

Furthermore, water exchange between soil and atmosphere is also influenced by substrate soil characteristics, including particle size, texture, and hydraulic conductivity (An et al., 2018; Shimojima et al., 1996; Wilson et al., 1994). In peat soils, factors such as the level of decomposition and the forming material of peat also affect water movement (Rezanezhad et al., 2016). If the moisture level is the same, peat soils tend to have lower evaporation rates compared to mineral soils, due to their higher water retention capacity, which helps prevent moisture loss (Caron et al., 2015; Feustel and Byers, 1936). The differences in soil characteristics may explain the observed differences in evaporation between Bonsai and the other two sites. Specially, at Bonsai, ground surface evaporation from bare soils was higher than that from soils covered by bryophytes and litter during the periods of low evaporative

demand. In contrast, at the other two sites that have peat substrates, bare soil evaporation was lower than the evaporation from soils with ground covers.

It should be pointed out that all observations and their potential explanations here are based on the condition that water availability is not a limiting factor, a condition generally met in wetland ecosystems. In contrast, in arid ecosystems, the effects of bryophytes and litter covers on ground surface evaporation may be opposite to those observed in this study, as these layers may maintain higher ground surface moisture levels, and thus higher evaporation compared to bare soils. For instance, Murphy and Lodge (2001) reported that evaporation under litter cover was higher in a cropland under dry soil conditions.

In addition to ground cover effects, the canopy intercepts incoming precipitation and solar radiation, creating an understory microclimate that becomes decoupled from atmospheric conditions (Campbell and Williamson, 1997; Farrick and Price, 2009; Kettridge et al., 2013b; Petrone et al., 2001; Putuhena and Cordery, 1996; Rouse, 2000; Thompson et al., 1999). This effect depends on various aspects of the canopy structure, including overstory tree species, canopy thickness, height and closure (Miller et al., 2007; Niu and Yang, 2004; Renaud and Rebetez, 2009; Sakaguchi and Zeng, 2009). Interestingly, ground surface evaporation in this study appear lower under the willow tree canopy than in open areas (Figure 4-6); however, statistical analyses did not find this difference to be significant. The lack of a significant canopy effect may be attributed to the thin canopy of the short willow trees at the study sites, with tree heights ranging from 1.0 to 2.5 m. Additionally, the limited size of our dataset might also play a role. Therefore, more field investigations are needed to further examine the impact of the canopy and its potential interaction with ground covers.

4.6.2 Estimating evapotranspiration partitioning in bryophytes and litter covered wetlands

Results of the controlled evaporation experiments strongly indicate the necessity of accounting for the impacts of bryophytes and litter covers when estimating wetland ground surface evaporation. However, estimating the resistance of bryophytes and litter covered

ground surface has been challenging. To the authors' knowledge, existing methods utilize either evaporation models that treat bryophytes and litter layers as porous media—requiring proper parameterization, including characteristic length, porosity, bulk density, and water retention curve (Enrique et al., 1999; Launiainen et al., 2015; Ogée and Brunet, 2002; Souza et al., 2022)—or obtain the ground surface resistance through inverse calculations from measured evaporation rates (Admiral and Lafleur, 2007a; Kim and Verma, 1996; Moore et al., 2022), which may not be robust when extrapolated to different meteorological conditions. The method used in this study, which estimates the ground surface resistance from the mass fractions of bryophytes and litter, is less parameter-intensive than the aforementioned methods.

Moreover, the method used in this study to estimate the ground surface resistance is not purely a site-specific, empirical approach. As mentioned, water availability is not a limiting factor in the study sites. In other words, the ground surface evaporation observed in this study is the Stage I evaporation, which is supported by internal capillary flow—a process directly controlled by the texture (e.g., pore size) of the porous media and their layering thickness (Lehmann et al., 2018; Or et al., 2013). The effectiveness of this method may be explained by the mass fractions of bryophytes and litters representing appropriate descriptive variables for the texture and layering thickness of the layered porous media. Although the mechanism requires further investigation, the method demonstrated in this study provides a new perspective for quantifying ground surface resistance for bryophytes and litter covered ground in data-limited sites.

Based on the partitioning results, ET from Sibbald and Bonsai during the study period was more T-dominated, while that from Burstall was more E-dominated. This indicates that wetlands, despite having significant coverage of vascular vegetation, can exist in states of either T-dominance or E-dominance. Conversely, having a vast area of standing water does not guarantee that the wetland ET will be dominated by E. For instance, Goulden et al. (2007) and Bijoor et al. (2011) found that T constituted roughly 80% of ET in a flooded *Typha* marsh. This is also consistent with the literature synthesis which reveals that wetland ET can be either E-dominated or T-dominated, irrespective of wetland type or whether the wetlands are flooded

or non-flooded. Furthermore, wetlands can transition between these states within a matter of days. For example, ET at Burstall shifted from T-dominated to E-dominated before and after late August. Hence, relying solely on visual assessment to determine whether T or E dominates ET in wetland ecosystems could be inaccurate. And utilizing an ET partitioning method based on assumptions regarding the prevalence of T or E dominance could introduce considerable biases. The ET partitioning method demonstrated in our study does not rely on assumptions about whether ET is T-dominated or E-dominated, or whether or not the water table depth is below the land surface, which offers a promising approach for estimating ground surface resistance and ET partitioning in bryophytes and litter covered wetland ecosystems.

4.6.3 Key environmental factors influencing evapotranspiration partitioning in wetland ecosystems

Wetland research has highlighted the important roles of LAI and water table depth in partitioning ET (Admiral and Lafleur, 2007b; Admiral et al., 2006; Booth and Loheide II, 2010; Lafleur, 2008; Lafleur et al., 2005; Moore et al., 2022; Peichl et al., 2013). Lafleur et al. (2005) proposed a conceptual framework that describes how shifts in the proportions of moss evaporation and shrub transpiration counterbalance each other as water table depth decreases, thereby maintaining consistent ET. While this study confirms LAI as the key environmental control on T/ET, it could not directly examine the influence of water table depth on ET partitioning due to insufficient measurements of water table depth at Sibbald and Bonsai, and a lack of variability in water table depth data at Burstall. However, based on Figure 4-11, the responses of T/ET to LAI vary between flooded and non-flooded wetlands, indicating the influence of water table depth on wetland ET partitioning.

Due to a notable scarcity of studies examining wetland ET partitioning, this study cannot quantify the uncertainties associated with the ET partitioning methodology or draw definitive conclusions regarding the response of T/ET to LAI and water table depth specific to different wetland types. Also, the limited number of studies makes it challenging to determine whether

the mean growing season LAI or the maximum growing season LAI is a more effective indicator for wetland ET partitioning.

The synthesis and the partitioning results from the three study sites collectively suggest that wetland ET partitioning is strongly controlled by LAI, with water table depth moderating the relationship between LAI and T/ET. Daily variations in meteorological and soil water conditions cause fluctuations in daily T/ET (Figure 4-7). While the presence of bryophytes and litter covers has a minor impact on the magnitude of T/ET, this impact is likely more pronounced in wetlands with higher water table levels.

4.6.4 Limitations

The limitations of this study largely arise from the use of S-W model. Firstly, the S-W model omits direct evaporation from the vascular plant canopy. During days with rainfall or dew, canopy interception can contribute substantially to the overall ET. For example, in a two-year water budget analysis of a sinkhole wetland in Tennessee, approximately 18.9% of the total gross precipitation was intercepted by the canopy and subsequently evaporated (Hill and Neary, 2012). The omission of evaporation from the vascular plant canopy likely results in an overestimation of λT and T/ET. Secondly, this study estimates the canopy stomatal resistance based on the stomatal conductance of the dominant vascular species and their proportional coverages, while not accounting for contributions from other species, which may lead to an underestimation of λT and T/ET.

Thirdly, the S-W model does not account for spatial heterogeneity, such as the distributions of vascular and nonvascular vegetation, microforms (e.g., hummocks, hollows and lawns), and the species-specific responses of vegetation to microclimatic variables shaped by heterogeneous landscapes. The calculation of below-canopy net radiation (Eq. 6) assumes a constant light extinction coefficient for the canopy, ignoring the variability of the light extinction coefficient caused by sun angle, plant structure (e.g., leaf shape and size), canopy configuration (e.g., height, density, layering, and species composition), and sky conditions (Baldocchi et al., 1984; Campbell, 1986; Kukal and Irmak, 2020; Wang et al., 2007; Zhang et

al., 2014). Fourthly, the S-W model also calculates above and below canopy aerodynamic resistance under the assumption of neutral atmospheric conditions. All of these factors contribute to the uncertainty associated with the estimation of wetland ET partitioning. This study also assumes a constant LAI for every month (Table C3), potentially underestimating the impact of phenology on ET and its partitioning. Despite these limitations, the close match of the estimated wetland λ ET and ground surface evaporation with the measurements suggests that the parameterization of the modified S-W model effectively captures the daily average site conditions.

It is also important to note that the conclusions regarding the effects of bryophytes and litter on ground surface evaporation and wetland ET partitioning, as well as the proposed method for calculating ground surface resistance, is drawn based on the condition that the ground surface evaporation is the Stage I evaporation. Whether these conclusions will hold at drier ecosystems remains an area for further research. The implications regarding the extent to which bryophytes and litter covers influences wetland ET partitioning are based on the simulations using the modified S-W model with arbitrary values of the mass fractions of ground covers that may not represent realistic ranges. While the modified S-W model has certain limitations, as previously noted, its advantages—including simplicity, low data requirements, and independence from assumptions about whether ET is E-dominated or T-dominated—make it a potentially useful tool for wetland ET partitioning and for supporting global-scale T/ET estimations. This study is particularly meaningful given that wetlands are currently underrepresented in global-scale studies (Janse et al., 2019). Last but not least, this work is limited to a short period of time—two months during the growing season—and lacks sufficient data to examine possible seasonal variations. Given that this study highlights LAI as the key driver in wetland ET partitioning, if LAI exhibits significant seasonal variations, the impacts of bryophytes and litter on wetland ET partitioning could also vary seasonally. Future research is strongly recommended to extend the study period to investigate potential seasonal variations in how bryophytes and litter covers affect wetland water use patterns and to validate the

robustness of the proposed method for ET partitioning in bryophytes and litter covered wetlands.

4.7 Conclusions

Ground covers, such as bryophytes and litter, significantly influence ground surface evaporation. Their effects vary by site and depending on interactions with evaporative demand and water availability. To account for the impacts of ground covers on wetland ET partitioning, a novel method, which integrates a simple method for estimating ground surface resistance based on mass fractions of bryophytes and litter into the two-source Shuttleworth–Wallace model, was proposed. This approach reasonably partitioned λET into λE from bryophytes and litter covered wetland surfaces, and λT from vascular vegetation at the three study sites. Hence, the use of this approach for partitioning evapotranspiration in wetlands featuring significant bryophytes and litter covers is strongly recommended.

Simulations using the modified Shuttleworth–Wallace model suggest that bryophytes and litter have a minor impact on the magnitude of T/ET , but their influence is likely more pronounced in wetlands with higher water table levels. To identify the key environmental controls on wetland ET partitioning, a literature synthesis was conducted to investigate the effects of LAI and water table depth on wetland ET partitioning during the growing season. The results revealed distinct exponential relationships between wetland T/ET and both average growing season LAI and maximum growing season LAI, with these relationships differing between flooded and non-flooded wetlands.

Overall, the results here suggest that wetland ET partitioning is strongly controlled by LAI, with water table depth moderating the relationship between LAI and T/ET . The impact of bryophytes and litter covers on T/ET is generally minor, but their effect becomes more pronounced in wetlands with elevated water tables. These findings offer new perspectives into the fundamental mechanisms driving wetland ET partitioning. This enhanced understanding will facilitate the performance of land surface models, consequently improving the accuracy

of forecasts related to the water and carbon budgets of wetland ecosystems and global-scale estimations.

4.8 Acknowledgements

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Chapter 5

Conclusions

In response to the potential water crisis due to projected decreases in summertime runoff in the Canadian Rocky mountains as a result of climate change (Rood et al., 2008), it is imperative to accurately quantify summertime ET in high-elevation wetlands to support water budget estimation and the design of sustainable water resource management strategies. In this context, the thesis examines how understudied land surface properties, such as microforms and ground covers, affect ground surface evaporation, ET, and ET partitioning in wetland ecosystems, as well as seeks model improvements to better represent these processes.

The results demonstrate that microforms alone do not significantly affect ground surface evaporation in the three study sites. Furthermore, the absence of substantial differences in evaporation between hummocks and hollows suggests that, when scaled to the entire wetland, microforms are unlikely to play a critical role in wetland ET and its partitioning in these sites. Consequently, wetland ET estimations at these sites that do not incorporate micro-topographical variations are unlikely to introduce significant bias. If it is necessary to account for the fine spatial variations in evaporation attributed to different microforms, conventional evaporation models can effectively capture these variations by utilizing soil temperature measurements obtained from these micro-topographical features.

In contrast to the role of microforms, ground covers significantly influence ground surface evaporation, but their importance in wetland ET and its partitioning is difficult to assess without model simulations. However, accurately modelling ground surface evaporation in the presence of ground covers poses challenges, primarily due to difficulties in estimating surface resistance. This challenge is especially pronounced in high-elevation wetlands covered by bryophytes and litter, where data-intensive parameterization is often required, yet data availability is generally limited. The semi-physical soil evaporative efficiency (SEE) model offers an effective solution for these data-limited environments. More importantly, the proposed SEE approach, which estimates surface resistance and SEE using meteorological data,

soil moisture data, and ground cover mass fractions, indicates that the effects of ground covers on ground surface evaporation are dependent on evaporative demand (i.e., due to the use of potential evaporation and aerodynamic resistance in the formulation) and water availability (e.g., soil moisture in the formulation) conditions. These interactions are supported by three key pieces of evidence, listed in order from strongest to weakest: (1) the significant interaction effects of ground cover, evaporative demand, and water availability observed in Chapter 4; (2) the significant interaction between ground cover and microforms in Chapter 2, where microforms significantly alter soil temperature profiles, potentially influencing evaporative demand; and (3) the need for correcting for below-canopy SEE, as the canopy alters the below-canopy microclimates (Appendix B Section B). Since the effects of ground covers depend on evaporative demand and water availability conditions, which vary across the three sites, the influence of ground covers is inherently site-specific.

The new SEE approach was further incorporated into the Shuttleworth-Wallace (S-W) model to simulate wetland ET and its partitioning in response to variations in ground cover mass fractions. The simulations indicate that the impact of ground covers on overall ET and its partitioning into ground surface evaporation and vascular plant transpiration in the studied wetlands is likely minor. This finding may seem at odds with the significant influence ground covers have on ground surface evaporation, but the two conclusions are in fact compatible: (1) including ground cover mass fractions in the modified S-W model highlights the role of ground covers in influencing surface resistance, a necessary variable for accurately estimating wetland ET and its partitioning; and (2) while ground covers cause substantial differences in ground surface evaporation, these may not translate into significant changes in ET due to the difference in the magnitude of E and ET. As shown in Figures C1 and C2, changes in mass fractions led to only limited variations in ET (up to 10%), whereas the percentage changes in ground surface evaporation were much greater (up to 25%). Thus, even though ground covers may not significantly impact the overall magnitude of wetland ET and its partitioning, their inclusion as a key variable remains essential for precise modelling.

The new knowledge that this thesis has contributed to the field lies in explaining how microforms and ground covers influence wetland ground surface evaporation, ET, and its partitioning. Given that microforms and ground covers are rarely incorporated into wetland ET estimation models, this study concludes that ignoring microforms is not a major concern for ET estimation, at least for the study sites in this thesis. This is because small-scale variability is dampened by compensatory processes driving by complex interaction among microforms, ground covers, water availability and evaporative demand, rendering the effects of microform on ET non-emergent at larger scales.

In contrast, ground covers play a pivotal role in shaping ground surface evaporation and should not be overlooked. This thesis illustrates how the effects of ground covers interact with evaporative demand and water availability, providing a mechanistic understanding of the processes governing ground surface evaporation. More importantly, this thesis develops practical methods for integrating ground covers into evaporation models, accounting for their interactive effects with evaporative demand and water availability.

In summary, the findings reduce uncertainties associated with land surface heterogeneity in ET estimation for high-elevation wetlands, and propose methods for estimating surface resistance, ET, and its partitioning in data-limited sites, with potential broader applicability beyond the study sites examined in this study.

This study has limitations, which have been discussed in the previous chapters. There are additional limitations that should be noted, though they are not expected to undermine the study's conclusions. In Chapter 2, the calculation of latent heat flux from the bryophyte layer (Eq. 12) used the bryophyte layer temperature as a proxy for surface temperature, and the calculation of aerodynamic resistance did not account for atmospheric stability conditions (Eq. 27). Although the selected models have demonstrated good performance in estimating latent heat from hummocks and hollows, addressing these limitations could potentially enhance model performance. In Chapter 3, the calculation of aerodynamic resistance for below-canopy conditions accounted for the impact of the overstory canopy on surface temperature but did

not consider potential changes in below-canopy air temperature, wind speed, or the canopy's structural properties affecting roughness length governing the transfer of momentum, heat and vapor. However, applying the methodology developed in Chapter 3 to the modified S-W model produced satisfactory results, suggesting the robustness of the methodology. In Chapter 4, the lack of surface runoff measurements and continuous groundwater level monitoring limited the water balance estimation for each study site, thus hindering a more hydrologically meaningful interpretation of these high-elevation wetland ecosystems.

The evaporation modelling presented in this thesis is one-dimensional, and does not account for lateral heat transfer in soils or small-scale air advection within each site, although it is recognized that these processes are also critical for improving wetland ET modeling. For instance, Dimitrov et al. (2010) demonstrated that incorporating air convective heat transfer within hummocks, driven by horizontal air circulation between the warmer hummock sides and cooler hummock interiors, enhanced the *ecosys* model's simulation of peat temperatures. Similarly, Guo and Schuepp (1994) highlighted that local horizontal heat advection has often been overlooked in the calculation of both local and cumulative regional surface heat and water fluxes in ecosystems like northern wetlands, leading to substantial errors.

The results of this thesis suggest several avenues for future research. Firstly, the physical basis for estimating surface resistance using bryophyte and litter mass fractions (Chapter 3) requires further investigation, including its applicability to different wetland types. Secondly, the interactive effects of water table levels with microforms and ground covers on wetland ET partitioning remain unclear and warrant further exploration. Thirdly, extending the study beyond two months would allow for the assessment of seasonal variations. Additionally, the findings could aid in estimating water storage in high-elevation wetlands, benefiting ecosystem service evaluation and hydrological studies. Lastly, integrating the proposed methodology with remote sensing could support larger-scale hydrological research.

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Appendix A

Chapter 2 Supplementary Information

Table A1. Fitted linear relationships between discrete soil temperature measurements at 5 cm and 15 cm depths in hummocks and hollows (T_{soil_j} , °C) and continuous soil temperature measurements at 15 cm depth ($T_{\text{soil}_{15}}$, °C).

Variables (T_{soil_j})	Fitted equations	R^2
Soil temperature at the 5 cm depth in hummocks ($T_{\text{soil}_5\text{HUM}}$, °C)	$T_{\text{soil}_5\text{HUM}} = 0.3563T_{\text{soil}_{15}} + 8.1738$	0.67
Soil temperature at the 5 cm depth in hollows ($T_{\text{soil}_5\text{HOL}}$, °C)	$T_{\text{soil}_5\text{HOL}} = 0.2738 T_{\text{soil}_{15}} + 9.0193$	0.73
Soil temperature at the 15 cm depth in hummocks ($T_{\text{soil}_{15}\text{HUM}}$, °C)	$T_{\text{soil}_{15}\text{HUM}} = 0.1267T_{\text{soil}_{15}} + 11.259$	0.25
Soil temperature at the 15 cm depth in hollows ($T_{\text{soil}_{15}\text{HOL}}$, °C)	$T_{\text{soil}_{15}\text{HOL}} = 0.0201 T_{\text{soil}_{15}} + 12.477$	0.01

Note: The fitted equations were determined from measured T_{soil_j} and corresponding $T_{\text{soil}_{15}}$ at the same time, averaged over all measurements during the study period.

Table A2. Comparison the goodness of fit of various structures of the mixed-effect models.

No.	Model structure	Degree of freedom	Model fit (AIC)	Model fit (REML)
Random intercept model				
1	$\text{lmer}(\lg(\text{Evaporation}) \sim \text{Round} * \text{GroundCover} * \text{Microform} + (1 \text{Round} : \text{Quadrat}))$	37	121.43	47.4
2	$\text{lmer}(\lg(\text{Evaporationrate}) \sim \text{Round} * \text{GroundCover} * \text{Microform} + (1 \text{Round} : \text{Quadrat} : \text{Microform}))$	37	110.89	36.9
3	$\text{lmer}(\lg(\text{Evaporation}) \sim \text{Round} * \text{GroundCover} * \text{Microform} + (1 \text{Round} : \text{Quadrat} : \text{CoverType}))$	37	122.24	48.2
Random intercept and slope model				
4	$\text{lmer}(\lg(\text{Evaporation}) \sim \text{Round} * \text{GroundCover} * \text{Microform} + (\text{Round} \text{Quadrat}))$	57	155.19	41.2

5	<code>lmer(lg(Evaporation)~Round*GroundCover*Microform+(Round Quadrat:Microform))</code>	57	128.54	14.5
6	<code>lmer(lg(Evaporation)~Round*GroundCover*Microform+(Round Quadrat:CoverType))</code>	57	140.13	26.1

Note: The model structure was represented using R programming syntax. The term `lmer()` denotes the models were established using the linear mixed-effect model function. The term `lg(Evaporation)` was the log-transformed ground surface evaporation with a base of 10. The symbol “variable 1* variable 2” indicated that the two variables and their interaction were included in the fixed-effect terms. The symbol “variable 1: variable 2” indicated that the variable 2 was nested in the variable 1 and only their interaction was considered in the model. The structure (1|variable) indicated that the effect of the variable was only considered as the random intercept, while the structure (variable 1|variable 2) indicated that the effect of variable 2 accounted for both random slopes and intercepts for every “variable 1:variable 2” group.

Table A3. Results of the repeated-measures split-plot ANOVA on evaporation.

Model structure: <code>lmer(lg(Evaporation)~Round*GroundCover*Microform+(Round Quadrat:Microform))</code>			
Factor	Degree of freedom	Chi-square	p-value
Round	5	66.04	<0.001
Ground Cover	3	14.43	0.002
Microform	1	1.09	0.30
Round × Ground Cover	12	8.30	0.76
Round × Microform	4	1.59	0.81
Ground Cover × Microform	2	4.88	0.087
Round × Ground Cover × Microform	7	7.96	0.34

Note: The model structure was represented using R programming syntax. Each term was explained in Table A1. The ANOVA test used was the Type III Wald Chi-square test. In the Factor column, “variable 1 × variable 2” represents the interaction effect between variable 1 and variable 2. If this interaction effect is significant, it indicates that the impact of variable 1 depends on the condition of variable 2, and vice versa.

Table A4. Results of the repeated-measured two-way ANOVA on soil temperature.

Model structure:	lmer(lg(SoilTemperature)~Depths*Microform+(1 Times))			
Factor	Degree of freedom	Mean square	F-value	p-value
Depth	4	0.15	31.92	<0.001
Microform	1	0.096	19.39	<0.001
Depth × Microform	4	0.0039	0.80	0.53

Note: The model structure was represented using R programming syntax. Each term follows the expressions explained in Table A1 and Table A2.

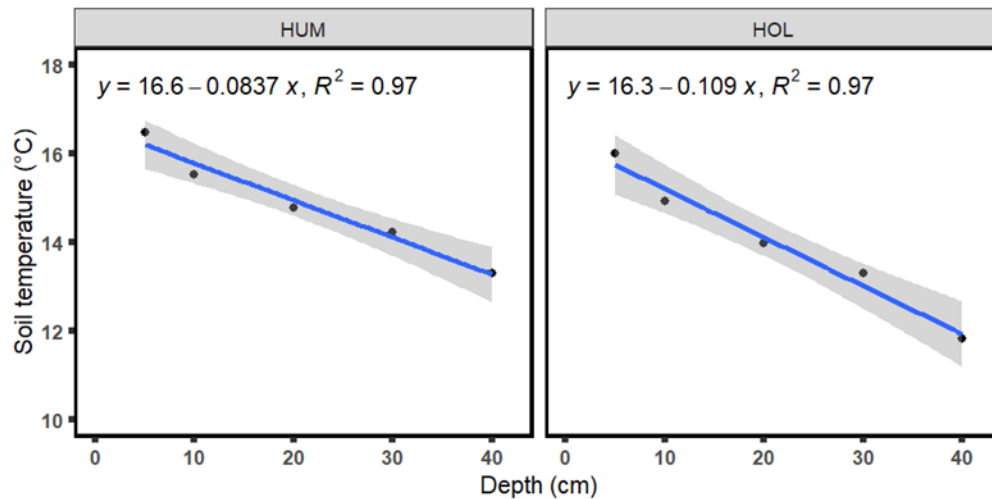


Figure A1. Average soil temperature at different depths in hummocks (HUM) and hollows (HOL) across the study period. Blue lines represent the fitted relationships, with gray shading indicating the 95% confidence interval.

Appendix B

Chapter 3 Supplementary Information

This document contains two sections. Section A is the supporting information on the measurements and the data processing procedure, and Section B is a summary of the observations from the evaporation experiments, regarding evaporation, ground cover biomass and microclimate.

Section A: Supporting statistics of the evaporation experiments and data quality control procedure

Table B1. The date and duration of evaporation experiments at the three sites.

Site	Round	Start Date	Duration
Sibbald	1-1*	7/12/2021	2
	1-2*	7/14/2021	3
	2	7/29/2021	5
	3	8/5/2021	4
	4	8/12/2021	4
	5	8/19/2021	4
	6	8/26/2021	4
	1	7/14/2021	3
	2	7/22/2021	4
	3-1*	7/26/2021	2
	3-2*	7/28/2021	2
	4	8/6/2021	4
Burstall	5	8/25/2021	2
	6	8/27/2021	4
	1	7/9/2021	4
	2	7/15/2021	4
	3-1*	7/19/2021	2
	3-2*	7/21/2021	2
	4	8/13/2021	5
	5	8/20/2021	4
Bonsai	6	8/25/2021	2

Note: * indicates the round of the evaporation experiments during which the micro-lysimeters were weighed midway through the experimental period, but no bryophyte or litter biomass was harvested.

Table B2. Summary of measurement devices and associated uncertainties.

Variable	Height (or depth)	Site	Canopy treatment	Device	Uncertainty
Net radiation	3 m	Sibbald, Bonsai	NC	NR-Lite2 (Kipp Zonen: Delft, Netherlands)	<u>≤5%</u>
	2 m	Burstall	NC		
Air temperature	3 m	Sibbald, Bonsai	NC	HMP-155 T/RH probe (Vaisala; Helsinki, Finland)	<u>±2% of RH_a and ±0.2°C</u>
	2 m	Burstall	NC		
Air relative humidity	3 m	Sibbald, Bonsai	NC		
	2 m	Burstall	NC		
Wind speed	3 m	Sibbald, Bonsai	NC	R.M. Young 05103 propeller anemometer (R.M. Young: Michigan, USA)	<u>±1% of wind speed and ±3° for wind direction</u>
	2 m	Burstall	NC		
Precipitation	3 m	Sibbald	NC	the TE525I rain gauge (Texas Electronics: Dallas, USA)	<u>±1.0%</u>
Precipitation	2 m	Burstall	NC	The RG3-M HOBO rain gauge with a M-RSA solar radiation shield (Onset Computer Corp., Massachusetts, USA)	<u>±1.0%</u>
Precipitation	2.5 m	Bonsai	NC	The OTT Pluvio ² precip gauge with an alter shield (OTT HydroMet: Kempten, Germany)	<u>±1%</u>

Soil heat flux	6 cm	Sibbald, Burstall, Bonsai	NC	HFP01 soil heat flux plate (HuskeFlux: Delft, Netherlands)	within -15% to +5% in most common soils
Soil temperature (continuous measurements)	15, 30 cm	Sibbald	NC	Type E Thermocouple, Omega, USA	±1.0°C
	5, 10 and 15 cm	Burstall	NC		
	5 and 10 cm	Bonsai	NC		
Soil temperature (manual measurements)	5, 10, 20, 30 and 40 cm	Sibbald, Burstall	NC	Type K Thermocouple, Omega: Connecticut, USA	±1.1°C
	5, 10, and 20 cm	Bonsai	NC		
Soil volumetric water content (continuous measurements)	15 cm and 30 cm	Sibbald, Burstall	NC	ECH2O EC-5 sensors (Meter Group, Hopkins, Washington, USA)	±0.03 m³ m⁻³ typical in mineral soils that have solution EC<8 dS m⁻¹ and ±0.02 m³ m⁻³ in any porous medium
	Top 30 cm-depth (vertically)	Bonsai	NC		
Soil volumetric water content (manual measurements)	Top 30 cm-depth (vertically)	Bonsai	NC and BC	CS-650 volumetric water content probe (Campbell Scientific: Utah, USA)	±1% (with soil-specific calibration) and ±3% (typical with factory VWC model) where solution EC<3 dS m⁻¹
Air temperature	1 m	Sibbald, Burstall, Bonsai	NC	HOBO U23 Pro V2 temperature/relative humidity probes (Onset: Bourne Massachusetts, USA)	±0.2°C and ±2.5% from 10% to 90% RH_a typical to a maximum of ±3.5% including hysteresis at 25°C (77°F); and ±5% typical below 10% and above 90% RH_a
Air relative humidity	1 m	Sibbald, Burstall, Bonsai	NC		
Air temperature	0.5 m	Sibbald, Burstall, Bonsai	BC		
Air relative humidity	0.5 m	Sibbald, Burstall, Bonsai	BC		

Photosynthetically active radiation (manual measurements)	Ground level	Sibbald, Burstall, Bonsai	NC and BC	LI-109R Quantum sensor (LiCor BioSciences, Lincoln, USA)	±10% traceable to the U.S. National Institute of Standards and Technology (NIST)
Leaf area index (manual measurements)	Ground level	Sibbald, Burstall, Bonsai	BC	LAI-2200C plant canopy analyzer (LiCor BioSciences, Lincoln, USA).	within ±10% of the measured LAI

Note: the canopy treatment includes two conditions: no canopy (NC) and below canopy (BC).

Table B3. Parameters for calculating aerodynamic resistance at neutral atmospheric condition for each ground cover treatment at each site.

Parameters	Treatment	Sibbald	Burstall	Bonsai
Total thickness (m)	S	0	0	0
	BS	0.005	0.01	0.005
	LBS	0.05	0.05	0.02
	PLBS	na	na	0.1
Zero plane displacement height (m)	S	0	0	0
	BS	0.003	0.007	0.003
	LBS	0.03	0.03	0.01
	PLBS	na	na	0.07
z_{om} (m)	S	0.005	0.005	0.005
	BS	0.001	0.001	0.001
	LBS	0.006	0.006	0.002
	PLBS	na	na	0.01
z_{oh} (m)	S	0.0005	0.0005	0.0005
	BS	0.0001	0.0001	0.0001
	LBS	0.0006	0.0006	0.0002
	PLBS	na	na	0.001
Z_u (m)	S			
	BS	3	2	3
	LBS			
	PLBS			

Table B4. Comparison of published values of parameters A and B from the literature with the predicted parameter B calculated from Eq. 14 in this study.

Reference	Site type	Area (km ²)	A	B	B predicted from Eq. 14
Sellers et al. (1992)	18 sites (the FIFE-87 project, all in prairie region)	34.87 (in total)	8.206	4.255	4.58
Kustas et al. (1998)	Grass and shrub dominated site	50	8.4	5.9	4.84
Crow et al. (2008)	Agricultural site	0.032 (inferred from Gish et al. (2005))	8.2	4.3	4.57
Merlin et al. (2011) (Auradé site)	Agricultural site	0.323	13.7	15.7	12.1
Merlin et al. (2011) (Lamasquère site)	Agricultural site	0.235	10.0	7.9	7.02

Data processing procedure

Conducting field evaporation experiments, particularly in wetlands, are extremely challenging. As a result, data collection is subject to measurement errors. Although efforts to minimize these errors, scattered evaporation data were observed across each experimental round. A few MLs exhibited positive weight changes, even in the absence of moisture supply during the experimental period, prompting the exclusion of the problematic data from further analysis. To mitigate measurement errors, data were averaged across six rounds for each treatment at each site. The averaged SEE of the three ground cover treatments under the below-canopy condition at Burstall site were slight larger than 1, probably due to instrumental bias in measuring the below-canopy microclimatic variables. However, the results presented in the main text indicate that this bias does not compromise the robustness of the conclusions.

Due to the scatter nature of the measurement data, some linear regressions between $\theta_{i,j}$ and $SEE_{i,j}$ exhibited low R^2 values, indicating weak correlations between them. For quality control of the data, any linear regression model that have an R^2 values less than 0.6 was discarded. To derive $\theta_{1/2_{i,j}}$ and $slope_{1/2_{i,j}}$ from the scatter data, the bin regression method demonstrated in Merlin et al. (2016) was utilized. The approach involved splitting $SEE_{i,j}$ from smallest to largest into six evenly distributed bins. Data with each bin were averaged, yielding a pair of θ and SEE for each bin. Three regression segments were then computed by joining two pairs of data from bin k and bin $k+3$ (i.e, 1st and 4th, 2nd and 5th, 3rd and 6th). The values of $slope_{1/2_{i,j}}$ was calculated as the average of the three slopes from these regression segments. Additionally, $\theta_{1/2_{i,j}}$ was calculated using $slope_{1/2_{i,j}}$ alongside the mean observations of SEE and θ for each treatment at each site. It is noted that deriving the $\theta_{1/2}$ and its slope at $SEE=0.5$ for $Burstall\_BS\_NC$ was not feasible due to limited sample size and the aforementioned measurement errors. Consequently, this category will not be included in any results requiring the input of $\theta_{1/2}$.

During the experimental period, the eddy covariance towers experienced intermittent outages, resulting in occasional unavailability of incoming solar radiation (R_g , $W\ m^{-2}$). Since R_g is a necessary input for the soil energy balance model in M16, values were extrapolated using R_n from climate stations along with the soil net radiation equation from Merlin et al. (2016), provided as:

$$R_n = (1 - \alpha)R_g + \epsilon(R_a - \sigma T_s^4) \quad (\text{Eq. B-1})$$

where α is the soil albedo (0.20), R_g ($W\ m^{-2}$) is the incoming solar radiation, ϵ is the soil emissivity (it is assumed 0.9 for both Sibbald and Burstall, and 0.95 for Bonsai from site measurement (Chau, 2023)), R_a ($W\ m^{-2}$) is the atmospheric longwave radiation and it is expression is provided in Merlin et al. (2016), σ ($Wm^{-2}K^{-4}$) is the Stephan-Boltzmann constant, and T_s (K) is the soil temperature.

Section B: Evaporation, biomass, and microclimate observations

Please note that this section is intended solely to give the reader an overview of the controlled experiment. A more rigorous statistical analysis is presented in Chapter 4.

1. Evaporation

Evaporation rates for each treatment at each site across six rounds of the experiments are presented in Figure B1. According to the data distribution, the Wilcoxon signed-rank test was employed to compare if significant differences exist between the medians of any two groups.

At Sibbald, the median evaporation rates for S and BS under BC conditions were significantly lower than those under NC conditions ($p=0.02$ and 0.047 for S and BS, respectively). Under NC, the median evaporation from S was significantly higher than that from BS ($p=0.006$) and LBS ($p=0.005$); however, no significant difference was observed between the evaporation rates of BS and LBS. Under BC, the median evaporation from LBS was significantly lower than that from S ($p=0.002$) and BS ($p=0.03$).

At Burstall, canopy significantly affected the median evaporation rates of S ($p=0.005$) and BS ($p=0.002$), but not LBS. Under NC, evaporation from LBS was significantly lower than from S ($p=0.01$) and higher than from BS ($p=0.03$). In contrast, under BC, no significant differences in median evaporation were detected among any of the three groups.

At Bonsai, canopy significantly affected the evaporation rate of S ($p=0.03$), but not that of LBS or PLBS. Under NC, evaporation from LBS was significantly different from S ($p=0.004$) and PLBS ($p=0.001$). Under BC, evaporation from LBS was significantly different from PLBS ($p=0.03$), but no significant differences were detected between S and LBS or between S and PLBS.

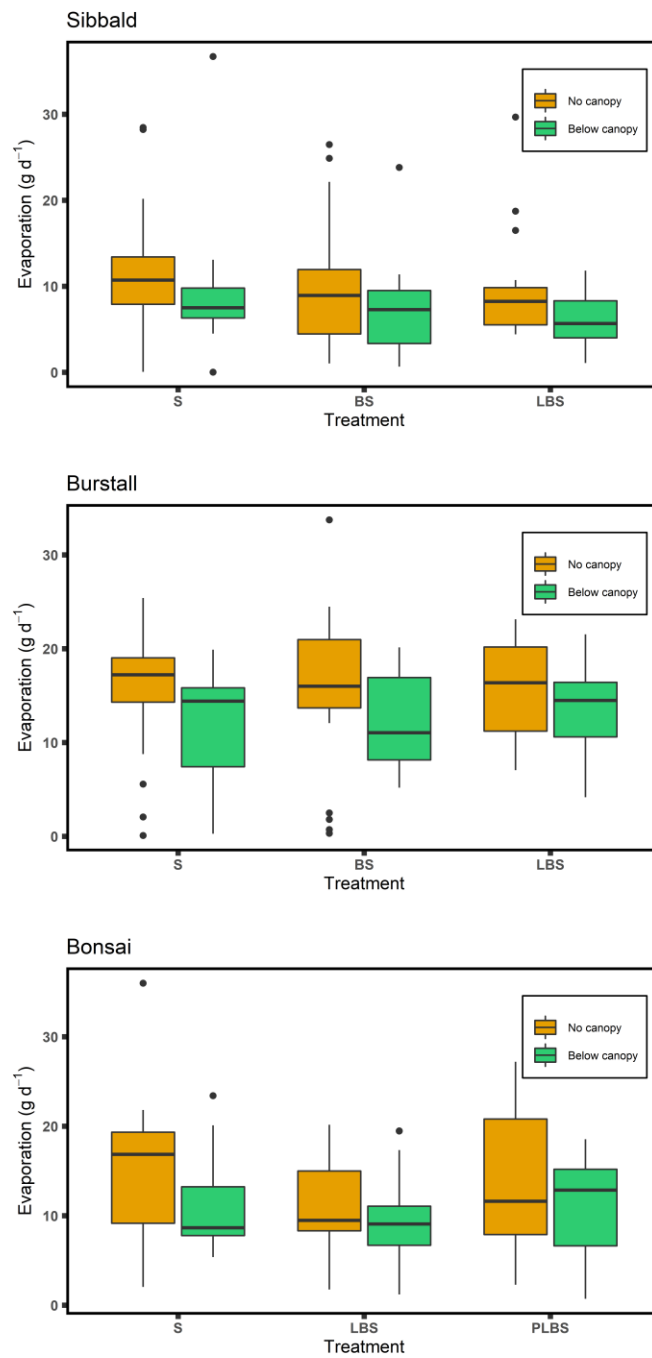


Figure B1. Evaporation rate of bare soil (S), soil-bryophyte (BS) and soil-bryophyte-litter (LBS) columns at Sibbald and Burstall, and bare soil (S), soil-bryophyte-litter (LBS) and soil-bryophyte-litter-ground vascular vegetation (PLBS) columns at Bonsai.

2. Biomass of bryophytes, litter, and ground vascular vegetation

The biomass of bryophytes, litter and ground vascular vegetation under NC and BC conditions is presented in Figure B2. At each site, no significant differences in biomass were detected between NC and BC for any ground cover type. Additionally, no significant correlation was found between the mass fraction of bryophytes and the mass fraction of litter (Figure B3).

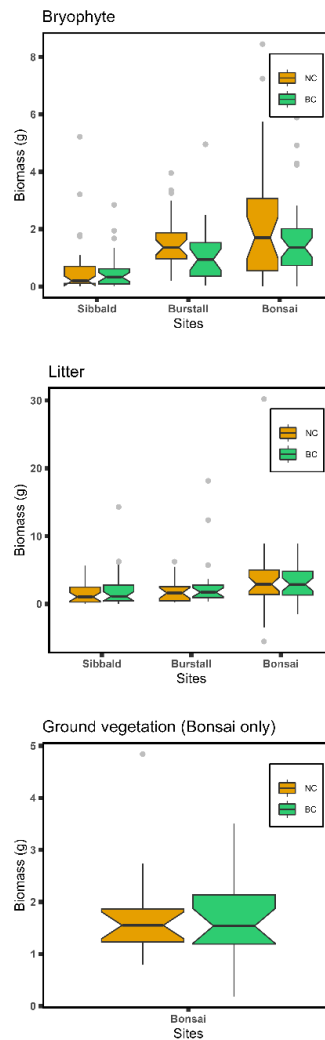


Figure B2. Biomass of bryophyte and litter at Sibbald, Burstall, and Bonsai, and ground vascular vegetation at Bonsai.

3. Microclimate

T_a and RH_a were significantly different between NC and BC conditions at all the three sites (all $P < 0.05$). The differences in T_a and RH_a between NC and BC are showed in Figure B3. In addition, PAR measured under BC was significantly lower than that under NC at all three sites

(all $p < 0.05$). On average, PAR under BC was 33% of that under NC at Sibbald, 54% at Burstall, and 40% at Bonsai.

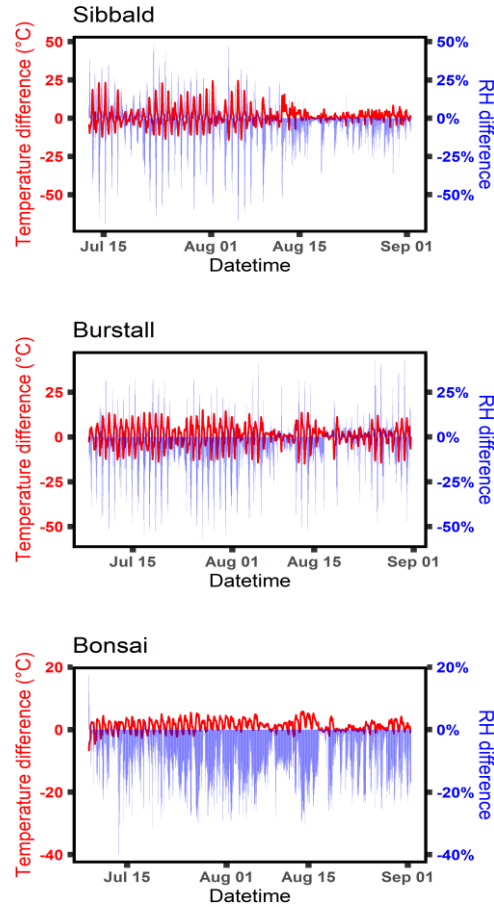


Figure B3. The difference of air temperature (T_{a_NC} minus T_{a_BC}) and the difference of relative humidity (RH_{a_NC} minus RH_{a_BC}) between no canopy (NC) and below canopy treatments (BC).

4. Soil temperature and soil moisture

Manually measured soil temperature at various depths across six rounds of the evaporation experiments were presented at Figure B4. At Sibbald, soil temperature at 5 cm depth

significantly differed between NC and BC ($p=0.03$). While at Burstall, soil temperature at all measured depths were significantly different between NC and BC (all $p < 0.03$).

At Bonsai, bare soil temperature at all measured depth were significantly different between NC and BC conditions (all $p < 0.001$). Similarly, significant differences were also detected in the temperatures of the soil covered by ground vascular vegetation at the same depth between NC and BC (all $p \leq 0.001$).

Without the presence of overstory vegetation, bare soil temperature and the temperature of the soil covered by ground vascular vegetation (SV) at both 5 cm and 10 cm depths significantly differed from each other when compared at the same depth (both $p < 0.03$). But there is not any significant difference were observed between S and SV under BC conditions at any measured depths.

As for the manually measured soil moisture at Bonsai, there was not any significant difference among any of the treatment groups.

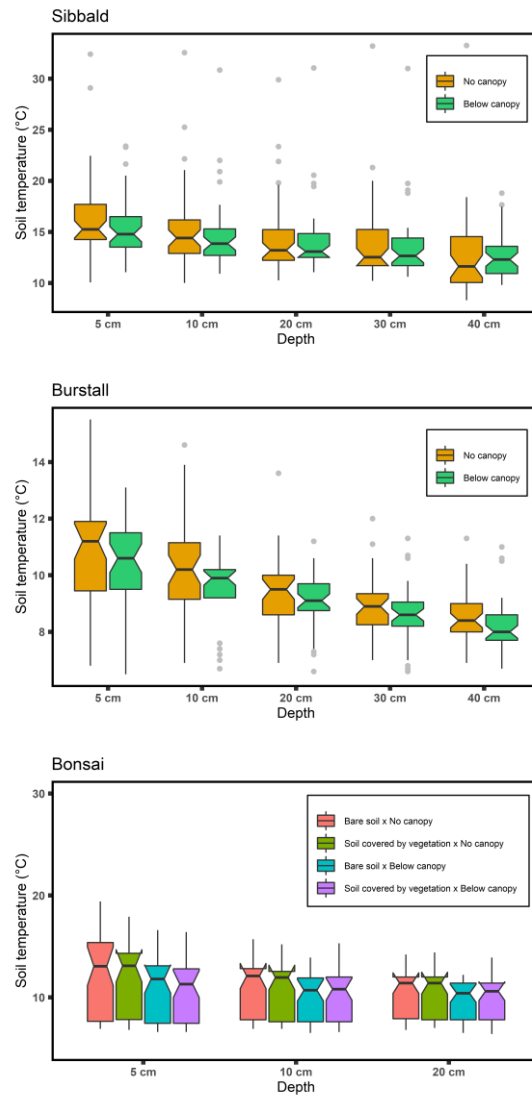


Figure B4. Soil temperature at 5 cm, 10 cm, 20 cm, 30 cm, and 40 cm depths at Sibbald and Burstall under no canopy treatment (NC) and below canopy treatment (BC), and soil temperature at 5 cm, 10 cm, and 20 cm depths at Bonsai of bare soil (S) and soil covered by ground vascular vegetation (SV) under no canopy treatment (NC) and below canopy treatment (BC).

Appendix C

Chapter 4 Supplementary Information

Table C1. The start date and duration of the controlled evaporation experiments at the three sites.

Site	Round	Start Date	Duration	The Day of Year
Sibbald	1.1*	7/12/2021	2	193-195
	1.2*	7/14/2021	3	195-198
	2	7/29/2021	5	210-213
	3	8/5/2021	4	217-221
	4	8/12/2021	4	224-228
	5	8/19/2021	4	231-235
	6	8/26/2021	4	238-242
Burstall	1	7/14/2021	3	195-198
	2	7/22/2021	4	203-207
	3.1*	7/26/2021	2	207-209
	3.2*	7/28/2021	2	209-211
	4	8/6/2021	4	218-222
	5	8/25/2021	2	237-239
	6	8/27/2021	4	239-243
Bonsai	1	7/9/2021	4	190-194
	2	7/15/2021	4	196-200
	3.1*	7/19/2021	2	200-202
	3.2*	7/21/2021	2	202-204
	4	8/13/2021	5	225-230
	5	8/20/2021	4	232-236
	6	8/25/2021	2	237-239

Note: * denotes the round of the controlled evaporation experiment in which the microlysimeters were weighed in the middle of the experimental period without harvesting bryophytes or litter biomass. It is note that the duration of the evaporation experiment for round #2 at Sibbald and round #4 at Bonsai was 5 days due to a bear encounter that restricted our access to the sites. We assumed this impact was minimal because light rainfall during the periods prevented the complete drying of the samples in the microlysimeters.

Table C2. The fitted relationships between porometer-measured leaf stomatal conductance (g_s , $m s^{-1}$) and vapor pressure deficit (VPD, kPa) at the eddy covariance measurement height.

Species	Best fitted relationship	R ²
Sibbald		
<i>Salix lasiandra</i>	$y = 0.0029x^2 - 0.0074x + 0.0125$	0.59
<i>Carex</i>	$y = 0.0008x^2 - 0.0021x + 0.0068$	0.16
Burstall		
<i>Salix bebbiana</i>	$y = -0.0063x^2 + 0.0181x - 0.0024$	0.86
<i>Salix planifolia</i>	$y = -0.0061x^2 + 0.0187x - 0.0029$	0.91
<i>Carex</i>	$y = -0.0039x^2 + 0.0105x - 0.0013$	0.89
Bonsai		
<i>Salix bebbiana</i>	$y = -0.0019x^2 + 0.0076x + 0.0044$	0.65
<i>Salix planifolia</i>	$y = -0.0049x^2 + 0.015x + 0.0002$	0.81
<i>Erigeron caespitosus</i>	$y = -0.0047x^2 + 0.0105x + 0.001$	0.65
<i>Parnassia</i>	$y = -0.0032x^2 + 0.0075x + 0.0017$	0.83

Note: $y = g_s$ ($m s^{-1}$) and $x=VPD$ (kPa). The parabolic relationships were chosen based on the best goodness of fit that yielded highest R². Interestingly, the fitted parabolic relationships between g_s and VPD for vascular vegetation at Sibbald open upwards, which is quite different from those at Burstall and Bonsai. Additional porometer measurements on Burdock (*Arctium minus*) presented at Sibbald showed the similar shape of the relationship: $y = 0.0004x^2 + 0.0017x + 0.0039$ (R² =0.84). We speculated that the different response of g_s to VPD at Sibbald compared to the other two sites was due to the strong decoupling effect in microclimate gradients (i.e., temperature and relative humidity) below and above the canopy, because Sibbald had an apparently denser overstory canopy than Burstall and Bonsai.

Table C3. Parameters for the modified Shuttleworth–Wallace model in the three study sites.

Parameters	Sibbald	Burstall	Bonsai
Measurement height (z, m)	3	2	3
Canopy height (h_c , m)	1.6	1.6	0.8
Zero plane displacement height (d, m)	1.008	1.008	0.504
Roughness length with complete canopy cover (z_0 , m)	0.208	0.208	0.104
Roughness length with bare substrate (Z_{0b} , m)	0.01	0.01	0.01
Saturated soil water content (θ_{sat})	0.94	0.94	0.485
Mass fraction of bryophyte layer (f_B)	0.001638	0.012	0.0038275
Mass fraction of litter layer (f_L)	0.030936	0.0396	0.005796
Leaf area index (LAI) in July	3.973	1.505	1.323
Leaf area index (LAI) in August	5.141	1.773	1.33

Note: d was calculated as 0.63 of h_c , and z_0 was calculated as 0.13 of h_c , following Allen et al. (1998). Z_{0b} was chosen as 0.01 following Shuttleworth and Wallace (1985). The mass fraction of bryophytes was calculated as the mean of f_B of all microlysimeter samples in the litter-bryophyte-soil (LBS) group, representing the natural conditions of the sites. Similarly, the mass fraction of litter was calculated as the mean of f_L of all microlysimeter samples in the litter-bryophyte-soil (LBS) group.

Table C4. Various structures of the linear mixed model (LMMs) and the goodness of fit of each model quantified by the Akaike's Information Criterion (AIC), the Restricted Maximum Likelihood (REML), the root mean square error (RMSE) and the mean square error (MSE).

No.	Model structure	Degree of freedom	AIC	REML	RMSE	MAE
Fixed-effect model						
1	lg(E)~Site*GroundCover*Canopy*EvaporativeDemand*WaterAvailability	29	570.87	n/a	0.55	0.30
Random intercept model						
2	lg(E)~Site*GroundCover*Canopy*EvaporativeDemand*WaterAvailability+(1 Quadrat)	30	646.55	586.6	0.55	0.30
3	lg(E)~Site*GroundCover*Canopy*EvaporativeDemand*WaterAvailability+(1 Quadrat:GroundCover)	30	646.55	586.6	0.55	0.30
4	lg(E)~Site*GroundCover*Canopy*EvaporativeDemand*WaterAvailability+(1 Canopy:Quadrat)	30	646.55	586.6	0.55	0.30
5	lg(E)~Site*GroundCover*Canopy*EvaporativeDemand*WaterAvailability+(1 Canopy:Quadrat:GroundCover)	30	646.55	586.6	0.55	0.30
Random intercept and slope model						
6	lg(E)~Site*GroundCover*Canopy*EvaporativeDemand*WaterAvailability+(Canopy Quadrat)	32	650.55	586.6	0.55	0.30
7	lg(E)~Site*GroundCover*Canopy*EvaporativeDemand*WaterAvailability+(Quadrat GroundCover)	32	650.53	586.5	0.55	0.30
8	lg(E)~Site*GroundCover*Canopy*EvaporativeDemand*WaterAvailability+(Canopy Quadrat:GroundCover)	32	650.55	586.6	0.55	0.30

Note: The term lg(E) was the log-transformed ground surface evaporation with a base of 10. All candidate fixed-effect terms were included. The symbol “variable 1* variable 2” indicated that the two variables and their interaction were included in the fixed-effect terms. The symbol “variable 1: variable 2” indicated that the variable 2 was nested in the variable 1 and only their interaction was considered in the model. The structure (1|Quadrat) indicated that the effect of quadrat was only considered as the random intercept, while the structure (variable|Quadrat) indicated that the effect of quadrat accounted for both random slopes and intercepts for every “variable:Quadrat” group. REML was not available for the fixed-effect models.

Table C5. The optimal fixed-effect model determined by the backward selection, the goodness of fit, and the Analysis of Variance (ANOVA) Table. The symbol : indicated only the interaction between the variables. The goodness of fit was indicated by the adjusted R-square (R^2), the Akaike's Information Criterion (AIC), the Root Mean Square Error (RMSE) and the Mean Square Error (MSE). DF is the degree of freedom.

The optimal fixed-effect model determined by the backward selection:

$\lg(E) \sim -2.92 + 0.09 \cdot \text{Site} + 2.10 \cdot \text{GroundCover} - 0.49 \cdot \text{Canopy} + 8.58 \cdot \text{EvaporativeDemand} - 4.30 \cdot \text{WaterAvailability} +$
 $0.03 \cdot \text{Site:GroundCover} - 0.38 \cdot \text{Site:Canopy} - 2.34 \cdot \text{Site:EvaporativeDemand} - 5.71 \cdot \text{GroundCover:EvaporativeDemand} +$
 $1.95 \cdot \text{Canopy:EvaporativeDemand} + 2.36 \cdot \text{Site:WaterAvailability} + 2.26 \cdot \text{GroundCover:WaterAvailability} -$
 $1.37 \cdot \text{Canopy:WaterAvailability} - 1.22 \cdot \text{EvaporativeDemand:WaterAvailability} + 1.58 \cdot \text{Site:GroundCover:EvaporativeDemand}$
 $-0.50 \cdot \text{Site:Canopy:EvaporativeDemand} - 1.54 \cdot \text{Site:GroundCover:WaterAvailability} + 0.95 \cdot \text{Site:Canopy:WaterAvailability} +$
 $1.13 \cdot \text{GroundCover:EvaporativeDemand:WaterAvailability} - 0.49 \cdot \text{Canopy:EvaporativeDemand:WaterAvailability}$

The goodness of fit of the optimal model:	Adjusted R^2 : 0.62	DF: 22	AIC: 559.13	MSE: 0.30
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ANOVA Table (Type III)

Fixed-effect terms	DF	Sum of squares	F values	p-value
Intercept	1	4.97	15.36	<0.001
Site	1	0.03	0.10	0.76
Ground cover	1	4.39	13.57	<0.001
Canopy	1	0.11	0.32	0.57
Evaporative demand	1	35.08	108.40	<0.001
Water availability	1	12.96	40.05	<0.001
Site : Ground cover	1	0.008	0.02	0.88

Site : Canopy	1	0.50	1.54	0.22
Site : Evaporative demand	1	38.22	118.08	<0.001
Ground cover : Evaporative demand	1	20.29	62.68	<0.001
Canopy : Evaporative demand	1	1.36	4.20	0.04
Site : Water availability	1	15.82	48.88	<0.001
Ground cover : Water availability	1	6.95	21.48	<0.001
Canopy : Water availability	1	0.99	3.07	0.08
Evaporative demand : Water availability	1	6.75	20.85	<0.001
Site : Ground cover : Evaporative demand	1	24.99	77.22	<0.001
Site : Canopy : Evaporative demand	1	1.36	4.20	0.04
Site : Ground cover : Water availability	1	12.55	38.77	<0.001
Site : Canopy : Water availability	1	2.07	6.39	0.01
Ground cover : Evaporative demand : Water availability	1	7.95	24.57	<0.001
Canopy: Evaporative demand: Water availability	1	0.76	2.35	0.13
Residuals	293	94.83	n/a	n/a

Table C6. The optimal mixed-effect model determined by the backward selection, the goodness of fit, and the Analysis of Variance (ANOVA) Table. The symbol : indicated only the interaction between the variables. The goodness of fit was indicated by the Akaike's Information Criterion (AIC), the Restricted Maximum Likelihood (REML), the Root Mean Square Error (RMSE) and the Mean Square Error (MSE). DF is the degree of freedom.

The optimal mixed-effect model determined by the backward selection:			
$\begin{aligned} \lg(E) \sim & -3.01 + 0.01*\text{Site} + 2.28*\text{GroundCover} - 0.47*\text{Canopy} + 9.17*\text{EvaporativeDemand} - 4.75*\text{WaterAvailability} + 0.13*\text{Site:GroundCover} - 0.22* \\ & \text{Site:Canopy} - 0.12*\text{GroundCover:Canopy} - 2.52*\text{Site:EvaporativeDemand} - 6.52*\text{GroundCover:EvaporativeDemand} + \\ & 1.12*\text{Canopy:EvaporativeDemand} + 2.64*\text{Site:WaterAvailability} + 2.78*\text{GroundCover:WaterAvailability} - 0.56*\text{Canopy:WaterAvailability} - \\ & 1.33*\text{EvaporativeDemand:WaterAvailability} - 0.19*\text{Site:GroundCover:Canopy} + 1.80*\text{Site:GroundCover:EvaporativeDemand} - \\ & 0.24*\text{Site:Canopy:EvaporativeDemand} - 1.89*\text{Site:GroundCover:WaterAvailability} + 0.46*\text{Site:Canopy:WaterAvailability} - \\ & 0.84*\text{GroundCover:Canopy:WaterAvailability} + 1.29*\text{GroundCover:EvaporativeDemand:WaterAvailability} - \\ & 0.37*\text{Canopy:EvaporativeDemand:WaterAvailability} - 0.30*\text{Site:GroundCover:Canopy:EvaporativeDemand} + \\ & 0.54*\text{Site:GroundCover:Canopy:WaterAvailability} + 0.20*\text{GroundCover*Canopy*EvaporativeDemand*WaterAvailability} + (1 \text{Quadrat}) \end{aligned}$			
The goodness of fit of the optimal model:	DF:30	AIC: 646.55	REML: 586.60
ANOVA Table (Type III Wald Chi-square tests)			
Fixed-effect terms	DF	Chi-square	p-value
Intercept	1	10.03	0.002
Site	1	0.0006	0.98
Ground cover	1	6.12	0.01
Canopy	1	0.12	0.73
Evaporative demand	1	58.27	<0.001
Water availability	1	32.92	<0.001
Site : Ground cover	1	0.27	0.60
Site : Canopy	1	0.21	0.65

Ground cover: Canopy	1	0.01	0.92
Site : Evaporative demand	1	65.51	<0.001
Ground cover : Evaporative demand	1	22.99	<0.001
Canopy : Evaporative demand	1	0.46	0.50
Site : Water availability	1	36.14	<0.001
Ground cover : Water availability	1	14.69	<0.001
Canopy : Water availability	1	0.22	0.64
Evaporative demand : Water availability	1	13.46	<0.001
Site : Ground cover : Canopy	1	0.29	0.59
Site : Ground cover : Evaporative demand	1	28.09	<0.001
Site : Canopy : Evaporative demand	1	0.31	0.58
Ground cover: Canopy : Evaporative demand	1	0.42	0.52
Site : Ground cover : Water availability	1	20.31	<0.001
Site : Canopy : Water availability	1	0.57	0.45
Ground cover : Canopy : Water availability	1	0.69	0.41
Ground cover : Evaporative demand : Water availability	1	11.10	<0.001
Canopy: Evaporative demand: Water availability	1	0.51	0.47
Site : Ground cover : Canopy : Evaporative demand	1	0.56	0.45
Site : Ground cover : Canopy : Water availability	1	1.05	0.31
Ground cover : Canopy : Evaporative demand : Water availability	1	0.16	0.69
Site: Evaporative demand : Water availability	0	n/a	n/a
Site: Ground cover: Evaporative demand : Water availability	0	n/a	n/a
Site: Canopy: Evaporative demand : Water availability	0	n/a	n/a
Site: Ground cover: Canopy: Evaporative demand : Water availability	0	n/a	n/a

Table C7. Sources of the literature synthesis, including site, coordinate, wetland type (based on Canadian Wetland Classification System), elevation (EL), study period, water table condition (WTC), method for ET partitioning, evaporation (E), transpiration (T), evapotranspiration (ET), the ratio of T to ET (T/ET), mean leaf area index during the study period (LAI), maximum leaf area index during the study period (LAI_{max}), and references.

No.	Site	Coordinate	Wetland Type	EL	Period	WTC	Method	E	T	ET	T/ET	LAI	LAI _{max}	Reference
1	Baiyangdian wetland (three reed belt stands)	116°01'E, 38°53'N	Reed dominated freshwater marsh	4.4 m	May to Sep in 2008 and May to July in 2009	Standing water above soil surface	Lysimeter	586.2 (mm)	NM	1420.3 (mm)	0.59	2.72	4.3	Xu et al. (2011a) and Xu et al. (2011b)
									NM	1848.4 (mm)	0.68	3.55	5.2	
									NM	2563.8 (mm)	0.77	5.55	8.7	
2	Momoge National Nature Reserve	45.9359° N, 123.6839° E	<i>P. australis</i> dominated Salt marsh	NM	June 20 th and 21 st 2013	Standing water above soil surface	Isotope	NM	NM	8.76 (mm d ⁻¹)	0.38	3.03	NM	Zhang et al. (2018a)
3	Momoge National Nature Reserve	45.9359°N, 123.6839°E	<i>Scirpus</i> dominated salt marsh	NM	June 18 th and 19 th 2013	Standing water above soil surface	Isotope	6.4 (mm d ⁻¹)	1.8 (mm d ⁻¹)	10 (mm d ⁻¹)	0.18	0.16	NM	Zhang et al. (2018b)
			<i>P. australis</i> dominated Salt marsh				Isotope	6.4 (mm d ⁻¹)	1.8 (mm d ⁻¹)	10 (mm d ⁻¹)	0.18	0.86	NM	
4	Seney National Wildlife Refuge (three peatland sites)	46.192° N, 86.018° W	<i>Sphagnum spp.</i> , vascular shrubs and graminoids dominated fen	205	Growing season of 2010 and 2011	0.05 m below peat surface	Porometer and eddy covariance system	346 (mm)	606 (mm)	952 (mm)	0.64	1.98	NM	Moore et al. (2022)
						0.29 m below peat surface		149 (mm)	652 (mm)	801 (mm)	0.81	2.01	NM	
						0.38 m below peat surface		146 (mm)	628 (mm)	774 (mm)	0.81	1.86	NM	
5	Eagle Bottom Marsh	NM	<i>Peltandra</i> dominated tidal freshwater marsh	NM	June 30 th , July 20 th and August 5 th in 1988	Standing water above soil surface	Lysimeter	0.13-0.52 (mm hr ⁻¹)	<0.8 (mm hr ⁻¹)	<0.8 (mm hr ⁻¹)	0.58 (averaged for the two sites)	1.39	3.96	Hussey and Odum (1992)
	Virginia Coastal Reserve	NM	<i>Spartina</i> dominated Salt marsh		August 12 th and	Standing water						0.54	0.89	

					September 14 th in 1988	above soil surface								
6	Wetland Morichales (the T2 site)	9°45'N, 63°27'W	Swamp	NM	March–April 1995	Within 0.1 m above the ground surface	Eddy covariance and models	3.1 (MJ m ⁻² d ⁻¹)	NM	11.6 (MJ m ⁻² d ⁻¹)	0.73	2.6	NM	San Jose et al. (2001)
7	Qinghai–Tibetan Plateau	32°50'49"N, 96°57'3"E	Alpine meadow	3980	Growing season in 2017 and 2018	Below ground surface (inferred from the site photos)	Eddy covariance and models	NM	341.245 (kg H ₂ O m ⁻²)	515.335 (kg H ₂ O m ⁻²)	0.66	NM	2.8	Li et al. (2022)
		33°12'14"N, 96°33'7"E	Alpine swamp	4220				NM	243.96 (kg H ₂ O m ⁻²)	585.245 (kg H ₂ O m ⁻²)	0.42	NM	2.5	
8	Heihe River Basin	38.05°N, 100.46°E	Alpine meadow	3044	Growing season in 2014 and 2015	Below ground surface	Eddy covariance and models	NM	NM	NM	0.79	2.25	NM	Tong et al. (2019)
		38.84°N, 98.94°E	Alpine swamp	3739				NM	NM	NM	0.55	1.6	NM	
9	San Joaquin Freshwater Marsh Reserve	33° 39' 43.008" N, 117° 51' 7.519" W	Freshwater marsh	3	Growing season of 2007	Standing water above soil surfaces	Isotope	NM	NM	0.25-2.25 (mm d ⁻¹)	0.78	2.3	NM	Bijoor et al. (2011) and Rocha et al. (2008)
10	Mer Bleue	45°25'N, 75°31'W	Peat bog	70	Growing season of 1999	0.2 to 0.5 m below peat surfaces	Porometer and eddy covariance system	ND	ND	ND	0.7 (estimated from the Figure 2 in Admiral and Lafleur (2007a))	NM	1.3	Admiral and Lafleur (2007a) and Admiral and Lafleur (2007b)
11	Ballards Marsh	42°30'N, 100°25'W	<i>Phragmites</i> dominated marsh	NM	Growing season of 1994	0.5 m above soil surfaces	Eddy covariance and models	1.0-3.2 (mm d ⁻¹)	2 (mm d ⁻¹)	3.75 (mm d ⁻¹)	0.53	1.4	2	Burba et al. (1999)
12	Bog Lake Peatland	47°32' N, 93°28' W	<i>Sphagnum</i> dominated fen	416	June 27, 1991	0.096 m below the <i>Sphagnum</i> surface	Eddy covariance and models	258 (W m ² , sum over the day)	222 (W m ² , sum over the day)	481 (W m ² , sum over the day)	0.46	0.6	0.7	Kim and Verma (1996)

Note: NM: not mentioned in the study; ND: not directly provided, given as a range, or provided as maximum values in the study.

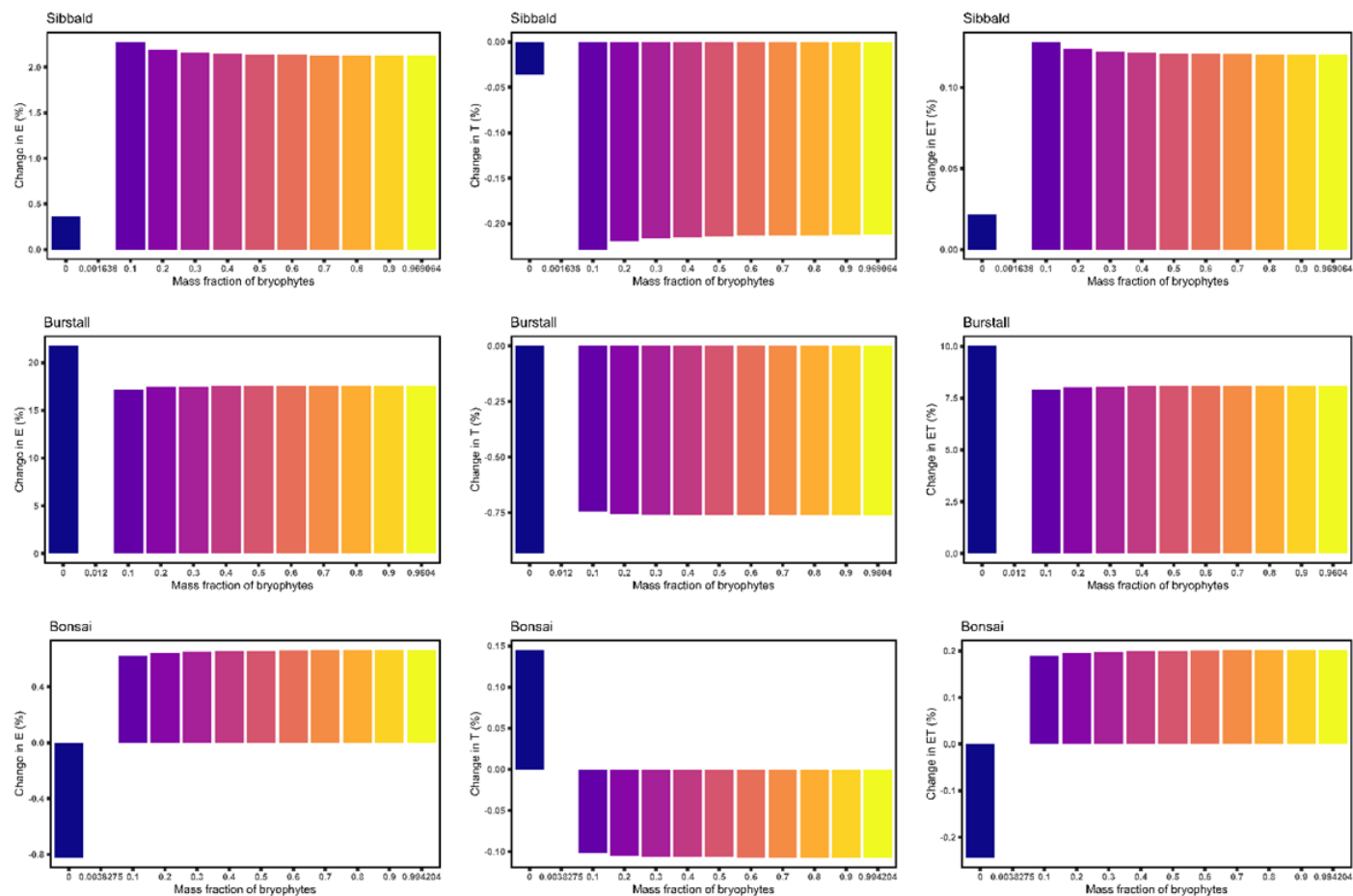


Figure C1. The percentage change in ground surface evaporation (E), vascular plant transpiration (T) and wetland evapotranspiration (ET) compared to the actual site condition for each mass fractions of bryophytes at Sibbald, Burstall and Bonsai, with each mass fraction of bryophytes represented by different colors.

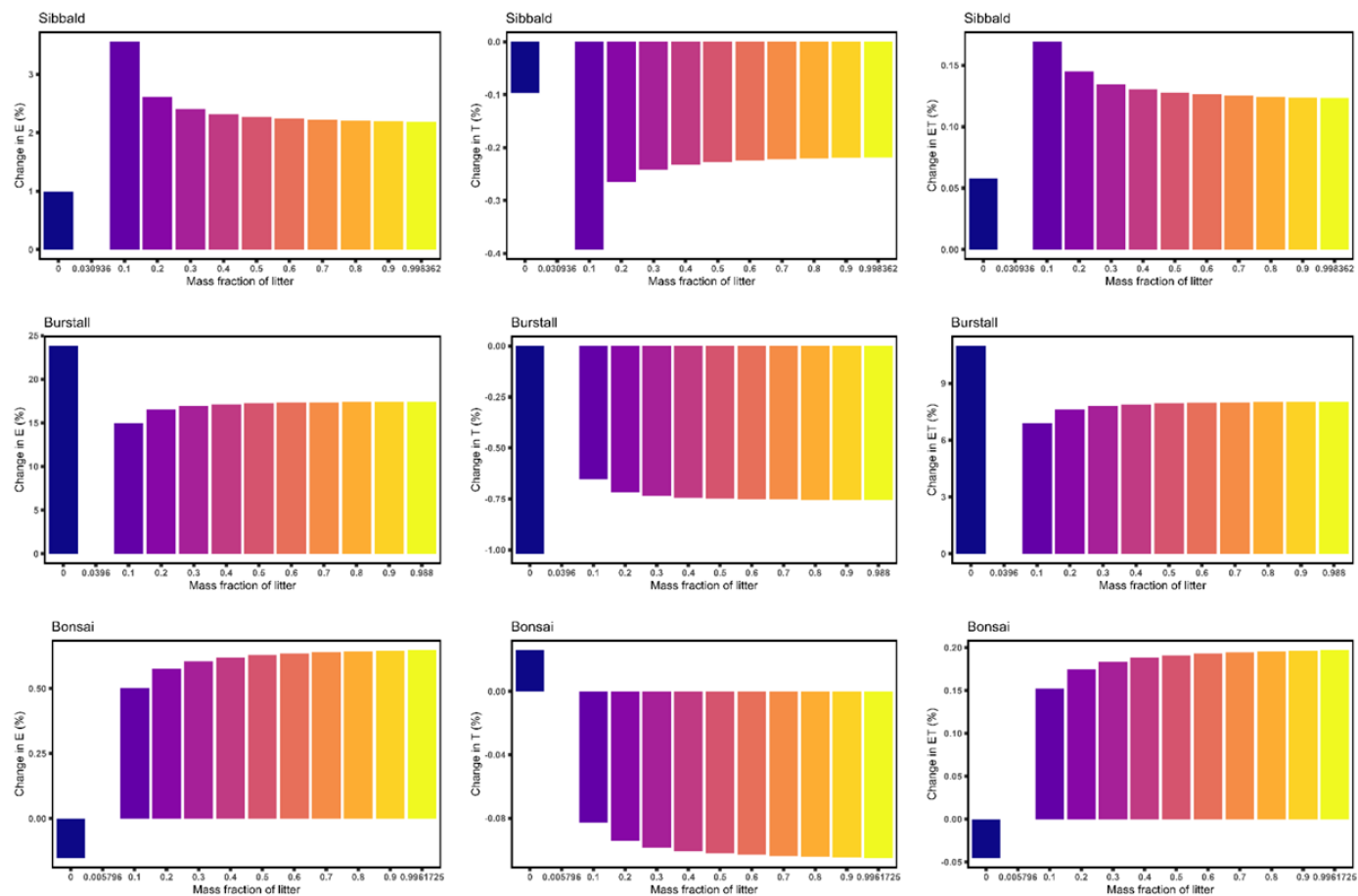


Figure C2. The percentage change in ground surface evaporation (E), vascular plant transpiration (T) and wetland evapotranspiration (ET) compared to the actual site condition for each mass fraction of litter at Sibbald, Burstall and Bonsai, with each mass fraction of litter represented by different colors.