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Technical note: How well do evapotranspiration partitioning approaches perform in moss-covered wetlands?

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Abstract. Evapotranspiration (ET) is the dominant hydrologic flux in wetlands, and partitioning into transpiration (T) and evaporation (E) is essential for understanding water and carbon dynamics, guiding sustainable water management practices, and predicting responses to climate change in these systems. However, the presence of moss layers in many wetlands challenges the assumptions of commonly used partitioning methods. This study evaluates the performance of nine eddy covariance (EC)-based ET partitioning approaches across multiple moss-covered wetland sites located in boreal and the Canadian Rocky Mountains. The partitioning results from each approach were compared against independent measurement-based estimates, which were obtained using flux chamber, micro-lysimeters, sap flow sensors, and EC systems. Results showed that none of the evaluated methods provided both accurate and precise estimates of ET partitioning (T:ET), and no single method emerged as the most suitable for studied ecosystems. Despite this, the general agreement between modelled and measured T:ET values indicates that many of these approaches still provide valuable insights. Applying multiple methods concurrently is recommended, where possible, to enhance confidence in partitioning results. For researchers with access to high-frequency EC data, priority should be given to high-frequency EC-based methods due to their more consistent performance across sites. The findings also highlight the limitations of current partitioning approaches under evaporation-dominated conditions, and underscore the need to examine the mechanistic role of mosses, as well as to improve how optimal stomatal conductance theory is conceptualized and implemented in model formulations.

1. Introduction

Evapotranspiration (ET) represents the total water flux from terrestrial ecosystems to the atmosphere through vegetation transpiration (T) and direct evaporation (E) from canopy and ground surfaces. Distinguishing the contributions of T and E is important for understanding the terrestrial carbon cycle, as T is directly related to vegetation carbon assimilation processes (Jarvis and Mcnaughton, 1986; Farquhar et al., 1980; Farquhar and Sharkey, 1982). Despite its importance, there is a broad consensus within the biogeosciences community that accurately quantifying T and E, whether through direct measurements or computational methods, remains a challenge (Kool et al., 2014; Stoy et al., 2019; Nelson et al., 2020; Zahn et al., 2024). Briefly, directly quantifying T and E involves a combination of multiple field-based measurements, such as stable isotope analysis, lysimeters, porometers, flux chambers, sap flow measurements, and eddy covariance systems (Kool et al., 2014). These methods can be labor-intensive, require site-

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specific instrumentation, and are often constrained in both spatial (e.g., plot-scale) and temporal (e.g., depending on measurement frequency) resolutions (Albert-Saiz et al., 2025). In contrast, modelling approaches, especially the eddy covariance (EC)-based ET partitioning methods to partitioning ET into E and T at the ecosystem level, may be convenient and enable the exploration of temporal variability for estimating E and T at the ecosystem scale. However, they rely on assumptions that are ecosystem-dependent, require accurate parameterization, and model validation is not always available due to the lack of in site measurements (Eichelmann et al., 2022; Zhou et al., 2016; Stoy et al., 2019). As reviewed by Stoy et al. (2019), these limitations highlight the need for ecosystem-scale experiments using multiple methods to measure E and T to understand their distinct responses to climate variability and change across diverse ecosystems and also to evaluate and refine the assumptions underlying ET partitioning approaches (Stoy et al., 2019).

Currently, research specifically addressing ET partitioning within wetland ecosystems remains notably scarce, even though wetlands, especially peatlands, are critical carbon sinks and play a critical role in regulating regional hydrology and global climate (Mitra et al., 2005; Leifeld and Menichetti, 2018; Strack et al., 2022; Frolking et al., 2006). Consequently, there is limited field data available to develop and evaluate reliable ET partitioning approaches for wetland ecosystems. Moreover, most of the existing studies have focused on hydroperiods where E mostly comes from standing water or saturated soils (Xu et al., 2011; Allen et al., 2017; Zhang et al., 2018; Hussey and Odum, 1992; Burba et al., 1999; Goulden et al., 2007; Kiniry et al., 2023; Bijoor et al., 2011; Eichelmann et al., 2022). However, it should be noted that many wetlands are not consistently in a saturated state (e.g., Jacobs et al. (2002), Wu et al. (2010), Kettridge et al. (2017), and Streich and Westbrook (2020)), which raises concerns about whether methods developed under flooded conditions can be applied reliably to non-flooded conditions or to estimate ET partitioning under changing environmental conditions. Furthermore, current studies report varying results regarding the dominance of T or E in wetland ET and their controlling environmental factors, which suggests that ET partitioning in wetland ecosystems is regulated by both structural properties including vegetation composition, density, and areas of open water, and environmental conditions such as climatic variables and water table (Goulden et al., 2007; Kiniry et al., 2023; Warren et al., 2018; Allen et al., 2017; Eichelmann et al., 2022; Admiral and Lafleur, 2007). Given that many ET partitioning approaches rely on assumptions about T dominance or dominant environmental controls, it remains uncertain if there is a universally reliable ET partitioning method for wetland ecosystems.

Despite the limited research focused specifically on wetlands, ET partitioning approaches are relatively abundant, particularly those based on EC data, as EC systems have been widely deployed across diverse ecosystems. Several of these EC-based methods have been tested across a range of ecosystems, including forests, grasslands, woody savannas, and croplands, and have shown broad applicability, not restricted to water-limited ecosystems (Yu et al., 2022; Nelson et al., 2020; Zhou et al., 2016; Li et al., 2019; Zahn et al., 2024). However, most of these methods have not been evaluated in wetlands. In fact, simply not restricted to water-limited ecosystems does not guarantee that these methods are suitable for wetlands, as the unique characteristics of wetlands, particularly moss-covered ground surfaces in many peatlands, may violate key assumptions on which these methods primarily rely. Specifically, mosses can photosynthesize and contribute to ecosystem carbon sequestration (Pacheco-Cancino et al., 2024; Street et al., 2013; Badorek et al., 2011; Kokkonen et al., 2022), but they do not contribute to transpiration fluxes. This decoupling may

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violate the assumption in some methods that photosynthesis and transpiration share identical sources and sinks. Moreover, most mosses cannot actively regulate water transport and water fluxes; instead, they rely on passive capillary rise to transport water (Proctor, 1982). When free capillary rise is limited by low soil-water pressures, the water potential of moss cells can rapidly equilibrate with the surrounding air, reducing both evaporation and photosynthetic activity, even when atmospheric demand for evaporation remains high (Goetz and Price, 2015; Mccarter and Price, 2012; Proctor, 1982; Kettridge and Waddington, 2013; Ketcheson and Price, 2013). In addition, mosses can absorb water directly from their surroundings through their leaves and stems, and store water equivalent to 300 to 500% of their dry weight for extended periods (Rouse, 2000; Bayfield, 1973). This remarkable water storage capacity, combined with their ability to rapidly equilibrate their water content with ambient humidity, helps conserve moisture in deeper soil layers during dry periods (Ketcheson and Price, 2013; Kettridge and Waddington, 2013), and cools the soil surface (Chen et al., 2019). These unique behaviors of mosses may therefore violate assumptions about key environmental controls on T or E fluxes, as well as the assumed relationships between carbon uptakes and water exchange used by some methods to separate T and E fluxes.

Although the presence of mosses may violate some of the assumptions used in EC-based ET partitioning approaches, it is uncertain whether these violations render the methods completely unsuitable for wetland research, or whether these methods can still offer insights into the dynamics of T and E fluxes. Intuitively, the extent to which these violations affect the accuracy of EC-based ET partitioning approaches depends on the relative contribution of mosses to wetland gross primary production (GPP) compared to vascular plants at a given site. Although multi-site analyses have shown a positive correlation between peatland carbon assimilation and moss cover percentage (Strack et al., 2016; Pacheco-Cancino et al., 2024), quantitative data on moss contributions to ecosystem-level GPP remains extremely scarce. Limited evidence suggests that mosses can play a considerable role: for instance, a field study in a raised mire complex in southern Finland reported moss contributions to cumulative community-level photosynthesis of a contribution of 1.5%, 35.2% and 41.2% in the undrained area in rich fen, poor fen, and bog, respectively (Kokkonen et al., 2022). Similarly, in a drained forested peatland dominated by moss on the forest floor, CO_2 assimilation by the forest floor represented 20 to 30% of the forest's total CO_2 uptake (Badorek et al., 2011). These findings indicate that while mosses can substantially contribute to ecosystem GPP, vascular plants generally dominate, accounting for over 50% of the ecosystem GPP. Consequently, the presence of mosses may not markedly compromise the performance of EC-based ET partitioning methods. Currently, there has been no evaluation of these approaches in wetland ecosystems. Therefore, the objectives of this study are to assess the performance of existing EC-based ET partitioning methods in moss-covered wetlands.

2. Methods

2.1 Overview of EC data-based ET partitioning approaches considered

ET partitioning approaches selected for this study were chosen based on three criteria: (1) they rely primarily on EC-based CO_2 and H_2O fluxes, (2) focus on the ecosystem level with daily or finer temporal resolution, are not restricted

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to water-limited conditions, and (3) have publicly available formulations or programming codes. Consequently, this study evaluates nine methods (Table 1) and excludes the methods developed by Wei et al. (2017), Scott and Biederman (2017), Rigden et al. (2018) and Reich et al. (2024). Note that Eichelmann et al. (2022) introduced an artificial neural networks (ANNs)-based ET partitioning methods for flooded ecosystems, its code is not publicly available and was therefore not evaluated here. To the best of the authors' knowledge, the ET partitioning methods evaluated in this study cover most of the existing EC-based approaches. Based on the type of EC data they utilize, either high-frequency or values aggregated at a half-hourly timestep, these approaches are grouped into two categories: the high-frequency EC data-based methods (Group 1), and ecosystem carbon-water coupling methods (Group 2). These approaches and their required data and limitations for application in moss-covered wetland ecosystems are summarized in Table 1.

Table 1. Overview of data requirements and potential limitations of EC-based ET partitioning methods in moss-covered wetlands. Group 1 includes methods using high-frequency EC data, while Group 2 includes methods using ecosystem-level EC data aggregated at specific timesteps.

Method	Group	Required Data	Examples of Potential Issues When Applied to Moss-covered Wetlands	References
Flux Variance Similarity (FVS)	1	High-frequency c, q, u, v, w, and WUE_{canopy}	The assumption of identical source/sink for transpiration and photosynthesis is invalidated by moss photosynthesis.	Scanlon and Kustas (2010)
Conditional Eddy Accumulation method (CEA)	1	High-frequency c, q, u, v, and w	The uneven and open canopy often found in wetlands, together with moss photosynthesis, can blur ground and vegetation signals used for flux partitioning.	Businger and Oncley (1990) and Zahn et al. (2024)
Modified Relaxed-Eddy Accumulation method (MREA)	1	High-frequency c, q, u, v, and w	The presence of short or multi-layered canopies, often found in wetlands, along with moss photosynthesis and respiration in the understory, may violate the similarity of turbulent transport of non-stomatal components from the soil.	Thomas et al. (2008) and Zahn et al. (2024)
Conditional Eddy Covariance method (CEC)	1	High-frequency c, q, u, v, and w	Same as CEA	Zahn et al. (2022)
Underlying water-use efficiency method (uWUE)	2	GPP, ET, and VPD	The assumption that T dominates ET during periods of high GPP/ET may not hold in E-dominated wetlands; and carbon assimilation is assumed to occur only from leaf-level photosynthesis.	Zhou et al. (2016)
Pérez-Priego method (PP)	2	GPP, C_a, P_a, T_{air}, VPD, LE, H, U_{star}, WS, Rg, Q, and Z	The big leaf representation used to estimate optimal stomatal conductance from EC-based P_h does not account for moss photosynthesis; and the complexity of the optimization procedure can sometimes fail in reaching a numerical solution.	Pérez-Priego et al. (2018)
Transpiration Estimation Algorithm (TEA)	2	GPP, RH, Rg, Rg_{pot}, T_{air}, VPD, Precip, WS, and year	The assumption that T:ET ~1 during periods with minimal surface moisture conditions may not hold in E-dominated wetlands.	Nelson et al. (2018)
Conductance Partitioning method (CP)	2	GPP, ET, VPD, and θ	The assumption that surface conductance is not sensitive to VPD may be invalidated by moss responses to ambient humidity.	Li et al. (2019)
Carbon-water relationship and stomatal conductance model (CWSC)	2	GPP, ET, VPD, C_a, P_a and g_1	Carbon assimilation is assumed to occur only from leaf-level photosynthesis; and publicly available g_1 dataset by plant functional types (PFTs) are lacking for wetland ecosystems.	Yu et al. (2022)

Note. c, high-frequency CO_2 concentration; q, high-frequency H_2O concentration; u, high-frequency streamwise wind speed, v, high frequency cross-stream wind speed; w, high frequency vertical wind speed; WUE_{canopy}, canopy-level water-use efficiency; GPP, ecosystem gross primary production; ET, ecosystem evapotranspiration; VPD, vapor pressure deficit; C_a: mean atmospheric CO_2 concentration; P_a, atmospheric pressure; T_{air}, air temperature; LE, latent heat flux; H, sensible heat flux; U_{star}, friction velocity; WS, mean wind speed; Rg, incoming shortwave radiation; Q,

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photosynthetic active radiation; Z, altitude; RH: relative humidity; Rg_{pot}, daily potential radiation; Precip, precipitation; θ, soil moisture; g_1, a parameter in the optimal stomatal conductance model. Some required variables differ from those listed in the original publications and instead reflect the data inputs used in the publicly available codes provided by the authors of each method. Specifically, the FVS, CEA, MREA and CEC methods were applied using the ET partitioning code developed by Zahn (2024); the PP method by Pérez-Priego and Wutzler (2018); the uWUE and TEA methods by Nelson (2020); and the CWSC method by Jiang and Yu (2021). Please refer to the corresponding references for further details.

2.2 Study sites

The best way to evaluate the ET partitioning approaches is by comparing their outputs to direct field measurements. However, to the best of the authors' knowledge, no publicly available datasets exist for wetland ET and its components. Therefore, we compiled data from four sites where field measurements of ET and its components had previously been conducted. The first three sites, Sibbald, Burstall, and Bonsai, are located in the Canadian Rocky Mountains, where field measurements were conducted during the 2021 growing season. The fourth site, Poplar, is situated in the western boreal plain near Fort McMurray, Alberta, Canada, and its field measurements were conducted during the 2013 growing season. Among the four sites, only Sibbald and Poplar are peatlands.

These sites are covered by mosses. At Sibbald, the moss layer is approximately 5 mm thick and includes species such as *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). At Burstall, the moss layer, about 1 cm thick, is dominated by peat moss (*Sphagnum* spp.) and feather moss (*Eurhynchium* spp.). At Bonsai, the moss cover consists primarily of brown moss (*Tetrodontium* spp.) with a thickness of up to 5 mm. At poplar, the moss layer is around 2.5 cm thick (Goetz and Price, 2015), dominated by *Tomenthypnum nitens* (Hedw.) Loeske and *Aulacomnium palustre* (Hedw.). It is important to clarify that the moss layer in this study refers mainly to the photosynthetically active (green) components of the mosses, including their shoots and capitula. Although all sites are moss-covered wetlands, they differ considerably in meteorological conditions, water table levels, vegetation composition, and canopy structure (Table 2 and Figure S1). During the study period, the growing season LAI was 4.56, 1.64, 1.33 and 2.82 for Sibbald, Burstall, Bonsai and Poplar, respectively, with the value at Poplar representing the tree canopy only.

Table 2. Summary of site characteristics, including geographic coordinates, wetland type, altitude, meteorological conditions during the study period, soil properties, water table depth, vegetation composition, and instrumentation used for measuring evapotranspiration and its components.

Site	Wetland Class	Latitude	Longitude	Elevation (m)	Temp.* (ºC)	Precip.* (mm)	Soil (0-15 cm)	WT depth (m)	Vascular vegetation	Instruments
Sibbald	Fen	51.06°N	114.87°W	1,490	14.0	137.7	Peat	0.5 to 1	The overstory is characterized by clusters of *Salix* spp., while the	Micro-lysimeter, porometer and eddy covariance system

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									understory consists of dense *Carex* spp.	
Burstall	Marsh	50.78°N	115.34°W	1,900	11.6	32.2	Peat	-0.1 to 0.1	The overstory is characterized by sparse *Salix* spp., while the understory consists of dense *Carex* spp.	Micro-lysimeter, porometer and eddy covariance system
Bonsai	Wet meadow	50.82°N	115.21°W	2,100	11.7	128.3	Silt and clay	>2	The overstory consists of sparsely distributed species such as *Salix* spp., *Larix* spp., *and Abies* spp., while the understory is abundant with species including *Erigeron* spp., *parnassia* spp., *and Equisetum* spp.	Micro-lysimeter, porometer and eddy covariance system
Poplar	Fen	56.56°N	111.33°W	322	18.4	320.8	Peat	-0.1 to 0.9	The overstory consists of a dense cover of *Larix laricina*, with sparse occurrences of *Picea mariana*, while the understory consists of a dense shrub layer including *Betula pumila*, *Equisetum fluviatile*, *Smilacena trifolia*, *Carex prairea*, and *Carex diandra*	Flux chamber, sap flow system, and eddy covariance system

Note. Elevation is the elevation above sea level (in meters). Temp* represents the mean air temperature during the measurement period, and Precip.* is total precipitation during the same period. Soil describes the dominant soil type within the top 15 cm where micro-lysimeters were installed. WT depth represents the position of the water table relative to the ground surface, with positive values indicating that the water table is lower than the ground surface and negative values indicating flooded conditions. Instruments summarize the main equipment used to measure or estimate E, T and ET at each site.

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2.3 Field measurements of evaporation, transpiration and evapotranspiration

Ecosystem-scale water and carbon fluxes at all sites were measured by eddy covariance systems operating throughout the respective measurement periods. The ratio of EC measurement height to canopy height (z/h) is 1.88 at Sibbald, 1.25 at Burstall, 3.75 at Bonsai, and 1.55 at Poplar. EC data processing followed common FLUXNET protocols (Kaimal and Finnigan, 1994; Foken and Leclerc, 2004; Aubinet et al., 2012; Burba et al., 2012; Leuning and Judd, 1996; Webb et al., 1980). Latent heat flux (LE) was gap-filled using the MDS method (LE_F_MDS). Note that GPP is a required input for many ET partitioning approaches. In this study, it was estimated from EC-measured net ecosystem exchange (NEE_VUT_USTAR50) using the night-time flux partitioning method described by Reichstein et al. (2005).

In addition to EC measurements, evaporation at Sibbald, Burstall and Bonsai was measured using micro-lysimeters on six separate occasions during July and August in 2021, with each measurement period lasting mostly 2 to 4 days (Wang et al., 2023; Wang and Petrone, 2022). Stomatal conductance of the dominant vascular vegetation (Table 2) at these three sites were measured by leaf porometer (Wang, 2025). At the Poplar site, transparent flux chambers and sap flow systems were used to measure ground evaporation and canopy transpiration during the 2013 growing season (Gabrielli, 2016). These measurements were conducted within the EC footprint of each site. Detailed descriptions of site characteristics, field measurements, instrumentation, and the upscaling of plot-level data to estimate ecosystem-level daily transpiration-to-evapotranspiration ratios (T:ET) are provided in Wang (2025) and Gabrielli (2016), and are not repeated here.

2.4 Data quality control procedure

Given the measurement techniques described above, it is important to clarify that evaporation measurements in this study represent only ground evaporation. However, during rainy periods, evaporation can occur from leaf surfaces. Excluding this canopy evaporation may introduce bias in estimating ecosystem-scale ET partitioning into E and T. To minimize this potential bias, all methods except for the CP method exclude rainy days and 1 to 2 days afterward, following the precipitation and potential evapotranspiration (PET)-based criteria described in Zhou et al. (2015) and Yu et al. (2022). Specifically, if PET $<$ Precip $<$ 2PET, 1 day after a rainy day was excluded, if Precip $>$ 2PET, 2 days were excluded. For the CP method, data screening follows its original protocol, which removes data during rainy hours and the 6 hours following rainfall (Li et al., 2019).

In addition to excluding rainy periods, all methods were prescreened to include only data from the growing season, during daytime hours, and under conditions where net radiation, GPP, LE, H and VPD were greater than zero. Half-hourly EC fluxes data with poor quality (i.e., the quality flag (QC) $>$ 1) were removed. For the CP method, additional filters were applied by excluding data with RH above 0.95, and by retaining only those periods where H exceeded 5 W m^{-2} and Rg exceeded 50 W m^{-2} (Li et al., 2019).

When aggregating half-hourly ET partitioning results to daily values, only days with more than 10 valid half-hourly values were included, following the procedure in Yu et al. (2022). Additionally, any half-hourly T:ET values that were negative or greater than 1 were excluded prior to daily aggregation.

2.5 Evaluation of ET partitioning approaches

Direct measurements of ET components offer an independent means to evaluate the performance of ET partitioning approaches. However, this study does not focus on comparing exact magnitudes of T:ET between measurement-based estimates and those derived from ET partitioning approaches. This is because most field measurements were conducted at the plot level, and upscaling to the ecosystem level introduces uncertainties, as a wetland is a mosaic of diverse habitats with varying extents of vegetation cover, open water, and exposed bare soil (Drexler et al., 2004), which makes spatial upscaling very challenging. In peatlands, such complexity is further increased by micro-topographical features, such as hummocks (local high points) and hollows (local low points), which have been shown to influence ground evaporation processes (Wang and Petrone, 2022).

In addition, the temporal resolution of measurements varies across methods. For example, flux chamber and porometer measurements provide instantaneous variables during daytime, whereas micro-lysimeters measurements in this study operated over multiple days, which yields averaged daily values. Reconstructing daily T:ET at the ecosystem level from these different measurements introduces additional biases. Moreover, all ET partitioning approaches, strictly speaking, fundamentally rely on the coupling between carbon and water fluxes during the daytime period when photosynthesis takes place. Consequently, ET partitioning results may not precisely align with measurements that include the nighttime period.

Furthermore, some required input variables were not directly measured and had to be approximated, which also introduces uncertainties. For example, the FVS method requires canopy-level water-use efficiency (WUE_{canopy}) as input, and its outputs are sensitive to the estimates of this parameter (Sulman et al., 2016). However, direct measurements of WUE_{canopy} and intercellular CO_2 concentration to estimate WUE_{canopy} were unavailable, as a result, the optimization method proposed by Scanlon et al. (2019) was used to estimate WUE_{canopy}. But this method is more appropriate for light-saturating conditions (Scanlon et al., 2019), which may not always occur. The FVS method that uses estimated WUE_{canopy} from this optimized method is hereafter referred to as FVSopt. The CWSC method requires the parameter g_1, which is not readily available for wetland ecosystems. Since most wetland plants are C3 species and mosses also follow a photosynthesis pathway similar to C3 plants (Aro and Gerbaud, 1984), g_1 values for each site were derived from the reported values for C3 species based on a moisture index (MI) of each site, following Lin et al. (2015). Specifically, Sibbald and Burstall have MIs of 0.77 and 0.72, respectively, and were therefore both given a g_1 value of 4.69 kPa$^{0.5}$. Bonsai, with an MI of 5.38, was assigned a g_1 value of 4.02 kPa$^{0.5}$. Poplar, with an MI of 0.48, was given a g_1 value of 3.77 kPa$^{0.5}$. However, these estimates may not accurately represent the actual g_1 at the site, which potentially affects model performance.

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Given those limitations, this study emphasizes evaluating whether T:ET values derived from partitioning approaches are broadly consistent with measurement-based estimates and exhibit similar temporal dynamics.

3. Results and Discussions

The ET partitioning results derived from Group 1 methods, which are based on high-frequency EC data, are presented in Fig. 1. As anticipated, the T:ET estimates from these methods do not always align closely with the measurement-based values. Nevertheless, when using the measurement-based values as a reference, Group 1 methods appear to perform relatively better at Sibbald and Poplar than at Burstall and Bonsai. According to Zahn et al. (2024), Group 1 methods tend to be more reliable under specific conditions: no strong vertical stratification or convection, EC sampling height near the canopy top (i.e., $z/h \approx 1$), moderate or low LAI, and the canopy does not have gaps that are too wide. However, these site characteristics alone do not fully account for the better performance observed at Sibbald and Poplar. The only consistent difference between the better-performing sites (Sibbald and Poplar) and the others (Burstall and Bonsai) is the relatively higher T:ET values observed at Sibbald and Poplar. Although the methods varied in performance across sites and differed in the magnitude of T:ET estimates at the same site, they generally captured similar temporal patterns and fluctuations that correspond well with the measurement-based T:ET values. An exception is observed at Burstall after August 15, when the measurement-based T:ET exhibits a sharp decline, whereas the T:ET estimated by Group 1 methods shows only a slight decrease.

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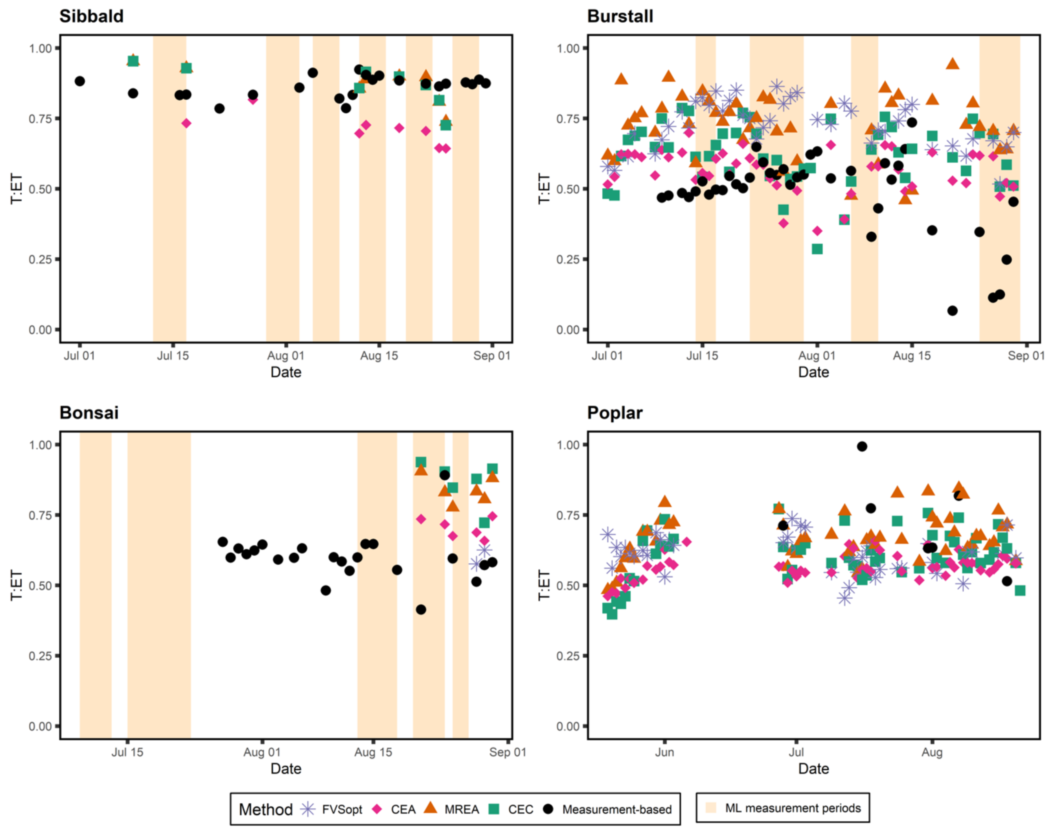

Figure 1: Comparison of T:ET estimates from high-frequency EC-based methods (Group 1) with measurement-based values across four study sites. Note that FVSopt did not produce any realistic T:ET values at Sibbald and was thus excluded. The light beige background (ML measurement periods) highlights periods during which micro-lysimeters (ML) were used to measure ground evaporation at Sibbald, Burstall and Bonsai. For periods outside of ML measurements, ET partitioning was obtained using the site-calibrated and validated Shuttleworth–Wallace (S–W) model (Wang, 2025).

The ET partitioning results from Group 2 methods, including uWUE, PP, TEA, CP and CWSC, are shown in Fig. 2. Compared to Group 1 methods, the performance of Group 2 approaches is less consistent across sites. For example, the CP method performed well at Sibbald but failed at the other three sites; at Bonsai, all CP-estimated T:ET values exceeded 1 and were therefore excluded. Despite differences in magnitude among methods and across sites, most of Group 2 methods also captured the temporal patterns and fluctuations observed in the measurement-based T:ET values. Notably, TEA was the only method that captured the sharp decline in T:ET observed at Burstall after August 15. In contrast, the PP method substantially underestimated T:ET and exhibited contrasting temporal trends relative to the measurement-based values at Sibbald and Burstall. This observation is different from the findings in Nelson et al. (2020) who reported similar results between the PP and uWUE methods. The exact cause of this bias remains unclear. However, since other methods aligned more closely and PP is the only method in this group that requires photosynthetically active radiation (Q) as an additional input, the discrepancy is likely related to this variable. It is

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possible that Q measured at a single location did not adequately reflect canopy-level conditions, potentially due to the uneven and multi-layered canopy structures in these study sites (Fig. S1). Another potential explanation is that the PP method's evaporation component may include not only ground evaporation but also canopy evaporation (e.g., dewfall), as suggested by Pérez-Priego et al. (2018). This inclusion of canopy evaporation could result in lower T:ET. However, this hypothesis could not be tested in the present study and requires further investigation.

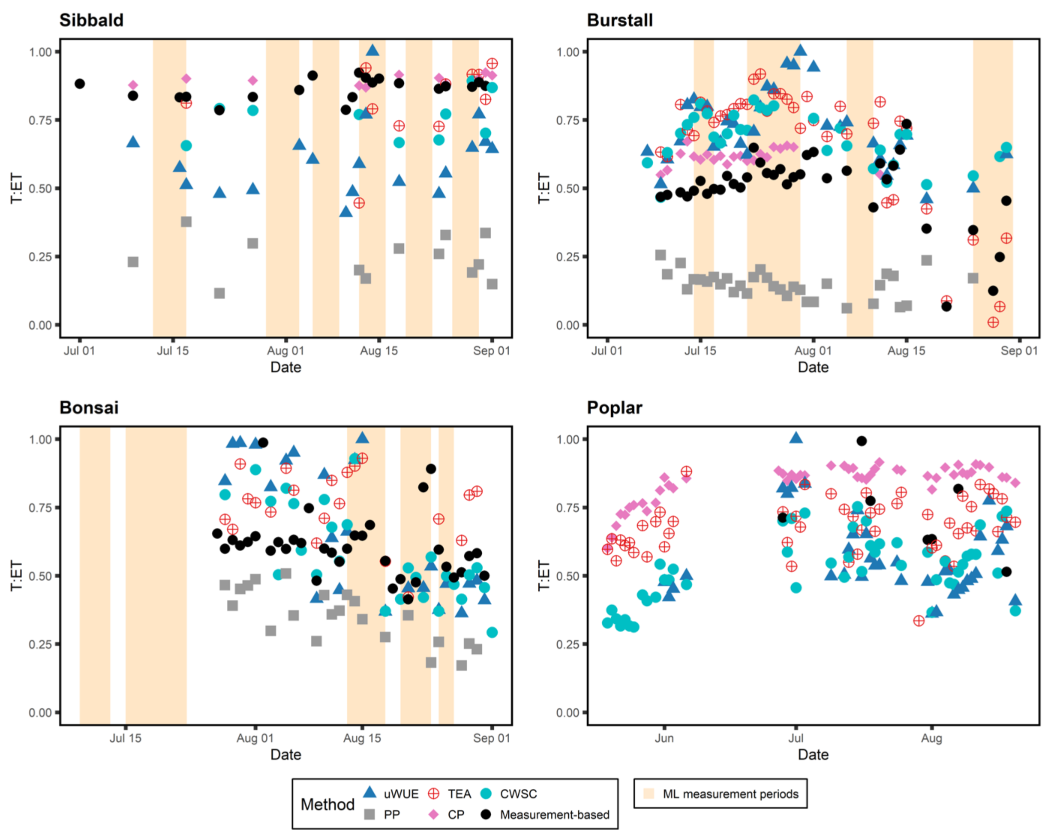

Figure 2: Comparison of T:ET estimates from Group 2 methods against measurement-based values across four study sites. Note that the CP method did not produce any realistic T:ET values at Bonsai and thus was excluded. The PP method was not performed at Poplar due to missing photosynthetically active radiation data. The light beige background (ML measurement periods) highlights periods during which micro-lysimeters (ML) were used to measure ground evaporation at Sibbald, Burstall and Bonsai.

The overall performance of each method, pooled across all study sites, is presented in Fig. 3. Except for the PP method, most methods produced T:ET estimates that scatter around the 1:1 line relative to the measurement-based values. There was no clear pattern indicating how variations in water table levels near the ground affected model performance. Notably, as illustrated in Fig. 3, when T:ET exceeds 0.5, the estimates tend to align more closely with the 1:1 line. However, for T:ET values below 0.5, Group 1 methods generally exhibit substantial overestimation, while most Group

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2 methods failed to provide realistic estimates and were therefore excluded. Surprisingly, the TEA method stands out as an exception among all methods when T:ET is lower than 0.5. However, this does not necessarily indicate its suitability for E-dominated ecosystems, as this method has been shown to overestimate T when sites have a relatively constant E component (Nelson et al., 2018). These findings highlight a limitation of these ET partitioning methods in evaporation-dominated ecosystems.

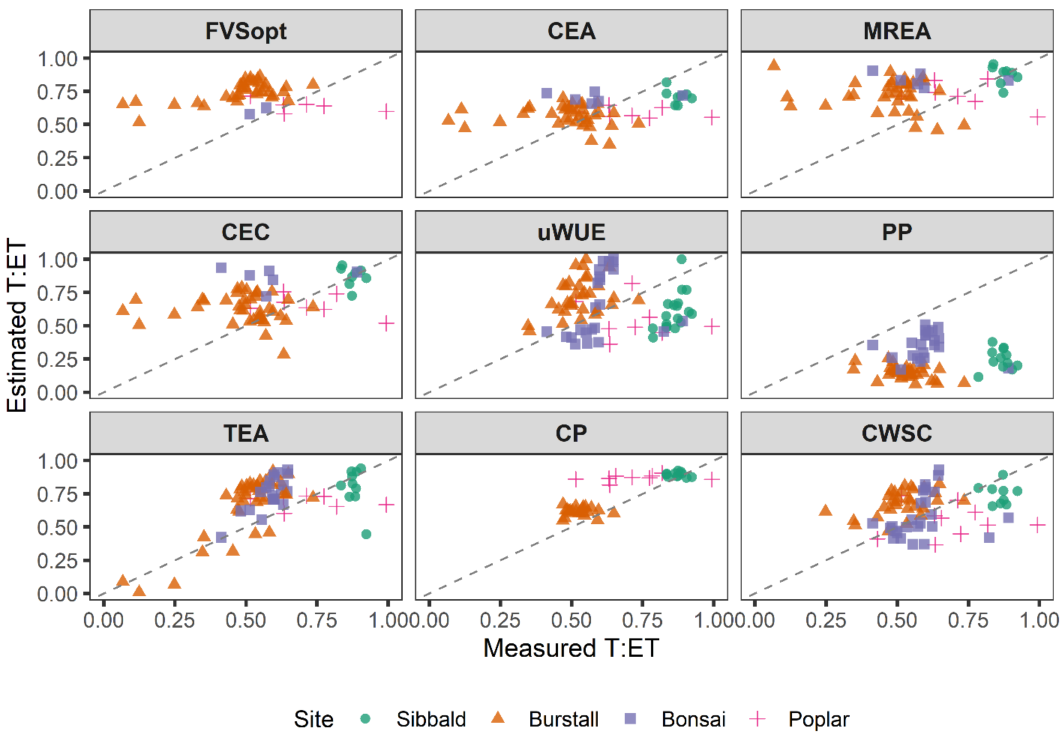

Figure 3: Performance of all ET partitioning methods pooled across sites, compared against measurement-based T:ET values.

Additionally, aside from MREA, CEA, and CEC, which are based on conditional sampling approaches, all other methods, to varying extents, utilize the theory of optimal stomatal conductance. Among these, uWUE, CP, and CWSC are formulated using the unified stomatal conductance model proposed by Medlyn et al. (2011). The general agreement between their T:ET estimates and the measurement-based values supports previous conclusions that an optimal ecosystem response to VPD is a reasonable assumption (Stoy et al., 2019), even in some moss-covered wetlands such as those examined in this study. However, as noted by Stoy et al. (2019), the way in which optimality is conceptualized and implemented in these models may need to be refined. Improvements could include incorporating effects of plant hydraulic architecture, soil moisture, temperature , atmospheric CO_2 concentration (Bernacchi et al., 2004; Medlyn et al., 2011; Lin et al., 2015; Nardini and Salleo, 2000), as well as considering the timescales over which assumptions

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about constant parameters in the unified stomatal conductance model can hold (Mäkelä et al., 1996), could improve model performance. This is illustrated by the comparison of results from uWUE, CP and CWSC. Both CP and CWSC, which account for soil moisture and atmospheric CO_2 concentration effects respectively, produced a narrower spread of T:ET estimates than uWUE, which suggests that including these additional constraints improves model performance at sub-daily and daily scales.

In sum, despite the variability in T:ET estimates and the limitations discussed above, these methods collectively provide a plausible range within which the true T:ET likely falls and reasonably captures T:ET temporal dynamics. This indicates that, despite the presence of mosses, which may challenge some assumptions of ET partitioning approaches, these methods collectively still offer valuable insights into wetland ET partitioning, particularly its temporal dynamics. This enables investigation of some urgent research questions in moss-covered wetland ecosystems, like how transpiration and evaporation components respond to changing climate and environmental conditions.

4. Summary and closing thoughts

The purpose of this study is to provide supporting evidence and recommendation for future research that plan to apply EC-based ET partitioning approaches in moss-covered wetlands, particularly in cases where direct validation through field measurements is not available. By comparing method-derived T:ET with direct field measurements of ET and its components at four different wetlands and by excluding rainy periods from analysis, this study found that all methods, despite having substantial differences in the magnitude of estimated T:ET, captured similar overall temporal patterns of T:ET. This observation is consistent with the evaluation of three ET partitioning methods (TEA, uWUE and PP) conducted by Nelson et al. (2020). This study also found that no single approach consistently outperformed the others across all sites and time periods. Therefore, for researchers interested in ET partitioning in similar wetlands, applying multiple methods concurrently is recommended when possible.

Our recommendation is consistent with the suggestion provided by Zahn et al. (2024) in their evaluation of Group 1 methods. But building upon that recommendation, findings from this study further suggest that Group 2 methods exhibit greater variability and inconsistency across sites. This is likely due to the distinct dominant environmental controls on which each Group 2 method is based, as well as the uncertainties associated with the additional meteorological or soil variables required beyond EC data by these methods. While Group 1 methods may not yield the most accurate estimates, Group 2 methods may provide either the most accurate or the least accurate results, depending on site-specific data quality. Without prior knowledge on the dominant environmental controls at a given wetland, and considering the greater potential for measurement uncertainties in Group 2 methods, Group 1 methods offer a more reliable staring point for estimating ET partitioning. However, high-frequency EC data are often accessible only to tower owners and are not widely shared. As such, this recommendation to prioritize Group 1 methods is intended for researchers with access to high-frequency data.

However, several caveats must be considered when interpreting the results of this study. First, the study did not examine the mechanisms by which mosses influence the results of ET partitioning approaches. This remains an

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important topic for future research. Secondly, the ET partitioning results presented here were filtered based on the data quality controls described in the Methods section. It is important to emphasize that rainy periods were excluded; if included, most Group 2 methods produced unrealistic T:ET values exceeding 1. Third, the evaporation component considered in this study refers exclusively to ground evaporation. Whether the findings can be extended to include canopy evaporation remains an open question. Lastly, the conclusions are most likely valid for sites with moss thickness similar to or less than that of those studied here. Uncertainty remains regarding their applicability to ecosystems with thicker moss layers and fewer vascular plants. Nonetheless, the study sites represent common wetlands and are expected to reflect a broad range of wetland ecosystems. Therefore, the conclusions are highly likely applicable to many wetland ecosystems.

Data Availability Statement

The measurement-based T:ET estimates were previous published in Gabrielli (2016) and Wang (2025), and the raw measurement data will be made available upon reasonable request to the corresponding author. The FVS, CEA, MREA and CEC methods were applied using the ET partitioning code developed by Zahn (2024); the PP method by Pérez-Priego and Wutzler (2018); the uWUE and TEA methods by Nelson (2020); and the CWSC method by Jiang and Yu (2021). We sincerely thank these authors for generously sharing their codes.

Author contribution

YW and RP jointly developed the research concept. YW carried out data compilation, data analysis, and manuscript drafting. RP supervised the project, secured funding, and contributed to manuscript writing. LZ assisted with code adaptation, development, and manuscript editing. All authors approved the final manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the first author used ChatGPT-4.0 only for grammar checking and language polishing. ChatGPT-4.0 was not used for content generation. After using this tool, the first author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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