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# How climate and vegetation type influence evapotranspiration and water use efficiency in Canadian forest, peatland and grassland ecosystems

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ABSTRACT

The effects of climatic factors and vegetation type on evapotranspiration ($E$) and water use efficiency (WUE) were analyzed using tower-based eddy-covariance (EC) data for nine mature forest sites, two peatland sites and one grassland site across an east–west continental-scale transect in Canada during the period 2003–2006. The seasonal pattern of $E$ was closely linked to growing-season length and rainfall distribution. Although annual precipitation ($P$) during the observation period was highly variable among sites (250–1450 mm), minimum annual $E$ was not less than 200 mm and was limited to 400–500 mm where annual $P$ exceeded 700 mm. Site-specific interannual variability in $E$ could be explained by either changes in total $P$ or variations in solar irradiance. A highly positive linear correlation was found between monthly mean values of $E$ and net radiation ($R_n$) at the grassland site (AB-GRL), the two peatland sites (AB-WPL and ON-EPL), and only one of the forest sites (coastal Douglas-fir, BC-DF49) whereas a hysteretic relationship at the other forest sites indicated that $E$ lagged behind the typical seasonal progression of $R_n$. Results of a cross-correlation analysis between daily (24-h) $E$ and $R_n$ revealed that site-specific lag times were between 10 and 40 days depending on the lag of vapour pressure deficit ($D$) behind $R_n$ and the decoupling coefficient, $\Omega$. There was significant seasonal variation in daytime mean dry-foliage Priestley–Taylor $\alpha$ with maxima occurring in the growing season at all sites except BC-DF49 where it was relatively constant (~0.55) throughout all years. Annual means of daytime dry-foliage $\alpha$ mostly ranging between 0.5 and 0.7 implied stomatal limitation to transpiration. Increasing $D$ significantly decreased canopy conductance ($g_c$) at the forest sites but had little effect at the peatland and grassland sites, while variation in soil water content caused only minor changes in $g_c$. At all sites, a strong linear correlation between monthly mean values of gross primary production (GPP) and $E$ resulted in water use efficiency being relatively constant. While at most sites, WUE was in the range of 2.6–3.6 g C kg$^{-1}$ $H_2O$, the BC-DF49 site had the highest WUE of the twelve sites with values near 6.0 g C kg$^{-1}$ $H_2O$. Of the two peatland sites, AB-WPL, a western treed fen, had a significantly higher WUE (~3.0 g C kg$^{-1}$ $H_2O$) than ON-EPL, an eastern ombrotrophic bog (~1.8 g C kg$^{-1}$ $H_2O$), which was related to peatland productivity and plant functional type.



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## 1. Introduction

Evapotranspiration ($E$) is a major component in the water balance of terrestrial ecosystems and must be taken into account in the assessment of regional water resources and management of watersheds (Brutsaert, 1982; McNaughton and Jarvis, 1983). The associated flux of latent heat is an important component of the surface energy balance that has a major impact on the behaviour and dynamics of the planetary boundary layer (PBL) (Baldocchi et al., 2000). Vegetation growth and potential photosynthetic carbon (C) uptake are closely related to $E$. Water use efficiency (WUE) is defined as the ratio of gross primary production (GPP) to transpiration, i.e. the amount of C assimilated per unit of water loss by transpiration (Cowan and Farquhar, 1977) or the inverse of the transpiration ratio (Briggs and Shantz, 1913). The study of $E$ and WUE among a variety of terrestrial ecosystems is therefore fundamental to understanding their role in local, regional and global water cycles and water vapour exchange between the Earth's surface and the atmosphere. Leaf-level demand for water has to be matched by soil water extraction by the plant. Restrictions on plant water uptake, reduction in stomatal conductance as well as feedbacks on leaf-level processes and evaporative losses may occur if plant water use exceeds soil water recharge (Beer et al., 2009). Cowan and Farquhar (1977) proposed that plants control stomata to optimally satisfy the trade-off between the amount of C assimilated and the amount of water transpired.

Aside from analyzing the impact of changes in environmental conditions at the leaf-level, it is crucial to investigate water and C exchange processes of entire ecosystems in a changing climate. In temperate and high latitudes, the period for substantial contributions of $E$ to water cycling in an ecosystem is usually restricted by temperature and water availability. Major factors affecting the seasonal course of both $E$ and GPP are seasonal changes in leaf-area index (LAI), physiological capacity of the plants in terms of stomatal control, meteorological conditions, and the length of the growing season (Falge et al., 2002). Furthermore, it is generally assumed that seasonal and interannual climate variability as well as interactive effects of plant nutrients and soil water supply might influence $E$ and GPP in different ways, and thus WUE, through their effects on energy partitioning and canopy conductance ($g_c$). Amount and seasonal distribution of evaporation from soil and wet leaf surfaces strongly correlate with precipitation ($P$) interception. Thus, vegetation type, stand structure and stand age (Jassal et al., 2009), are expected to play a significant role in the interplay between $E$ and GPP. While there has been recent work on the effects of water deficit, (e.g., Law et al., 2000; Kljun et al., 2006) and the constancy of WUE (Krishnan et al., 2008), it is also of considerable importance to investigate site-specific water cycles and drought effects on water balances and C sequestration.

To analyze these interrelationships between transpiration and evaporation, canopy properties and meteorological variables, both the Penman-Monteith and Priestley–Taylor equations have proven to be very valuable tools (e.g., Oke, 1987; Shuttleworth, 1992). Furthermore, the McNaughton-Jarvis vegetation–atmosphere decoupling coefficient has been useful in helping to predict the response of different vegetation types to changing meteorological conditions (McNaughton and Jarvis, 1983). This study provides an opportunity to determine the effect of coupling on the strength of the empirical relationship between $E$ and the available energy flux, i.e., as expressed in the Priestley Taylor alpha using data from a range of forest, grassland and peatland ecosystems.

Networks of eddy-covariance (EC) flux towers with their associated meteorological measurements offer an opportunity to quantify $E$ and GPP across a variety of climate zones and vegetation types. EC is the currently preferred method to measure continuously exchanges of carbon dioxide ($CO_2$), water vapour and sensible heat between ecosystems and the atmosphere over time scales of hours to decades, thus enabling the evaluation of seasonal and interannual variability in these exchanges and the elucidation of their climatic controls (Baldocchi et al., 2001; Coursolle et al., 2006; Barr et al., 2007). Within the framework of the Canadian Carbon Program (CCP) and the Fluxnet-Canada Research Network (FCRN), EC towers have been operating for several years in boreal, maritime, prairie and temperate ecosystems in Canada. While recent studies have focused on the effects of climate, age and disturbance on C fluxes (Lafleur et al., 2003; Arain and Restrepo-Coupe, 2005; Flanagan and Johnson, 2005; Amiro et al., 2006; Coursolle et al., 2006; McCaughey et al., 2006; Barr et al., 2007; Bergeron et al., 2007; Chen et al., 2009), less attention has been paid to the relationships between $E$ and canopy characteristics (e.g., Blanken et al., 1997; Blanken and Black, 2004; McLaren et al., 2008) as well as the linkage of $E$ to C exchange (e.g., Ju et al., 2006; Ponton et al., 2006; Jassal et al., 2009; Mkhabela et al., 2009).

The overall aim of this paper is a cross-ecosystem synthesis of simultaneous, continuous measurements of $E$ and GPP at 12 CCP flux tower sites and their controlling factors and relationships to canopy characteristics. We selected nine mature forest sites, two peatland sites and one grassland site and analyzed the period from 2003 to 2006. The sites stretch across southern Canada in a coast-to-coast transect from British Columbia to New Brunswick. Forests and peatlands cover more than 40%, and grasslands cover approximately 25% of Canada's land surface. All together they store 88 Gt of C (12 Gt in standing biomass and 76 Gt in soil and peat), 500 times greater than Canada's annual anthropogenic C emissions (0.18 Gt $yr^{-1}$) (Kurz and Apps, 1999). Specifically, our objectives are to (i) determine the effect of $P$, net radiation ($R_n$) and vapour pressure deficit ($D$) on the amount and seasonal progression of $E$, (ii) investigate relationships between $E$ and the parameters in the Penman-Monteith and Priestley–Taylor equations as well as the degree of coupling between vegetation and the atmosphere, and (iii) characterize the WUE of individual sites with the aim to understand better the relationship between water fluxes and C assimilation among different ecosystems.

## 2. Materials and methods

### *2.1.1. Selected sites, data acquisition, availability, and processing*

A total of twelve sites were selected from the CCP flux tower network to represent an east–west continental-scale transect in Canada (Table 1). The sites were located across several ecozones including coniferous temperate forest in coastal British Columbia (BC), grassland and peatland sites in Alberta (AB), coniferous and deciduous boreal forests in Saskatchewan (SK), coniferous boreal forest in Manitoba (MB), mixedwood boreal forest in Ontario (ON), coniferous boreal forest in Quebec (QC), coniferous temperate forest and peatland in ON, and coniferous maritime forest in New Brunswick (NB). All sites on this transect were situated between 42°N and 56°N latitude. For the purpose of this study, only mature forest sites were chosen. At all sites, the EC method was used to measure fluxes of water vapour and $CO_2$ to obtain $E$ and GPP (Coursolle et al., 2006). Water vapour and $CO_2$ fluxes were calculated as the covariance between the vertical wind speed and the water vapour and $CO_2$ mixing ratio, respectively, using 30-min block averaging (Aubinet et al., 2000; Webb et al., 1980). Details about EC and weather instrumentation and measurements for the particular sites can be found in the publications listed in Table 1. Also given are site names, vegetation type classes, further information about site-specific vegetation characteristics and filter criteria for low-turbulence situations, i.e. the $u_*$ threshold.