



OPINION

Relationship between stem density and dry-canopy evaporation rates in coniferous forests

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Summary Our previous study summarized published data on dry-canopy evaporation in coniferous forests during the growing season and found a decrease in the Priestley–Taylor coefficient α with canopy height. We speculated that the decrease in α was caused by a decrease in stomatal conductance with tree height. However, the decrease in α may also be explained by changes in leaf area index (LAI) and/or stem density with canopy height. We found no clear relationship between LAI and α in our previous study. Here, we examined the relationship between stem density and α and found no clear relationship, indicating that the decrease in α with increasing canopy height is not explained by changes in stem density. Thus, our results support the previous speculation that decrease in α was caused by a decrease in stomatal conductance with tree height.

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Introduction

The examination of relationships between forest properties (e.g., broad-leaved or coniferous trees composition, leaf area index [LAI], canopy height) and dry-canopy evaporation rates has been a major goal in the study of forest hydrology. Researchers have examined these relationships based on field measurements (e.g., Baldocchi and Vogel, 1996; Zimmermann et al., 2000), model experiments (e.g., Baldocchi and Meyers, 1998; Komatsu, 2004), and the literature surveys (e.g., Komatsu, 2003a,b, 2005).

In a summary of published data on dry-canopy evaporation in coniferous forests during the growing season, Komatsu (2005) found a negative relationship between canopy height and the Priestley–Taylor coefficient. The Priestley–Taylor coefficient α represents evaporative control by vegetation and is defined as (Priestley and Taylor, 1972; Raupach, 2001)

$$\alpha = \frac{E}{E_{eq}}, \quad (1)$$

where E is the evaporation rate and E_{eq} is the equilibrium evaporation rate. E_{eq} expresses the evaporation rate of an extended wet surface and is written as $E_{eq} = \Delta / (\Delta + \gamma) \cdot (R_n - G) / \lambda$, where Δ is the slope of the saturation vapor pressure function, γ is the psychrometer

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constant, R_n is the net radiation, G is the soil heat storage, and λ is the latent heat of water vaporization. The decrease in α with increasing canopy height indicates greater evaporative control in taller coniferous forests (Komatsu, 2005). In this paper, the term “evaporative control” indicates not only purely physiological transpiration control but also transpiration changes stemming from interactions between tree physiology and the surrounding environment. For example, large trees might exhaust water reserves in the soil surrounding their roots much more rapidly than small trees, resulting in reduced canopy conductance for a large portion of the day. Such a phenomenon is also referred to as “evaporative control” in this paper.

Komatsu (2005) speculated that the negative relationship between canopy height and α is explained primarily by physiological changes with canopy height. Many researchers

(e.g., Ryan et al., 2000; Irvine et al., 2004) have reported a decrease in stomatal conductance with increasing tree height for coniferous trees, which supports this speculation.

However, the relationship between canopy height and α may be explained by structural changes with canopy height. Canopy structure, such as LAI and stem density, varies according to canopy height (e.g., Waring and Running, 1998; Murakami, 2002). These parameters may affect dry-canopy evaporation rates. Many researchers have estimated canopy transpiration rates based on sap flux measurements by multiplying tree sap flux and the sapwood area of the forest (e.g., Vertessy et al., 1997; Kumagai et al., 2005). Because the sapwood area of the forest is related to stem density, stem density is a possible factor affecting canopy transpiration rates, and therefore, dry-canopy evaporation rates. When calculating dry-canopy evaporation rates using

Table 1 α Values for coniferous forests summarized from earlier papers

Canopy height (m)	Projected LAI	Stem density (ha ⁻¹)	Measurement method ^a	α	Reference
15	6.5	1678	SF	0.35	Alsheimer et al. (1998)
16	5.3	1007	SF	0.58	Alsheimer et al. (1998)
18	7.1	1006	SF	0.44	Alsheimer et al. (1998)
24	7.9	504	SF	0.38	Alsheimer et al. (1998)
25	6.5	322	SF	0.24	Alsheimer et al. (1998)
26	7.6	446	SF	0.42	Alsheimer et al. (1998)
11	4.5	5900	EC	0.60	Arain et al. (2003)
9	6.5	1200	EC	0.63	Arneth et al. (1998)
14	1.7 ^b	1878	EC	0.50	Baldocchi et al. (1997)
24	2.7	313	EC	0.39	Berbigier et al. (1996)
14	2.8	3873	EC	0.43	Bernhofer et al. (1996)
9	6.6	840	BREB	0.72	Black (1979)
10	7.5–8.0	1840	BREB	0.76	Black (1979)
14	9	2400	SF	0.78	Cienciala et al. (1994)
22	7.5–10	780	EC	0.43	Dekker et al. (2000)
13	?	883	ECEB	0.81	Diawara et al. (1991)
6	?	616	EC	0.51	Fitzjarrald and Moore (1994)
20	2.3	385	EC	0.65	Granier et al. (1990)
10	2.5	2660	EC	0.47	Hamada et al. (2004)
33	?	1105	EC	0.40	Humphreys et al. (2003)
11	4.5	5900	EC	0.61	Jarvis et al. (1997)
14	5 ^b	800	BREB	0.46	Kelliher et al. (1986)
3	2.8 ^b	2900	ECEB	1.01	Kelliher et al. (1990)
9	2.2 ^b	450	ECEB	0.89	Kelliher et al. (1990)
12	1.2 ^b	1750	EC	0.59	Kelliher et al. (1997)
16	1.3 ^b	290	EC	0.38	Kelliher et al. (1998)
13	2.1	1300	EC	0.64	Kellomaki and Wang (1999)
10	7.5–8.0	575	EC	0.39	Lee and Black (1993a,b)
16	2.6	393	BREB	0.69	Lindroth and Halldin (1986)
19	2.6–3.2	520	EC	0.79	Ogee et al. (2003)
18	3.7	840	EC	0.47	Ohta et al. (2001)
16	?	800	BREB	0.49	Stewart and Thom (1973)
3	?	12,000	BREB	0.89	Tajchman et al. (1979)
8	? ^c	2800	EC	0.53	Yamanoi and Ohtani (1992)

^a BREB: Bowen ratio energy balance method; EC: eddy correlation method; ECEB: eddy correlation energy balance method; SF: sap flux method.

^b Estimated by the authors of this paper by dividing the total surface area index by 2.4, which is an intermediate value for conifers (Landsberg and Gower, 1997).

^c Although a leaf area index (LAI) value is present, no definition of the LAI is given.

multilayer canopy models, LAI is required as input data (e.g., Lai et al., 2000; Kumagai et al., 2006). Thus, LAI is a possible factor affecting dry-canopy evaporation rates. Therefore, it would be informative to examine the relationships between canopy structure and α . If no clear relationships between canopy structure and α are observed, Komatsu's (2005) speculation is supported.

We previously examined the relationship between LAI and α and found no clear relationship (Komatsu, 2005). Here, we examine the relationship between stem density and α .

Materials and methods

To examine the relationship between stem density and α , we used published α data from coniferous forests. The report by Komatsu (2005) presents all the data and describes the data selection and calculation procedures. The α values were defined for daytime in the growing season; daytime was considered the period with positive solar radiation. The α values were calculated by substituting the observed E and E_{eq} from the original published data into Eq. (1). The α data were based on several different measurement methods; the effect of observation method on α values is examined in Komatsu (2005).

Results and discussion

Table 1 shows the α data used in this study. This table is essentially the same as Table 1 of Komatsu (2005), except that stem density data are included. We obtained 34 samples with available stem density data.

We found no clear relationship between stem density and α (Fig. 1), in contrast to the negative relationship between canopy height and α found by Komatsu (2005). Thus, the decrease in α with increasing canopy height was not explained primarily by changes in stem density with canopy height.

In fact, stem density was not tightly correlated with canopy height (Fig. 2). Although we found that stem density tended to decrease with increasing canopy height, the correlation between canopy height and stem density was not tight ($R^2 = 0.23$). In general, stem density is tightly

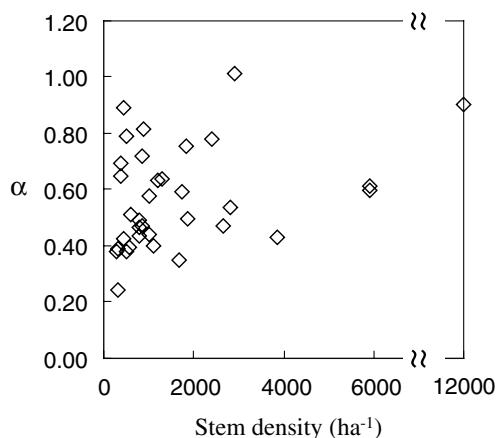


Figure 1 The relationship between stem density and the Priestley–Taylor coefficient α for coniferous forests.

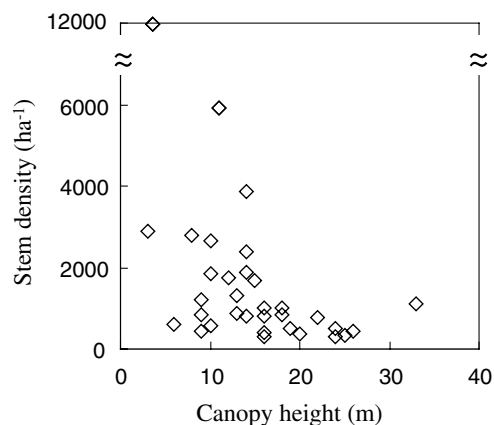


Figure 2 The relationship between canopy height and stem density for coniferous forests.

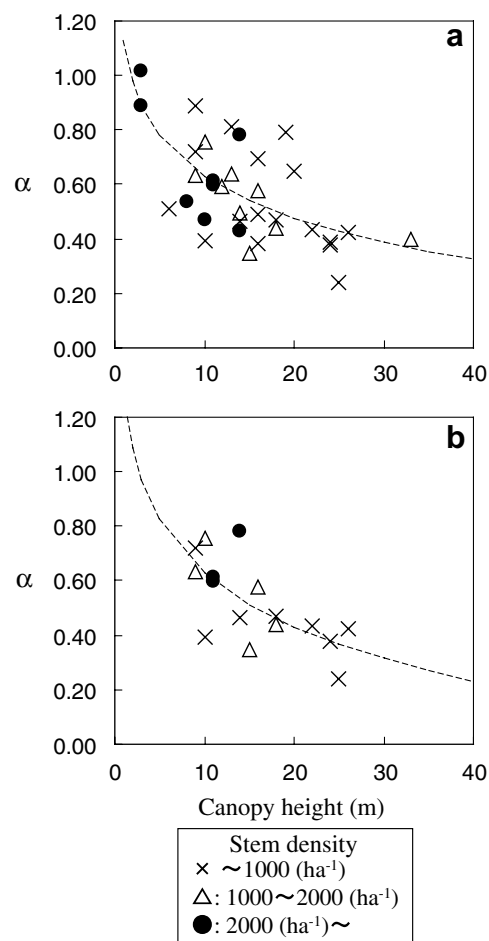


Figure 3 (a) The relationship between canopy height and the Priestley–Taylor coefficient α for coniferous forests. The least-squares regression was $\alpha = -0.212 \ln h + 1.13$ ($R^2 = 0.41$), where h is canopy height. (b) The relationship between canopy height and the Priestley–Taylor coefficient α for coniferous forests, but excluding data with projected LAI of < 3.0 . The least-squares regression was $\alpha = -0.286 \ln h + 1.29$ ($R^2 = 0.46$), where h is canopy height.

correlated with canopy height for forests with similar species compositions (e.g., Kikuzawa, 1999; Ohta and Hattori, 2002). However, the summarized data were from forests with different species compositions. Thus, there was no tight correlation for forests with different species compositions (Fig. 2).

There was no clear relationship between stem density and α , even when the relationship between canopy height and α was taken into consideration. Fig. 3a shows the relationship between canopy height and α , classified according to stem density. Higher/lower stem density data did not show systematically higher/lower α values than those expected from the regression, indicating that stem density is not a critical factor explaining the variation in α among coniferous forests.

Komatsu (2005) emphasized that the relationship between canopy height and α was not as clear when projected LAI was <3.0 as when LAI was ≥ 3.0 . This would be caused by a major contribution of forest floor evaporation to dry-canopy evaporation and large variation in forest floor evaporation rates among forests with a projected LAI of <3.0 . Therefore, the inclusion of α data with projected LAI of <3.0 may mask a systematic relationship between stem density and α . However, higher/lower stem densities did not show systematically higher/lower α values than those expected from the regression, even when α data with projected LAI of <3.0 were excluded (Fig. 3b).

Thus, the relationship between canopy height and α was not explained by changes in stem density with canopy height, supporting Komatsu's (2005) speculation that the relationship between canopy height and α is explained mainly by physiological changes that occur with canopy height. We should note that the conclusions obtained here may depend on the data used in this study. The data were obtained under various climatic, geochemical, and geomorphological conditions. Thus, further research is recommended to examine whether using data for specific conditions would alter our conclusions.

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