Spatial variations in evapotranspiration over East Asian forest sites.

II. Surface conductance and aerodynamic conductance

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Abstract:

Evapotranspiration over forest surfaces is mainly constrained by environmental and forest structural components through their influence on surface conductance (G_s) and aerodynamic conductance (G_a). Tower based eddy covariance data from 16 forest sites in East Asia (2°S to 64°N) were used to examine the sensitivity of Matsumoto and Nakai models for predicting G_s and G_a , respectively. Daytime dry-canopy data for the growing season were used in this study. Comparisons between model predictions and observed G_s and G_a showed good agreement, suggesting that the models were suitable for predicting G_s and G_a with reasonable accuracy. However, the model for G_s was unable to predict G_s accurately when soil water content was low (~10%). In this circumstance, effective soil water content and a more comprehensive method for modelling the soil water content function must be used. G_s in East Asia was largely depended on vapour pressure deficit and secondarily on soil water content. G_a was largely affected by leaf area index compared with stand density.

KEYWORDS Matsumoto-model; Nakai-model; surface conductance (G_s); aerodynamic conductance (G_a); forest; East Asia

INTRODUCTION

Evapotranspiration (ET) is a major component influencing the global hydrologic process and thus climate. Surface conductance, G_s , and aerodynamic conductance, G_a , are important variables for determining the ET over vegetated surfaces (Maximov *et al.*, 2008; Khatun *et al.*, 2011). G_s is known to be controlled by several environmental components (e.g., radiation, temperature, vapour pressure deficit, and soil water content) (Matsumoto *et al.*, 2008). G_a is governed by wind speed and surface aerodynamic

properties, such as roughness length (z_0) and zero-plane displacement (d), which are the functions of forest structural components (e.g., stand density, ρ_s , and leaf area index, LAI) (Nakai *et al.*, 2008). It is therefore important to quantify how different environmental and forest structural components control G_s and G_a to understand the relationship of ET to these components.

G_s is usually calculated using the inverse form of the Penman–Monteith equation (Monteith, 1965), and G_a has generally been computed from wind speed and friction velocity based on observed flux data. However, the accurate calculation of G_s and G_a using flux data is sometimes difficult because of the heterogeneity of the landscape and the large number of controlling factors involved, including climate, plant biophysics, soil properties and topography.

A number of empirical models have been proposed to calculate G_s for many stands of various vegetation categories, including grasslands, crops and broadleaved and coniferous forests (e.g., Jarvis, 1976; Ball *et al.*, 1987; Leuning, 1995). On the basis of the Jarvis model, Matsumoto *et al.* (2008) developed a pooled model of three temperate and two sub-arctic forests that allows the expression of G_s in different forests under different climatic zones using a common parameter set.

Many different approaches have been developed to calculate d and z_0 (e.g., Pinard, 2000; Raupach, 1994; Choudhury and Monteith, 1988). However, existing approaches generally utilise highly simplified representations of vegetation structure. Nakai *et al.* (2008) proposed a new model to calculate d and z_0 using forest structure data such as LAI ($m^2 m^{-2}$) and ρ_s (trees ha^{-1}).

However, the Matsumoto and Nakai models that predict G_s and G_a are derived from small numbers of measurements. In this study, we compiled the measurement data from 16 forest sites in East Asia to evaluate the effectiveness of the Matsumoto and Nakai models in relation to our data sets. We also examined the dependence of G_s and G_a on environmental and forest structural components using these

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Received 27 June, 2011
Accepted 24 November, 2011

models. This information will be useful for land surface parameterisation in regional climate simulations, particularly in East Asia.

MATERIALS AND METHODS

Site description, measurement system, quality control and data selection for turbulent fluxes

Data were collected from 16 forest sites in East Asia that were distributed geographically from 2°S to 64°N latitude and 98°E to 142°E longitude (see Figure S1 for the geographic and climatic positions in detail). The study included one tropical rain forest (PDF), four tropical monsoon forests (SKR, MKL, MMP and KMW), one subtropical monsoon forest (QYZ), two warm-temperate forests (SMF and GDK), one temperate forest influenced by the monsoon (CBS), four cool-temperate forests (TMK, MBF, MMF and TSE), and three sub-arctic forests (SKT, YLF and TUR).

An eddy covariance and a meteorological measurement system were used at each site to measure sensible heat flux (H), latent heat flux (λE), friction velocity (u_*) and basic environmental components. The principal investigators performed quality controls at each site. We collected 30- and 60-min averages of flux and meteorological data for this study. Data for daytime (net radiation $>0 \text{ W m}^{-2}$) and dry-canopy conditions (excluding data collected during rainfall events and within 10 h after these events) for the growing season were used for the analysis. After excluding the wet-canopy data, more than 60% of daytime data were available for most of the measurement years. To avoid variations in the closure of energy balance among the sites, closure was forced to 1 by the Bowen ratio closure method.

The site description (Table S1), eddy covariance instruments (Table S2) and quality control and data selection for turbulent fluxes (Text S1) are described with more details in the supplements. The calculation of G_s and G_a based on observed data is described in Text S2.

Estimation of G_s and G_a

According to the Jarvis-type model (Jarvis, 1976), G_s is a function of several environmental variables and is expressed as

$$G_s = G_{smax} f_1(Q) f_2(D) f_3(T) f_4(\theta) \quad (1)$$

where G_{smax} is the maximum surface conductance and $f_1(Q)$, $f_2(D)$, $f_3(T)$, and $f_4(\theta)$ are the functions of the photosynthetic photon flux density (Q , $\mu\text{mol m}^{-2} \text{ s}^{-1}$), vapour pressure deficit (D , kPa), air temperature (T , °C) and volumetric soil water content (θ , %), respectively. Each function represents the influence of that factor on G_s and ranged from 0 to 1.

According to Matsumoto *et al.* (2008), the functions are expressed as follows:

$$f_1(Q) = \frac{Q(Q_{max} + k_1)}{Q_{max}(Q + k_1)} \quad (2)$$

$$f_2(D) = \left[\frac{1}{1 + (D/D_{0.5})^{k_2}} \right] (1 - k_3) + k_3 \quad (3)$$

$$f_3(T)$$

$$= \left(\frac{T - T_{min}}{T_{opt} - T_{min}} \right) \left(\frac{T_{max} - T}{T_{max} - T_{opt}} \right)^{((T_{max} - T_{opt}) / (T_{opt} - T_{min}))} \quad (4)$$

$$f_4(\theta) = \frac{(\theta - \theta_{min})(\theta_{max} - \theta_{min} + k_4)}{(\theta_{max} - \theta_{min})(\theta - \theta_{min} + k_4)} \quad (5)$$

where $D_{0.5}$, T_{min} , T_{opt} , T_{max} , θ_{min} and k_1 – k_4 are the fitting parameters; Q_{max} and θ_{max} are fixed parameters. T_{min} , T_{opt} and T_{max} are the minimum, optimum and maximum T values, respectively; θ_{min} and θ_{max} are the minimum and maximum θ values; and Q_{max} is the maximum Q value. Detailed descriptions of all fitting and fixed parameters were provided by Matsumoto *et al.* (2008). According to the pooled model, the values of the fitting parameters are $k_1 = 310$, $k_2 = 3.0$, $k_3 = 0.10$, $k_4 = 20$, $D_{0.5} = 1.25$, $T_{min} = 2$, $T_{opt} = 22$, $T_{max} = 37$ and $\theta_{min} = 10$ and fixed parameters are $Q_{max} = 2100$ and $\theta_{max} = 50$; $G_{smax} = 0.037 \text{ m s}^{-1}$, when $LAI \geq 3$; $G_{smax} = G_{sMAX} (LAI/6 + 0.5)$ when $0 < LAI < 3$; and G_{sMAX} is the maximum G_s with highest LAI .

The effects of each variable on the variation of G_s were calculated as the contribution of each function ($\alpha_x = \beta_x - \omega_a$) to modelling accuracy using the root mean-square error (RMSE) value (Matsumoto *et al.*, 2005). α_x is the contribution index (m s^{-1}) of one function, i.e., $f(x)$ to the variability of G_s , β_x is the RMSE between the observed and estimated values in which a function for a certain variable was excluded, and ω_a is the RMSE between the observed and estimated values containing all of the functions in Equation (1). More description is in Text S3.

G_a was calculated as (Businger, 1956)

$$\frac{1}{G_a} = \left(\ln \frac{z - d}{z_0} \right)^2 \left(\frac{1}{k^2 U_z} \right) \quad (6)$$

where z is the measurement height (m), U_z is wind speed at height z (m s^{-1}), and k is von Karman's constant (0.40).

According to the Nakai *et al.* (2008) model, d and z_0 are expressed as

$$\frac{d}{h} = 1.0 - \frac{1.0 - \exp(-\alpha \rho_s)}{\alpha \rho_s} \frac{1.0 - \exp(-\beta LAI)}{\beta LAI} \quad (7)$$

$$\frac{z_0}{h} = 0.264 \left(1.0 - \frac{d}{h} \right) \quad (8)$$

where d/h and z_0/h are the zero-plane displacement and roughness length, respectively, normalised by canopy height h , and α and β are the fitting parameters.

RESULTS AND DISCUSSION

Surface conductance

Figure 1 shows the relationship between growing season mean G_s and environmental variables (Q , T , D and θ). The line represents potential G_s calculated by a single fitting function [$G_{smax} \times$ Equation (i); $i = 2, 3, 4$ and 5] and the pooled values of fitted parameters (k_1 – k_4). The points represent the actual G_s (G_{sobs}) calculated from the inverse Penman–Monteith equation. Each potential line follows the upper boundary of the actual values, indicating that the

pooled model clearly expresses the response characteristics of stomata to each variable as of the study of Matsumoto *et al.* (2005). However, at two sites (SKR and SKT) with low θ , G_{sobs} exceeded the potential curve represented by $f(\theta)$. This suggests that $f(\theta)$ could not accurately represent the G_{sobs} for low-water conditions in the shallow soil layer, whereas the other functions of this model are potentially applicable to our data set.

The linear regression between modelled G_s (G_{smod}) calculated by the pooled model and G_{sobs} (Figure 2a) gave a slope of 1.06 with a high level of significance ($P < 0.005$) and RMSE of 0.005 m s^{-1} . This result indicates that the pooled model is capable of predicting G_s . However, the relatively low R^2 value (0.51) indicates that G_{smod} did not always fit the calculated value well. This result might be explained by the large underestimation of G_s by the pooled model at tropical monsoon site SKR and boreal site SKT and overestimation of G_s at cool-temperate sites MMF and TSE.

Figure 1. Relationship between surface conductance (G_s) and environmental components: (a) photosynthetic photon-flux density Q ; (b) air temperature T ; (c) vapour pressure deficit D ; and (d) soil water content θ . The line represents potential G_s calculated by single fitting function, and points represent actual G_s calculated from observed data. Closed squares, open squares, and closed triangles indicate tropical, temperate and boreal sites, respectively.

The poor agreement at SKR and SKT might be partially attributable to the use of top layer θ in calculating the $f(\theta)$. The low water-holding capacity of the sandy soil at SKR and SKT may cause a low-water condition in the top soil layer that greatly affects model values of G_s . However, G_{sobs} at these sites was not affected by low θ (Figure 2). Trees might be able to use deeper soil water when the top layer becomes dry (e.g., Tanaka *et al.*, 2004; Li *et al.*, 2006). On the other hand, the pooled model overestimated G_s at two cool-temperate sites (MMF and TSE). At these sites, the G_{smod} values were approximately double than those of the G_{sobs} . Higher θ values at these sites resulted in higher G_s model output. However, in real situation, θ had lower impact on the actual G_s . These sites are belonging to maritime climate and are characterized by low temperature and high humidity resulting in low atmospheric evaporative demand. The lower values of latent heat flux and higher values of Bowen ratio due to low atmospheric evaporative demand might affect the actual G_s (see Equation (1) in Text S2). Without these exceptional four sites, the linear regression between G_{smod} and G_{sobs} gave a slope of 0.90 and R^2 of 0.75 with $P < 0.0005$ and RMSE of 0.003 m s^{-1} . This high correlation illustrates that in absence of the water stress ($\theta \sim 10\%$) condition or high water content ($\theta > 40\%$) condition with low evaporative demand, the pooled model is suitable for the prediction of G_s .

Figure 2b shows the contribution (α_x) of each function to the variability of G_s . Among all of the variables, D was the dominant component of variability in G_s , and the order of α_x for each function was $f(D) > f(\theta) > f(Q) > f(T)$. The values of $f(D)$ were reduced by the higher values of D at most of the sites and were a greater controlling factor for G_s . The exceptions were found at cool-temperate sites, where the values of $f(D)$ were nearly 1 and not a controlling factor for G_s . At tropical, warm-temperate and some boreal sites, where $\theta < 30\%$, $f(\theta)$ was the greater controlling factor. The values of $f(Q)$ were > 0.80 at all sites except two boreal sites. At boreal sites, G_s was quite affected by Q . At most of the studied sites, T was between 17°C and 27°C [$f(T) > 0.90$] and did not act as a controlling factor. However, at some cool-temperate and boreal sites, T was between 12°C and 15°C and exerted a control on G_s . Therefore, G_s in East Asian forests was not directly determined by Q and T . Even if the functions of Q and T were excluded from the pooled model, R^2 and P values became slightly larger than those of the complete model. This was probably the result of the

Figure 2. (a) Relationship between estimated (G_{smod}) and observed (G_{sobs}) G_s ; and (b) relative contributions (α_x) of each environmental function to G_s variability.

Figure 3. (a) Relationship between estimated (G_{amed}) and observed (G_{aobs}) aerodynamic conductance (G_a); and (b) relative contributions (α_x) of forest structural components (ρ_s and LAI) to the variability in G_a .

high correlation between T and D ($R^2 = 0.74$), indicating that the effect of T was incorporated into D and the narrow range of growing season mean Q and T . However, without the functions of Q and T , RMSE was increased, indicating that estimation of G_s without these functions was less satisfactory at our sites. Therefore, including all functions in the model enhances the applicability of the model at studied sites. Because of previous studies on the response of G_s to environmental components (e.g., Ogink-Hendriks, 1995; Matsumoto *et al.*, 2005) have been limited in terms of latitude ranges, the results of some single-site studies on the response of G_s to environmental factors based on seasonal variation have discussed here. In those studies, radiation was the dominant factor for the seasonal variation in G_s , with results based on hourly values (Ogink-Hendriks, 1995) and daily mean values (Matsumoto *et al.*, 2005) for the growing season. Both hourly and daily mean values can exhibit low radiation that limits G_s . In our study, the growing season mean values of Q were mostly $>700 \mu\text{mol m}^{-2} \text{s}^{-1}$ [$f(Q) > 0.80$] and were not a controlling factor. However, the higher T in the growing season accelerated D , which might have greatly determined dry-canopy G_s .

Aerodynamic conductance

Normalised displacement height (d/h) (Equation 7), and roughness length (z_0/h) (Equation 8) were calculated for 10 forest sites (Table S1) because of the lack of ρ_s and LAI data at other sites. The values of d and z_0 estimated by Nakai-model (d_{mod} and z_{0mod}) showed a good agreement with those of observed d and z_0 (d_{obs} and z_{0obs}) (Figure S2 and detailed in Text S4). However, the validity test of Nakai-model for estimating d and z_0 was limited at six sites only (two tropical, two temperate and two boreal sites) because of the lack of wind profile data at other sites.

G_a estimated by Nakai-model (G_{amed}) was compared with observed G_a (G_{aobs}) calculated by measured friction velocity and wind speed. Linear regression between G_{amed} and G_{aobs} (Figure 3a) gave a slope of 0.91 and R^2 of 0.70 with a high level of significance ($P < 0.002$), and RMSE of 0.015 m s^{-1} . This result indicates that the Nakai-model is highly satisfactory for the prediction of d and z_0 , and is thus applicable to the prediction of G_a .

To quantify the contribution (α_x) of ρ_s and LAI to the variability in G_a , RMSE was calculated between G_{aobs} and G_{amed} using the estimated values of d/h and z_0/h , where ρ_s and LAI were excluded from Equation 7 one by one (Text

S5). As shown in Figure 3b, LAI made a larger contribution than did ρ_s to the variation in G_a , because of the close relationship of the roughness parameters (d/h and z_0/h) to LAI compared with ρ_s , i.e., d/h increased and z_0/h decreased clearly with the increase in LAI , however, d/h increased and z_0/h decreased with the increase in ρ_s upto certain limit and after that changing only slightly as ρ_s increased (Figure S3).

SUMMARY AND CONCLUSIONS

Our results indicate that both the Matsumoto and Nakai models can be applied to broad climate and forest types using growing season mean data. However, G_s was poorly modelled at extremely low soil water condition (θ of approximately 10%). The use of appropriate θ values and a more comprehensive method for modelling the soil water function are needed under this condition. G_s depended on the environmental components in the order $D > \theta > Q > T$. The dependence of G_a on LAI was higher than that on ρ_s . This study is the first to predict G_s and G_a using the Matsumoto and Nakai models in East Asian forests. The results provide useful information for predicting G_s and G_a and indicate that the estimation of these parameters is possible in the absence of flux data at a larger scale.

ACKNOWLEDGEMENTS

The data were provided by CREST sites, AsiaFlux sites, ChinaFlux sites, principal investigator of Korean site, Professor Dr. Joon Kim, Seoul National University, Korea. This research was funded by the Core Research for Evolutional Science and Technology (CREST), the Global Water and Energy Cycle Experiment–Asian Monsoon Experiment-Tropics (GEWEX/GAME-Tropics), the Japanese Ministry of the Environment, the Korea Science and Engineering Foundation, and the Japan Society for the Promotion of Science (JSPS).

SUPPLEMENTS

Supplement 1. This includes:

Table S1. Description of the study sites

Table S2. Measurement system, height, year, closure rate

and growing season length

Text S1. Description of quality control and data selection for turbulent fluxes

Text S2. Calculation of G_a and G_s based on observed data

Text S3. Calculation of dependence of G_s on environmental components

Text S4. Calculation of zero-plane displacement (d) and roughness length (z_0)

Text S5. Calculation of dependence of G_a on forest structural components

Figure S1. Locations of the study sites: (a) geographic and (b) climatic (based on the annual sum precipitation and annual mean temperature).

Figure S2. Relationship between: (a) estimated (d_{mod}) and observed (d_{obs}) zero-plane displacement (d) and (b) estimated (z_{0mod}) and observed (z_{0obs}) roughness length (z_0).

Figure S3. Relationship between normalized zero-plane displacement (d/h), roughness length (z_0/h) and (a) stand density (ρ_s), (b) leaf area index (LAI).

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