Spatial variations in evapotranspiration over East Asian forest sites.

I. Evapotranspiration and decoupling coefficient

Rehana Khatun¹, Takeshi Ohta⁴, Ayumi Kotani¹, Jun Asanuma², Minoru Gamo³, Shijie Han⁴, Takashi Hirano⁵, Yuichiro Nakai⁵, Nobuko Saigusa⁶, Kentaro Takagi⁶, Huimin Wang⁷ and Natsuko Yoshifujii⁰

¹ Graduate School of Bioagricultural Sciences, Nagoya University, Nagoya, Japan
² Terrestrial Environment Research Center, Tsukuba University, Tsukuba, Japan
³ National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan
⁴ Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang, China
⁵ Graduate School of Agriculture, Hokkaido University, Sapporo, Japan
⁶ Forestry and Forest Products Research Institute, Tsukuba, Japan
⁷ National Institute for Environmental Studies, Tsukuba, Japan
⁸ Field Science Center for Northern Biosphere, Hokkaido University, Horonobe, Japan
⁹ Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China
¹⁰ Graduate School of Agriculture, Kyoto University, Kyoto, Japan

Abstract:

Evapotranspiration (ET) is not only a vital component of water budget, but also plays an important role in the energy budget of the earth-atmospheric system, ultimately driving many regional and global scale climatological processes. This paper describes the ET characteristics and factors controlling ET across the 17 forest sites in East Asia (2°S to 64°N latitude). ET was measured using the eddy covariance technique at each site. Daytime dry-canopy data for the growing season were used in this study. Growing season mean ET gradually decreased as latitude increased, with a range of 4.4 to 1.2 mm d⁻¹. The growing season mean decoupling coefficient (Ω) ranged from 0.42 to 0.11 across the studied sites. At low-latitude forest sites, Ω was close to 0.50, indicating that the bulk surface was partially decoupled from the atmosphere and ET was strongly controlled by net radiation and vapour pressure deficit. At high-latitude forest sites, Ω was low (~0.12), indicating that the bulk surface was well coupled to the atmosphere and ET was partially controlled by surface conductance. The value of Ω was determined mainly by the ratio of aerodynamic conductance to surface conductance across the studied forests of East Asia.

KEYWORDS Spatial variations; evapotranspiration; decoupling coefficient; aerodynamic conductance; surface conductance; East Asia

INTRODUCTION

Evapotranspiration (ET) is an important process of interest to a wide range of disciplines, including ecology, hydrology and meteorology. Many important ecosystem parameters and processes, such as soil moisture content, vegetation productivity, ecosystem nutrient and water budgets are all influenced by ET (Wever et al., 2002). Study on ET among a variety of terrestrial ecosystems is therefore fundamental to understand the characteristics of water vapour exchange and its role in local, regional and global water cycles (Brümmer et al., 2011). In recent decades, eddy covariance measurements of energy, water vapour and CO₂ exchange have been conducted worldwide in numerous ecosystems (e.g., Baldocchi et al., 2001). AsiaFlux was established in 1999 as the Asian arm of the worldwide flux research network (FLUXNET) to measure energy, water vapour and CO₂ exchange in Asian region. Although AsiaFlux has been conducting the measurements of water vapour and energy exchanges in a variety of ecosystems, however, most of the studies have examined the seasonal and interannual variations in ET based on the data obtained at single site (e.g., Kumagi et al., 2004; Kosugi et al., 2007; Iida et al., 2009). Matsumoto et al. (2008) investigated the ET characteristics at five forest sites of sub-arctic and temperate regions in East Asia. However, understanding the variations in ET for a large number of forest sites across East Asia is still quite limited.

The climates of East Asia have several different characteristics when compared to their counterparts in Europe and the Americas (Hirata et al., 2008). A clear variation in the forest types also exists from sub-arctic to tropical regions in East Asia. Consequently, ET characteristics in East Asia might be different with ET characteristics of Europe and the Americas. Therefore, it is important to investigate the ET characteristics across the forests of East Asia for identifying the factors which regulate ET under a wide range of climates and forest types.

ET from a vegetated surface is governed by the radiant energy supply, atmospheric humidity deficit, atmospheric turbulence and stomatal control ability of the canopy (Kelliher et al., 1995). The McNaughton-Jarvis vegetation–atmosphere decoupling coefficient (Ω) has been useful to indicate the relative importance of environmental and physiological factors in controlling dry-canopy ET (McNaughton and Jarvis, 1983). Many previous studies used...
Ô values for examining the environmental or physiological factors controlling ET worldwide (e.g., Wilson and Baldocchi, 2000; Kumagai et al., 2004; Kosugi et al., 2007; Iida et al., 2009; Jassal et al., 2009).

We used data from 17 forest sites across East Asia to investigate the spatial variability in ET. The specific objectives were (1) to determine how ET responds to environmental and physiological factors by calculating Ô and (2) to examine how Ô is determined in the forests of East Asia.

MATERIALS AND METHODS

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

Data were collected from 17 forest sites over 38 measurement years in East Asia that were distributed geographically from 2°S to 64°N latitude and 98°E to 142°E longitude. Figures 1a and 1b show the geographic and climatic positions of the study sites. 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 monsoons (CBS), four cool-temperate forests (TMK, MBF, MMF and TSE), and four sub-arctic forests (SKT, YPF, YLF and TUR).

An eddy covariance and a meteorological measurement system were used at each site for measuring sensible heat flux (H), latent heat flux (LE), friction velocity (u∗) and basic environmental components. The principal investigators performed quality controls for the high-frequency flux data (4–10 Hz). We collected 30- and 60-min averages of flux and meteorological data. Daytime (net radiation >0 W m−2) and dry-canopy conditions data (excluding data collected during rainfall events and within 10 h after these events) for the growing season were used. To estimate the controls of both physiological and environmental factors, we choose only dry-canopy data for this study. However, in the morning, canopy surface may become wet due to the dew formation. To avoid this condition, in the morning, we used data when Rn exceeded 100 W m−2. Therefore, around 8:00 to 18:00 data were available for a day. After excluding the wet-canopy data, more than 60% of daytime data were available for most of the measurement years.

The energy balance closure rate ranged from 50% to 97% across the sites (Table S2). To avoid variations in energy balance closure among the sites, closure was forced to 1 by the Bowen ratio closure method.

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.

Calculation of the decoupling coefficient, surface conductance and aerodynamic conductance

McNaughton and Jarvis (1983) reformulated the Penman–Monteith equation as

\[ \lambda E = \Omega \lambda E_{eq} + (1 - \Omega) \lambda E_{imp} \]  

where \( E_{eq} \) is the equilibrium evaporation rate, and \( E_{imp} \) is the imposed evaporation rate. \( E_{eq} \) depends mainly on the available energy, whereas \( E_{imp} \) is ‘imposed’ by the atmosphere on the natural canopy surface through the effect of vapour pressure deficit (D) (see Equation (4)), so that \( E_{imp} \) is proportional to the physiological conductance.

\( \Omega \) explains the degree of coupling between vegetation and the atmosphere and ranges from 0 to 1. When \( \Omega \) approaches 0 (see Equation (2)), this indicates that the bulk surface is well coupled to the atmosphere and that ET is mainly controlled by D and surface conductance \( (G_s) \) (see Equatin (4)). In contrast, when \( \Omega \) approaches 1, this shows that the bulk surface is completely decoupled from the atmosphere and ET is mainly controlled by net radiation \( (R_n) \) (see Equation (3)).

\( \Omega, E_{eq} \) and \( E_{imp} \) were calculated as

\[ \Omega = \frac{\Delta / \gamma + 1}{\Delta / \gamma + 1 + G_a / G_s} \]  

\[ E_{eq} = \frac{\Delta (R_n - G)}{\lambda (\Delta + \gamma)} \]  

\[ E_{imp} = \frac{\rho C_p G_s D}{\lambda \gamma} \]  

where \( \Delta \) is the rate of change in the saturation water vapour pressure with temperature (hPa K−1), \( \gamma \) is the psychrometric constant (hPa K−1), \( G_a \) is the aerodynamic conductance (m s−1), \( G_s \) is the surface conductance (m s−1), G is the ground heat flux (W m−2), \( \lambda \) is the latent heat of vapourisation (J kg−1), \( \rho \) is the density of moist air (kg m−3) and \( C_p \) is the specific heat of air at constant pressure (J Kg−1 K−1).

Figure 1. Locations of the study sites: (a) geographic and (b) climatic (based on the annual sum of precipitation and annual mean temperature).
$G_s$ was calculated using the inverted Penman–Monteith equation (Iida et al., 2009) as

$$G_s^{-1} = \frac{\beta}{\gamma} - 1 + \frac{\rho C_p}{\beta E} D$$

where $\beta$ is the Bowen ratio. In this study, $\lambda E$ and $\beta$ are achieved from eddy covariance measurements. $G_s$ was calculated (Kumagai et al., 2004; Kosugi et al., 2007) as

$$G_s = \frac{u^2}{\alpha}$$

where $u$ is the wind speed (m s$^{-1}$) and $u_*$ is the friction velocity (m s$^{-1}$) obtained from eddy covariance measurements.

**RESULTS AND DISCUSSION**

**Variation in environmental components and evapotranspiration**

The growing season mean values of $R_n$, air temperature ($T$), $D$, and $u$ across the studied sites are presented in Figure 2. $R_n$ was higher at low latitudes and gradually decreased with an increase in latitude, becoming low at high latitudes and ranging from 464 to 240 W m$^{-2}$ (Figure 2a). A negative correlation was also found between latitude and $T$, which ranged from 30°C to 13°C (Figure 2b). At high latitudes, $T$ was slightly higher, because the growing season of these sites is limited to summer months and is under continental climate effects. The $D$ was also high at low latitudes, gradually decreased up to 45°N, and then again increased with an increase in latitude (Figure 2c). At high latitudes, $D$ was slightly higher than at some mid-latitude sites located from 42°N to 45°N. The four sites in this latitude range were cool-temperate forests with a maritime climate characterised by low temperatures and high humidity, which resulted in a lower $D$. In contrast, the sites at high latitudes had a continental climate with relatively high temperatures and low humidity in summer, resulting in a higher $D$. Values of $u$ were relatively low at low latitude compared to mid- and high-latitude forest sites (Figure 2d).

Growing season mean ET ranged from 4.4 to 1.2 mm d$^{-1}$, showing a gradual decrease with an increase in latitude (closed plots in Figure 3). Because of previous studies have been limited in terms of latitudinal variations in ET, we compared our results with that of some single-site studies focused on the seasonal variations in ET and its controlling factors (some results presented in Figure 3 using open plots and detailed in Table S3). At low and mid-latitudes, our results and those of previous studies were generally similar. However, at some mid-latitude sites (i.e., Kosugi et al., 2007; Wilson and Baldocchi, 2000), ET values were lower than in our results. These forests were characterised by relatively small $G_s$ (0.006 m s$^{-1}$) and suffered from severe drought, respectively, resulting in low ET. In contrast, ET from high-latitude European and American forests (i.e., Jassal et al., 2009; Baldocchi et al., 1997; Grell et al., 1997) tended to be larger than those from Asian forest sites. These sites were characterised by higher annual mean temperature, annual sum precipitation and LAI than that of our sites.

**Control factors of evapotranspiration and decoupling coefficient**

The growing season means of $\Omega$ were between 0.42 and 0.11 from low to high latitudes (closed plots in Figure 4a). At low latitudes, $\Omega$ was ~0.50 indicating that low-latitude forests of East Asia were partially decoupled from the atmosphere. In this condition, ET is usually controlled by $R_n$, $D$ and $G_s$ (e.g., Wilson and Baldocchi, 2000). However, in our study, $G_s$ was not a strong controller of ET for low-latitude sites. Therefore, $R_n$ and $D$ were the main controllers of ET at these sites. In contrast, $\Omega$ was low at high latitudes indicating that high-latitude forests of East Asia were well coupled to the atmosphere. Under the well coupled condition, ET is primarily controlled by $D$ and $G_s$ (e.g., Martin et al., 2001; Jassal et al., 2009). In our study, ET was mainly controlled by $G_s$ at high-latitude forests.

Low latitudinal broadleaf forest sites were characterised by relatively higher values of $G_s$ and lower values of $G_a$ (Figure 4b) as well as higher values of $T$ (hence higher values of $\lambda$) (Figure 4c), resulting in higher $\Omega$. However, $\Omega$ was very low at the SKR site (14°48’N). The ratio of

![Figure 2. Spatial distribution of environmental components: (a) net radiation ($R_n$), (b) air temperature ($T$), (c) vapour pressure deficit ($D$) and (d) wind speed ($u$). Points and vertical bars indicate the growing season means and standard deviations, respectively.](image)

![Figure 3. Spatial distribution of evapotranspiration (ET). Closed plots and vertical bars indicate the growing season means and standard deviations, respectively, in this study. The open plots denote results from previous studies.](image)
across the forests of East Asia, we examined the sensitivity of the lowest canopy height and highest stand density may have caused this region in each ratio was tested in Equation (2) using increments of 5a, 5b). However, the rate of change with respect to the variations in environmental components between these sites. At the SKR site, \( G_a/G_s \) was higher (hence higher \( G_a/G_s \)) due to higher wind speed compared to MKL site, which greatly decreased \( \Omega \) at the SKR site. In contrast, \( \Omega \) did not vary between evergreen broadleaf (KMW, 18°48′N; \( \Omega = 0.41 \)) and deciduous broadleaf (MMP, 18°25′N; \( \Omega = 0.40 \)) forests at low latitude. At these sites, the ratios of \( G_a/G_s \) and \( \Delta /\gamma \) were almost equal. At mid-latitude, \( \Omega \) was higher in a deciduous broadleaf forest (MBF, 44°23′N; \( \Omega = 0.34 \)) than in a mixed forest (MMF, 44°19′N; \( \Omega = 0.23 \)). At the MBF site, \( G_s \) was approximately double than that of MMF site, possibly because of differences in environmental factors; i.e., the \( D \) was lower at the MBF site than at MMF site. In addition, \( G_a \) was lower at MBF site compared to MMF site. At MBF site, stand density was higher, which may have caused the lower \( G_a \). Again, at high latitude, \( \Omega \) did not differ greatly between deciduous conifer (YLF, 62°15′N; \( \Omega = 0.13 \)) and evergreen conifer (YPF, 62°14′N; \( \Omega = 0.11 \)) forests. These sites are characterised by almost equal \( G_a/G_s \) and \( \Delta /\gamma \) ratios. This suggests that factors controlling \( \Omega \) differed by location because of differences in environmental (\( T \) or \( D \) or \( u \)) and forest structural (\( LAI \) or stand density) factors, not because of differences in forest types (evergreen and deciduous forest; broadleaf and coniferous forest).

**SUMMARY AND CONCLUSIONS**

Our study demonstrated that considerable variations existed in ET across the forests of East Asia and these variations illustrated the importance of environmental and physiological factors in determining the rates of ET. The values of \( \Omega \) indicated that at low-latitude forest sites, bulk surface was partially decoupled from the atmosphere and ET was primarily controlled by \( R_d \) and \( D \). In contrast, at high-latitude forest sites, bulk surface was well coupled to the atmosphere and \( G_s \) was the strongest controlling factor of ET. The variations in \( \Omega \) were determined largely by the values of aerodynamic conductance and surface conductance at all studied forest sites.
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SUPPLEMENTS

Supplement 1. This includes:
Table S1. Description of the study sites
Table S2. Measurement system, height, year, closure rate and growing season length
Table S3. Values of evapotranspiration (ET) from previous single-site studies
Table S4. Values of the decoupling coefficient (Ω) from previous single-site studies
Text S1. Description of the quality control and data selection for turbulent fluxes

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