Research Article

Micrometeorological observations above a Japanese red pine forest within the growing season

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Abstract: Knowledge of vegetation-atmosphere interactions has great importance in ecological research, and to recognize these effective interactions, the collection and interpretation of micrometeorological data are essential. The main goal of this study was to understand the trends of evapotranspiration (ET) and other micrometeorological parameters within the growing season above a Japanese red pine forest in Japan. To measure ET, the Bowen ratio-energy balance approach was employed. These measurements were used with the Penman-Monteith reference evapotranspiration (ET_0) in order to create crop coefficients (K_c) by the ratio of $ET:ET_0$. Mean daily ET on the dry and rainy days was found to be 3.22 and 2.11 mm day^{-1}, respectively, which was statistically different. K_c values were inconsistent from day to day and ranged between 0.37 and 1.24, and, in general, were less than unity (average: 0.84, standard error: 0.01). Significant differences in K_c were found between rainy days (wet canopy) and dry days (dry canopy). No remarkable changes were observed between rainy and dry days in the average contribution of latent heat flux, ground heat flux, and sensible heat flux to the energy budget. The data indicated that the Penman-Monteith equation may be useful for estimating the ET from the red pine forest within the growing season, and, in particular, when the rainy and dry days were separated.

Key words: Bowen ratio-energy balance method, crop coefficient, evapotranspiration, red pine forest

Introduction

Forest ecosystems, as open systems, are linked to the atmosphere and to the pedosphere by fluxes of energy and matter (Schume et al. 2005). Thus, knowledge of vegetation-atmosphere interactions and their influence on forest microclimate is of great importance in ecological research (Ahmadi et al. 2009). A microclimate also affects ecological processes such as water cycle, plant regeneration and growth, soil respiration, nutrient cycling, and habitat formation (Motzer 2005; Usta 2006; Sarıyıldız and Küçük 2008).

In forest ecosystems, the collection and interpretation of micrometeorological data are needed to understand the effective interactions between vegetations and their atmospheric environments.

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In addition, microclimatic information is valuable in making proper decisions for managing forest ecosystems, for optimizing wood and nonwood production, and for adopting management tools such as harvesting and silvicultural practices to minimize any adverse effects of forest stand on the environment. Basic data on microclimates provide very important input for ecological field studies and ecosystem modeling (Chen et al. 1999; Motzer 2005).

Evapotranspiration (ET), which represents the main direction of water loss from plant and soil surfaces (Kırnak et al. 2002) and links water, energy, and carbon cycles, is frequently a major component of the water balance for terrestrial ecosystems, especially for forests. It has a great influence, not only on the energy distribution, but also on water conditions at the local and regional scales (Shimoyama et al. 2003; Maruyama et al. 2004; Lafleur et al. 2005; Perez et al. 2008; Zhou and Zhou 2009).

Forest ET is generally larger than that of other vegetation types such as grassland (Zhang et al. 2001; Matsumoto et al. 2008). Forests cover about 30% of the total global land area, but ET from forests accounts for 45% of the total ET from the global land surface (Oki and Kanae 2006; Matsumoto et al. 2008). Measurement of surface latent heat flux, and hence ET from forests, is important for purposes such as regional water balance studies and description of the atmospheric boundary layer (Amarakoon 2000).

The microclimate within the forest largely depends on the distribution of energy over the different fluxes (Lindroth 1985). The partition of the net radiation above forest ecosystems into the different fluxes, particularly into the latent and sensible heat fluxes, determines the water vapor and heat content of the atmosphere, ultimately driving many regional- and global-scale climatological processes. Depending on tree species, site conditions, and the physiological state of the trees, quantification of the latent and sensible heat fluxes can be different in forest ecosystems (Sturman and McGowan 2009; Giambelluca et al. 2009).

Moreover, the crop coefficient is the ratio of ET to reference ET as calculated by the FAO Penman-Monteith equation (Allen et al. 1998). A crop coefficient represents an integration of the effects of the canopy characteristics that distinguish the crop from the reference surface (Peacock and Hess 2004). Using a crop coefficient, there is no need to have a separate ET equation or measurement for each vegetation type and season. Once crop coefficients have been developed, the coefficients can be used to estimate ET (Peacock and Hess 2004).

Approximately 40% of the forested land surfaces in Japan now comprise coniferous forests (Komatsu et al. 2007) and the country is enjoying vast expanses of red pine (*Pinus densiflora*) forests. This widespread conifer is a native evergreen tree in Japan that may reach 15 m in height at a medium growth rate. It flowers from May to June, and seed ripening starts in January and ends in February. It prefers light (sandy) and medium (loamy) well-drained soils, and it can grow in nutritionally poor soil. Red pine prefers acid and neutral soils, and it is considered a shade-intolerant and drought-hardy tree that requires dry or moist soil.

The red pine forest plantations occupy approximately 9% of the total man-made forested areas in Japan (Matsui 1980), which are located mostly in mountainous regions in which studies on H_2O vapor flux measurements are accompanied with difficulties; therefore, little is known about the surface-atmosphere exchange of water and energy above the red pine forests of Japan. Micrometeorological measurements thus provide a description of microclimatic conditions of red pine forest with firsthand data on the red pine stand atmospheric environment.

The key goal of the present research was to describe the trends in ET and crop coefficient and the surface atmosphere exchange of H_2O vapor, as well as the trends in other micrometeorological variables within the growing season, from April to November, in a red pine forest located on flat land. Distribution of energy over the different fluxes above the Japanese red pine forest was also discussed.

Materials and methods

Study site

Micrometeorological measurements were carried out above a red pine plantation forest stand located in the city of Ina, Nagano Prefecture, about 250 km northwest of Tokyo, Japan (35°52′N, 137°58′E; 800

m a.s.l.) (Figure 1). The region has a relatively cooler and less humid climate than Tokyo.

The plantation forest covers 50 ha, and the mean height of the trees is 15 m (as of 2001). About 90% of the red pine trees are 39-48 years old. The average stand density is 1500 stems ha⁻¹. There are many high mountains (about 2500 m) on both sides of the measurement site, which is located in a valley oriented toward the southwest (Chen et al. 2008). Therefore, the main wind is from the southwest in the daytime. The Tenryu River runs south of the site. There is a road 50 m to the northeast that runs northeast-southwest. The city of Ina is 6 km to the south (Chen et al. 2008). The red pine forest is located on an area of flat land; the stand structure is almost homogeneous.
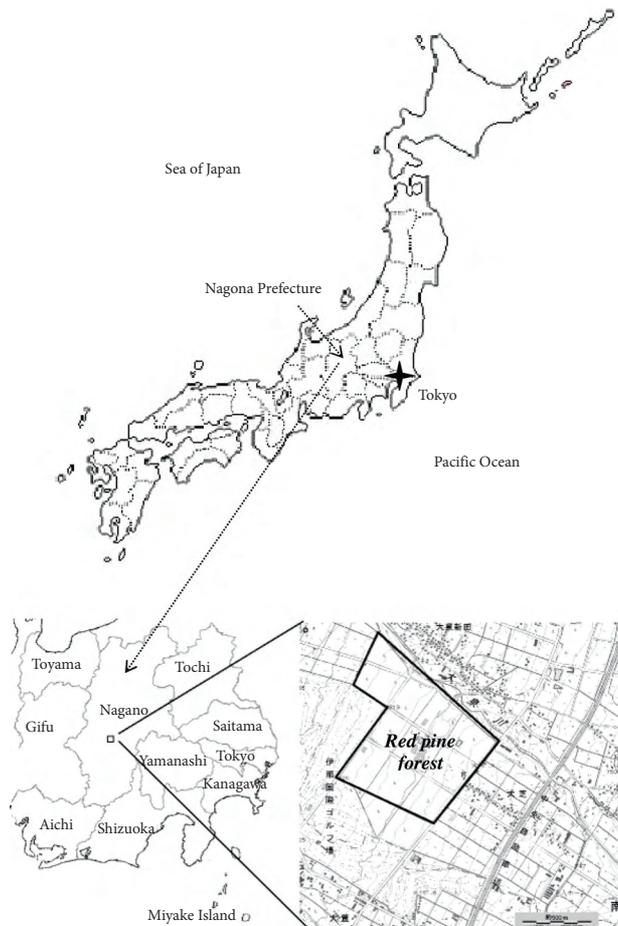

Figure 1. Location of the observation site in Nagano Prefecture. The area enclosed by the thick black line is the red pine forest.

Long-term meteorological records (1985-2008) measured at Nagano Meteorological Station (35°59´N, 137°59´E; 729 m a.s.l.) were extracted from the climate database generated by the Japan Meteorological Agency (http: //www. data. kishou. go.jp).

Meteorological records indicate that the mean cumulative rainfall during the growing season is 1198 mm and that July is the wettest month (average rainfall of 217 mm). An average of 83.5% of the total annual precipitation falls between April and November, within the growing season (Figure 2).

Long-term meteorological records also indicate that the mean annual air temperature is 10.3 °C and that January and August are the coldest and warmest months, with average temperatures of –1.3 °C and 23.0 °C, respectively (Figure 2).
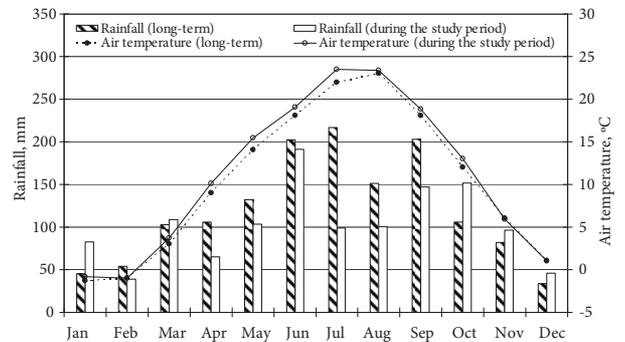

Figure 2. Monthly rainfall (mm) and average air temperature (°C) during the study period (2000-2002). The hashed bars and dashed line indicate the long-term (1985-2008) monthly averages.

Bowen ratio-energy balance

ET measurements were performed using the Bowen ratio-energy balance method (BREB). The BREB method, based on micrometeorological observations, is an indirect method for estimating ET that has been widely used in a variety of field conditions (Inman-Bamber and McGlinchey 2003). The BREB remains an attractive approach for measuring ET because of its rather low cost and its long-term reliability (Cellier and Olioso 1993; Lee et al. 2004).

The method estimates the ET by calculating the partition of convective fluxes between latent and

sensible heat (Peacock and Hess 2004), based on the energy balance equation at the surface, described as:

$$R_n - G = LE + H \tag{1}$$

Here, R_n (MJ m^{-2} day^{-1}) is the net heat gain from radiation above the pine forest, G (MJ m^{-2} day^{-1}) is the ground heat loss, LE (MJ m^{-2} day^{-1}) is the latent heat loss, and H (MJ m^{-2} day^{-1}) is the sensible heat loss.

The latent heat loss is calculated from the reorganization of Eq. (2):

$$LE = \frac{R_n - G}{1 + \beta} \tag{2}$$

incorporating the Bowen ratio, β:

$$\beta = H \,/\, LE \tag{3}$$

Within a few meters of the surface, H and LE may be expressed as follows.

$$LE = \frac{-\rho C_P}{\gamma} \, k_v \, \frac{\Delta e}{\Delta z} \tag{4}$$

$$H = -\rho C_P \, k_H \, \frac{\Delta T}{\Delta z} \tag{5}$$

Here, ρ is atmospheric density (kPa), Cp (1.013 × 10^{-3} MJ kg^{-1} °C) is the specific heat of the air at a constant pressure, γ (kPa °C^{-1}) is the psychrometric constant, Δe (kPa) is the change in vapor pressure with height, ΔT (°C) is the change in temperature with height, and z (m) is height. K_H and K_V (m^2 s^{-1}) are the turbulent transfer coefficients for heat and vapor.

β is calculated from gradients of temperature and vapor pressure measured at 2 heights above the canopy, by combining Eqs. (4) and (5). Generally, K_H and K_V are not known, but are assumed to be equal under the neutral and unstable condition in the air layer (this condition is satisfied in the daytime), and, therefore, they cancel out of the equation, as follows.

$$\beta = \gamma \, \frac{\Delta T}{\Delta e} = \gamma \, \frac{T_L - T_U}{e_L - e_U} \tag{6}$$

Here, the subscripts L and U refer to the lower and upper temperatures and vapor pressures.

Instrumentation

Micrometeorological parameters for obtaining the ET and other micrometeorological measurements were observed using an automatic weather station (AWS) system developed by Aoki et al. (1996). The BREB system consisted of a net radiometer, 2 soil heat flux plates, and 2 dry- and wet-bulb psychrometers.

A net radiometer (MF-11, EKO Seiki, Tokyo, Japan) installed at a height of 16 m above the soil surface, i.e. 1 m above the maximum forest canopy, measured the net radiation flux density (R_n).

Temperatures and relative humidity above the canopy were measured at 2 levels, 17 and 21 m above the ground, with a handmade (self-produced) 10-paired copper-constantan thermocouple thermometer (shielded and ventilated).

The soil heat flux was measured with 2 heat flux plates (MF-11, EKO Seiki) buried approximately 1 cm under the soil surface.

The following microclimate variables were also measured at the study site: solar radiation, with a solarimeter (MF-11 EKO Seiki) installed in the same arm of the net radiometer, 16 m above the soil surface; precipitation, with a tipping-bucket rainfall gauge (NOAH-11 ETL) established above the canopy; and wind speed, with a propeller (WS-D32 KOMATSU) installed at the height of 21 m above the ground surface.

All of the above-mentioned instruments were mounted on an experimental tower 23 m in height. To obtain the longest and unobstructed wind fetch, the tower was installed at a central location in the red pine forest.

The fetch requirements for the BREB are often suggested to be 100 times the height of the upper sensor (Angus and Watts 1984; Heilman et al. 1989; Stannard 1997). However, the fetch requirements are also a function of surface roughness (Brutsaert 1982). If it is assumed that the lower 10% of the internal boundary layer is in equilibrium with the surface, then the minimum fetch requirement, x_f, for near-neutral atmospheric conditions is as follows (ASCE 1996, after Brutsaert 1982).

$$x_f = \left[\frac{30(z - d)}{z_0^{0.125}} \right]^{1.14} \tag{7}$$

Here, z (m) is the maximum sensor height, d (m) is the zero plane of displacement, and z_0 (m) is the surface roughness length of momentum. d and z_0 were calculated using the equations given by Brutsaert (1982):

$$d = 0.67h \tag{8}$$

$$z_0 = 0.123h \tag{9}$$

where h is the vegetation height.

Measurement period and data treatment

The installed instruments were operative within the growing seasons, from April to November, in 2000, 2001, and 2002. Their instantaneous data were collected at 1-min intervals by a data logger and averaged over 10 min, and all data were finally averaged into the daytime mean. Daytime ET was then calculated from daytime latent heat flux as ET = LE/λ.

Reference evapotranspiration (ET$_0$)

The FAO Penman-Monteith combination equation, a universal adoption, is the preferred and reliable method for determining reference ET worldwide (Inman-Bamber and McGlinchey 2003). The FAO defined the reference crop as a hypothetical crop with an assumed height of 0.12 m, a fixed surface resistance (70 s m^{-1}), and an albedo (0.23) closely similar to the evaporation of an extension surface of green grass of uniform height, which is actively growing and sufficiently watered. The recommended method is said to overcome the shortcomings of the previous FAO-Penman method and provides results that are more consistent (Goyal 2004). According to the FAO Penman-Monteith equation, the ET$_0$ can be expressed as follows in Eq. (10).

$$ET_0 = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,(900\,/T + 273))\,u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34 u_2)} \tag{10}$$

Here, ET$_0$ (mm day^{-1}) is the reference ET, T (°C) is the mean daily air temperature at a height of 2 m, u_2 (m s^{-1}) is the wind speed at a height of 2 m, e_s (kPa) is the saturation vapor pressure, e_a (kPa) is the actual vapor pressure, $e_s - e_a$ (kPa) is the saturation vapor pressure deficit (VPD), Δ (kPa °C^{-1}) is the slope of the vapor pressure curve at the daily mean air temperature, and γ (kPa °C^{-1}) is the psychrometric

constant calculated as $PC_p/\lambda\varepsilon$, in which P (kPa) is the air pressure, C_p (1.013 × 10^{-3} MJ kg^{-1} °C) is the specific heat of the air at a constant pressure, λ (MJ kg^{-1}) is the latent heat of the vaporization of water (λ = 2500.9 – 2.366T), ε is the ratio of the molecular weights of water vapor and air (0.622), and T is the air temperature at the height of the lower arm of the installed tower (Inman-Bamber and McGlinchey 2003).

Atmospheric pressure (P) was calculated by Eq. (11) (Gaylon and Norman 1998), as follows.

$$P = 101.3 \left(\frac{293 - 0.0065\,z}{293} \right)^{5.26} \tag{11}$$

Here, z is the station elevation above sea level (m).

The saturation vapor pressure (kPa) was first satisfied by Eq. (12), as follows.

$$e_s = a \times \exp\left(\frac{bT}{T + c} \right) \tag{12}$$

Here, a = 0.611, b = 17.502 KPa, and c = 240.97 °C.

The actual vapor pressure (kPa), e_a, was computed by Eq. (13):

$$e_a = e_s - \gamma\,dT \tag{13}$$

where dT is the difference between the dry- and wet-bulb temperatures.

Relative humidity (RH) at the daily mean air temperature was then calculated using Eq. (14).

$$RH = (e_a\,/\,e_s) \times 100 \tag{14}$$

The slope of the saturation vapor pressure curve was then calculated by the mean air temperature at the lower arm and the saturation vapor pressure, as shown in Eq. (15).

$$\Delta = bc \times e_s\,/\,(c + T)^2 \tag{15}$$

R_n can be estimated using Eqs. (16-18), based on the method of Allen et al. (1998), the FAO-56 method for estimating the net radiation (Goyal 2004; Maruyama et al. 2004).

$$R_n = R_{ns} - R_{nl} \tag{16}$$

$$R_{ns} = (1 - \alpha)\,R_s \tag{17}$$

$$R_{nl} = \sigma \left(\frac{T_{mean}^4}{2} \right) (0.34 - 0.14\sqrt{e_a})(1.35\frac{R_s}{R_{so}} - 0.35)$$

$$(18)$$

Here, R_{nl} and R_{ns} are respectively the net outgoing longwave and net incoming shortwave radiations (MJ m^{-2} day^{-1}), σ is the Stefan-Boltzmann constant (4.903 × 10^{-9} MJ K^{-4} m^{-2} day^{-1}), α is the canopy reflection or albedo for the hypothetical grass reference crop (0.23), T_{mean} is the daily mean air temperature (°C), R_{so} is the clear-sky radiation (MJ m^{-2} day^{-1}) = (0.75 + (2z × 10^{-5}))/R_a, z is the station's elevation above sea level (m), R_a is the extraterrestrial radiation changed by latitude (MJ m^{-2} day^{-1}), R_s is the measured or calculated solar radiation (MJ m^{-2} day^{-1}), R_s/R_{so} is the relative shortwave radiation, and e_a is the actual vapor pressure of the air (kPa) (Goyal 2004).

Comparisons were also made between the measured and estimated net radiations to assess the FAO method for estimating the net radiation from solar radiation, air temperature, vapor pressure, and clear-sky radiation (Inman-Bamber and McGlinchey 2003).

The soil heat flux at the daily scale beneath the grass reference surface was relatively small and thus could be ignored in the FAO Penman-Monteith combination equation. Therefore, $G_{day} = 0$ (MJ m^{-2} day^{-1}) (Goyal, 2004; Maruyama et al. 2004).

Daily average values were used for R_n, T, and e_a in the FAO Penman-Monteith combination equation.

To calculate the wind speed at 2 m above the surface, the wind speed data were converted by the following equation, as recommended by the FAO (Allen et al. 1998).

$$u_2 = u_z (4.87 / \ln (67.8z - 5.42)) \quad (19)$$

Here, u_2 (m s^{-1}) is the wind speed at 2 m above ground surface, u_z (m s^{-1}) is the measured wind speed at z m above ground surface, and z (m) is the height of the measurement above the ground surface.

We also made a comparison between the ET_0 calculated by the measured R_n and that by the estimated R_n.

Crop coefficient (K_c)

In the present research, K_c is the ratio of the ET to the ET_0, calculated by the measured R_n as in Eq. (20).

$$ET = K_c ET_0 \quad (20)$$

Results

Micrometeorological regime

Temperature and rainfall within the growing season of the study period (2000-2002) were not similar to the long-term (23-year) average (Figure 2). Total annual rainfall during the study period was 954 mm, compared with the long-term average of 1199 mm, showing that the study period was substantially drier than the long-term average. However, the seasonal distribution of rainfall during the study period was almost identical to the long-term average. For example, most of the rainfall recorded during the study period (78%) occurred within the growing season (April-November), while growing-season rainfall historically accounts for 83% of the total annual rainfall.

The growing-season air temperature was, on average, 16.2 °C during the study period, compared with a long-term average temperature of 15.3 °C. Moreover, the peaks of air temperature were observed in July and August, both during the long-term measurements and during the study period.

Daily incident solar radiation, air temperature, vapor pressure deficit, wind speed, and rainfall within the growing seasons of the studied years are shown in Figure 3. The data indicated a daily solar radiation of 13.3 MJ m^{-2} day^{-1} (n = 549, SE = 1.07) within the growing season. The peak and minimum were observed around the middle of the growing season, in July and August (16.1 MJ m^{-2} day^{-1}), and in November (6.8 MJ m^{-2} day^{-1}), respectively. The growing season usually commenced from the start of April and lasted until the end of November each year, corresponding with the increase in incident solar radiation and consequently in air temperature.

The measurements also showed that a total of 224 rainfall events occurred within the measured growing seasons. Heavy rainfall events (>60 mm in 1 day) were also observed on 6 days. Among the measured years, 2000 with 1238 mm (83% of the annual rain) and 2002 with 774 mm (63% of the annual rain) had the wettest and driest growing seasons, respectively. Meanwhile, 852 mm of rain fell during the growing season of 2001 (64.5% of the annual rain).

The atmospheric evaporative demand (measured as the average daily VPD) and daily mean air

temperature were at the seasonal maximum at the middle of the growing season.

Wind speed had no specific trend within the growing season; the daily average wind speed was 1.8 m s^{-1} with a high variability (n = 570, SE = 0.03). As a whole, the pine forest experienced very windy days (>4 m s^{-1}) on 4 days of the measurements.

Net radiation

R_n is an important variable in the FAO reference ET_0. To assess the FAO-56 method for estimating R_n from solar radiation, air temperature, vapor pressure, and clear-sky radiation, a comparison was made to understand the bias in the R_n estimate and, consequently, in the ET_0 for the study site (Figure 4).
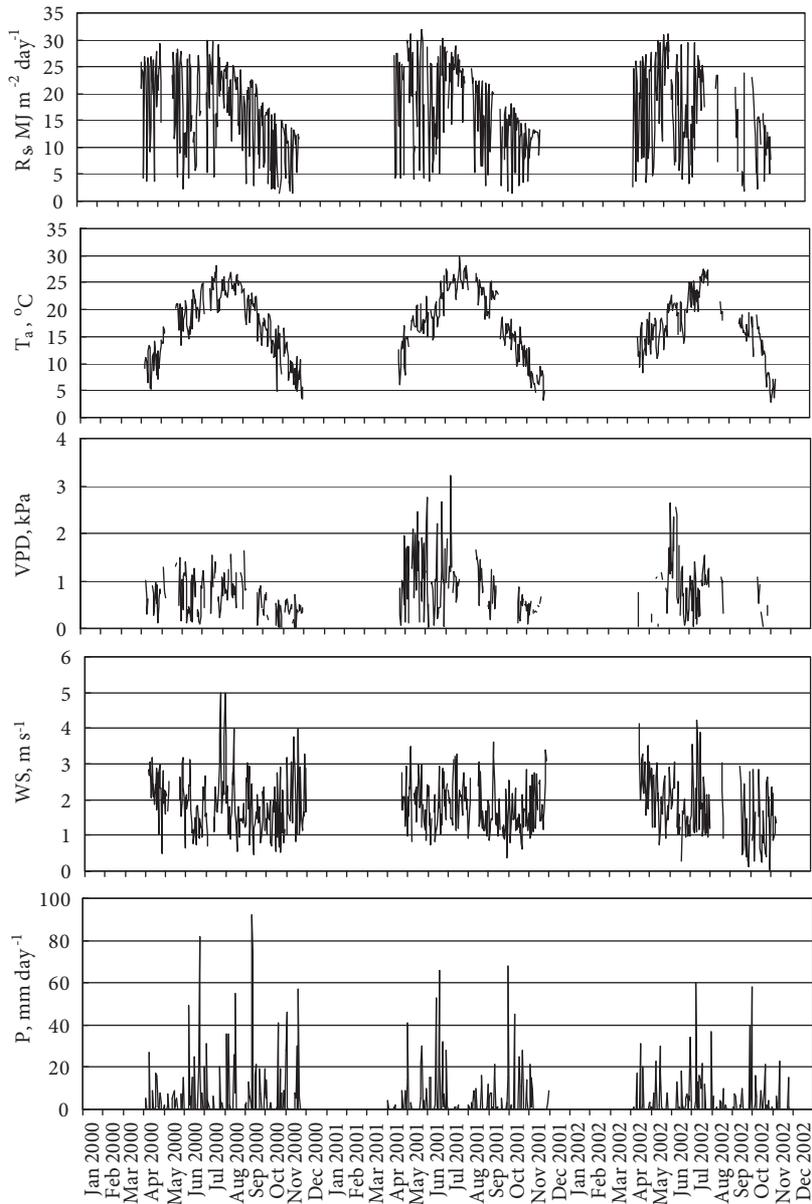

Figure 3. Climate data for the red pine forest in the measured years. From the top, the daily total solar radiation (R_s), the daily mean air temperature (T_a), the daily mean vapor pressure deficit (VPD), the daily mean wind speed (WS), and the daily rainfall (P).
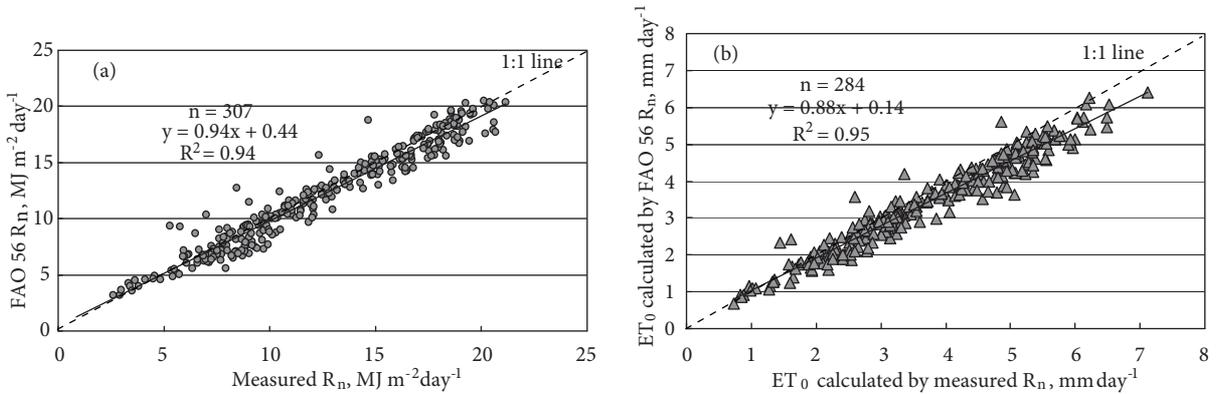
Figure 4. a) Net radiation (R_n) estimated from FAO-56 daily time step equations against the measured R_n at the study site and b) correlation between the reference evapotranspiration (ET_0) by the measured R_n and by that of the estimated R_n through FAO-56; n = number of measured days.

At the red pine forest, the R_n as estimated by the FAO-56 was slightly biased. The root mean square error (RMSE) of the estimated R_n, when using the FAO method, was calculated as follows.

$$RMSE = \sqrt{1/n \sum_{i=1}^{n} \{R_n(measured) - R_n(estimated)\}^2}$$

(21)

Here, n is the number of data points as shown in Figure 4a.

The RMSE was 1.15 MJ m^{-2} day^{-1} on a 1-day scale. Since the daily average value of the measured R_n within the growth period was 11.45 MJ m^{-2} day^{-1}, the error of the R_n estimation on a 1-day scale was approximately 10%. The ET_0 calculated by the measured R_n was subsequently compared with that calculated by the FAO-56 R_n (Figure 4b). The RMSE of the ET_0 estimation was computed as 0.45 mm day^{-1} on a 1-day scale. Given that the daily average value of the ET_0 was 3.75 mm day^{-1}, the error of the ET_0 estimation on a 1-day scale was about 12% of the average ET.

We also found a very strong correlation ($r^2 = 0.976$, n = 548) between the measured values of the daily R_n and R_s at the study site (not shown).

Energy balance

For an average maximum tree height of 15 m, the minimum fetch requirement was approximately 370 m in all directions. However, our observations showed that fetch lengths in the study site were between 500 and 1000 m, in 8 directions from the BREB station.

Figure 5 shows energy fluxes over the growing seasons of the measured years. The data showed that the red pine forest received an average net radiation of 11.45 MJ m^{-2} day^{-1} within the growing season. The daily average of net radiation on the rainy and dry days was computed as 7.2 and 13.4 MJ m^{-2} day^{-1}, respectively. However, the variation of the daily net radiation of the rainy days was higher than that of the dry days (rainy days, n = 170, SE = 0.37; dry days, n = 359, SE = 0.24). The peak of the monthly net radiation was observed in the middle of the growing season, in July and August (13.8 MJ m^{-2} day^{-1}), and then it decreased and reached its minimum in November (6.8 MJ m^{-2} day^{-1}).

The average contribution of the latent heat flux, ground heat flux, and sensible heat flux to the energy budget was calculated over the growing season. The average values were 37.4% (n = 322, SE = 0.68) of the net radiation used in the sensible heat flux, 59.8% in the latent heat flux (SE = 0.66), and 2.8% (SE = 0.08) in the ground heat flux. This shows the importance of the latent heat flux in the energy balance at this site.

The energy balance for rainy and dry days was also investigated independently. In general, a higher proportion of energy was lost as latent heat flux on rainy days (63.3%) than on dry days (57.7%). However, the absolute flux of latent heat on rainy days was lower than that of dry days, 5.2 MJ m^{-2} day^{-1} compared with 7.9 MJ m^{-2} day^{-1}.
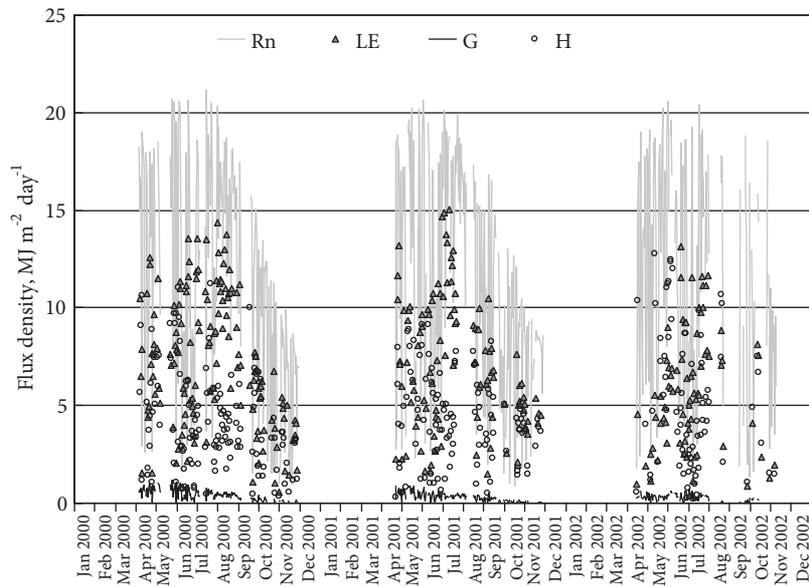
Figure 5. Energy fluxes for the growing seasons of the measured years, calculated using the Bowen ratio-energy balance (BREB) approach. The net radiation (R_n) can be seen together with its division into the sensible heat flux (H), the latent heat flux (LE), and the ground heat flux (G). All fluxes may be read on the y-axis.

Moreover, the total energy allocated to sensible heat flux on rainy and dry days was found to be 33.5% and 39.5%, respectively. The absolute flux of sensible heat on rainy and dry days, however, was 2.7 and 5.5 MJ m^{-2} day^{-1}, respectively (Figure 5). Statistically, both allocations, (LE:R_n)% and (H:R_n)%, were insignificant on rainy and dry days equally.

The data indicated that the daily ground heat flux was very small compared with the daily net radiation, and the total energy dissipated by the ground heat flux remained fairly constant within the dry and rainy days, at 2.8% and 3.2%, respectively (Figure 5).

Evapotranspiration and crop coefficient

Figure 6a shows the changes in the daily ET in the red pine forest within the growing seasons of the measured years. The monthly average ET, shown as bolded triangles, initiated an increase in April and May, synchronized with the start of the growing season (3.00 mm day^{-1}), and then reached the same time peak in the middle of the growing season, in July and August (4.50 mm day^{-1}). The peak of the ET coincided with the peaks of the daily incident solar radiation and the daily air temperature (Figure 3).

The monthly average ET then decreased and reached its minimum in November, around the end of the growing season (1.60 mm day^{-1}). The decrease in the monthly average ET may be related to meteorological and plant factors affecting the evapotranspiration process.

The daily average of ET within the growing season was 2.8 mm day^{-1}, with a high variation (n = 322, SE = 0.07), such that the ET varied between 0.24 and 6.15 mm day^{-1}.

Figure 6b shows the trend of daily K_c for the red pine forest within the growing seasons of the measured years. The monthly average values of K_c, shown as filled circles, suggest that K_c began to increase in May (0.65) and reached a peak in July (0.94). Within the growing season, the daily K_c value ranged between 0.37 and 1.24 and the daily average of K_c was found to be 0.84 (n = 283, SE = 0.01).

It is to be expected that the ET will be different on days upon which it has been raining compared with days that are dry. The average ET on rainy days was 2.11 mm day^{-1} (n = 118, SE = 0.12), as opposed to 3.22 mm day^{-1} (n = 204, SE = 0.08) on dry days ($t_{0.01}$ = −7.3).
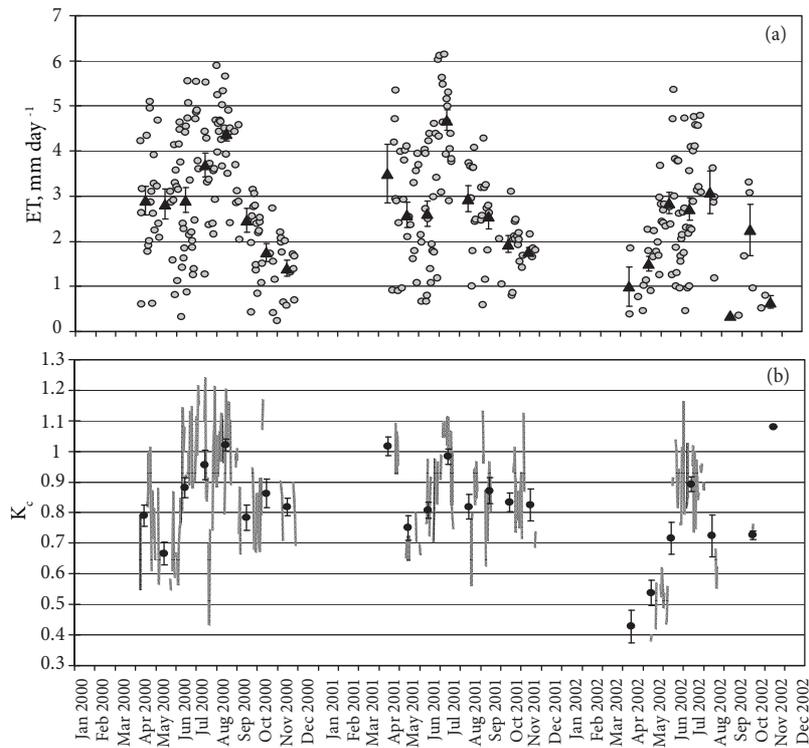
Figure 6. a) Changes in the daily average estimates of evapotranspiration (ET) from the red pine forest using the Bowen ratio-energy balance (BREB) approach and b) daily crop coefficients (K_c), i.e. the ET:ET_0 values. Bars are standard errors of the mean monthly ET and K_c values.

On 67% of the measured days, K_c was less than unity. It was found that, overall, rainy days (days with >0.1 mm rain) tended to have a K_c value closer to unity than dry days. The average K_c value on days with rain was 0.93 (n = 82, SE = 0.02), versus 0.81 (n = 201, SE = 0.01) on dry days ($t_{0.01}$ = 5.6). Although this is a significant difference, there was variation within both groups. Among the rainy days, this was somewhat linked to the timing of the rainfall. Rain that fell at night had much less impact on the ET than rain that fell in the middle of the day. The high K_c related to rainfall may only be present for some of the days, when the canopy was actually wet.

Moreover, the daily average of ET within the growing season in 2002 was lower (mean = 2.40 mm day^{-1}, n = 75, SE = 0.14) in comparison to 2000 (mean = 2.97 mm day^{-1}, n = 140, SE = 0.12) and 2001 (mean = 2.89 mm day^{-1}, n = 107, SE = 0.13).

Estimating evapotranspiration

The daily rates of ET, as measured by the BREB and plotted against the ET_0, can be seen in Figure 7. Although the overall best-fit line (not shown in Figure 7) gave an average crop coefficient of 0.70, there was a relatively good and statistically significant relationship (r^2 = 0.66) between the ET_0 and ET on a daily basis when all days were included. When the dry days and rainy days (dry and wet canopies) were separated, there was an improved relationship between ET_0 and ET.

This was particularly true for wet canopy days (r^2 = 0.8846), although there was still scatter among dry canopy days (r^2 = 0.5733). However, both relationships were statistically significant. We concluded that the application of the Penman-Monteith equation may be advantageous for estimating the ET from the red pine forest within the growing season.
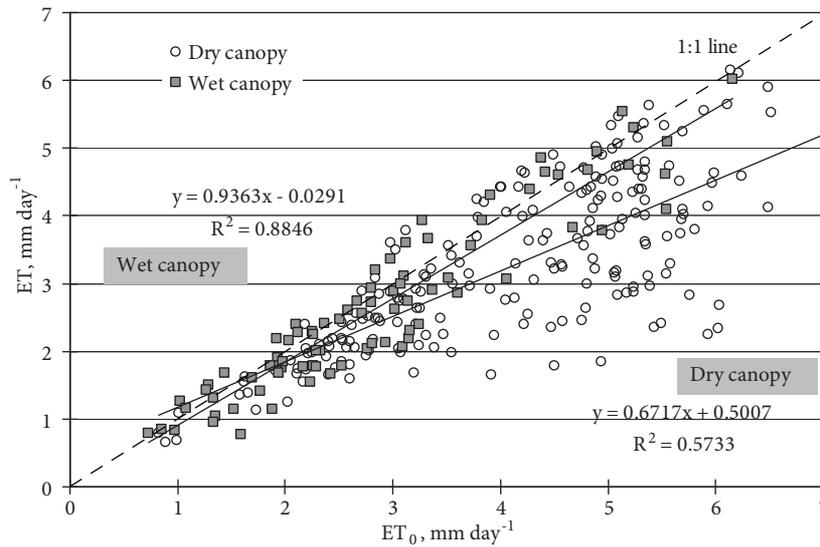
Figure 7. The relationship between the reference evapotranspiration (ET_0) and the evapotranspiration (ET). Closed squares represent days with rain (wet canopy) and open circles represent dry days (dry canopy). Best-fit lines forced through the origin are shown separately for rainy and dry days to create crop coefficients (K_c).

Discussion

The FAO-56 method was found to be an appropriate method for estimating ET_0 via estimation of the net radiation in the pine forest. The reliability of the R_n estimate at a particular site affects the ET_0 to a varying extent, depending on the relative sizes of the energy and aerodynamic components of the Penman-Monteith equation. It should be emphasized that the ET_0 is a reference for comparison with the ET and that errors in estimating the R_n only affect the comparison between the ET and the ET_0, not the ET itself (Inman-Bamber and McGlinchey 2003). It is necessary to assess the site specifically in the FAO-56 method for estimation of the net radiation, which is the first step in calculating the ET_0.

The energy budget created from the BREB data indicated that the latent heat component was significant. The absolute values of the energy budget components, though different on rainy and dry days, showed no remarkable change in the average contributions of the latent heat flux, the ground heat flux, and the sensible heat to the energy budget.

The nearly equal allocation of the energy budget components on dry and rainy days, despite the different amount of net radiation, approximately

double on dry days compared with rainy days, showed that the ET from the red pine forest was affected by the amount of energy rather than by the energy allocation.

ET from the red pine forest, on the majority of the measured days, was less than the ET_0. Although we found a relatively good linear relationship between the reference and measured ET from the red pine forest, the difference between them may be predictable in light of the discrepancy in the physiological characteristics between the red pine forest and the short grass-like crop that was the basis of the reference evapotranspiration. The most obvious canopy difference is that of height, and this leads to differences in surface roughness. The ET_0 computation assumes a fixed value for surface resistance (including the stomata) in opposition to the ET, depending on stomatal conductance. It is then logical that during the dry days, when stomatal conductance is declining, the ET value is lower when compared to the ET_0.

Therefore, the ET_0 value may be a practical method of estimating and modeling red pine forest evapotranspiration. The results showed that there was a variation in K_c that was dependent on

meteorological conditions. On days with rainfall, i.e. days when the canopy was wet for at least some of the evaporative period, the K_c values were larger than on dry, bright days.

In using crop coefficients for the pine forest, different coefficients may initially be considered for days with rain and days without. The difference is probably related to the fact that the rate of evaporation of intercepted raindrops is faster than the rate of transpiration from the plant, which is constrained by stomatal resistance. The resistance parameters within the Penman-Monteith equation are not constant. Stomatal resistance, in particular, is recognized to be different day by day with weather conditions.

Conclusions

We observed micrometeorological parameters above a Japanese red pine forest within the growing season. This study can offer forest ecology researchers multiple years of energy balance and other micrometeorological information from the Japanese red pine forests, a little-studied forest type. It was found that the ET from the red pine forest was highly affected by the net radiation, since the energy allocation was similar on rainy and dry days.

Measured ET rates from the red pine forest were lower than the reference ET on the majority of days. The crop coefficient, however, varied with meteorological conditions. On rainy days, i.e. days when the canopy was wet for at least some of the evaporative period, the evaporation was much closer to the reference, as the ET of the intercepted rainfall was not exposed to stomatal conductance. Canopy interception of precipitation was particularly important, with crop coefficients being significantly higher on rainy days, possibly due to the higher rates of evaporation of intercepted water, owing to the lack of stomatal resistance. On a daily basis, estimating the ET through the reference ET was found to be useful, in particular when dry and rainy days were separated.

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