Do coniferous forests evaporate more water than broad-leaved forests in Japan?

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Summary It is a commonly held belief in Japan, based on a US case study, that coniferous forests evaporate more water than broad-leaved forests. If this is true, converting coniferous forests into broad-leaved forests would result in an increased water yield. However, it is not known whether the US case study is applicable to Japanese forests.

A simple model was developed to calculate annual forest evapotranspiration E based on the review of 67 dry-canopy and 16 wet-canopy evaporation studies. We calculated the E values for broad-leaved and coniferous forests under meteorological conditions found in Japan. E of broad-leaved forests was approximately the same as E of young coniferous forests and higher than E of old coniferous forests. The results predicted by the model were supported by water balance data from three Japanese experimental catchments. The conclusion from the data is that coniferous forests do not evaporate more water than broad-leaved forests in Japan.

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Introduction

Evapotranspiration from land surface is a major factor affecting water yield and therefore usable water resources (e.g., Langford, 1976; Bosch and Hewlett, 1982). Many researchers have examined evapotranspiration from various land surface types, such as forests, grasslands, and crops (e.g., Shuttleworth and Calder, 1979; Hornbeck et al., 1993; Wilson et al., 2001; Noisetto et al., 2005). Since a significant portion (67%) of the land surface in Japan is covered

with forest (Fujimori, 2000), an examination of the forest evapotranspiration is particularly critical for water resource management in Japan.

Japan has developed large areas of coniferous plantation forests for timber production which occurred mainly after the Second World War (Tadaki, 1988; Fujimori, 2000). Most of these forests were developed by converting the native broad-leaved forests into their coniferous counterparts. Approximately 40% of forested land surface in Japan now comprise of coniferous plantation forests (Fujimori, 2000; Murakami, 2003).

Recently, Japanese people have come to expect environmental control of forests rather than for use for timber

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production because Japan now imports large amounts of timber and forest products (Fujimori, 2000). Therefore, Japanese people have begun to consider how they should manage domestic forests for environmental control.

From the viewpoint of water resource management, people believe that coniferous forests evaporate more water than broad-leaved forests: annual evapotranspiration of coniferous forests is greater than that of broad-leaved forests. Thus, the process of converting coniferous forests into broad-leaved forests will result in an increased water yield (Tsukamoto, 1998; Kuraji, 2003).

This common belief is based on a case study at the Coweeta experimental watersheds in the US performed by Swank and Douglass (1974). Their results are widely known as this paper has been cited many times in Japanese forest hydrology literature (e.g., Tsukamoto, 1992; Kuraji, 2003). Swank and Douglass (1974) measured the annual water yield change of a broad-leaved forest into a coniferous forest after a clear-cut. Water yield after the clear-cut was greater than that of the broad-leaved forest period by 10–150 mm year⁻¹ and typically by 50 mm year⁻¹. Water yield after the development of a coniferous forest (i.e., after canopy closure) was smaller than that of a broad-leaved forest period by 140–180 mm year⁻¹ and typically by 170 mm year⁻¹. This indicates that coniferous forests evaporate more water than broad-leaved forests and the evaporation change caused by forest conversion from broad-leaved forests to coniferous forests is more drastic than the clear-cut of broad-leaved forests.

However, it is not known whether Japanese coniferous forests evaporate more water than broad-leaved forests (Komatsu et al., 2005). It is unclear if Swank and Douglass' (1974) results from Coweeta can be applied to Japan because meteorological conditions are different between the regions. Furthermore, Brown et al. (2005) pointed out that results in Coweeta may not be general by employing the method of Zhang et al. (2001) which formulated annual forest evapotranspiration estimated by the catchment water balance method as a function of annual rainfall. Brown et al. (2005) applied Zhang et al.'s (2001) formulation to forest evapotranspiration data summarized from earlier papers. They found that annual evapotranspiration of broad-leaved forests from Coweeta varied greatly from Zhang et al.'s (2001) formulation. The results indicated that results in Coweeta may not be applicable to other regions.

Our research examines whether annual evapotranspiration of coniferous forests is greater than that of broad-leaved forests in Japan. If the difference in annual evapotranspiration between broad-leaved and coniferous forests is smaller than that caused by a forest clear-cut, we do not consider the difference as significant. We are only concerned about a difference in annual evapotranspiration which is comparable to that caused by a forest clear-cut.

A simple model was developed, based on published dry- and wet-canopy evaporation studies, to calculate annual evapotranspiration for broad-leaved and coniferous forests. We then formulated a hypothesis to answer the question whether annual evapotranspiration of coniferous forests is greater than that of broad-leaved forests in Japan and confirmed the hypothesis based on catchment water balance data. The evapotranspiration results based on catchment water balance data for a specific area may not be applicable

for other regions in Japan which have different meteorological conditions (Komatsu et al., 2005; Komatsu, in press). Therefore, we formulated a hypothesis using an evapotranspiration model which allowed us to determine whether the result can be generalized.

The model

We developed a simple model that allows us to calculate annual evapotranspiration of broad-leaved and coniferous forests under meteorological conditions in Japan with the input of monthly solar radiation, air temperature, and annual rainfall. The model does not deal with snow and therefore, we cannot apply the model to regions with heavy snowfall. This limitation is not critical for our purpose because regions with heavy snowfall do not frequently suffer from water shortage (Fig. 1).

The model formulates annual evapotranspiration E as

$$E = E_d + E_w, \quad (1)$$

where E_d and E_w are annual dry- and wet-canopy evaporation. The following describes modeling of E_d and E_w .

Dry-canopy evaporation, E_d

E_d is modeled, based on the Priestley–Taylor equation (Priestley and Taylor, 1972) as

- Area with frequent water shortage
- Area with heavy snowfall in winter
- Experimental catchment
- Meteorological station

Figure 1 A map showing areas with frequent water shortage and with heavy snowfall. We also indicate the locations of experimental catchments and meteorological stations, whose data we used in this study.

$$E_d = \sum_{i=1}^{12} \alpha_i \frac{\Delta_i}{\Delta_i + \gamma} \frac{R_{n_i} - G_i}{\lambda}, \quad (2)$$

where α is the Priestley–Taylor coefficient, Δ is the slope of saturation vapor pressure function, γ is the psychrometer constant, R_n is the net radiation, G is the soil heat storage, and λ is the latent heat of water vaporization. The subscript i denotes month of the year. R_n and G are defined for daytime which means periods with positive solar radiation, because dry-canopy evaporation occurs mainly during daytime (Komatsu, 2005). Assuming constant ratio of net radiation to solar radiation and no soil heat storage, this equation is transformed as

$$E_d = \sum_{i=1}^{12} \alpha_i \frac{\Delta_i}{\Delta_i + \gamma} k \frac{S_i}{\lambda}, \quad (3)$$

where k is the ratio of net radiation to the solar radiation and S is solar radiation.

The validity of a constant k assumption will be discussed in “ k Parameterization”.

The assumption of no soil heat storage (i.e., $G = 0$) does not cause large errors in estimating E of Japanese forests. Projected leaf area index (LAI) of Japanese evergreen forests is usually greater than 3 throughout the year (Tsukamoto, 1998; Murakami, 2003). Similarly, projected LAI of Japanese deciduous forests during a growing season is usually greater than 3 (Murakami, 2003). Canopies with projected LAI ≥ 3 are usually closed and therefore, G occupies a small portion of forest energy balance (e.g., Watanabe et al., 2001; Oguri and Hiyama, 2002). Even for deciduous forests in winter, an assumption of no soil heat storage would not cause large errors in annual evapotranspiration estimates for the following two reasons. First, many deciduous forests in Japan are only partially deciduous, not fully deciduous. Park et al. (2000) estimated LAI values in winter for two Japanese deciduous forests as 3.4 and 2.7. Thus, many Japanese deciduous forests are not very sparse even in winter. Second, even for fully deciduous forests, considering the G term would not be critical for E estimates. α in winter is much smaller than during a growing season for a fully deciduous forest (e.g., Watanabe et al., 2001; Wilson and Baldocchi, 2000). Therefore, dry-canopy evaporation in winter occupies only a small portion of E and inaccuracies in $R_n - G$ estimates will not cause a large error in E estimates. Additionally, G contribution to the forest energy balance becomes less significant for a longer time scale, though it can be significant at an hourly time scale (e.g., Baldocchi et al., 2000; Bouka Biona et al., 2001). This fact also justifies the no soil heat storage assumption of our model. We also assumed no canopy air heat storage for the same reason.

For calculating E_d by Eq. (3) parameterization of α and k is required, which is detailed below.

Parameterization of α

Two different schemes were prepared to parameterize α of broad-leaved forests. One scheme assumes α of broad-leaved forests as

$$\alpha_i = 0.83 \quad (i = 1, 2, \dots, 12). \quad (4)$$

The other scheme assumes α of broad-leaved forests as

$$\alpha_i = 0.00 \quad (i = 1, 2, 3, 4, 12), \quad (5)$$

$$\alpha_i = 0.83 \quad (i = 5, 6, \dots, 11). \quad (6)$$

Both schemes assume $\alpha = 0.83$ for growing seasons ($i = 5, 6, \dots, 11$). This value of 0.83 was determined based on Komatsu's (2005) review in which α values in growing seasons from published papers were summarized. Of the 67 α values examined by Komatsu, 22 were for broad-leaved forests and the average of the samples was 0.83. We note that α values of forests are usually lower than the value originally proposed by Priestley and Taylor (1972), has been pointed out by many researchers (e.g., Shuttleworth and Calder, 1979; Baldocchi et al., 1997).

We did not consider any forest properties (e.g., canopy height and LAI) for parameterizing α of broad-leaved forests, which contrasts to the case for coniferous forests (see below). Komatsu (2005) examined relationships of forest properties with α values but no systematic relationships were found between canopy height and α and between LAI and α for broad-leaved forests.

The former scheme assumes constant α throughout the year (fully evergreen) while the latter assumes α declines in winter (fully deciduous with no forest floor evaporation). Many broad-leaved forests in Japan, located in regions without heavy snowfall, are partially deciduous where evergreen and deciduous trees coexist (e.g., Park et al., 2000; Oguri and Hiyama, 2002). As actual broad-leaved forests are usually mixed deciduous and forest floor evaporation exists in winter, a realistic E_d value will be between the E_d values calculated based on these two schemes.

Both schemes do not consider α decline with soil water deficit. α decline with soil water deficit has been reported in many observational studies (e.g., Vourlitis et al., 2002; Komatsu and Hotta, 2005). However, such a phenomenon is not common in Japan. Kondo et al. (1992), Murakami et al. (2000), Sawano (2003), and Komatsu et al. (2006) succeeded in reproducing seasonal evapotranspiration trend of Japanese forests using evapotranspiration models without considering the effect of soil water deficit on dry-canopy evaporation. Further, annual equilibrium evaporation relative to incident rainfall is usually ≤ 1.0 in Japan (Kondo, 2000) and soil water deficit does not usually limit evapotranspiration in these conditions (Zhang et al., 2001). These facts imply that considering the effect of soil water deficit on dry-canopy evaporation is not critical for calculating evapotranspiration of Japanese forests.

α of coniferous forests is given by

$$\alpha_i = -0.371 \ln h + 1.53, \quad (7)$$

where h is canopy height (m). This equation is derived from Komatsu's (2005) review. Komatsu (2005) obtained 45 samples of α values for coniferous forests and found a clear decrease in α with increasing canopy height (Fig. 2). He modeled this decrease in α as Eq. (7) which is applicable only to coniferous forests with projected LAI ≥ 3.0 (Komatsu, 2005). This limitation is not critical for our model experiments as coniferous forests in Japan are usually within this limitation (Tsukamoto, 1998; Murakami, 2003). The decrease in α with increasing canopy height is supported by Komatsu's (2003) review of surface conductance which tightly correlates with α (McNaughton and Jarvis, 1991; Raupach, 1998). Komatsu (2003) summarized surface con-

Figure 2 Relationship between canopy height h and the Priestley–Taylor coefficient α for coniferous forests. This figure is drawn based on α data summarized in Komatsu (2005).

ductance data from 34 coniferous forest sites and found a clear decrease in surface conductance with increasing canopy height, which implies a decrease in stomatal conductance with tree heights since surface conductance relates to stomatal conductance (Kelliher et al., 1995), and which agrees with reports of stomatal conductance decline with tree height (e.g., Ryan et al., 2000; Irvine et al., 2004).

Although we did include canopy height as a parameter when modeling α , we did not include LAI as a parameter (Eq. (7)). Komatsu (2005) and Komatsu et al. (submitted for publication) examined the relationship between LAI and α for coniferous forests and no systematic relationship was found. This would suggest that LAI is not the primary factor determining dry-canopy evaporation rates of coniferous forests. This suggestion agrees with earlier studies by Kelliher et al. (1995), Raupach (1995), and Komatsu (2003, 2004). Kelliher et al. (1995) and Raupach (1995) showed, using multilayer canopy models, that surface conductance and dry-canopy evaporation are relatively insensitive to LAI when projected LAI ≥ 3.0 . Komatsu (2003) examined the relationship between LAI and surface conductance based on literature survey and found no systematic relationship between them. Further, Komatsu (2004) succeeded in reproducing variation in dry-canopy evaporation between different coniferous forests using a big-leaf model without considering LAI of each forest.

For coniferous forests, we assumed constant α throughout the year though α can decline in mid-winter. Komatsu et al. (in press-b) examined the relationship between monthly equilibrium evaporation $\{\Delta/(\Delta + \gamma)\} \cdot \{(R_n - G)/\lambda\}$ and monthly total heat pulse velocities measured on a coniferous forest site located 60 km southeast from Tokyo. The heat pulse velocity showed clear, positive correlation with equilibrium evaporation in the period between March and December. However, the heat pulse velocity was lower than expected by the correlation during January and February. These two months are among the coldest in the year and monthly mean air temperature was $<5^\circ\text{C}$. This indicates that α declined due to low temperature in these months. Thus, α calculated by our model can be overestimated in mid-winter which can lead overestimation of E_d in mid-win-

ter. However, this overestimation of E_d does not appear to be significant. We tested another parameterization scheme of α for coniferous forests which assumed $\alpha = 0$ for months with monthly mean air temperature $<5^\circ\text{C}$. Even when using this parameterization, our calculation results were nearly the same and our conclusions were completely the same as those based on Eq. (7). In months with a monthly mean air temperature $<5^\circ\text{C}$, input radiation energy (S) is also small. Thus, dry-canopy evaporation in these months contributes only a small portion of E . Consequently, accurate α determination is not critical in these months.

We did not consider α decline with soil water deficit for coniferous forests for the same reasons as those for broad-leaved forests.

k Parameterization

k is modeled identically for both broad-leaved and coniferous forests. Net radiation tightly relates to solar radiation by $R_n = aS + b$, where a and b are empirical parameters (Landsberg and Gower, 1997). As R_n and aS are commonly $\gg b$, k can be roughly approximated by a . Thus, we summarized a values from earlier publications. We obtained seven samples for broad-leaved forests (Federer, 1968; Aoki et al., 1975; Pinker et al., 1981; Shuttleworth et al., 1984; Bastable et al., 1993; Tani et al., 2003; Kumagai et al., 2004) and 12 samples for coniferous forests (Moore, 1976; Jarvis et al., 1976; Gash et al., 1989; Gholz and Clark, 2002; Komatsu, unpublished data). Mean($\pm$ SD) of a was $0.83(\pm 0.03)$ for broad-leaved forests and $0.86(\pm 0.05)$ for coniferous forests. The difference in mean a values was comparable to SD values for broad-leaved and coniferous forests. Thus, we found no clear difference in a values between the two forest types. Most a data analyzed above were for forests in foreign countries (e.g., Federer, 1968; Moore, 1976). However, results of the above analysis would be applicable to Japanese forests because albedo is the primary factor determining a values and because we found no systematic difference in albedo between foreign and Japanese forests (e.g., Landsberg and Gower, 1997; Kondo, 2000).

On the other hand, a clear difference in albedo between broad-leaved (e.g., Kondo, 2000; Oguri and Hiya, 2002) and coniferous forests (e.g., Hattori, 1986; Komatsu et al., in press-a) has been reported, implying a difference in k value between broad-leaved and coniferous forests. However, the difference in albedo between broad-leaved and coniferous forests is $\sim 5\%$ (e.g., Landsberg and Gower, 1997; Kondo, 2000) and this difference is not significant enough to qualitatively alter the calculation results in our model.

The value of $k = 0.80$ was determined based on Jarvis et al.'s (1976) review. Jarvis et al. (1976) summarized k values of coniferous forests from published papers and reported that k ranged between 0.7 and 0.9 and was typically 0.8.

We assumed constant k throughout the year based on Komatsu et al.'s (in press-a) study. In the study by Komatsu et al. (in press-a), the seasonal trend of k was measured above an evergreen coniferous forest in Japan. k was observed to vary slightly between seasons and the constant k assumption is valid for their site. Seasonal variation of k is much smaller than that of solar radiation. Thus, seasonal

variation in dry-canopy evaporation calculated by Eq. (3) is primarily determined by the variation in solar radiation rather than the variation in k .

Although Komatsu et al. (in press-a) obtained slight seasonal variation in k for an evergreen forest in Japan, k might show greater variation on deciduous forests than on evergreen forests. Despite the lack of reports thus far that examined the seasonal variation in k in a Japanese deciduous forest, we undertake the assumption that constant k will not cause large inaccuracies in E estimates for the following three reasons: First, many Japanese deciduous forests are partially deciduous, not fully deciduous. Seasonal k variation of partially deciduous forests may not be as drastic as that of fully deciduous forests. Secondly, accurate k estimates are not a critical factor for E estimates even for fully deciduous forests. α in winter is much lower than α in the growing season for fully deciduous forests (e.g., Wilson and Baldocchi, 2000) which indicates dry-canopy evaporation in winter is a minor component of E . Thus, inaccuracy in k estimates in winter will not cause a large error in E estimates. Lastly, there is a report that suggests k in winter is not greatly different from that during the growing season even for a fully deciduous forest. Schmid et al. (2000) collated radiation and energy balance data for each month measured above a fully deciduous broad-leaved forest in the US (Fig. 4 of Schmid et al., 2000). As calculated k values were not present in the study, k values were calculated from the data. k in July (during the growing season) was 0.71 and k in February (during winter) was 0.79. Thus, there is approximately a 10% difference in k between July and February. This difference is small compared to the difference in R_n . R_n in July is ca. 300% greater than that in February for their site. Schmid et al. (2000) showed photosynthetically active radiation (PAR) data instead of solar radiation data. Thus, we assumed that PAR is 50% of solar radiation (e.g., Jones, 1992) when calculating k values.

Wet-canopy evaporation, E_w

E_w is simply modeled as

$$E_w = \beta P, \quad (8)$$

where β is interception ratio and P is annual rainfall.

For calculating E_w , parameterization of β is required. β of broad-leaved forests is modeled as

$$\beta = 0.19, \quad (9)$$

and β of coniferous forests is modeled as

$$\beta = 0.0000498D + 0.120, \quad (10)$$

where D is stem density (ha^{-1}).

These equations are determined based on a summary of earlier observational studies. We summarized 16 samples of interception ratio values (β) measured on Japanese forests from published papers (Table 1). To collect the information presented in Table 1, we applied three criteria: First, the observation periods should be longer than one year. Monthly interception ratio values can display variability between months (Hattori et al., 1982; Cape et al., 1991) which contrasts with annual interception ratio values which are relatively constant between years (e.g., Tanaka et al., 2005). β is defined for annual rainfall (Eq. (8)) and there-

fore, we rejected interception ratio data based on short-term (<1 year) observations (e.g., Majima and Tase, 1982; Hosoda et al., 1990; Sanada et al., 1991). Second, the data collected from observation sites located in regions with heavy snowfall are excluded. Examining forest water cycles in heavy snowfall regions is beyond our scope, as described above, and therefore we rejected data from those regions (e.g., Murai, 1970; Gomyo et al., 2004). Third, the data collected from observation sites located on small islands far from the main island (e.g., Okinawa islands) are excluded. Meteorological conditions in these small islands are quite different from those of the mainland (National Astronomical Observatory, 2001). Furthermore, coniferous plantation forests are not common in these islands (National Astronomical Observatory, 2001). Thus, developing a model that is applicable to these islands is beyond our scope and therefore, we rejected data from such sites.

The value of $\beta = 0.19$ for broad-leaved forests was derived from the average value of interception ratio data for broad-leaved forests is shown in Table 1. We did not include stem density as a parameter when modeling β of broad-leaved forests (Eq. (9)), which contrasts to β modeling of coniferous forests (Eq. (10)). Stem density is not a meaningful parameter for broad-leaved forests. Many broad-leaved forests in Japan are not plantations and often include many seedlings on the forest floor. Stem density values can significantly vary whether seedlings in the forest floor are counted or not.

β of coniferous forests is modeled using stem density as an input. Stem density of coniferous forests is well defined since they are usually plantations. Fig. 3a shows the relationship between stem density D and interception ratio β for coniferous forests. We found a positive correlation between these two factors. Eq. (10) was determined by linear regression of the relationship between D and β (Fig. 3a).

We should note that the positive correlation between D and β is empirical, since D correlates with LAI (Murakami, 2003) and with canopy height h (Fig. 4). Wet-canopy evaporation amounts are affected by canopy water storage capacity and evaporation rates from a wet-canopy (Hewlett, 1982; Suzuki, 1991). LAI is the primary factor determining canopy water storage capacity (e.g., Crockford and Richardson, 1990; Liu, 1998; Llorens and Gallart, 2000). D and LAI are positively correlated for coniferous forests except for the very young stages (<ca. 15 years old) (Murakami, 2003). Thus, the positive relationship between D and β will include the effect of LAI on wet-canopy evaporation which has been reported in many studies (e.g., Aston, 1979; Park et al., 2000; Fleischbein et al., 2005), although we could not examine the relationship between LAI and β itself due to lack of LAI data in most studies summarized in Table 1. h is a factor affecting canopy roughness and therefore evaporation rates from a wet canopy: greater h indicates more significant roughness and therefore higher evaporation rates, i.e., positive correlation between h and evaporation rates (e.g., Hewlett, 1982; Suzuki, 1991). D and h are negatively correlated (Fig. 4), which implies a negative correlation between D and β . We actually obtained a positive correlation between D and β . Thus, the effect of LAI on β might be more significant than the effect of h on β . Vertessy et al. (2001) examined the change in annual evapotranspiration components with forest age for Australian ash forests.

Table 1 Interception ratio β observed on Japanese forests

Species	Stem density (ha ⁻¹)	Canopy height (m)	Mean DBH (cm)	Projected LAI	Measurement duration (month)	Precipitation (mm year ⁻¹)	Interception ratio β	References
Broad-leaved								
<i>Ilex pedunculosa</i>	6000	7			12	1793	0.20	Iwatsubo and Tsutsumi (1967)
<i>Lithocarpus edulis</i>	3418	10.2	10.8		12	1584	0.18	Sato et al. (2003a,b)
<i>Quercus serrata</i> , etc.	3502	6	6.9	4.4 ^a	24	1478	0.13	Park et al. (2000)
<i>Quercus serrata</i> , etc.	5070	20	7.1	6.4 ^a	36	1396	0.24	Park et al. (2000)
Coniferous								
<i>Chamaecyparis obtusa</i>	3200	8	7.6		12	1793	0.26	Iwatsubo and Tsutsumi (1967)
<i>Chamaecyparis obtusa</i>	2051	11	16.1		12	1543	0.21	Hattori et al. (1982)
<i>Chamaecyparis obtusa</i>	1325	13.5	18.2		12	1087	0.19	Hattori and Chikaarashi (1988)
<i>Chamaecyparis obtusa</i>	1750	13.5	18.2	5.7	12	1336	0.23	Hattori and Chikaarashi (1988)
<i>Chamaecyparis obtusa</i>	923	19.3	34.2		30	2053	0.14	Tanaka et al. (2005)
<i>Cryptomeria japonica</i>	1467	15.2	23.2		12	1584	0.26	Sato et al. (2003a,b)
<i>Cryptomeria japonica</i>	750	25	29		12	1150	0.12	Haibara and Aiba (1982)
<i>Cryptomeria japonica</i>	513	26.5	38.5		41	2304	0.16	Tanaka et al. (2005)
<i>Cryptomeria japonica</i> /	783	18	32	3.7	24	1734	0.13	Murakami et al. (2000)
<i>Chamaecyparis obtusa</i>								
<i>Pinus densiflora</i>	1575	7	12		12	1513	0.14	Mitsudera et al. (1984)
<i>Pinus densiflora</i>	2300	12	20		12	1291	0.21	Taniguchi et al. (1996)
<i>Pinus densiflora</i>	1700	12	20		12	1291	0.30	Taniguchi et al. (1996)

^a LAI values in summer.

Figure 3 (a) Relationship between stem density D and interception ratio β for coniferous forests. This figure is drawn based on interception ratio data shown in Table 1. (b) Same as (a), but classified by tree species.

Figure 4 Relationship between canopy height h and stem density D for coniferous forests. This figure is drawn based on data shown in Table 1.

They also obtained lower β for older forests (Fig. 7 of Vertessy et al., 2001) which indicates negative correlation between canopy height and β .

We did not consider tree species composition for modeling β of coniferous forests. Leaf shape differs between tree

species which implies different water storage capacities exist between species (Klaassen et al., 1998). However, in our work, no systematic difference in β values between tree species was found (Fig. 3b).

Materials and methods

Methods of developing a hypothesis

We calculated E values to answer whether annual evapotranspiration of coniferous forests is greater than that of broad-leaved forests in Japan.

We prepared two parameter sets, fully evergreen and fully deciduous forests, and calculated E values for each. E of coniferous forests was modeled by canopy height h and stem density D . h and D are inversely related for coniferous plantation forests with D decreasing with increasing h (Fig. 4). Thus, we assume two contrastive cases. One case assumes $h = 10$ m and $D = 2000$ ha⁻¹, which are typical values for young (~20 years) coniferous forests. The other case assumed $h = 20$ m and $D = 800$ ha⁻¹, which are typical values for old (~60 years) coniferous forests.

Japanese meteorological data was derived from Chronological Scientific Tables (National Astronomical Observatory, 2001), which include monthly solar radiation, air temperature, and annual rainfall data. E values were calculated for 15 meteorological stations (Fig. 1) located in the regions without heavy snowfall. Meteorological station data from small islands far from the main island was also excluded.

Methods of examining the hypothesis

Using readily available catchment water balance data (i.e., annual rainfall and runoff data), we compared E values, estimated by the water balance method (i.e., annual rainfall minus runoff), between broad-leaved and young coniferous forests and between broad-leaved and old coniferous forests.

Catchment water balance data from Sarukawa, Tatsunokuchi, and Hitachi-Ohta experimental catchments, which are located near Miyazaki, Takamatsu, and Tokyo meteorological stations, respectively, was used (Fig. 1). Sarukawa and Tatsunokuchi data was used to compare E values between broad-leaved and young coniferous forests and Hitachi-Ohta data was used to compare E values between broad-leaved and old coniferous forests. Table 2 shows E data used in this study.

Ichigo-sawa and Sango-sawa are the two catchments in Sarukawa that were used. Catchment water balance data is available for periods between 1959 and 1964 (Shirai and Takeshita, 1968) and between 1967 and 1986 (Forest Influences Unit, Kyushu Branch Station, 1982; Takeshita et al., 1996). However, data is missing in the period between 1960 and 1964 for Sango-sawa catchment (Shirai and Takeshita, 1968). These two catchments were originally covered with broad-leaved forests before being clear-cut in 1965 and 1966 with coniferous seedlings planted in 1967 (Forest Influences Unit, Kyushu Branch Station, 1982). It usually takes ca. 15 years before coniferous seedlings develop continuous forest cover (Murakami, 2003). Thus,

Table 2 Water balance data used in this study

Catchment, forest type	Year	Rainfall (mm)	Runoff (mm)	Evapotranspiration (mm)
<i>Sarukawa, Ichigo-sawa</i>				
Broad-leaved	1959	3036	1820	1216
	1960	2499	1358	1141
	1961	3765	2696	1069
	1962	3139	2105	1034
	1963	2873	1862	1011
	1964	3125	2027	1098
Clear-cut	1967	2120	1415	704
	1968	2227	1663	564
	1969	2378	1581	797
	1970	2861	2159	702
	1971	3234	2513	721
Young coniferous	1982	2958	1622	1336
	1983	3410	2191	1219
	1984	2838	1553	1285
	1985	3328	1952	1376
	1986	2465	1404	1061
<i>Sarukawa, Sango-sawa</i>				
Broad-leaved	1959	3036	1883	1153
	1960	2499	—	—
	1961	3765	—	—
	1962	3139	—	—
	1963	2873	—	—
	1964	3125	—	—
Young coniferous	1982	2958	1906	1052
	1983	3410	2318	1092
	1984	2838	1584	1254
	1985	3328	2130	1198
	1986	2465	1291	1174
<i>Tatsunokuchi, Minami-dani</i>				
Young coniferous	1971	1131	335	796
	1972	1498	531	967
	1973	955	168	786
	1974	1244	—	—
	1975	1179	306	873
	1976	1508	633	876
	1977	1100	266	834
Broad-leaved	1996	1099	134	965
	1997	1109	—	—
	1998	1328	351	976
	1999	1184	302	883
	2000	958	123	835
<i>Hitachi-Ohta</i>				
Broad-leaved	1910	1771	1013	758
	1911	1558	886	672
	1912	1501	881	620
	1913	1297	657	640
	1914	1713	916	797
Old coniferous	1981	1354	774	580
	1982	1604	998	606
	1983	1349	884	465
	1984	804	340	464
	1985	1604	990	614

we assumed data between 1982 and 1986 is for young coniferous forests.

Catchment water balance data from the Minami-dani catchment in Tatsunokuchi is available for the period between 1959 and 2000 (Forest Influences Unit and Okayama Experimental Site Kansai Branch Station, 1979; Goto et al., 2005). Coniferous seedlings were planted in 1960 after a forest fire from the previous year and were left to develop until the mid-1970s (Forest Influences Unit and Okayama Experimental Site Kansai Branch Station, 1979). Insect damage began to occur in the late 1970s and by 1998 the coniferous forest cover had completely transitioned to a broad-leaved forest (Goto et al., 2005).

We used data from one catchment in Hitachi-Ohta. Catchment water balance data is available for periods between 1909 and 1919 (Tokyo Forestry Branch, 1923) and between 1980 and 1985 (Murakami et al., 2000). The original broad-leaved forest in the catchment was clear-cut in 1915 and coniferous seedlings were planted. These seedlings developed to an old coniferous forest by the 1980s (Murakami et al., 2000).

Results

Developing a hypothesis

Model calculations using meteorological data from 15 stations are shown in Fig. 1. We obtained qualitatively the same results for all datasets from the 15 stations. Results based on the meteorological data from the Miyazaki, Takamatsu, and Tokyo meteorological stations, which are located near the Sarukawa, Tatsunokuchi, and Hitachi-Ohta experimental catchments (Fig. 1), are typical examples of the model experiment. Fig. 5 shows rainfall, solar radiation, and air temperature data for the Miyazaki, Takamatsu, and Tokyo meteorological stations.

For the Miyazaki case, E values of broad-leaved forests were $1387 \text{ mm year}^{-1}$ and $1227 \text{ mm year}^{-1}$ for fully evergreen and deciduous scenarios, respectively (Fig. 6a). A realistic E for broad-leaved forests will be between the E values for these two different scenarios. E values of young and old coniferous forests were $1287 \text{ mm year}^{-1}$ and 856 mm year^{-1} , respectively.

The E of young coniferous forests was between the E values of broad-leaved forests with two different scenarios. Comparative E values between broad-leaved and young coniferous forests were caused by comparative α values in the growing season and comparative β values for these two forest types. α in the growing season was 0.83 and 0.68 for broad-leaved and young coniferous forests, respectively. As a result, E_d was comparative between forest types: E_d was 920 mm, 763 mm, and 749 mm for broad-leaved evergreen, broad-leaved deciduous, and young coniferous forests, respectively. The difference in E_d between broad-leaved evergreen and deciduous forests was caused by the different α values in winter for these two forest types. β was 0.19 and 0.22 for broad-leaved (both evergreen and deciduous) and young coniferous forests, respectively. As a result, E_w was comparative between forest types: E_w was 467 mm and 539 mm for broad-leaved and young coniferous forests, respectively.

Figure 5 Rainfall, solar radiation, and air temperature data for (a) Miyazaki, (b) Takamatsu, and (c) Tokyo meteorological stations. The data was obtained by averaging results for a recent 30 year period (National Astronomical Observatory, 2001). Annual rainfall is 2457 mm for Miyazaki, 1124 mm for Takamatsu, and 1467 mm for Tokyo. Annual mean solar radiation is 13.9 MJ d^{-1} for Miyazaki, 13.4 MJ d^{-1} for Takamatsu, and 11.6 MJ d^{-1} for Tokyo. Annual mean air temperature is 18.3°C for Miyazaki, 15.8°C for Takamatsu, and 15.9°C for Tokyo.

E values of broad-leaved forests were higher than the E of old coniferous forests. The higher E value for broad-leaved forests as compared to old coniferous forests was primarily caused by higher α values in the growing season and secondarily caused by higher β values for broad-leaved forests. α in the growing season was 0.83 and 0.42 for broad-leaved and old coniferous forests, respectively. As a result, E_d of old coniferous forests was smaller than those of other forest types: E_d was 464 mm for old coniferous forests. β values were comparable between broad-leaved and coniferous forests at 0.19 and 0.16, respectively. As a result, E_w of old coniferous forests was slightly smaller than those for other forest types: E_w was 392 mm for old coniferous forests.

Figure 6 Evapotranspiration E calculated by the model based on (a) Miyazaki, (b) Takamatsu, and (c) Tokyo meteorological station data.

Different E values from the Miyazaki case were obtained from the Takamatsu and Tokyo cases (Fig. 6b and c). E values for Takamatsu and Tokyo cases were smaller than those for Miyazaki case. For example, E values of broad-leaved evergreen forests for Takamatsu and Tokyo cases were respectively 1079 mm and 1018 mm, which were smaller than the value for Miyazaki case ($E = 1387$ mm). This difference was caused by smaller solar radiation, lower air temperature, and smaller rainfall for Takamatsu and Tokyo (Fig. 5b and c). The effect of smaller rainfall was more significant than the effect of smaller solar radiation and lower air temperature, resulting in higher ratios of E_d relative to E for Takamatsu and Tokyo cases (Fig. 6): For example, E_d/E of broad-leaved evergreen forests was 0.80 for the Takamatsu case and 0.73 for the Tokyo case, while 0.66 for the Miyazaki case.

Despite these differences, the results for Takamatsu and Tokyo cases are qualitatively the same as the Miyazaki case (Fig. 6b and c). The E of young coniferous forests was between the E values of broad-leaved forests with two differ-

ent scenarios. E values of broad-leaved forests were higher than those of old coniferous forests. These results were held for cases of 12 meteorological stations other than Miyazaki, Takamatsu, and Tokyo (Fig. 1). Thus, E of coniferous forests is the same or lower than E of broad-leaved forests regardless of meteorological differences between the 15 stations. This is the hypothesis that is examined using catchment water balance data in the next section. Examination in the next section focuses on qualitative aspects of the hypothesis. We are not concerned about quantitative accuracy of E values calculated by the model.

The model calculations described above assumed that input meteorological data (solar radiation, rainfall, and air temperature) were not affected by forest type (i.e., broad-leaved/coniferous). Air temperature among the input data may be affected by forest type. However, the effect of forest type on air temperature would not be so significant as to qualitatively alter our model calculations for the following two reasons. First, there have been no studies reporting change in air temperature with conversion from broad-leaved to coniferous forests within limits of our knowledge. This fact implies the change in air temperature is, if any, not drastic. Second, even when assuming a 3 °C air temperature change with forest type our model calculation results are not qualitatively altered. Air temperature affects E through $\Delta/(\Delta + \gamma)$ term in Eq. (3). A 3 °C difference in air temperature alters $\Delta/(\Delta + \gamma)$ by ~5% when air temperature is 20 °C, a typical value for a growing season in Japan. A 5% change in $\Delta/(\Delta + \gamma)$ and therefore E_d estimates does not alter our model calculation results qualitatively.

Examining the hypothesis

Fig. 7a shows E values for 1959–1964 (broad-leaved forest period) and for 1982–1986 (young coniferous forest period) in Sarukawa. For the Ichigo-sawa catchment, E for 1959–1964 was lower than that for 1982–1986 by ca. 160 mm year⁻¹. We also calculated E change caused by the forest clear-cut. E just after clear-cut (1967–1971) was 698 mm year⁻¹ for Ichigo-sawa catchment. Forest clear-cut in this catchment caused 400 mm year⁻¹ change in E . The difference in E for the Ichigo-sawa catchment is smaller than the difference in E caused by a forest clear-cut, which contrasts to results from Coweeta. Additionally, the difference in E relative to incident rainfall for this catchment was smaller than that for the Coweeta catchment. The E difference and rainfall were 160 mm and 2900 mm for Ichigo-sawa catchment, while they were 170 mm (Swank and Douglass, 1974) and 1700 mm (Swank and Miner, 1968) for the Coweeta catchment. E in 1959 was as high as E for 1982–1986 in the Sango-sawa catchment. (Note: E data of Sango-sawa was missing between 1960 and 1964.) Thus, E for broad-leaved forests was approximately as high as E for young coniferous forests, which agrees with our hypothesis.

E values estimated by the water balance method can be influenced by incident rainfall amounts (e.g., Zhang et al., 2001). Therefore, the results in Fig. 7a may be dependent on the differences in annual rainfall between 1959–1964 and 1982–1986. Even when considering this difference in annual rainfall, our conclusions were not altered. Fig. 8

Figure 7 Evapotranspiration E estimated by the water balance method for (a) Sarukawa, (b) Tatsunokuchi, and (c) Hitachi-Ohta experimental sites. E values are averaged for each period.

Figure 8 Relationship between rainfall and evapotranspiration E for the Ichigo-sawa catchment in Sarukawa. Data and regression lines for a broad-leaved forest, a coniferous forest, and a forest clear-cut are displayed.

shows relationships between rainfall and E for periods of a broad-leaved forest, a young coniferous forest, and a forest clear-cut, respectively. The E difference between periods

of broad-leaved and coniferous forests was smaller than the E difference between periods of broad-leaved forest and forest clear-cut.

Fig. 7b shows E values for 1996–2000 (broad-leaved forest period) and for 1971–1976 (young coniferous forest period) in Tatsunokuchi. E for 1996–2000, broad-leaved forest period, was approximately as high as E for 1971–1976, young coniferous forest period, which agrees with our hypothesis. This result was not altered when the difference in rainfall between 1996–2000 and 1971–1976 was considered.

Fig. 7c shows E values for 1910–1914 (broad-leaved forest period) and for 1981–1985 (old coniferous forest period) in Hitachi-Ohta. E for 1910–1914, broad-leaved forest period, was higher than E for 1981–1985, old coniferous forest, which agrees with our hypothesis. This result was not altered when considering the difference in rainfall between 1910–1914 and 1981–1985 periods.

The hypothesis developed in “Developing a hypothesis” was supported by water balance data from Sarukawa, Tatsunokuchi, and Hitachi-Ohta experimental catchments.

Discussion

The results obtained in this study differ from Swank and Douglass’ (1974) results. Swank and Douglass (1974) reported that E of broad-leaved forests was lower than that of coniferous forests based on catchment water balance data observed in Coweeta. The difference in E caused by converting these two forest types was greater than the difference in E caused by forest clear-cut. Our study showed that E of coniferous forests is as high as or lower than E of broad-leaved forests based on model experiments with the input of meteorological data and catchment water balance data observed in Japan.

This difference between Swank and Douglass and our results may be explained by the difference in rainfall between Coweeta and Japan. Although annual rainfall values are comparable between Coweeta and Japan the seasonality of rainfall differs. Annual rainfall in Coweeta ranges between 1700 and 2500 mm year⁻¹ (Swank et al., 2001) and monthly rainfall amounts are evenly distributed throughout the year (Lieberman and Hoover, 1951; Pechanec, 1957). Annual rainfall in Japan used in the model experiments ranged between 1100 and 2700 mm year⁻¹ (National Astronomical Observatory, 2001) and monthly rainfall amounts are greater during summer than during winter (Fig. 5).

Large amounts of rainfall in winter can cause a large difference in wet-canopy evaporation between coniferous evergreen and broad-leaved deciduous forests. In contrast, small amounts of rainfall in winter can cause only a small difference in wet-canopy evaporation in winter between coniferous evergreen and broad-leaved deciduous forests. Many studies (e.g., Helvey and Patric, 1965; Helvey, 1967; Swank et al., 1972) have examined rainfall interception of broad-leaved and coniferous forests in eastern part of the US including Coweeta experimental watersheds. These studies have reported higher β values for coniferous forests over broad-leaved forests. For example, Swank et al. (1972) obtained β values that ranged between 0.15 and 0.26 for seven coniferous forests. These values were greater than the β

value calculated based on a typical regression equation for broad-leaved forests obtained by a review of 22 broad-leaved forest sites ($\beta = 0.11$). Rainfall interception studies in the UK, where rainfall amounts tend to be greater in winter than in summer (National Astronomical Observatory, 2001), also reported higher β values for coniferous forests than broad-leaved forests (Ward and Robinson, 2000; Dingman, 2001). Fig. 3.4 of Ward and Robinson (2000) shows β values for 17 broad-leaved and 19 coniferous forest sites in the UK. Most β data ranged between 0.10 and 0.35 for broad-leaved forests and between 0.25 and 0.50 for coniferous forests. In contrast to the results in US and UK, our summary of rainfall interception studies in Japan where small amounts of rainfall occurs in winter shows that β values tend to be similar for coniferous and broad-leaved forests. Based on β data in Table 1, β of the broad-leaved forests ranged between 0.13 and 0.24 and the average ($\pm$ SD) was 0.19 ($\pm$ 0.05) ($n = 4$). β of the coniferous forests ranged between 0.12 and 0.30 and the average ($\pm$ SD) was 0.20 ($\pm$ 0.06). Thus, a clear difference was not observed in β values between broad-leaved and coniferous forests which earlier studies have observed based on data from the US and UK. This supports the notion that the difference in rainfall seasonality is a possible factor in explaining the discrepancy between our results and Swank and Douglass'. If our explanation is correct, our conclusions may be applied to similar Asian regions where rainfall amounts are greater in summer than in winter (National Astronomical Observatory, 2001). There appear to have been no studies other than ours that have compared annual evapotranspiration of broad-leaved and coniferous forests in Asian regions. Thus, further studies in Asian regions are required to examine validity of our explanation.

Furthermore, our explanation is consistent with the discussion contained in Swank and Douglass's (1974) research paper. That paper showed that a runoff difference between coniferous and broad-leaved forests was greater in winter and spring than in summer and autumn. Based on this fact, they suggested that the E difference between coniferous and broad-leaved forests is mainly due to the wet-canopy evaporation difference in winter between these two forest types.

In addition, many broad-leaved forests in Japan are not fully deciduous. This contrasts with the situation in the US where many broad-leaved forests are fully deciduous (e.g., Schmid et al., 2000; Wilson et al., 2001). This might be an additional factor to explain the difference between Swank and Douglass' and our results. Partially deciduous forests intercept greater amounts of rainfall in winter than fully deciduous forests. Park et al. (2000) estimated canopy rainfall storage capacity of two broad-leaved forests at the Shirasaka and Yamashiro experimental sites in Japan. LAI of the Shirasaka experimental site was 6.4 in summer and 3.4 in winter and the canopy storage capacity was 0.68 mm in summer and 0.39 mm in winter. Thus, the canopy storage capacity differed by 0.29 mm between the two seasons at the Shirasaka site. LAI of the Yamashiro experimental site was 4.4 in summer and 2.7 in winter and the canopy storage capacity of Yamashiro was 0.74 mm in summer and 0.56 mm in winter. Thus, canopy storage capacity differed by 0.18 mm in Yamashiro site between summer and winter. These differences in canopy storage capacity obtained in

these partially deciduous forests were smaller than those for fully deciduous forests. Zinke (1967) and Hormann et al. (1996) reviewed canopy storage capacity data from earlier publications (e.g., Trimble and Weitzman, 1954; Rutter et al., 1975; Dolman, 1987). According to their review, canopy storage capacity differences between summer and winter ranged between 0.30 mm and 0.81 mm ($n = 6$) for fully deciduous broad-leaved forests.

Conclusions

Our research attempted to confirm if Japanese coniferous forests evaporate more water than broad-leaved forests. A simple model was developed for calculating the annual forest evapotranspiration, E , based on a review of 67 dry-canopy evaporation and 16 wet-canopy evaporation studies. We calculated E values for broad-leaved and coniferous forests using meteorological data from Japan. E of broad-leaved forests was comparable to E of young coniferous forests and higher than E of old coniferous forests. These model predictions were supported by water balance data from three Japanese catchments. In contrast to the commonly held belief, we conclude that Japanese coniferous forests do not evaporate more water than their broad-leaved counterparts.

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