

Variation of evapotranspiration with stand age and climate in a small Japanese forested catchment

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Abstract

Evapotranspiration (ET) was measured in both a young (stand age 4–7) and a mature (stand age 62–66) forest basin covered with a mixed stand of Japanese cypress (*Chamaecyparis obtusa*) and Japanese cedar (*Cryptomeria japonica*). To obtain ET, runoff data were analyzed on a monthly basis using a short-time period water-budget method. Canopy interception (I) was also measured in the mature (stand age 72–75) forest basin. Annual ET changes in the young forest basin showed a clear upward trend, and ET had higher values in hot summer (1994) than in the other summers. These results were simulated by a model based on the Penman–Monteith equation, and results agree with field measurements. This model predicts an ET-stand age relationship, which shows a peak in ET at 20 years, reflecting an LAI-stand age relationship data obtained from the literature. The response of ET to hot (1994), cool (1993), and mean (1981–1994 average) summer conditions was simulated for both the young and the mature forest basins. In hot summer ET was large for the young forest in comparison with a mean summer but the same level in the mature forest. In cool summer, however, ET was smaller in the mature forest than that of a mean summer but the same level in the young forest. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Two thirds of Japan is covered with forest and 41% of it is plantation forest (Japan FAO Association, 1997) that has been managed for the production of timber. The main purpose of forest management in Japan is about to change from timber production to soil and water conservation. The main reasons for this are that social demands for a stable water supply and disaster prevention have become stronger with the increase in water demand, drought, and flood damage. Another key reason is that forestry is no longer economically viable, given the low price of imported

timber. Therefore, forest management practices in Japan need to be reassessed to determine which system is most suitable for a stable water supply and to examine water budget under extreme weather conditions.

This paper contributes to such goals by focusing on evapotranspiration (ET) and the growth of trees under cool, hot and mean summer conditions. In a forest basin, ET is mainly governed by forest structure and climate. Forest structure is changed by tree growth and silvicultural practice. In this study, we focus on ET dependence on stand age for typically managed forest, though silvicultural practice also has a strong impact on ET. For a given forest structure, ET varies with weather conditions, so we also need to assess the climate effects on ET. Since a hot summer with less

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rainfall in Japan often leads to a shortage of water, ET evaluation for hot summer has primary importance. ET for mean and cool summers is also investigated to compare the effects of these summers.

Several previous studies have evaluated the effects of vegetation changes on ET. Bosch and Hewlett (1982) reviewed 94 catchment experiments and showed statistically that annual streamflow increment following the treatments is proportional to the reduction in forest cover: that is, ET decreases with the reduction in forest cover. However, there are some exceptional results which show streamflow decreases after several years of treatment. Langford (1976) reported that dense eucalypt (*Eucalyptus regnans*) regrowth after wildfire had a higher water use than mature forest in Victoria, Australia. Rowe and Pearce (1994) showed that forest catchments in New Zealand which were clearcut and planted with *Pinus radiata* were rapidly colonized by bracken (*Pteridium esculentum*) and Himalayan honeysuckle (*Leycesteria formosa*), and this vegetation cover was using more water than the original forest cover after an average of about five years of treatment.

Kuczera (1987) showed that regional mean annual streamflow from catchments forested with mountain ash (*E. regnans*) in Victoria, Australia, bears a strong relationship with forest age. Based on his studies, Haydon et al. (1996) explained the difference of transpiration and interception in stand age in the same area: they measured the sapwood cross-sectional area, which they assumed is an indicator of transpiration rate based on Dunn and Connor (1991, 1993), and the throughfall rate in several *Eucalyptus* stands at different ages. Their computation based on the measurement roughly reproduced Kuczera's findings.

Although these studies are instructive, none of the approaches can estimate the response of ET to climate change independent of forest affects. Thus, to evaluate changes in ET due to forest changes by separating the effects of climate, a physically based model, that is, the Penman–Monteith (P–M) equation, must be applied.

Rampisela et al. (1990) used the P–M equation in a forested catchment. They determined the forest parameters to fit the water budget in the catchment referring to the reported parameters (Stewart and Thom, 1973; Calder, 1977). Dunn and Mackay (1995) also employed the P–M equation in a large

river basin to simulate the influence of land use changes on evapotranspiration. The parameters they used were estimated from literature data checked by field observation. Both of them did not take the topographic effect into consideration and the meteorological data they used were equivocal, because they were obtained by point measurements in a mountainous catchment or large basins. However, their methods retain sufficient realism to investigate the water balance in the catchments.

We adopt a similar approach and apply the model to estimate ET in a forested catchment. ET from both a young and a mature forest basin is simulated by the model and the validity of the model is confirmed with measured data. The model is then used to demonstrate how forest growth influences ET, and how climate changes might impact ET and forest management conditions.

2. Site description and observation

The Hitachi Ohta Experimental Watershed is located on the Pacific coast of eastern Japan at an altitude of 280–340 m, latitude 36°34'N and longitude 140°35'E (Fig. 1). The entire basin is 15.68 ha, consisting of four sub-basins with gauging weirs (Fig. 1). Surficial geology is metamorphic, primarily schist and amphibolite. Slopes of the catchment are steep sloped (mean gradient 32.4°). Sidle et al. (1995) describes the catchment in detail.

Forest cover is a mixed stand of Japanese cypress (*Chamaecyparis obtusa*) and Japanese cedar (*Cryptomeria japonica*), planted in 1919. Those two species are typical of Japanese managed forests. The areal ratio of *C. obtusa* to *C. japonica* was 77–23%. The forest structure in 1993 is as follows: the mean height of the stand; 18 m, the average diameter at breast height; 32 cm, the stand density: 783 ha⁻¹ and the volume: 553 m³ ha⁻¹. Leaf area index (LAI) was 3.7 in 1997, measured by the LAI-2000 Plant Canopy Analyzer (LI-COR Inc., Lincoln, Nebraska, USA). Understorey contains *Eurya japonica*, *Camellia japonica* and *Callicarpa mollis* with 1–3 m height, and *Ardisia japonica*, *Hydrangea hirta*, *Microlepia marginata*, *Hydrangea involucrata* and *Pilea hamaoi* (Kato et al., 1995). The entire forest stand, except the forested basin B (2.48 ha), was clearcut from 1985 to

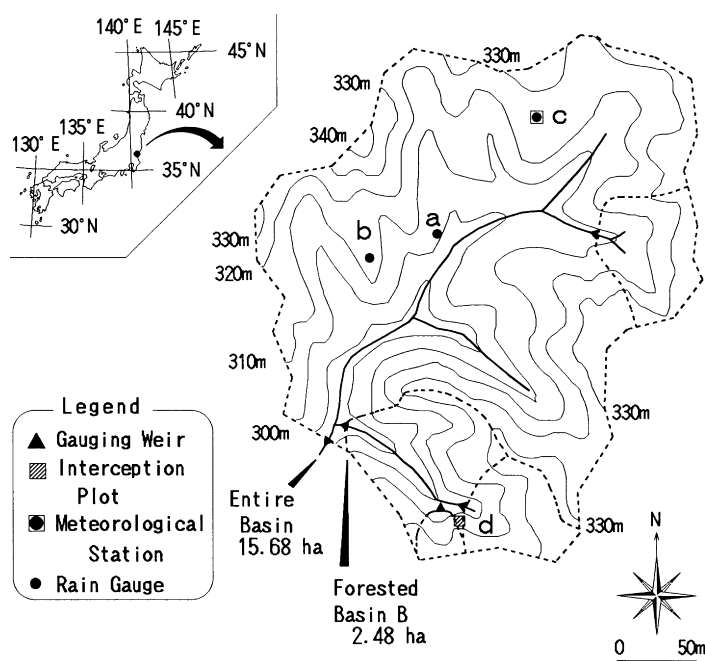


Fig. 1. Hitachi Ohta Experimental Watershed and instrumentation. The watershed, except for basin B, was harvested in 1985–1986. Basin B was retained in mature forest.

1986. After the clearfelling, the same species were planted in 1987 and 1988. The ratio of *C. obtusa* to *C. japonica* in this young forest basin was 88–12% with the mean height of the stand 2.9 and 4.7 m, the average diameter at breast height 3 and 6 cm, and the volume 5 and 25 m³ ha⁻¹ in February 1995 and December 1997, respectively. The stand density and LAI were 2944 ha⁻¹ and 3.8, respectively, in 1997, and *Miscanthus* had been dominant understory throughout the study period. For this young forest, weeding, a common silvicultural practice in Japan, was performed every summer for five years after planting to avoid forest suppression by weeds and shrubs.

The rain gauge had been installed at point *a* in Fig. 1 during 1980–1985. After the clearfelling it was moved to point *b* in Fig. 1 and another was installed at point *c*. Since then, average rainfall data at *b* and *c* was measured. The mean annual precipitation on the watershed was 1486 mm (1981–1994). Snow in this region is negligible and does not affect the water budget in the basin.

The net rainfall under the mature forest was measured at point *d* in basin B since 1990, which

includes both throughfall and stemflow. Throughfall was measured by two troughs, 638 and 651 cm long, respectively, 20 cm deep and 20 cm wide. Stemflow gauges were set on six trees. Meteorological factors were recorded every 10 min at the opening at point *c* since 1989. Air temperature and relative humidity were measured at the height of 2 m above ground, and wind speed and global radiation at 5 m.

3. Data analysis for water budget and method

Annual and monthly ET was estimated based on discharge and precipitation data for the mature forest basin (1981–1985) and the newly planted young forest basin (1991–1994). The discharge for the young forest basin was obtained as the difference between discharge for the entire basin and that for the forested basin B. The method used to estimate monthly ET was the short-time period water-budget (SPWB) method proposed by Linsley et al. (1958) and applied by Hamon (1961), Takase and Maruyama (1978), Suzuki (1980, 1985) and Suzuki and Fukushima (1985). An outline of the method follows.

Assume that water storage in the basin $S(t)$ and the discharge rate $q(t)$ is satisfied by:

$$S(t) = f[q(t), dq/dt] \quad (1)$$

$S(t_1)$ is equal to $S(t_2)$ when times t_1 and t_2 have equivalent values of $q(t)$ and dq/dt . Thus ET for the time period from t_1 to t_2 can be calculated because the change in water storage in the basin $\Delta S = S(t_2) - S(t_1)$ is equal to zero:

$$ET = \int_{t_1}^{t_2} p(t) dt - \int_{t_1}^{t_2} q(t) dt \quad (2)$$

where $p(t)$ is rainfall intensity.

The times t_1 and t_2 are determined when the following three conditions are satisfied:

1. There is no precipitation on the start day t_1 and the end day t_2 , nor antecedent precipitation two days before those days.
2. Only days for which the difference of daily discharge rate is less than or equal to 5% can be selected.
3. The period must be between 9 and 59 days.

These conditions were set by Suzuki (1985) by trial and error. The first condition is to remove the quick-flow which has large dq/dt , and the second is to find the equivalent q at times t_1 and t_2 . The period less than or equal to eight days is excluded because too short a period results in a large variation of daily ET, especially if the period includes extremely hot or cool days. The period greater than or equal to 60 days was also excluded since too long a period makes the seasonal changes in ET undetectable. On the second condition Suzuki (1985) and Suzuki and Fukushima (1985) adopted 2% as the difference of discharge rate. However, we used the value of 5% to increase the number of samples. The ET values obtained by SPWB were averaged on a monthly basis.

Canopy interception was derived from the difference between gross precipitation and net precipitation for the years 1991–1994 in the mature forest basin (Fig. 1). Rain events were delimited when no rainfall was observed more than 6 h since the cessation of rainfall.

4. Models

We assumed that evapotranspiration consists of transpiration and canopy interception. For a forest without canopy closure, evaporation from the open parts should also be taken into account, and for a closed forest, that of understory and/or forest floor must be addressed. In this study, however, we lump those effects in the forest parameters.

4.1. P–M equation and transpiration

In applying the P–M equation to the catchments, there are some problems. First, the method can theoretically apply to flat land only where the topographic effect is not taken into consideration, while the actual catchments have varying topography. Second, forest parameters cannot be given a priori, because they must usually be measured. Last, meteorological data required for calculations are equivocal, since they are obtained by point measurements. Although those difficulties have prevented the application, some hydrologists have used the model (P–M equation) under broad assumptions as mentioned in Section 1.

Transpiration was calculated by the P–M equation (Monteith, 1965):

$$E = \frac{\Delta(R_n - G) + \rho C_p (q_{\text{sat}}(T_a) - q(T_a))/r_a}{\lambda \Delta + C_p(1 + r_c/r_a)} \quad (3)$$

where E is the water vapor flux, Δ the slope of the saturated specific humidity–temperature curve, R_n the net radiation, G the soil heat flux, ρ the air density, C_p the specific heat at constant pressure, q_{sat} the saturated specific humidity, q the specific humidity, T_a the air temperature, r_a the aerodynamic resistance, r_c the canopy resistance, and λ the latent heat of vaporization. The downward long-wave radiation was estimated from air temperature, relative humidity, and the duration of sunshine (Kondo et al., 1991). The upward long-wave radiation was calculated by Stefan–Boltzman’s law. We assumed $G = 0$ and albedo was 0.1.

Water vapor flux E in Eq. (3) gives transpiration T which is assumed to occur from sunrise to sunset unless the canopy is wet. The canopy is presumed to be wet during rainfall and for 6 h afterward.

Table 1

Published data on aerodynamic resistance multiplied by wind speed ur_a and tree height h . $z = h + 2$ and $ur_a = \text{constant}$ are assumed in Eq. (8) except Hattori et al. (1993) and Mizutani and Ikeda (1995); for those sources, refer to the footnotes

Source	ur_a (sm^{-1})	h (m)
Hattori et al., 1981	3.3	11.0
Hattori et al., 1993	9.6 ^a	7.0
Mizutani and Ikeda, 1995	7.3 ^b	14.3
Teklehaimanot et al., 1991	5.8	10.0
Rampisela et al., 1990	1.4 ^c	12.0

^a $z = h + 1.5$, $r_a = 9.6/U^{10.9}$.

^b $z = h + 4.2$.

^c Calculated from the values of z_0 and d in the paper by using Eq. (8).

4.2. Canopy interception

Canopy interception was simulated by a combination of the P–M equation and the Kondo model (Kondo et al., 1992). This model calculates interception I for each rain event. For a low intensity rain event, which is defined if inequality $\Omega^*P < E\tau + S_{\text{MAX}}$ annexed to Eq. (4) is satisfied, the evaporation rate from the canopy is larger than the capture rate of raindrops. Thus all the rainwater caught by the canopy evaporates, and I can be expressed by:

$$I = \Omega^*P \quad \text{for } \Omega^*P < E\tau + S_{\text{MAX}} \quad (4)$$

where Ω^* is the chance of the raindrop hitting the canopy, P the rainfall amount in the rain event, E the water vapor flux for a wet surface given by Eq. (3) for $r_c = 0$, τ the duration of the rain event, and S_{MAX} the water storage capacity on the canopy.

For a high intensity rain event, which is defined if inequality $\Omega^*P \geq E\tau + S_{\text{MAX}}$ added to Eq. (5) is satisfied, canopy interception consists of two components: evaporation from the wet surface during rainfall and evaporation from the residual water on the canopy after the rain event. Thus, I is written as:

$$I = E\tau + S \quad \text{for } \Omega^*P \geq E\tau + S_{\text{MAX}} \quad (5)$$

where S is the water stored on the canopy just after the rain event. S and Ω^* are:

$$S = S_{\text{MAX}}[1 - \exp(-P/S_{\text{MAX}})] \quad (6)$$

$$\Omega^* = \Omega[1 - \exp(-F \cdot \text{LAI}/\Omega)] \quad (7)$$

where Ω is the degree of canopy closure ($0 \leq \Omega \leq 1$, $\Omega = 1$ for closed canopy), F the leaf inclination factor and LAI the leaf area index.

5. Forest parameters

We defined a set of forest parameters as a function of stand age. Those parameters include aerodynamic resistance r_a , canopy resistance r_c , water storage capacity on the canopy S_{MAX} , leaf area index LAI, degree of canopy closure Ω , and the leaf inclination factor F . F is assumed to be constant ($= 0.5$) at any stand age.

5.1. Aerodynamic resistance

The aerodynamic resistance r_a was estimated using the logarithmic boundary layer equation:

$$r_a = \frac{1}{\kappa^2 u} \left[\ln \left(\frac{z - d}{z_0} \right) \right]^2 \quad (8)$$

where κ ($= 0.4$) is von Karman's constant, u the wind speed at the reference height z , d the zero plane displacement and z_0 is the roughness length. We used the relation $d = 0.78h$ and $z_0 = 0.07h$ reported by Hattori (1985), where h is the tree height.

For the mature forest basin, we assumed $z = h = 18$ m and this gives $r_a = 8.2/u$, where u was measured by anemometer at the height of 5 m. This implies that the measured u at the site is equal to the catchment average wind speed at the top of the canopy. For the young forest basin, we fixed z at 5 m but changed h from 1.8 m (1991) to 2.9 m (1994) based on field measurements. Thus, r_a decreased from 70.2 to 42.3 $/u$. Those values of r_a , for both the mature and the young forest basin, gave reasonable values of interception as shown in Section 7.

To estimate r_a at any stand age, we summarized the dependency of ur_a on h as shown in Table 1. In this table the value of ur_a instead of r_a is presented because ur_a is constant assuming that r_a is inversely proportional to u in Eq. (8). In Fig. 2(a), ur_a reported by Jarvis et al. (1976) and ur_a calculated above by Eq. (8) for the mature and the young forest, are shown against the tree height. We can convert the height h to stand age by using the h -stand age relation in Fig. 2(b), which is derived from Ohtomo (1983) for *C. obtusa* in eastern Japan. We then obtain Fig. 2(c)

which shows the dependency of ur_a on stand age. This figure demonstrates that ur_a is constant from the stand age of about 20 years.

5.2. Canopy resistance

Canopy resistance r_c was estimated by Calder (1977):

$$r_c = \frac{C[1 - A \cos(2\pi(D - 222)/365)]}{1 - B\delta e} \quad (9)$$

where the constants A , B , and C are determined by observation. For the mature forest those parameters were assumed to be constant and the reported values were used: $A = 0.37$, $B = 0.036h \text{ Pa}^{-1}$, and $C = 130 \text{ sm}^{-1}$. A and B are the average of results from three studies (Calder, 1977; Rampisela et al., 1990; Mizutani and Ikeda, 1995). The value of C , which is nearly equal to the annual average of daytime r_c , is the mean of results from five studies (McNaughton and Black, 1973; Stewart and Thom, 1973; Hattori et al., 1981; Yamanoi and Ohtani, 1992; Hattori et al., 1993). D is the days since 1 January, δe is water vapor pressure deficit. Eq. (9) does not include the effect of soil moisture content, so this equation is probably only valid under moist soil conditions. These conditions are probably satisfied in most Japanese forests:

Kondo et al. (1994) demonstrated that the forest soil content in Japan rarely restrains forest evaporation efficiency by using the runoff model (tank model) and SPWB.

At any stand age we obtain r_c by changing the constant C in Eq. (9). Assuming that the constant C of any stand age is inversely proportional to the leaf area index LAI, then C can be calculated from the leaf area index of mature forest LAI_m and C of mature forest C_m as shown in Eq. (10)

$$C = \frac{\text{LAI}_m}{\text{LAI}} C_m \quad (10)$$

To calculate C from Eq. (10) we need to know the LAI-stand age relation, which will be discussed in Section 5.4.

5.3. Parameters for canopy interception

The following forest parameters are required for the canopy interception model as mentioned in Section 4.2: interception storage capacity S_{MAX} , degree of canopy closure Ω , leaf inclination factor F , and leaf area index LAI. For the mature forest these parameters are supposed to be constant: $S_{\text{MAX}m} = 0.98 \text{ mm}$ (determined by measurement for 1991–1994) and

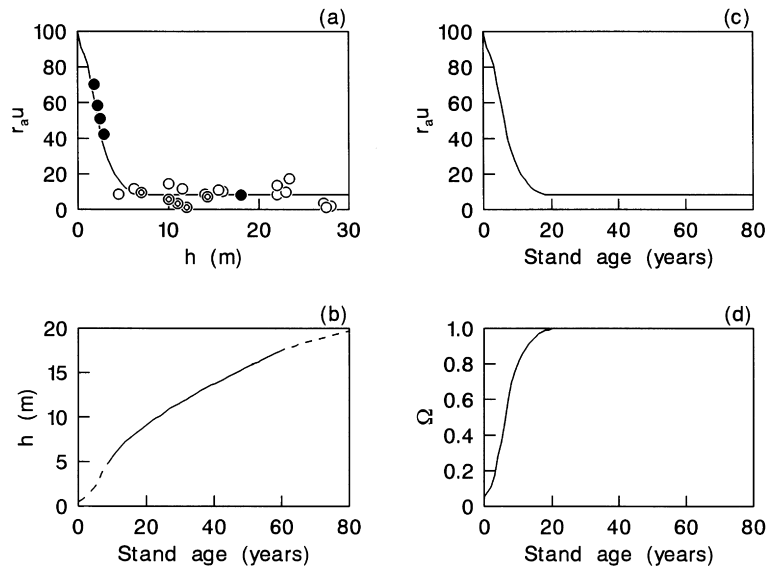


Fig. 2. Aerodynamic resistance multiplied by wind speed ur_a , tree height h , stand age and degree of canopy closure Ω . (a) ur_a and h , ●: this study, ○: Jarvis et al., 1976, ⊙: Table 1. The solid line in the figure is to guide the reader's eye. (b) Stand age and h (Ohtomo, 1983). (c) Stand age and ur_a . The solid line was converted from Fig. 2(a) using Fig. 2(b). (d) Stand age and Ω .

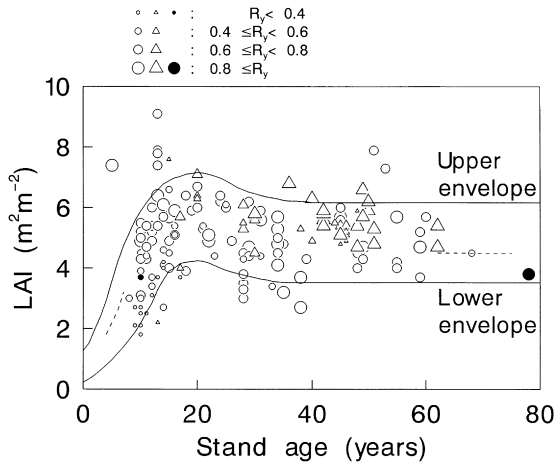


Fig. 3. Stand age and LAI. ●: measured, Δ: *C. obtusa* (Cannell, 1982; Ishii et al., 1998), ○: *C. japonica* (Cannell, 1982; Ishii et al., 1998). —: lower and upper envelopes, - - -: assumed LAI for simulation in Section 7. Size variations in symbols represent differences of yield index R_y . Some of the LAI for *C. japonica* was predicted from dry leaf weight by the regression line in Fig. 4.

$\Omega = 1$. For the young forest we assumed that S_{MAX} is proportional to LAI:

$$S_{MAX} = \frac{LAI}{LAI_m} S_{MAXm} \quad (11)$$

where the values of Ω are shown in Fig. 2(d), and canopy is assumed to close at age 20.

5.4. Leaf area index

Measured LAI values are plotted in Fig. 3. However, these are not sufficient to show the dependence of LAI on stand age, so we added published LAI-stand age data to the figure (Cannell, 1982; Ishii

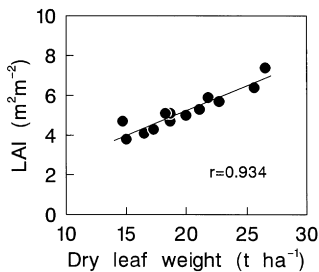


Fig. 4. LAI and dry leaf weight for *C. japonica*. The original data were derived from Cannell (1982).

et al., 1998). Published data on LAI is limited, although much has been reported on dry leaf weight (Cannell, 1982). Thus, LAI was plotted against dry leaf weight (Fig. 4), then, based on the regression line in Fig. 4, dry leaf weight was converted to LAI to obtain sufficient data. For *C. japonica*, the dry leaf weight shows a strong relationship with LAI (Fig. 4). Therefore, the dry leaf weight was converted to LAI and plotted in Fig. 3 along with published LAI. However, for *C. obtusa*, we could not find a significant relationship between dry leaf weight and LAI. Thus, for *C. obtusa* we plotted only the reported LAI in Fig. 3.

The two broken lines in Fig. 3 represent the assumed LAI, used in the simulation in Section 7 for the mature and the young forest. The two solid lines are the upper and lower envelopes to indicate the rough trend, which peaks at around age 20. LAI declines slightly after age 20, then appears to remain constant. Note that $LAI \neq 0$ at stand age = 0 because stand age is defined to be zero when the sapling is planted whose $LAI \neq 0$ and LAI includes weeds and shrubs.

Data in Fig. 3 are classified according to yield index R_y which is defined as the ratio of the observed volume to the maximum volume for a stand of equivalent mean dominant height (Ando, 1962, 1968; Newton, 1997). A plant population has its maximum density at which the maximum volume is reached due to natural thinning under the following two conditions; a plant population is even-aged and mono-specific, and a growth condition is homogeneous except stand densities. R_y indicates relative stand density for a certain mean tree height of a specific species, and the maximum volume can be calculated as a function of mean tree height for *C. japonica* and *C. obtusa* (Ando, 1968).

Fig. 3 shows high data dispersion. This is due to variation in site class and climatic conditions. Data categorization based on such factors is difficult because the site class varies over several tens of meters, and greatly affects tree growth. However, LAI tends to increase with R_y for a stand age until 20 years old, and the upper and lower envelopes roughly correspond to large and small R_y , respectively. As canopy closes at about age 20, it is reasonable that LAI increases with R_y for less than this age, while this trend is not clear for ages over 20 years.

The two measured values at the site, at the age of 10 and 78, are consistent with values reported in the

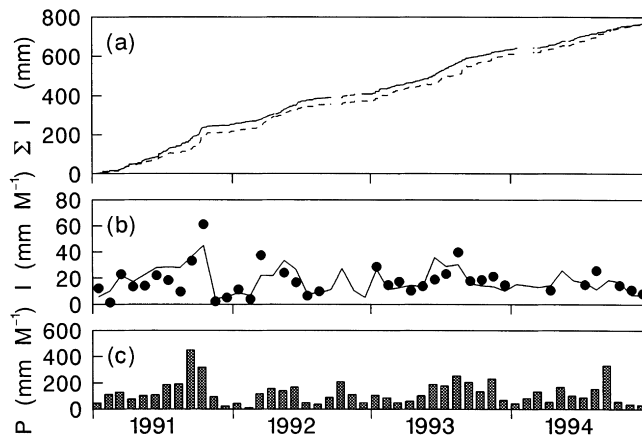


Fig. 5. Measured and simulated canopy interception. (a) Cumulative canopy interception ΣI , - - -: observation, —: simulation. (b) Monthly interception I , ●: observation, —: simulation. (c) Monthly precipitation P .

literature. However, the LAI-2000 underestimates LAI of conifer canopy. Gower and Norman (1991) and Ishii et al. (1998) proposed correcting the LAI-2000's predictions by multiplying by a coefficient. The coefficient is around 1.5; it varies depending on tree species or stand structure. If measured LAI is multiplied by the coefficient, 1.5, the values are 5.7 for the young forest and 5.6 for the mature forest. These values are still consistent with the literature (Cannell, 1982; Ishii et al., 1998).

6. Meteorological data

On-site precipitation data was available throughout the study period but other meteorological data was available only after 1991. Before 1991, data from the Mito Meteorological Observatory (25 km southwest of Hitachi Ohta) were used. These data were converted by correlating meteorological data from both sites from 1991 to 1994, and using regression equations to estimate on-site data for years prior to 1991.

Table 2

Observed and estimated annual water budget in the mature forest basins (the entire basin and basin B), and the young forest basin; the observed ET is the difference between precipitation and discharge

Year	P (mm)	ET_{obs} (mm)	ET_{cal} (mm)	T_{cal} (mm)	I_{obs} (mm)	I_{cal} (mm)
<i>Mature forest</i>						
1981	1354	580	494	336	—	158
1982	1604	606	525	320	—	205
1983	1349	465	522	321	—	201
1984	804	464	482	343	—	139
1985	1604	614	552	345	—	207
1991	1826	—	—	—	216	253
1992	1171	—	—	—	—	191
1993	1642	—	—	—	240	228
1994	1282	—	—	—	—	178
<i>Young forest</i>						
1991	1826	313	316	248	—	68
1992	1171	343	360	299	—	61
1993	1642	419 ^a	355	255	—	100
1994	1282	480	477	375	—	102

^a Discharge data in 1993 includes nine days unrecorded period and are estimated by the sequence of the data since no large rain event was observed in the period.

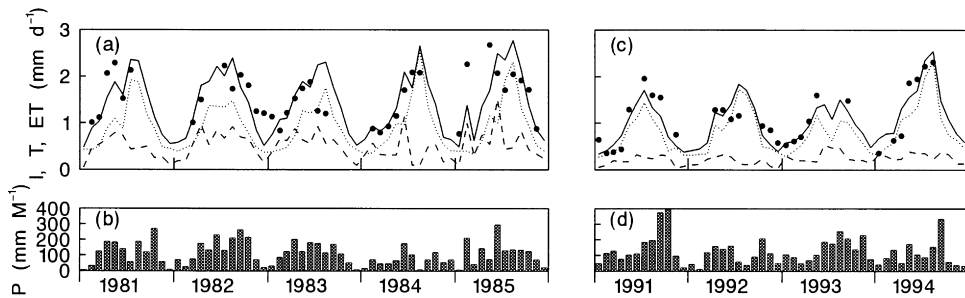


Fig. 6. Monthly mean daily evapotranspiration ET, transpiration T , interception I , and monthly precipitation P . (a) and (b) Mature forest basin. (c) and (d) Young forest basin. ●: observed ET by short time-period water-budget method (SPWB), —: simulated ET, - - -: simulated I ,: simulated T .

The converted data were averaged on a monthly basis and means were used for calculation. This was because rain events in Mito did not necessarily coincide with rain events in Hitachi Ohta. For the calculation of T , hourly data were averaged from sunrise to sunset and for the computation of I , hourly data were averaged during rain events in Mito. Humidity data obtained at the site during rain events was inaccurate, because the measurable range of the sensor, a high polymer hygrometer, was less than 95%. Thus, we used monthly average humidity (hourly data during the rainfall) from Mito.

Finally, we used the Nash Sutcliffe criteria (NSC) to evaluate the accuracy of our simulations. NSC is defined by:

$$NSC = 1 - \frac{\sigma_e^2}{\sigma_0^2} \quad (12)$$

where σ_e^2 is the variance of the difference between the measurement and the estimation, and σ_0^2 is the variance of the measurement. NSC approaches a value of one with an increase of model accuracy. If NSC is less than zero, it means that the average of observations is better than the estimation.

7. Results and discussion

7.1. General observations

The cumulative canopy interception in the mature forest (basin B) is shown in Fig. 5(a). Both the simulated and the measured values were 769 mm for the years 1991–1994. This value is different from total

observed interception (I_{obs}) for 1991–1994 in Table 2, since annual I_{obs} data for 1992 and 1994 include periods of missing data and are not in Table 2. Interception accounted for 14.8% of total precipitation. Monthly values of canopy interception are displayed in Fig. 5(b). The predicted results match the observed values well (NSC = 0.540) and both values coincided with the sequence of monthly precipitation P shown in Fig. 5(c). These results indicate that the interception model worked well on a monthly basis.

As shown in Fig. 6(a) and (c), the simulated ET of the mature and the young forest basin (solid line) corresponded with the observed ET (solid circles) obtained by SPWB (NSC = 0.297 and 0.657, respectively). The dashed and dotted lines represent predicted canopy interception I and transpiration T , respectively. The canopy interception rate is nearly synchronized with the precipitation pattern in the mature forest (Fig. 6(a) and (b)), though it is not clear in the young forest (Fig. 6(c) and (d)). The cause of this is explained as follows. For mature forest, the first term of the right side ($E\tau$) in Eq. (5), which has small r_a , is more dominant than the second term. Therefore, interception I increases with duration of rain event τ which bears a strong relationship with rainfall amount P . However, for young forest, the first term with large r_a is less dominant than the second term, and the amount of interception is less sensitive to duration of rain event. Consequently, I is sensitive to P for mature forest but not for young forest. The values of I , T and ET exhibited different seasonal variations each year depending on climate conditions. For example,

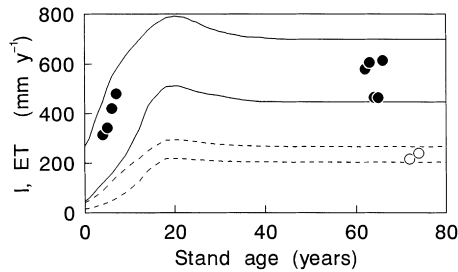


Fig. 7. Stand age and evapotranspiration ET, interception I . Meteorological data averaged from 1981 to 1994 were used. ●: observed ET, ○: observed I , —: simulated ET, - - -: simulated I . Two lines for ET and I correspond to the upper and lower envelopes in Fig. 3.

the young forest had small ET values in the cool summer of 1993, but had higher ET values for the hot summer of 1994. The effect of weeding in 1991 and 1992 cannot be detected in Fig. 6(c).

Table 2 summarizes the observed and the calculated annual water budget discussed in this section, including annual data for Fig. 6(a)–(d). The discharge data used for the annual estimates included faulty records for nine days in 1993. These were estimated by assuming base flow through periods of missing data, since those periods did not include large rain events, that is, total rainfall was 7.0 mm. The observed ET in the mature forest basin varies (464–614 mm year⁻¹) with precipitation P . On the other hand, the measured ET in the young forest basin increases with the growth of the stand (313–480 mm year⁻¹). The values of NSC for the annual ET predictions are 0.275 for the mature forest and 0.765 for the young forest.

7.2. Changes in ET with stand age

Application of the model with the estimated forest parameters enables the simulation of ET with stand growth. The average meteorological data from 1981 to 1994 were used for this computation. The result shown in Fig. 7 exhibits a peak of ET around age 20 reflecting the upper and lower envelopes of LAI in Fig. 3, which correspond to high and low values of yield index R_y , respectively, for ages less than 20 years as mentioned in Section 5.4. The measured ET and I are also plotted in the figure, though we have no data for the 8–61 year stands which includes the period predicted peak ET. To confirm the peak in ET

we need to continue hydrographic observations at our site or incorporate data from other catchments.

It is noteworthy, however, that ET from the young forest basin had already reached 480 mm year⁻¹ at the age of seven in 1994, which is almost similar to the mature forest basin (464–614 mm year⁻¹). Since the canopy of this young forest stand had not yet closed, ET of this stand should increase at least until canopy closure, before decreasing to the value of the mature forest. Molchanov (1963) showed that greatest amounts of transpiration are observable with pine aged 40 years, with oak aged 60 years, with spruce aged 60 years, with ash and aspen aged 20–40 years, in the former USSR. He also presented that the greater interception occurs in pine, oak and spruce stands aged 40–60 years, as well as in ash and aspen stands aged 20–40 years. Kuczera (1987) and Haydon et al. (1996) showed that streamflows from catchments forested with mountain ash (*E. regnans*) are lowest at the age of 20–30 years.

Several studies have shown that leaf biomass in forest stands tends to peak between ages 15 and 40 years. Maruyama and Sato (1953) showed Japanese red pine (*Pinus densiflora*) has a green leaf weight peak at age 15. A mixed stand of *Abies veitchii* and *Abies mariesii* at Mt. Shimagare, Japan, shows a dry leaf weight peak about the age of 30 (Oshima et al., 1958), and European red pine (*Pinus sylvestris*) and European birch (a mixed stand of *Betula verrucosa* and *Betula pubescens*) peaks around the age of 20 and 24, respectively (Ovington, 1957; Ovington and Madgwick, 1959). *C. japonica* forest has a fresh leaf weight peak at about age 20 (Yuruki, 1964), and has a dry leaf weight peak at age 20–25 (Ando et al., 1968). *A. veitchii* forests at Mt. Fuji, Japan, exhibit needle biomass peak at about 100 t ha⁻¹ of the total biomass which appears at stand age about 30 years (Tadaki et al., 1970), and *A. veitchii* forests at Mt. Asahi, Japan, also demonstrate dry leaf and LAI peaks at about 40 years of age (Tadaki et al., 1977). In all of these species a slight decline follows the peak, then leaf biomass is almost constant.

The peak appears not only for leaf biomass but for net primary production (Yuruki, 1964; Ando et al., 1968; Tadaki et al., 1970, 1977), and it coincides with canopy closure (Whittaker and Woodwell, 1968; O'Neill and DeAngelis, 1981; Jarvis and Leverenz, 1983; Waring and Schlesinger, 1985;

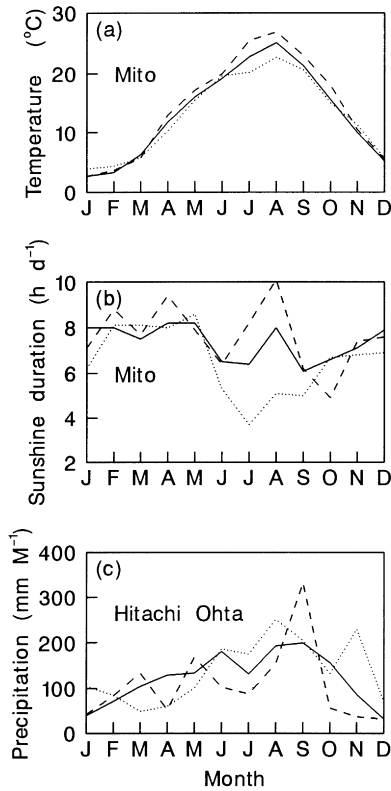


Fig. 8. Temperature and sunshine duration in Mito, and precipitation in Hitachi Ohta. - - -: Hot summer (1994), ····: cool summer (1993) and —: mean summer (1981–1994 average).

Pearson et al., 1987). There is a hypothesis to explain the cause of the biomass peak (Yoda et al., 1965; Kira and Shidei, 1967; Kramer and Kozlowski, 1979): the decrease in net primary production after canopy closure is caused by changes in the balance between photosynthesis and respiration, and respiration increases by grown woody tissues. However, Ryan and Waring (1992) showed that there is a nonsignificant change in respiration of woody tissues in stems and branches for 40 year old and 245 year old of subalpine lodgepole pine forest (*Pinus contorta*), which could not explain the hypothesis.

Kanda and Hanai (1998) showed that leaf biomass has a peak during the process of canopy closure, and that peak periods depend on tree density by a dry-matter production model. The higher stand density is, the earlier peak period appears. This trend was pointed out by Ando et al. (1968), while Yuruki (1964) mentioned that leaf biomass even in very

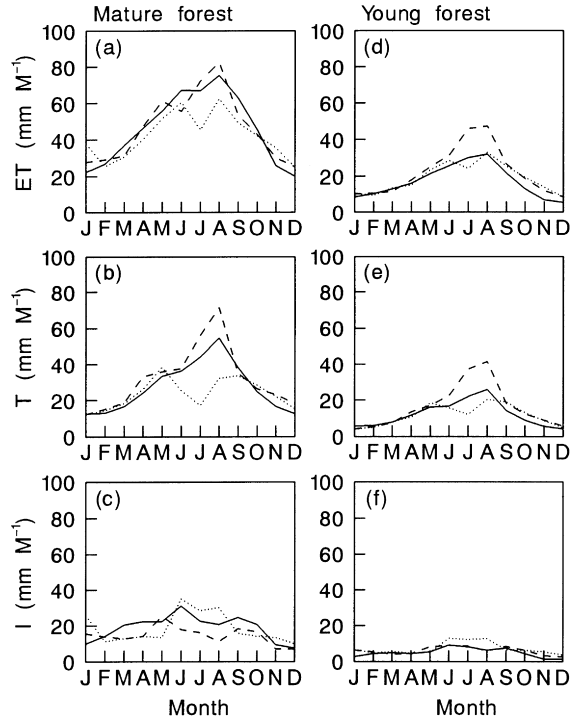


Fig. 9. Response of evapotranspiration ET, transpiration T and interception I to hot, cool and mean summer: (a)–(c) mature forest, (d)–(f) young forest. - - -: Hot summer (1994), ····: cool summer (1993) and —: mean summer (1981–1994 average).

young (four years old) forest can reach its maximum if the canopy completely closes.

Both the solid lines (ET), and the broken lines (I) in Fig. 7 correspond to the upper and lower envelope of LAI in Fig. 3. $ET (= T + I)$ demonstrates a clear peak in Fig. 7, but I seems to plateau without an obvious peak. This implies that T , which is sensitive to LAI in Eqs. (3), (9), and (10), is the main source of variation in ET with forest age. The following two studies support this result: both ET peaks of pine, oak, spruce, aspen, and ash stands at multiple age classes (Molchanov, 1963), and the reduction of mean annual streamflow at stand age of 20–30 years (Haydon et al., 1996) are mainly explained by changes in transpiration and, to a lesser degree, by changes in interception loss.

7.3. Response of ET to climate changes

We simulated the response of ET to different

climatic conditions, including cool (1993), hot (1994), and mean (1981–1994) summers for both the mature (age 62) and the young (age four) forests. For the simulation of mean summer conditions, average weather data from 1981 to 1994 were used. As previously mentioned, in the young forest basin summer ET was small in 1993 and large in 1994. Fig. 8(a)–(c) shows temperature and sunshine duration in Mito and precipitation in Hitachi Ohta. The dashed line represents the hot summer, and the solid and dotted lines represent the mean and cool summers, respectively. Temperature and sunshine duration have high values in the hot summer and low values in the cool summer relative to the mean summer. The amount of precipitation was smaller in the hot summer and larger in the cool summer than that of the mean.

The simulated monthly ET, T , and I for the mature and young forests are shown in Fig. 9(a)–(f). In the mature forest, the ET difference in Fig. 9(a) is small between the hot and mean summers (5 mm in July and 7 mm in August), but large between cool and mean summers (21 mm in July and 13 mm in August). In the young forest, however, the difference in ET in Fig. 9(d) is large between the hot and mean summers (16 mm in July and 15 mm in August), but small between the cool and mean summers (6 mm in July and 0.9 mm in August).

This contrast is mainly attributable to the difference in canopy interception rate for the mature and the young forest. In the mature forest, I in hot summer in Fig. 9(c) is small (6 mm and 10 mm smaller than that of mean summer in July and August, respectively) enough to cancel the large value of T in Fig. 9(b) (12 mm and 17 mm larger in July and August, respectively). On the other hand, I in cool summer in Fig. 9(c) is not large (6 mm and 9 mm larger in July and August, respectively) enough to compensate for the small value of T in Fig. 9(b) (27 mm and 22 mm smaller in July and August, respectively). In the young forest there is almost no difference in I between hot and mean summers in Fig. 9(f) (0.5 mm larger in July and 0.3 mm smaller in August); thus, it cannot diminish the large value of T in hot summer in Fig. 9(e) (15 mm and 16 mm larger in July and August, respectively). I during cool summers in Fig. 9(f) is higher than the mean value (4 mm and 7 mm higher in July and August, respectively), and balances the

value of T in cool summer in Fig. 9(e) (10 mm and 6 mm smaller in July and August).

8. Conclusions

Evapotranspiration (ET) was determined by the short-time period water-budget (SPWB) method in the mature and the young forest basin under moist soil conditions. Canopy interception (I) was measured in the mature forest. I accounted for 14.8% of total precipitation for the years 1991–1994. The observed ET in the mature forest basin varied (464–614 mm year⁻¹) with precipitation P for the years 1981–1985, while the measured ET in the young forest basin increased with the growth of the stand (313–480 mm year⁻¹) for the years 1991–1994.

Application of the model based on the Penman–Monteith equation reproduced the observed water budget reasonably well. The simulation of the stand age–ET relationship showed that ET peaks around age 20 years, reflecting the variation of LAI. We cannot check the simulated peak directly, since no water budget data are available. However, the observed ET of the young (seven years) forest would be assumed to increase for several years, because the canopy had not yet closed in 1994. Hence, after ET reaches the maximum in a decade or so, it should decrease to the value of a mature forest.

The computation also demonstrates that ET behavior for cool (1993) and hot summers (1994) differs between the young (age four) and the mature forest (age 62). The young forest shows higher ET (16 mm in July and 15 mm in August) in hot summer compared with mean summer (1981–1994 average), while the ET difference between cool and mean summers is small (6 mm in July and 0.9 mm in August). In the mature forest basin, however, the difference in ET for hot and mean summers is small (5 mm in July and 7 mm in August), but is large between cool and mean summers (21 mm in July and 13 mm in August).

To refine and extend our model, we need water balance data in catchments with forest structure information from which forest parameters can be determined. The effects of thinning and branch-cutting on catchment water budgets should be a high

research priority for forest hydrologists and forest management planners.

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