# Modelling and Annual Estimation of Canopy Interception, Transpiration and Evaporation from the Forest Floor in a Deciduous Secondary Forest in Western Japan

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**Abstract:** The annual rates of canopy interception, transpiration, and evaporation from the forest floor were estimated in the deciduous secondary forest in westren Japan. The study forest has some peculiar characteristics, such as the amount of significant radiation reaching the forest floor and the different water movement through the canopy between the leafy and leafless seasons. the seasonal changes in canopy interception ($E_f$), transpiration ($E_s$), and evaporation from the forest floor ($E_i$) may be peculiar. $E_f$, $E_s$, and $E_i$ were estimated to be 57.0mm, 270.8mm and 147.3mm in the leafy period, respectively, and 69.9mm 91.9mm and 89.1mm in the leafless period, respectively. The breakdown of $E_f$, $E_s$, and $E_i$ in total evapotranspiration (E) was compared with a coniferous evergreen forest located nearby. The difference in E at Yamashiro and Kiryu was not significant However, the breakdown of E into $E_f$, $E_s$, and $E_i$ differed between them.

***Keywords:*** Tank model; Thornthwaite-Holtzman model

## 1. INTRODUCTION

Deciduous secondary forests consisting of tall deciduous trees and evergreen shrubs cover around 0.6 million ha in western Japan. These secondary forests grow from the excessive litter left after harvesting timber and fuel wood. It is thought that they should be conserved as part of the local ecological system. However, many of their characteristics, such as their ecology, geophysics, etc., remain unknown. Consequently, the movement to conserve deciduous secondary forests in western Japan is not well founded.

The hydrological characteristics of a forest affect local climate, water supply capacity, etc., and are a major determinant of a forest's importance. Therefore, it is important to investigate the hydrological characteristics of secondary forest in western Japan. The first characteristic is the amount of significant radiation reaching the forest floor. This is thought to cause much evaporation from the forest floor. Second, water movement through the canopy is thought to differ between the leafy and leafless seasons. Therefore, the seasonal changes in canopy interception, transpiration, and evaporation from the forest floor may be peculiar. These considerations suggest that deciduous secondary forests in western Japan have many hydrological characteristics that differ from those of the coniferous evergreen forests reported on in many studies, especially in evapotranspiration. Therefore, the first objective of this study was to estimate annual canopy interception, transpiration, and evaporation from the forest floor. The second was to compare the results with those for a nearby coniferous evergreen forest.

## 2. METHODS

### 2.1 Observation Site

Observations were made in the Yamashiro experimental basin, which is located in the hilly mountains of western Japan (34° 47'N, 135° 51'E). The basin area is 1.6 ha. Deciduous broad-leaved trees, like *Quercus serrata* and *Lyonia japonica elliptica*, dominate as tall trees and shrubs.

Evergreen species like *Ilex pendunculosa* coexist, but mainly as shrubs (Table 1). The total basal areas at breast height were 13.3 and 6.3 $m^2 ha^{-1}$ for deciduous and evergreen species, respectively. The leaf area indices were estimated with a Plant Canopy Analyzer (LI-COR Inc., LAI-2000) as 4.42 and 2.70 in the leafy and leafless periods, respectively. In 1989-1991, the annual average temperature was 15.9°C; the annual average relative humidity was 74.7%; and the annual precipitation was 1647.2 mm [Abe et al., 1997]. In 1989-1990, the annual evapotranspiration rate was estimated to be 785.1 mm using the water balance method, and corresponded to 48.6% of the precipitation [Abe et al., 1997].

Figure 1 shows the canopy closeness in the Yamashiro basin. Only 0.6% of the forest floor area at the Yamashiro site was not screened by canopy during the leafy period; therefore, the canopy was judged as closed. On the other hand, 49.7% of the area was screened by a canopy of tall deciduous trees with no evergreen shrubs. This suggests that around half of the forest floor is not screened by a leafy canopy in the leafless period. Therefore, the annual solar radiation on the forest floor changes drastically. The relative ratio of the solar radiation on the forest floor to that above the forest canopy was measured as 15 and 40% in the leafy and leafless periods, respectively.

**Table 1.** Dominant species in Yamashiro experimental basin (in $m^2 ha^{-1}$).

| | |
|---|---|
| Evergreen species: | |
| -*Ilex pendunlosa* Mig. | 2.95 |
| -*Eurya japonica* Thunb. | 0.73 |
| -Others | 2.61 |
| Sub total | 6.29 |
| Deciduous species: | |
| -*Quercus serrata* Thunb. Ex Murray | 4.48 |
| -*Lyonia japonica elliptica* (Wall.) Drude var. (Sieb. Et Zucc.) Hand-Mazz. | 1.93 |
| -*Alnus sieboldiana* Matsumura | 1.81 |
| -*Clethra barbinervis* Sieb. Et Zucc. | 1.25 |
| -*Robinia pseudocacia* | 0.83 |
| -Others | 3.01 |
| Sub total | 13.31 |
| Total | 19.60 |

The basin contained very mobile mineral soil that originated from weathered granite. The mineral soil layer was generally thin and immature, and the litter layer lay directly on the mineral soil layer or regolith. The mass and depth of the litter layer were measured in observation plots located at the top, upper, middle, and foot parts of slopes, and are shown in Figure 2. The mass of litter was almost less than 400 g $m^{-2}$ throughout the year in every part of the slope. The depth was minimal in autumn. The maximum depth was around 3 cm.

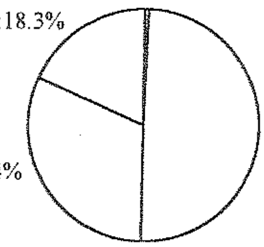


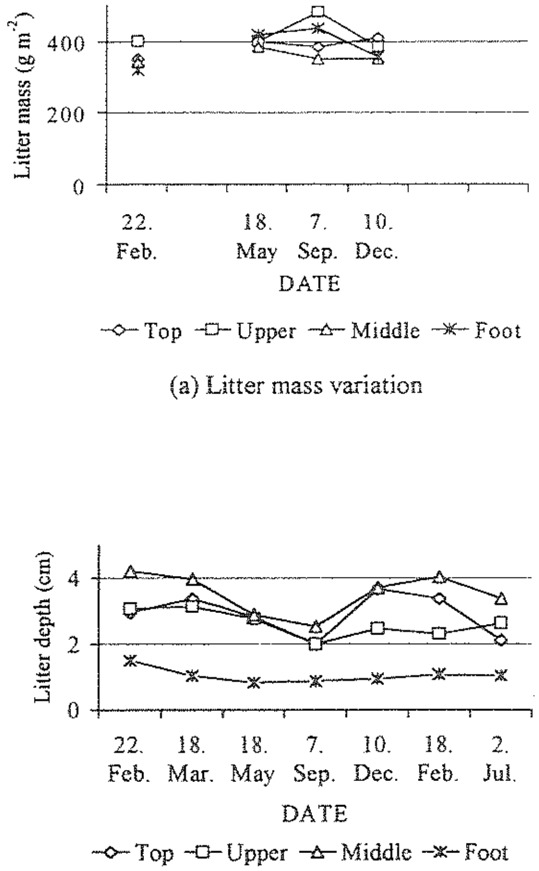

**Figure 1**. Canopy closeness in Yamashiro experimental basin.
A: Screened by no deciduous and no evergreen canopies.
B: Screened by deciduous and no evergreen canopies.
C: Screened by deciduous and evergreen canopies.
D: Screened by no deciduous and evergreen canopies.

## 2.2 Observation Methods

A tower was constructed on the ridge of the basin to observe the forest micrometeorology. The average relative height of the upper canopy surface from the tower base was 6 m. The observation instruments and their heights are shown in Table 2. Precipitation was measured with a rain gauge (Ikeda Instruments, SKI-1) installed in a field. Discharge was estimated using the water level at a gauging weir using a 90° discharge notch with a float-type water gauge (Ikeda Instruments, ADR-105WP). The observations were conducted in 1992. The leafy period was from May to October.

# 3. MODEL

Evapotranspiration (E), evaporation from the forest floor ($E_f$), and canopy interception ($E_i$) were




(a) Litter mass variation

(b) Litter depth variation

**Figure 2.** The variation of Litter mass and depth in Yamashiro experimental basin measured in 1990-1991.

**Table 2.** Observation instruments and their settled heights at the tower

| Item | Sensor name | Height(m) |
|---|---|---|
| Solar radiation | MS-42 (Eko Co.) | 12 |
| Net radiation | CN-11 (Eko. Co.) | 10 |
| Dry and wet bulb Temperatures | MH-020 (Eko. Co.) | 8, 10 |
| Decline of dry and wet Bulb temperatures | MH-020 (Eko. Co.) | Between 8 and 10 |
| Wind verosity | A701 (Nakaasa) | 8, 10 |
| Soil heat flux | CN-81 (Eko. Co.) | -0.05 |

estimated using the three models explained below. Transpiration ($E_s$) was calculated using

$$E_s = E - E_f - E_i \tag{1}$$

### 3.1 Evapotranspiration Model

The heat balance above the forest canopy surface was expressed as:

$$R_n - G = H + \lambda E \tag{2}$$

Where, $R_n$ is the net radiation; G is the soil heat flux; H is the sensible heat flux; and $\lambda$ is the vaporization heat of water. On the other hand, Thornwaithe et al. [1939] used the following equation when the atmosphere was neutral:

$$H = \rho C_p(u_2 - u_1)(TD_1 - TD_2)(\kappa/B)^2 \tag{3}$$
$$B = \ln(z_2-d)/(z_1-d) \tag{4}$$

Where, u is the wind velocity; TD is the dry bulb temperature; z is the height (subscripts 1 and 2 indicate observation heights); d is the zero plane displacement; $\kappa$ is Karman's constant; $\rho$ is the atmospheric density; and $C_p$ is the constant pressure specific heat.

Equation 3 can be rewritten as:

$$H = \rho C_p A u_2 (TD_1 - TD_2) \tag{5}$$
$$A = (1 - u_1/u_2)(\kappa/B)^2 \tag{6}$$

Replacing Eq.(2) with Eq.(5), $\lambda E$ is calculated as:

$$\lambda E = R_n - G - \rho C_p A u_2 (TD_1 - TD_2) \tag{7}$$

When the atmosphere is neutral, the wind velocity assumes a logarithmic profile, *i.e.*,

$$u_i = u^* \kappa^{-1} \ln((z_i-d)/z_0) \tag{8}$$

Where, $u^*$ is the friction velocity; $z_0$ is the roughness length; and the subscript i indicates the observation height.

When Eq.(8) is substituted for Eq.(6), parameter A is given as a function of d, $z_0$, $z_1$, $z_2$, $\kappa$ $\rho$ and $C_p$, and can be expressed as Eq.(9). Here, if d and $z_0$ are constant, parameter A can be also considered as a constant.

$$A = (1 - \ln((z_1-d)/z_0) / \ln((z_2-d)/z_0))(\kappa/B)^2 \quad (9)$$

### 3.2 Model of Evaporation from the Forest Floor

$E_f$ was estimated using the model proposed by Tamai et al. [2000]. This model focuses on a deciduous forest with soil that contains very little organic matter and is completely immature. Its suitability for the Yamashiro experimental basin was verified. This model is a tank model with two tanks. The upper and lower tanks correspond to the litter and mineral soil layers, respectively. In this model, precipitation is stored in the two tanks and evaporated depending on the micrometeorology on the forest floor.

### 3.3 Canopy Interception Model

The water balance in a forest canopy can be expressed as:

$$E_i = P - P_t - P_s \quad (10)$$

Where, P is the precipitation; $P_t$ is the throughfall; and $P_s$ is the stem flow.

Based on the linear relationships between $P_t$, $P_s$, and P, Hattori et al. [1994] reported the following linear relationship between $E_i$ and P:

$$E_i = sP + t \quad (11)$$

where s and t are constants. The values of s and t in deciduous forests differ in the leafy and leafless periods [Hattori et al., 1994]. Therefore, it is necessary to determine s and t in both periods, separately.

## 4. PARAMETERIZATION

### 4.1 Evapotranspiration Model

Tamai et al. [1999] evaluated the monthly value of parameter A in Eq.(7) for the Yamashiro experimental basin by combining the water and heat balances. The monthly integrated weather data and $\lambda E$ rates were substituted into the right and left sides of Eq.(8), respectively, and the monthly values of parameter A were back-calculated. Hattori et al. [1994] estimated the monthly $\lambda E$ rates using the short-period water balance method. Parameter A was around 0.12 and 0.077 in the leafy and leafless periods, respectively. These values were used in this study.

### 4.2 Model of Evaporation from the Forest Floor

In this study, the forest floor was considered to consist of 400 g m$^{-2}$ of litter layer on top of a mineral soil layer 20 cm deep. In this model, each layer was regarded as a tank. The precipitation distribution was modeled as follows. First, the forest canopy intercepts precipitation. Next, the precipitation reaching the forest floor saturates the litter layer tank. Third, the overflow from the litter tank saturates the mineral soil tank. Finally, the overflow from the mineral soil tank is discharged into the deeper soil layer. The amount of precipitation reaching the forest floor was calculated as the difference between the measured precipitation above the canopy and $E_i$. The maximum litter water gravimetric content ratio was determined to be 200% experimentally. This means that the litter tank volume corresponding to 400 g m$^{-2}$ was 0.8 mm. The maximum soil water volumetric content ratio in Yamashiro experimental basin is 42% [Torii, unpublished]. Therefore, the mineral tank volume corresponding to 20-cm-deep soil was determined to be 84 mm. The solar radiation rate on the forest floor was calculated by multiplying the measured solar radiation above the canopy by the solar radiation ratio. The ratio was 15 and 40% in the leafy and leafless periods, respectively.

### 4.3 Canopy Interception Model

Parameters s and t were parameterized as Eq.(12) with the measurements of $P_t$ and $P_s$ in 100m$^2$ observation square lots in the Yamashiro experimental basin (Figure 3).

$$E_i = 0.1239\,P + 0.63 \quad \text{(leafy period)} \quad (12)$$
$$0.0821\,P + 0.88 \quad \text{(leafless period)}$$

$P_t$ was collected from 3 gutters in the plots, each 0.2m wide and 4.0m long, and measured with a water gauge. $P_s$ was collected in trenches made of rubber and aluminum plate, which were placed around all the trunks in the plots and drained into measurement tanks.

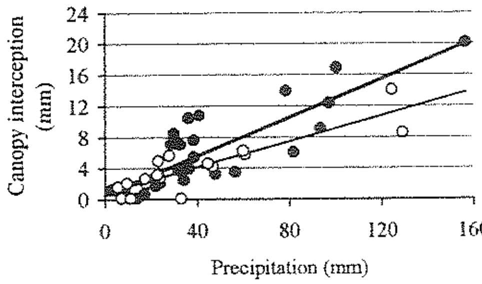



**Figure 3.** Relationships between precipitation and canopy interception.
Close circle: observed rate in leafy period.
Open circle: observed rate in leafless period.
Thick line: Eq.(12) in leafy period.
Thin line: Eq.(12) in leafless period.

## 5. RESULTS AND DISCUSSION

The monthly rates of $E_f$, $E_s$, and $E_i$ are shown in Figure 4. $E_s$, in December was estimated to be minus. This was caused by the acceptable error in the calculation process and judged to be very small rate in actual. $E_f$ was highest in April at 15.6 mm month$^{-1}$ and lowest at 7.5-10.5 mm month$^{-1}$ in the leafy period. The solar height and lack of leaves on deciduous trees allowed the maximum amount of radiation to reach the forest floor in April. $E_f$, $E_s$, and $E_i$ were estimated to be 57.0mm, 270.8mm and 147.3mm in the leafy period, respectively, and

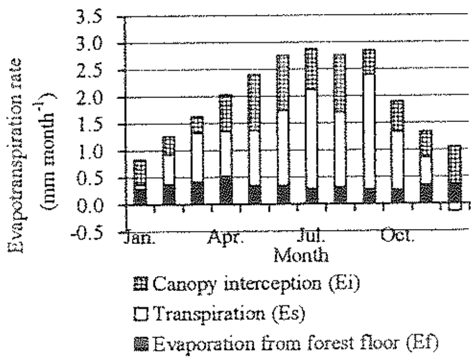



**Figure 4.** Monthly rates of canopy interception ($E_i$), transpiration ($E_s$) and evaporation from forest floor ($E_f$).

69.9mm 91.9mm and 89.1mm in the leafless period, respectively (Figure 5). The share of $E_f$, and $E_s$, were larger and smaller, respectively, in the leafless period than those in the leafy period caused by the canopy closeness.

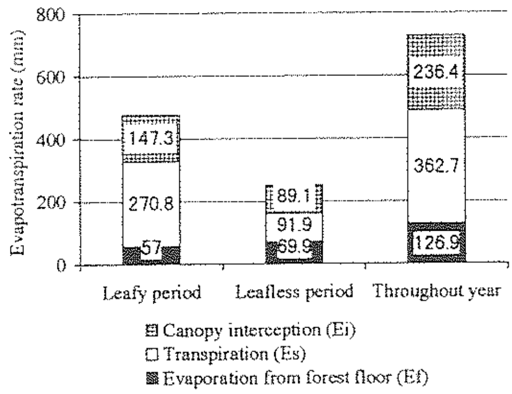



**Figure 5.** Shares of canopy interception ($E_i$), transpiration ($E_s$) and Evaporation from forest floor ($E_f$). Values in figure mean the rates.

The breakdown of $E_f$, $E_s$, and $E_i$ in E was compared with a report [Suzuki, 1980] for a coniferous evergreen forest located in Kiryu (34° 58'N, 136° 0'E), 25 km northeast of the Yamashiro basin (Figure 6). The dominant species in Kiryu are *Chamaecyparis obtusa* and *Pinus densiflora*. The ratios of $E_i$ to E in Yamashiro and in Kiryu were 37 and 63%, respectively from November to April. The large difference was because the canopy in Yamashiro was leafless during this period. Instead of a small $E_i$, the share of $E_f$ was 29% in Yamashiro

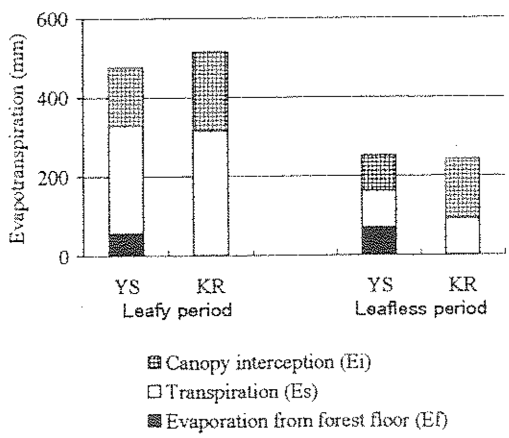



**Figure 6.** Comparison of evapotranspiration between Yamashiro (YS) and Kiryu (KR) experimental basins.

in the leafless period, larger than that in Kiryu at any time of year. This is because very little radiation generally penetrates a *Chamaecyparis obtusa* forest canopy.

The difference in E at Yamashiro and Kiryu was not significant: 475.1 mm and 514.0 mm in leafy period (May-October) and 250.9 mm and 242.5 mm in leafless period (November-April), respectively. However, the breakdown of E into $E_f$, $E_s$, and $E_i$ differed between them.

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