# Measurement and estimation of transpiration from an evergreen broad-leaved forest in Japan

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ABSTRACT : Methods to measure and estimate transpiration of a forest composed of evergreen broad-leaved trees (*Pasania edulis Makino*) are studied. Heat pulse velocity has been measured along with soil moisture and micrometeorological factors at the Fukuoka Experimental Forest, the Research Institute of Kyushu University Forests in Fukuoka, Japan (33°38'N, 130°31'E, alt. 75m). Tree cutting measurement was conducted to convert the heat pulse velocity into sap flow and transpiration. A big leaf model to calculate transpiration and interception loss is examined and the estimated values are compared with the measured values obtained from the heat pulse measurement. The results show that 1) *Pasania edulis Makino* posessing radial pore structure had relatively high water content and high heat pulse velocity even within the central part of the stem near the pith, 2) the heat pulse velocity was well correspond to the water uptake in the tree cutting measurement, 3) the estimation of sap flow based on the heat pulse velocity is accurate, and 4) the big leaf model using the parameters obtained from measurement of a portable photosynthesis system in one day in summer gives reasonable estimation of transpiration independent of seasons and weather.

## 1 INTRODUCTION

Evaluation of evapotranspiration from forests has been strongly required especially since 1980s when global environment became a serious problem to be tackled worldwide. Therefore it has been widely investigated through various projects such as GAME, IGBP/BAHC and FLUXNET. However, standard methods to evaluate evapotranspiration from forests have not yet established while standard guidelines for computing crop evapotranspiration from FAO (Allen *et al.*, 1998) have been widely used in practice. It is mainly because forests are large in scale and heterogeneous in various aspects such as ecology, topography, structure and so on. Thus it is still highly required to accumulate reliable data to establish the method to evaluate evapotranspiration from forests. In this respect, we conducted an integrated measurement of evapotranspiration from an evergreen broad-leaved forest and examined a model to estimate evapotranspiration. In this paper, first the method to measure sap flow of evergreen broad-leaved tree having radial pore structure is discussed, and second a big leaf model which evaluates interception loss and transpiration separately is examined.

## 2 MATERIALS AND METHODS

### *2.1 Site description*

This study was conducted at a forest composed of 22-year-old *Pasania edulis Makino* (*Lithocarpus edulis Nakai*) in the Fukuoka Experimental Forest, the Research Institute of Kyushu University Forests in Fukuoka, Japan (33°38'N, 130°31'E, alt. 75m). *Pasania edulis Makino* is a evergreen tree naturally grown around hills of western Japan and planted in gardens, parks and streets. Leaves are broad, deep green and lustrous. They are concentrated at the crowns except the forest edge where leaves are vertically arranged. The average tree height was about 9m and the average diameter at the breast height was 13.2cm. The average stocking was 0.285 stems/m$^2$ and the canopy was almost closed.

Soils at the study site are humus in the surface layer of 0~25cm depth and heavy clay in the layer of 25~80cm depth. Saturated hydraulic conductivity is about $1.5\times10^{-2}$ cm/s at 10cm depth and about $3.0\times10^{-5}$cm/s at the depth of 29cm (Imura *et al.*, 2000).

### 2.2 *Soil moisture and micrometeorological measurement*

Volumetric soil moistures were measured using TDR and FDR sensors, and soil matric potentials were measured using tensiometers with electrical pressure sensors.

Global solar radiation, downward longwave radiation and gross rainfall were measured on the lawn near the forest. Reflected solar radiation and upward longwave radiation were measured above the canopy of the forest. Profiles of wind speeds, air temperatures, vapor pressure, and solar radiation were measured along a tower installed in the forest. Throughfall were measured at 36 cross sections of 2 × 2m meshes using small storage raingauges. Four 0.2mm tipping bucket raingauges were installed next to four of the storage raingauges for the continuous measurement of throughfall. Stemflows were measured by 500cm$^3$ tipping bucket raingauges on three trees of which the breast height diameters were 12.0~13.5cm.

These data were recorded every 10 minutes.

### 2.3 *Sap flow and tree cutting measurements*

Sap flow was measured by means of heat pulse method. It is the method to measure sap velocity by applying heat pulse and detecting the temperature rise of surrounding tissue. Two thermistor probes were inserted in a stem above and below a heating probe that was also inserted in the stem. The heat pulse velocity $v_h$ was calculated as:

$$v_h = \frac{X_l - X_u}{2t_e} \quad (1)$$

where $t_e$ is the time requires for the two thermistors to reach the same temperature, $X_l$ and $X_u$ are the distances between the heat probe and the lower and upper thermistors respectively (Closs, 1958). In the routine observation, the heat pulse velocity was measured at the height of 60cm.

Stem cutting measurement was conducted to calibrate the heat pulse method during September 4~9, 2000. Two trees were cut in the measurement: one at the height of 30cm on September 4 and the other at the height of 50cm on September 8. After cutting, the tree was hang up by a crane. The cut end was immersed in water in a plastic container and the tree was sawn again underwater. The piece of wood cut underwater was immediately wrapped in a plastic bag to prevent water loss and stored until further measurement of its physical properties. The cut end was slide into a plastic bucket underwater. The tree and the bucket were taken out from the container together and independently fixed. Water level in the bucket was manually observed and restored every 15 minutes to measure the volume of water uptake.

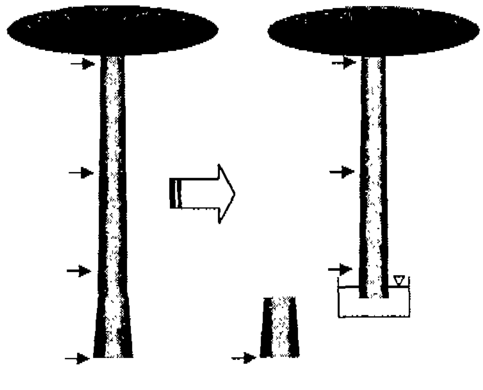

Fig.1 Outline of tree cutting measurement. Arrows show the location of heat pulse measurement

The heat pulse measurements at the height of 0.0, 0.8, 4.0 and 8.0m were also conducted during the tree cutting measurement. At 0.8m height, heat pulse velocities were measured at four directional points. Two of them were measured at the fixed depth of 1.0cm and the other two were measured at 9 depths (1.0, 1.5, 2.0, 2.5,3.0,3.5,4.0,5.0 and 6.0cm) by moving thermister proves every 15 minutes. After cutting, the set of heat pulse sensor at 0.0m was left in the stamp and those at 0.8m were located about 40cm above the cut end and about 20cm above the soaked water surface.

The heat pulse velocities were measured and recorded every 15 minutes.

Stomatal conductance was measured by a portable photosynthesis system (Li-cor LI-6400) during tree cutting measurement.

At 8:00 a.m. in the final day of each measurement, coloring liquid was added to the water to check the movement of water.

### *2.4 Measurement of physical properties of the wood*

At 6:00 p.m. in the final day of the first measurement, the tree was lifted up and taken apart to pieces to measure the physical properties of the wood. Cores of wood at the height of 45cm and 140cm were taken with increment borers. They were immediately wrapped in polyethylene films, taken into a laboratory, separated into segments of 1cm length and measured the weights to obtain the distributions of tree-stem water contents.

Density and water content of wood were measured using the pieces of wood obtained in the tree cutting. Volumes of the pieces were measured by water displacement. After measuring the weight of these pieces, they were soaked in water for about three days. Then they were dried for 36 days in a laboratory, 8days at 70°C and 16days at 85°C in an oven.

Structural properties were measured using the pieces separated after tree cutting measurement. A digital photomicrograph of the cut end was taken and areas of vessels were measured. The reach of colored liquid was visually investigated.

### *2.5 Estimation of evapotranspiration*

Big leaf model was used to estimate evapotranspiration in this study. Basic equation of the big leaf model is expressed as follows:

$$ET = \rho C_E u \{q_{sat}(T_s) - q_a\} \qquad (2)$$

where, $ET$ is evapotranspiration flux, $\rho$ is density of air, $C_E$ is bulk transfer coefficient for evaporation, $u$ is wind speed, $q_{sat}(T_s)$ is relative humidity at the surface of the canopy ($q_{sat}$ is saturated relative humidity and $T_s$ is surface temperature at the surface), $q_a$ is relative humidity above the canopy.

The surface temperature of the canopy was estimated from the upward longwave radiation $L_d$ above the canopy using Stefan-Boltzman equation as follows:

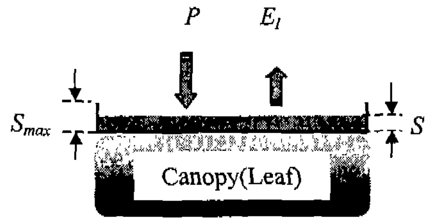


Fig.2 Tank model of the canopy

$$T_s = \{L_d / (0.95\,\sigma)\}^{0.25} - 273.15 \qquad (3)$$

where $\sigma$ is Stefan-Boltzman constant.

In the estimation of evapotranspiration, interception loss $E_I$ and transpiration $E_T$ were separately estimated depending on the wetness of the canopy. Interception storage $S$ was estimated from start and end times of precipitation, amount of gross rainfall, cease and restart times of sap flow assuming the tank above the canopy (see Fig.2).

Relationship between the wetness of the canopy and environmental factors related to evapotranspiration in the big leaf model is schematically depicted in Fig.3 In the figure, $r$ is the resistance, which is the reciprocal of product of bulk transfer coefficient and wind speed $Cu$. Subscriptions $E$ , $H$ indicate evaporation and sensible heat respectively. Subscription $C$ indicates canopy resistance.

Interception loss $E_I$ and transpiration $E_T$ were estimated in the following procedure using 10 minutes data.

*2.5.1 Interception loss $E_I$ (when canopy is wet)*

1) When canopy is wet, intercepted storage on the canopy is evaporated and there is no transpiration.
2) Canopy is saturated, thus surface relative humidity $q_s$ is expressed by the saturated relative humidity of the surface temperature $q_{sat}(T_s)$.

$$q_s = q_{sat}(T_s) \qquad (4)$$

3) Resistance of evaporation is equal to the resistance of sensible heat. Thus bulk transfer coefficients of evaporation and sensible heat are equivalent.

$$r_E = r_H \qquad (5)$$

$$C_E \ u = C_H \ u \qquad (6)$$

4) Interception loss $E_I$ is estimated by the following equation:

$$E_I = \rho C_H \ u \{q_{sat}(T_s) - q_a\} \qquad (7)$$

5) Bulk transfer coefficient $C_H$ is calculated from equation (7) by assuming that the gross rainfall and interception loss are equivalent during short periods from cease to restart of sap flow when gross rainfalls are relatively small.

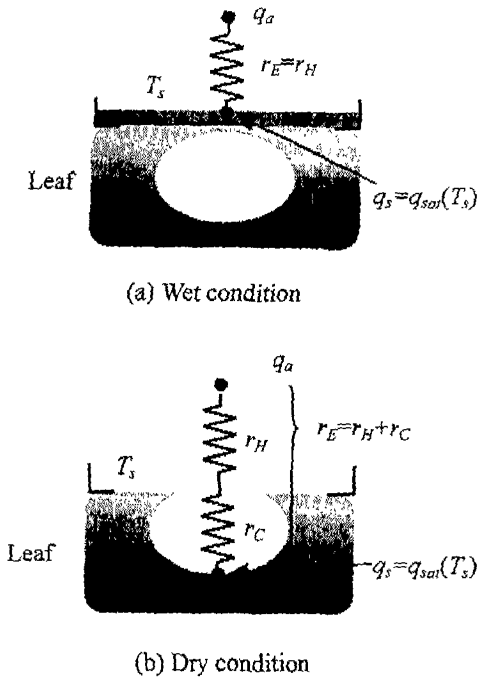


Fig.3 Outline of a big leaf model

*2.5.2 Transpiration $E_T$ (when canopy is dry)*

1) When canopy is dry, transpiration is occurred through stomata and there is no evaporation from the surface of the leaf.

2) Intercellular space is saturated and the relative humidity $q_s$ is expressed by the saturated relative humidity of the surface temperature $q_{sat}(T_s)$.

$$q_s = q_{sat}(T_s) \qquad (8)$$

3) Resistance of the transpiration is equal to the sum of the resistances of sensible heat and stomatal resistance.

$$r_E = r_H + r_c \qquad (9)$$

$$C_E u = C_H u / (1 + C_H u r_c) \qquad (10)$$

4) Transpiration $E_T$ is estimated from the following equation:

$$E_T = \rho C_H u \{q_{sat}(T_s) - q_a\} / (1 + C_H u r_c) \qquad (11)$$

5) Stomatal resistance $r_s$ is calculated from stomatal conductance $g_{SW}$.:

$$r_s = \rho_a / g_{SW} \qquad (12)$$

Stomatal conductance $g_{sw}$ is expressed by functions of global solar radiation *Rs* and vapor pressure deficit *VPD*.

$$g_{SW}=g_{SW\,max}f_1(Rs)\,f_2(VPD) \tag{13}$$

where $g_{SW\,max}$ is the maximum of $g_{SW}$, and the functions of $f_1(Rs)$ and $f_2(VPD)$ are expressed as follows:

$$f_1(Rs) = Rs/(a+Rs) \tag{14}$$

$$f_2(VPD) = 1-b\ VPD \tag{15}$$

These parameters are calculated using the data obtained on July 26, 2000 by means of the portable photosynthesis system.

6) Canopy resistance $r_c$ is calculated using the equations and parameters obtained in the above-mentioned process of stomatal resistance $r_s$ except that the constant $b$ is divided by 10 to adjust from a single leaf to the canopy emperically.

## 3 RESULTS AND DISCUSSIONS

### *3.1 Physical properties of examined Pasania edulis Makino*

*Pasania edulis Makino* is a tree having radial pores structure. Vessels are radially distributed from the pith to the cambium. Areal ratio of vessels measured with the digital photomicrograph was 4.78%.

Physical properties of the stem samples are shown in Table 1. Average volumetric water content of the stems at sampling was about 0.45cm$^3$/cm$^3$. Water content was almost evenly distributed from the pith to the cambium as shown in Fig.3.

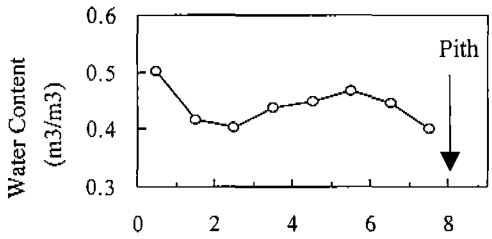


Fig.3 Water content of the stem at sampling

Table 1 Physical properties of the stem samples

| Sample No. (Date of sampling) | | Tree-1 Sep.5, 2000 | Tree-2-1 Sep.8, 2000 | Tree-2-2 Sep.8, 2000 | Average |
|---|---|---|---|---|---|
| Water content at sampling | cm$^3$/cm$^3$ | 0.458 | 0.432 | 0.456 | 0.445 |
| Saturated water content | cm$^3$/cm$^3$ | 0.475 | 0.459 | 0.470 | 0.468 |
| Bulk density at sampling | g/cm$^3$ | 1.092 | 1.086 | 1.119 | 1.099 |
| Saturated bulk density | g/cm$^3$ | 1.109 | 1.113 | 1.133 | 1.118 |
| Dry bulk density | g/cm$^3$ | 0.633 | 0.654 | 0.663 | 0.650 |

### *3.2 Relationship between heat pulse velocity and water uptake*

Fig.4 shows the distribution of relative heat pulse velocity at 0.8m height of the Tree-1. The maximum velocity was appeared at 1.5cm from the stem surface. The Heat pulse velocity was gradually decrease toward the pith but it was detected even near the center at 1.3cm from the pith. In case of ring porous trees such as *Cyptomeria japonica* D.DON and *Chamaecyparis obtusa*, no sap flow was detected in heart wood (Takizawa *et al.*, 1996). In case of diffuse-porous trees such as *Maonolia saliciforia* MAXIM, sap flow is almost evenly distributed but no sap flow exists in the central part (Takizawa *et al.*, 1996). The distribution of heat pulse velocity of the trees having radial pores have not yet reported. Thus the result shown in Fig.4 will be another

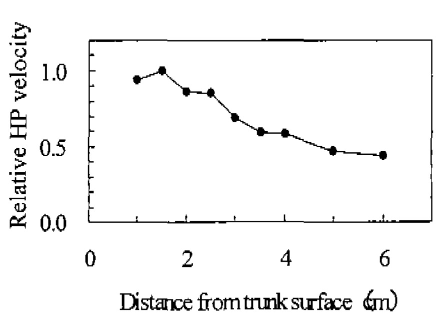


Fig.4 Distribution of relative heat pulse velocity

milestone for the sap flow measurement.

Conversion coefficient from the heat pulse velocity at 1cm depth to the average one was calculated using the distribution pattern of Fig.4 and obtained as 0.667.

Fig.5 shows the water uptake from the tree cut end and the heat pulse velocity at the fixed point of 0.8m height. Sudden increase of water uptake after cutting in case of a conifer experienced 7 continuous dry spell days reported by *Takizawa et al.* (1996) was not detected. Since the distance between the cut end and the location of the heat pulse measurement was short (about 40cm), the variations of them were well correspond. However, the ratio of water uptake to heat pulse velocity on the second and third days became slightly larger than the one on the first day. The stomatal conductance measured with the portable photosynthesis system also slightly increased from the second day. These facts suggest that water conductivity of the tree became larger from the second day by the effect of free water uptake from the cut end. Thus, assuming that the water conductivity of the tree before cutting was kept on the first day, we calibrate the heat pulse velocity to sap flow using the data of the first day.

The heat pulse velocity was corrected by Swanson and Whitfield's method (1981). The corrected heat pulse velocity of the fixed point was converted to an average heat pulse velocity by multiplying a conversion constant 0.667 obtained from the velocity distribution. Then the total area of the stem at the measuring point, 166.6cm$^2$, was multiplied to the average heat pulse velocity to obtained an apparent heat pulse flow. The calibration coefficient of the apparent heat pulse flow to the water uptake, i.e.sap flow, was 1.254. Measured and estimated sap flow rate are well coincide with a root mean square error of 3g/min.

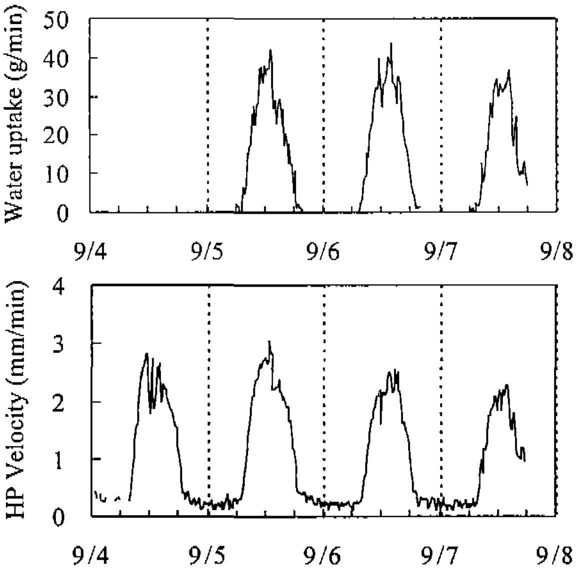


Fig.5 Variations of water uptake and heat pulse velocity at 1cm depth 0.8m height

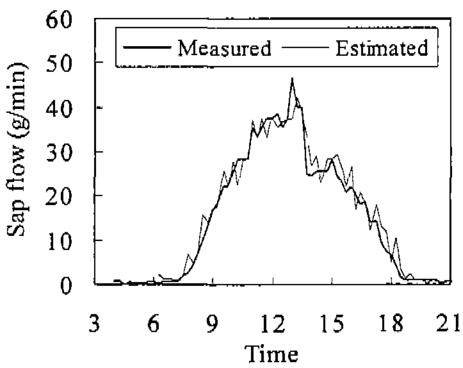


Fig.6 Diunal variations of measured and estimated sap flow

*3.3 Relationship between estimated and measured transpiration*

Heat pulse velocity had been measured at 60cm height on the Tree-2 since June 1999 until the tree cutting measurement on September 8, 2000. The sap flow $J$ was calculated from the heat pulse velocity using the calibration coefficient obtained by the tree cutting measurement. Transpiration is calculated by scaling up from the calculated sap flow of a single tree to the forest as follows:

$$T = J\,(A_{ave}/A_{meas})\,n \qquad (16)$$

where $T$ is transpiration, $A$ is cross-sectional stem area at the breast height and $n$ is average stock per square meter. The subscription *ave* and *meas* indicate the average and the value of measured tree.

Some seasonal transpiration calculated using the heat pulse velocity is shown in Fig.7. There have been argument about propriety of continuous measurement at the same point. In this case, heat pulse velocity had been continuously measured at the same point. As shown in Fig.7, however, we could reasonably measure heat pulse velocity. Transpiration peaked at the beginning of August. It was then gradually decreased. Transpiration in December became about half of the one in August. These tendency corresponded with the one of solar radiation. Since the last half year of 1999 was relatively wet, it could be assumed that the transpiration in this period was mainly affected not by soil moisture nor vigor of the tree but by climatological factors.

Estimated transpiration by means of the big leaf model is also shown in Fig.7. Although the parameters used in the big leaf model is obtained from the photosynthesis and transpiration measurement of leaves in one days in summer, the estimated values are well coincided with the measured values throughout the year. This result induces that the stability of the parameters in the big leaf model at least in this half year.

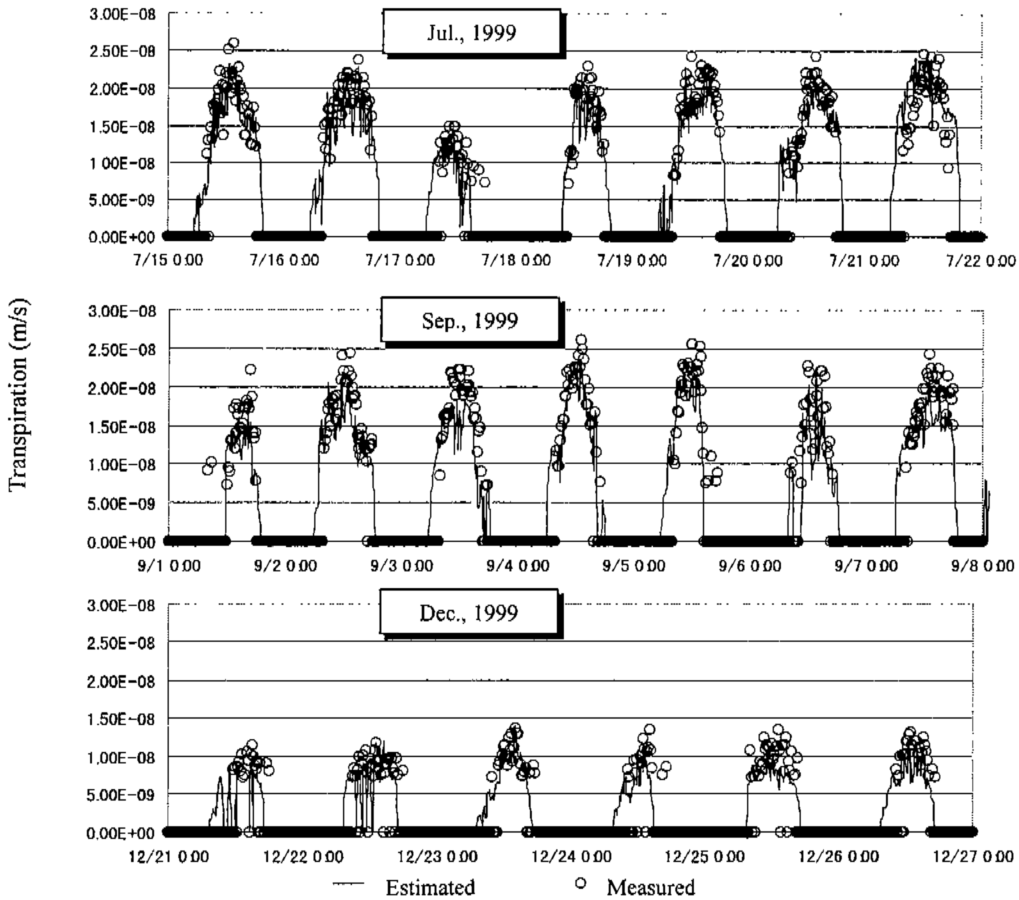


Fig.7 Seasonal variations of measured and estimated transpiration in 1999

## 4 CONCLUSION

In this study, methods to measure and estimate transpiration of a forest consisted of evergreen broad-leaved trees (*Pasania edulis Makino*) are studied. Heat pulse velocity has been measured along with soil moisture and micrometeorological factors. Tree cutting measurement was conducted to convert the heat pulse velocity into sap flow and transpiration. A big leaf model to calculate transpiration and interception loss is examined and the estimated values are compared with the measured values obtained from the heat pulse measurement.

The results show that:

1) *Pasania edulis Makino* posessing radial pore structure had relatively high water content and high heat pulse velocity even within the central part of the stem near the pith,
2) the heat pulse velocity was well correspond to the water uptake in the tree cutting measurement,
3) the estimation of sap flow based on the heat pulse velocity is accurate, and

4) the big leaf model using the parameters obtained from the photosynthesis and transpiration measurement of leaves in one days in summer gives reasonable estimation of transpiration independent of seasons and weather.

Heat pulse methods have been favorably developed owing a great deal to high-tech sensors and advanced data loggers. Reliability of the heat pulse methods to evaluate transpiration has been confirmed by extensive researches on the methods (Green andClothier, 1988; Schiller and Cohen, 1995). Usefulness of the methods to investigate forest ecosystem has been widely recognized (Loustau *et al.*, 1996; Kristen, 1996; Goldstein *et al.*, 1998). However, most of the method are still based on the simple assumptions of heat conductance in tree xylems. Thus they are still developing technologies to be modified and to be extended for multiple-purpose use Although we have not yet interrelated the data of the forest ecosystem, we could find the ways to measure and estimate transpiration and the physiological features of sap flow of the evergreen broad-leaved tree having radial pore structure.

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