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MEASUREMENT OF TREE TRANSPIRATION USING LARGE WEIGHING LYSIMETERS

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SYNOPSIS

The difference of transpiration processes between coniferous and broad-leaved trees is one of the most interesting topics in forest hydrology and water resources engineering. Direct measurement of transpiration is indispensable for detailed discussions of the topics. As known the lysimeter is the most effective tool to directly measure transpiration of the trees. For this reason, two large weighing lysimeters were developed in this study. A Japanese zelkova (*Zelkova serrata*) and a Japanese cedar (*Cryptomeria japonica*) were planted in containers of the lysimeters, and transpiration was measured. Transpiration was highly correlated with common meteorological parameters and heat pulse velocity. The latter is known as a reliable index of transpiration rate. Transpiration was measured by the lysimeters within the range of acceptable errors. Significant differences in the actual transpiration rates and processes were not found between coniferous and broad-leaved trees.

INTRODUCTION

Precise evaluation of evapotranspiration is indispensable for calculating the water balance of catchment basins in the course of the planning of water resources development and management. In reality, evapotranspiration is one of the most important hydrological processes, because it dominates rainwater flowing into the stream. Evaporation takes place on the surface of the trees during rainfall events and reduces the rainfall reaching the ground, while transpiration takes place through the inside of the trees between rainfall events and reduce the soil water. They affect the water circulation in the forests through the different processes. Thus, evaporation and transpiration should be evaluated separately. The meteorological method, for instance the Penman-Monteith equation (1, 2, 3) have been proposed. However, the Penman-Monteith equation contains an unknown parameter called "canopy resistance" being difficult to be identified without the measurement of the transpiration rate. The pressure chamber method enables us to measure the transpiration rate of the individual leaf. Therefore, the difficulty of evaluating transpiration in the forests has obliged us to evaluate them as 'evapotranspiration' for a long time. The comparison of the transpiration rate among different species have been tried and reported (4, 5). However, the information on transpiration from stands and forests is hardly found and the significant difference among the species was not reported.

The direct measurement of transpiration in the forests is actually impossible. Transpiration takes place through a soil-plant-atmosphere continuum, the so-called 'SPAC'. As transpiration is strongly affected by physiological processes of trees, such as the uptake of soil water by roots, sap flow in the stem, and transpiration from stomata of leaves, it is very difficult to quantify transpiration precisely. For this reason, authors (6) have been trying to mainly establish a methodology for evaluating transpiration in coniferous forests (*Cryptomeria japonica*). A mathematical model (Heat Pulse Transpiration Model) evaluating transpiration rate was developed, using heat pulse velocity as an index of sap velocity and meteorological data easily obtained in the fields. However, the model has not verified by the measurement of the transpiration rate yet. Direct measurement of transpiration in the developed trees is necessary to verify the model. Furthermore, the difference of transpiration processes between coniferous and broad-leaved trees is of great interest and importance to the efficient forest management for water resources planning. It is essential to carefully measure transpiration of both trees and investigate the difference between them with a consistent methodology. The rare measurement of transpiration using a large weighing lysimeter in Japan was reported by the Environmental Research Center, University of Tsukuba (7). The container of the lysimeter is a circular cylinder measuring 2.0 m in diameter and 2.0 m in depth, respectively. The change of the weight of the container is measured by an optical mechanical system. However, the maximum weighing capacity is 1500 kg; evapotranspiration of grass has been measured, but not of trees.

As mentioned above, it is impossible to measure transpiration of several developed trees at a height of 20 m in the fields at the same time. The conditions of the measurements are limited, and it makes a compromise with the height and age of the trees. In this study, two large weighing lysimeters were developed. Transpiration of both a Japanese zelkova (*Zelkova serrata*) and a Japanese cedar (*Cryptomeria japonica*) of 5.0 m high and 10 years old were simultaneously measured by the weighing lysimeters. The validity of the method and the difference of transpiration rate between a Japanese zelkova (*Zelkova serrata*) and a Japanese cedar (*Cryptomeria japonica*) are discussed.

MEASURING FACILITIES AND METHOD

Measuring facilities

Two large weighing lysimeters were developed in a yard of the Tokushima Prefecture Forestry General Technology Center (5-69 Shomachi, Tokushima 770-0045, Japan). Schematic illustrations of the lysimeters are shown in Figs. 1, 2 and 3.

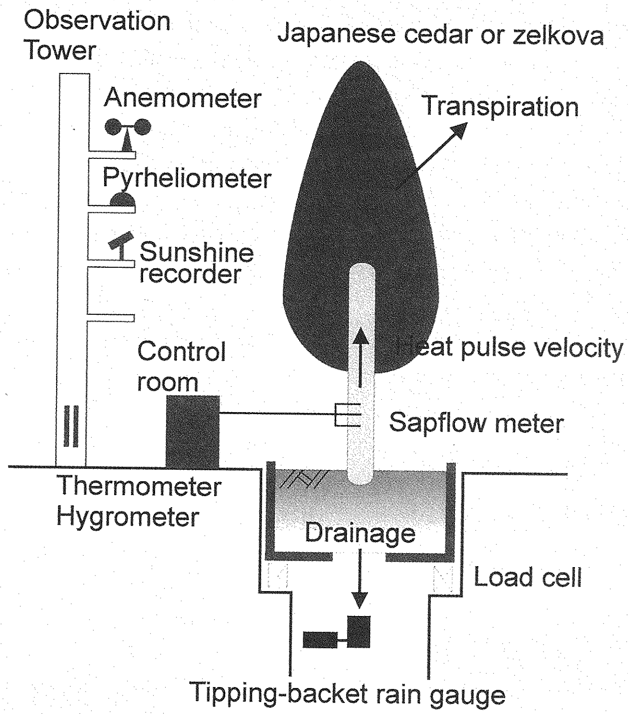


Fig. 1 Side view of lysimeters and observation tower

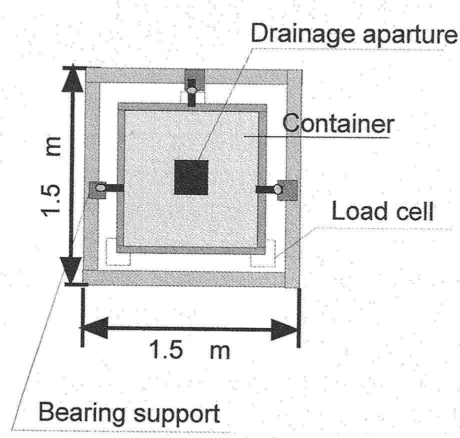


Fig. 2 Ground plan of "Lysimeter A"

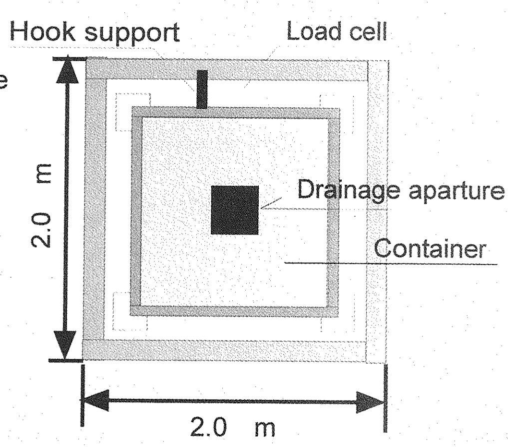


Fig. 3 Ground plan of "Lysimeter B"

A Japanese cedar (*Cryptomeria japonica*), 5.0 m in height and 10 years old, respectively, was planted in the square container of "Lysimeter A". The container of "Lysimeter A" is 2.0 m in length, 2.0 m in width, and 1.0 m in depth. The container, the soil, and the tree weigh approximately 6700 kg. The container is borne by four load cells the rated load of which is 3000 kg (Minebea Co. Ltd., C3P1-3T-U) shown in Photo 1. The amount of the weight of the lysimeter is transferred to a personal computer (NEC Co. Ltd., PC9800FX/U2) through an amplifier (UniPulse Co. Ltd., F8000-OP2) and an A/D transformation card (I/O Data Co. Ltd., PIO-9032C) every minute. The nominal lower limits of the measurement are 200 g and 300 g for "Lysimeter A" and "Lysimeter B", respectively. The soil surfaces of both containers are covered with vinyl sheets in order to prevent evaporation from the soil surfaces.

Another Japanese zelkova (*Zelkova serrata*), 4.0 m in height and 10 years old, respectively, was planted in the square container of "Lysimeter B". The container of "Lysimeter B" is 1.5 m in length, 1.5 m in width and 1.0 m in depth in order to reduce the dead load. The container, the soil, and the tree weigh approximately 2700 kg. The container is borne by three load cells the rated load of which is 3000 kg (Yamato Co. Ltd., CR2-3T-U) shown in Photo 2. The amount of the weight of the lysimeter is transferred to a personal computer (NEC Co. Ltd., PC9800FX/U2) in the same way as "Lysimeter A".

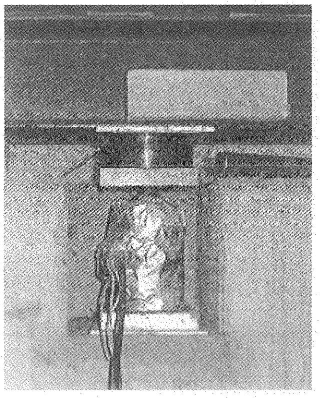


Photo 1 Load cell for "Lysimeter A"

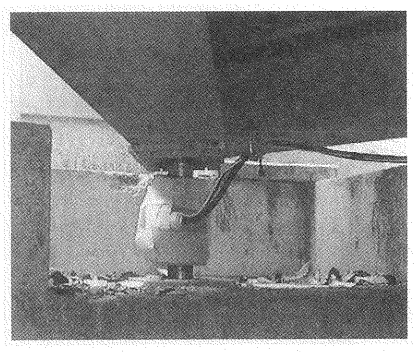


Photo 2 Load cell for "Lysimeter B"

A drainage aperture was opened on the bottom of each container in order to prevent rotting of the roots. Thus, the measurement of the water drained from the container is necessary. A tipping-bucket rain gauge (Yokogawa Weathac Co. Ltd., B-011-10) of a volume of 15.7 cc was installed in a working pit below each container. The drained water is measured by the rain gauge and transferred to a data logger (Oriental Electric Inc., JWA90R). Heat pulse velocity being an index of sap flow is measured by a "Sap Flow Meter" (Hayashi Denko Co. Ltd., HP-2) every 30 minutes and transferred to a personal computer (NEC Co. Ltd., PC9801FA) through a memory card. The distances between a heater and two thermisters are 10 mm and 7 mm. They were installed into holes at a diameter of 2.0 mm and at a depth of 10 mm. Major meteorological parameters (air temperature, relative humidity, wind speed, and net radiation) were taken by instruments (Yokogawa Weathac Co. Ltd., E-734-10, E-

771-11, A-772, and H-221) mounted on a 12 m observation tower and transferred to a personal computer (NEC Co. Ltd., PC9801FA) through a GPIB interface every 5 minutes. The containers were supplied with water every two days in order to maintain the suction of approximately –100 cm in the water head. Thus, the soil moisture did not seem to affect the transpiration process.

Data Processing

The lysimeters are not protected against wind in order to realize the natural experimental condition. The crude data of the weight contain highly frequent fluctuations because of the wind. Therefore, the data were to be smoothed by the method of the moving average at regular intervals of one hour. The hourly transpiration ΔW can be defined fundamentally as the decreasing weight of the lysimeters during one hour. However, the crude data contain the "virtual transpiration", namely the decrease caused by both the drainage from the containers and the air under the bottom of the container, because the air seems to affect the deformation of the container and the resultant change of its weight. The virtual transpiration is to be corrected in order to evaluate true transpiration precisely. The correction of the weight of the container has to be done individually because the influence seems to depend on the size of the container.

The effect of the drainage from the containers ΔWD was corrected by subtracting the cumulative drainage from the crude data of the weight. The effect of the surrounding air on the weight of the containers was formulated like the following procedure;

1) The trees are completely covered with thick shades.
2) The change of weight of the containers is measured before the trees are planted in the containers.
3) The air temperature is monitored under the bottom of the containers.
4) The relation between the change of weight and air temperature is evaluated.

A significant correlation was found between them as shown in Eqs. 1, 2 and 3, and Figs. 4 and 5. The theoretical measuring error of the container is 600kg. Eqs. 1 and 2 give the accurate correction terms, because the maximum errors found in Figs.5 and 6 are approximately 600-700 kg.

Lysimeter A (Japanese cedar):

$$WT(I) = 0.781\Delta T + 0.203 \quad (kg) \tag{1}$$

$$WT(I) = W(I) - W_6 \quad (kg)\ ; \qquad \Delta T = T(I) - T_6 \quad (℃) \tag{2}$$

Lysimeter B (Japanese zelkova):

$$WT(I) = 0.349\Delta T + 0.270 \quad (kg) \tag{3}$$

where $WT(I)$ = the correction term at an arbitrary time I, W_6 = the weight data at 6.00 a.m., $W(I)$ = the weight data at an arbitrary time I, $\Delta T(I)$ = the change of air temperature under the containers, $T(I)$ = the air temperature at an arbitrary time I, and T_6 = the air temperature at 6.00 a.m..

The real transpiration was evaluated by Eqs. 4 and 5.

$$\Delta W(I) = (W(I-\Delta t) + WT(I-\Delta t)) - (W(I) + WT(I)) \tag{4}$$

$$ET(I) = \Delta W(I) - \Delta WD(I) \tag{5}$$

where $ET(I)$ = the real transpiration at an arbitrary time I, $\Delta W(I)$ = transpiration including the virtual one at an arbitrary time I, Δt = a time interval of one hour, and $\Delta WD(I)$ = the cumulative drainage during one hour.

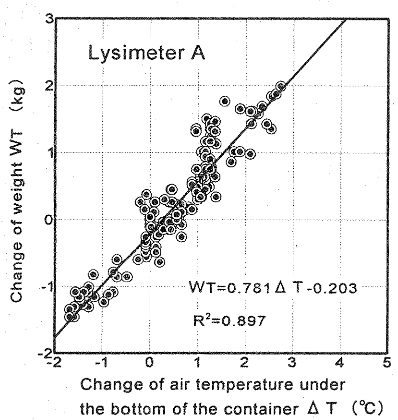


Fig.4 Relation between the change of weight and air temoerature under the bottom of the container (Lysimeter A)

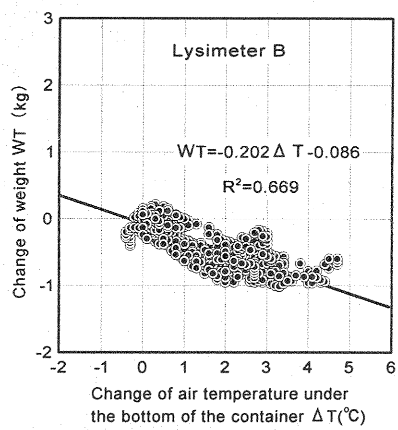


Fig. 5 Relation between the change of weight and air temoerature under the bottom of the container (Lysimeter B)

RESULTS

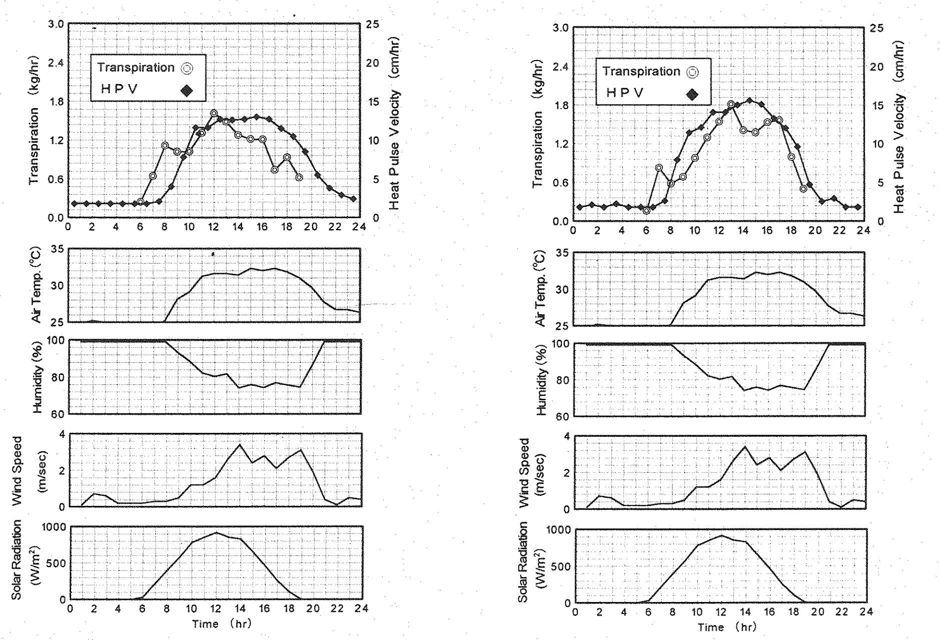
Diurnal Course of Transpiration and Other Parameters

The diurnal courses of transpiration, heat pulse velocity (HPV), air temperature, relative humidity, wind speed, and solar radiation are shown in Figs.6, 7, and 8. It is found that the diurnal courses of transpiration are almost similar to the measurements of solar radiation and heat pulse velocity being the index of transpiration rate. As a large part of the unexpected unevenness of the hourly transpiration is less than 400 g, it may remain within the range of the measuring error. Therefore, the transpiration measured by the large weighing lysimeters is reliable.

According to the figures, transpiration of a Japanese zelkova seems to be larger than that of a Japanese cedar. The same results were obtained on other days. However, these results never demonstrate that a Japanese zelkova transpires the vapour more than a Japanese cedar, because the size of the canopy, i.e. the transpiration areas, is different from each other. Thus, the transpiration rate from the unit area of the canopy is necessary to discuss the difference of transpiration processes among the different species.

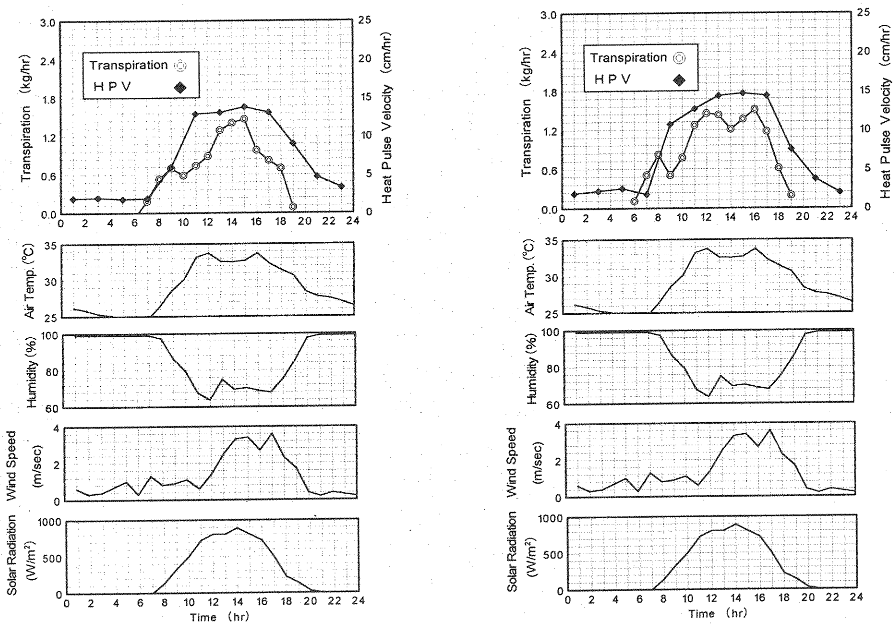
Time Lag between Transpiration and Heat Pulse Velocity

The time lag between transpiration and heat pulse velocity in several trees of different size has been reported. The authors (8) confirmed that the diurnal course of heat pulse velocity is about one hour behind transpiration. Suzuki et al. (9) reported that the time lag of a Japanese cypress (*Chamaecyparis obtusa*), about 12 m high, was approximately one hour, too. The same time lags are found in Figs. 6, 7, and 8. The relation between transpiration and heat pulse velocity is shown in Figs. 9, 10 and 11. The clockwise loops drawn by the solid line and opened circles are found in the figures because heat pulse velocity is behind transpiration. The time lag between transpiration and heat pulse velocity of one hour is corrected, and the relation between them is illustrated by a dotted line and closed circles in the same figures. In the case of a Japanese cedar, the loops close when the time lag of one hour is corrected. Thus, the time lags are almost of the same length as the results reported before. In the case of a Japanese zelkova, the loops tend to change from clockwise to counterclockwise when the time lag of one hour is corrected. Presumably, the time lags are between half and one hours. In general, the difference of the time lag cannot be found between a Japanese cedar and a Japanese zelkova being of almost the same age and height.



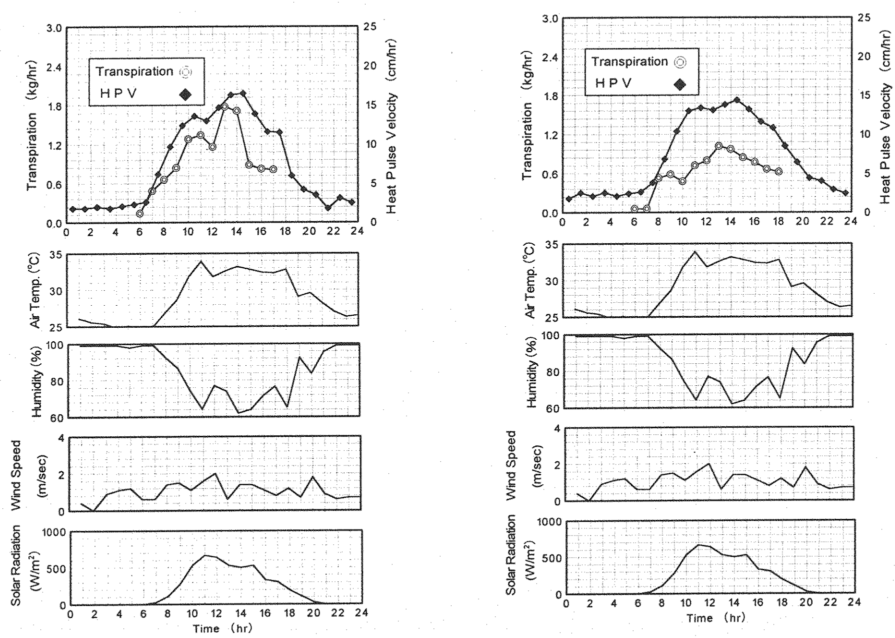
(a) Japanese cedar (Lysimeter A) (b) Japanese zelkova (Lysimeter B)

Fig. 6 Diurnal course of transpiration, heat pulse velocity and meteorological parameters



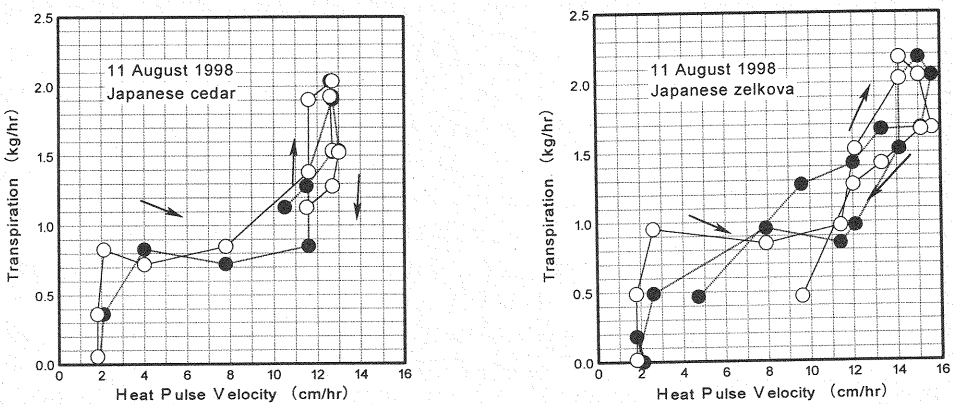
(a) Japanese cedar (Lysimeter A) (b) Japanese zelkova (Lysimeter B)

Fig. 7 Diurnal course of transpiration, heat pulse velocity and meteorological parameters



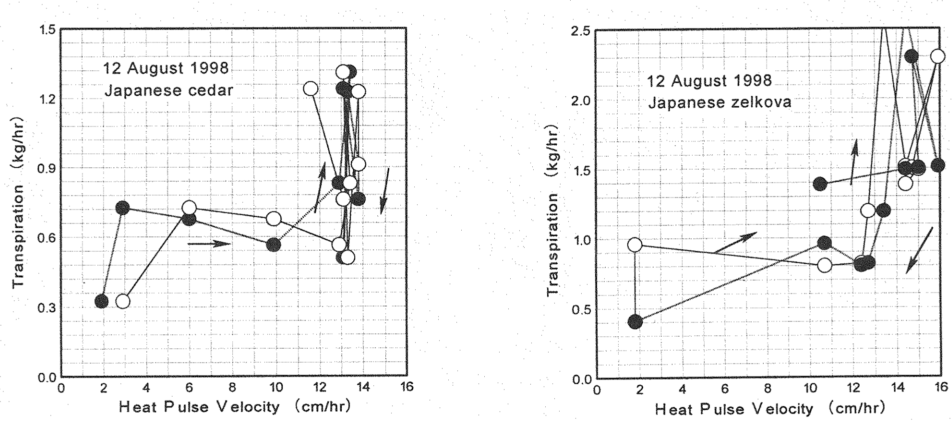
(a) Japanese cedar (Lysimeter A) (b) Japanese zelkova (Lysimeter B)

Fig. 8 Diurnal course of transpiration, heat pulse velocity and meteorological parameters



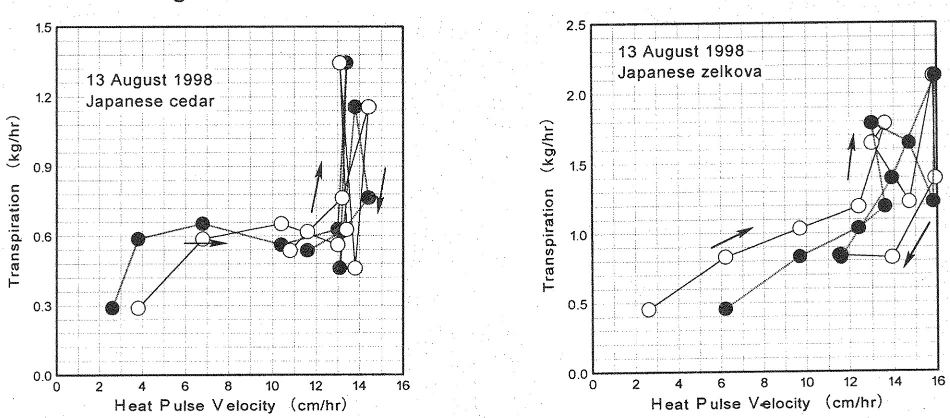
(a) Japanese cedar (11 August 1998) (b) Japanese zelkova (11 August 1998)

Fig. 9 Relation between transpiration and heat pulse velocity



(a) Japanese cedar (12 August 1998) (b) Japanese zelkova (12 August 1998)

Fig. 10 Relation between transpiration and heat pulse velocity

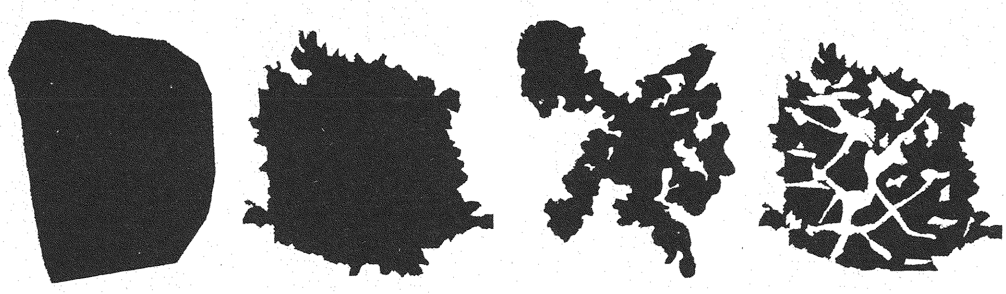


(a) Japanese cedar (13 August 1998) (b) Japanese zelkova (13 August 1998)

Fig. 11 Relation between transpiration and heat pulse velocity

Comparison of Transpiration between Coniferous and Broad-Leaved Trees

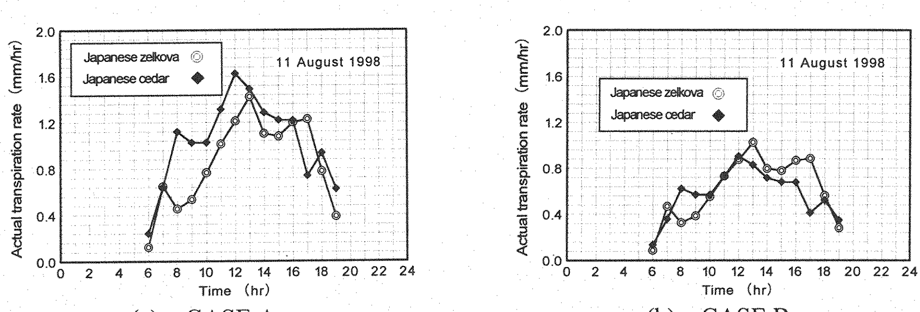
In this study, the area of the canopy projected on the ground was presumed to contribute to transpiration. The Leaf Area Index (LAI) is usually used for evaluating the area of canopy to take into account the overlap of the leaves. However, the LAI was not considered in this study, because the leaves were distributed only on the tip of each branch and did not overlap. Thus, the area contributing to transpiration was defined using the photographs taken above the canopy. When the photographs were taken, a scale of 1.0 m was installed at the same height of the canopy in order to compute the actual transpiration area of canopy A. Two kinds of areas were considered in this study. The definition of the actual transpiration area is shown in Fig.12. In 'CASE A' the transpiration area was defined as an inside area of an envelope curve of the canopy. In 'CASE B' it was defined as the area of which gaps among the leaves and branches are left out. The actual transpiration areas in 'CASE A' for Japanese zelkova A_{ZA} and Japanese cedar A_{CA} were determined as A_{ZA} = 12741cm^2 and A_{CA} = 9948cm^2, respectively. In 'CASE B' they are A_{ZB} = 17671cm^2 and A_{CB} = 17892cm^2, respectively.



(a) CASE A (cedar) (b) CASE A (zelkova) (c) CASE B (cedar) (d) CASE B (zelkova)

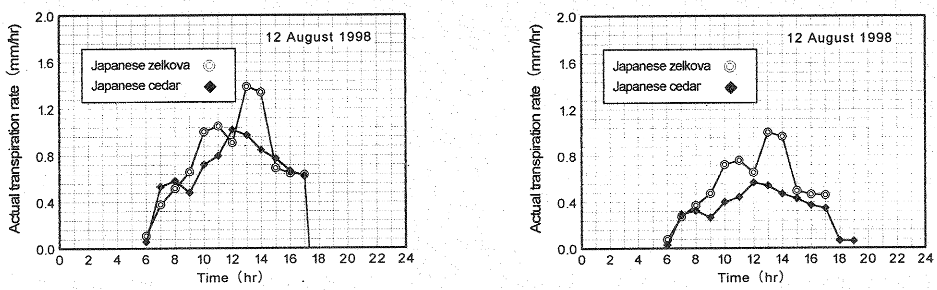
Fig. 12 Definition of transpiration area

The actual transpiration rate from a unit area is defined by dividing the area of canopy (transpiration area) into transpiration in order to precisely compare the difference of transpiration between the species. The comparison of the actual transpiration rate between a Japanese cedar and a Japanese zelkova is shown in Figs. 13, 14, and 15.



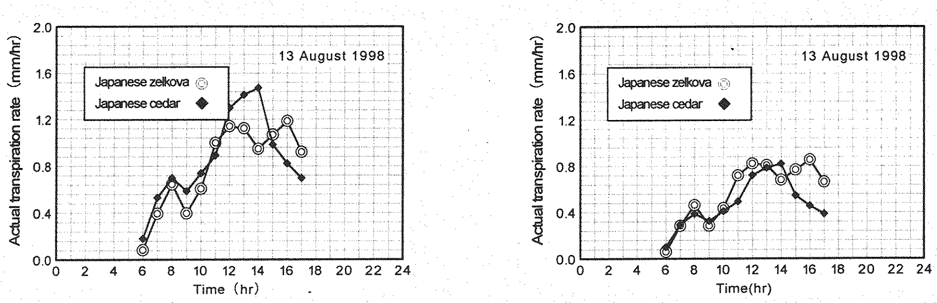
(a) CASE A (b) CASE B

Fig. 13 Comparison of actual transpiration rates (11 August 1998)



(a) CASE A (b) CASE B

Fig. 14 Comparison of actual transpiration rates (12 August 1998)



(a) CASE A (b) CASE B

Fig. 15 Comparison of actual transpiration rates (13 August 1998)

The significant difference of the actual transpiration rates between a Japanese cedar and a Japanese zelkova cannot be found in the figures,

although both diurnal courses of the actual transpiration rate do not agree due to some measuring errors of transpiration and the area of canopy. The comparison of the daily transpiration is shown in Table. 1. There is no significant difference of daily transpiration between the species either. The deficit of soil moisture did not seem to affect the transpiration process, because the soil water potential was always over -200 cm in the water head. Thus, it was suggested that there was no significant difference of the actual transpiration rate between a Japanese cedar and a Japanese zelkova within the experimental results.

CONCLUDING REMARKS

In this study, transpiration of a Japanese zelkova (hardwood) and a Japanese cedar (conifer) at an approximate age of 10 years was measured by large weighing lysimeters. Subsequently, the difference of the actual transpiration rate between the species was investigated. It was demonstrated that the large weighing lysimeters were measuring transpiration within a range of experimental errors. Thus, the results were acceptable and the bright prospect for measuring transpiration, using the large weighing lysimeters, was obtained. It was presumed that there was no significant difference of the actual transpiration rate between a Japanese zelkova and a Japanese cedar. For a long time, the transpiration of broad-leaved trees was regarded larger than that of coniferous trees. However, the measurements suggested the contrary. In future, authors are going to apply the "Heat Pulse Transpiration Model (10)" to the results obtained from the measurement of transpiration using the large weighing lysimeters, and investigate the difference of transpiration processes between broad-leaved and coniferous trees in order to discuss it by a consistent methodology.

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REFERENCES

1. Monteith, J. L.: Evaporation and environment, In The state and movement of water in living organisms (Fog, G. E. ed.), Symp. Soc. Exp. Biol., Academic Press, New York, pp.205-234, 1965.
2. Calder, I. R.: A modelof transpiration and interception loss from a spruce forest in Plynlimon, Central Wales, J. Hydrology, Vol.33, pp.247-265, 1977.
3. Rampisera, D.A., Suzuki, M. and Fukushma, Y.: Aplication of the Penman-Montheith Model to the Estimation of the Evapotranspiration rate of a forested Watershed, J. Jpn. For. Soc., Vol.72, No.1, pp.198-297
4. Joo, S., Yahata, H. and Suzaki, T: Photosynthesis and transpiration in several tree species of the stands for the environmental conservation, J. Jpn. For. Soc. Kyushu Branch, No.42, pp.129-130, 1989.
5. Yoshikawa, Ken and Wang, L.: Effects of Soil Water Conditions on the Transpiration Rate of Cut Branch of Several Tree Species, J. Jpn. Soc. Reveget. Tech, Vol.17, No.4, pp.203-212, 1992.
6. Hashino, M. and H. Yoshida: Estimation model of single tree transpiration based upon heat pulse velocity and micrometeorological data, IAHS Publication, No.212, pp.137-144, 1993.
7. Nakagawa, S.: Study on evaporation from pasture, Environ. Res. Cent. Papers, The University of Tsukuba, pp.18-26, 1980.
8. Hashino, M. and H. Yoshida: Transpiration Model Associated with Sap Flow and Meteorological, IAHS Publication, No.204, pp.317-328, 1991.
9. Suzuki, M.: Hydrological Research on Transpiration in Mountain Catchment, Report of the Grant-in-Aid for Scientific Research, Ministry of Education, Science, Sports and Culture, pp.1-59, 1990 (in Japanese).

APPENDIX – NOTATION

The following symbols are used in this study:

$ET(I)$	= real transpiration;
HPV	= heat pulse velocity;
I	= arbitrary time;
$T(I)$	= air temperature under the container at an arbitrary time I;
T_6	= air temperature under the container at 0600 in the morning;
$W(I)$	= weight of the lysimeter at an arbitrary time I;
$WT(I)$	= corrected weight at an arbitrary time I;
W_6	= weight of the lysimeter at 0600 in the morning;
Δt	= time interval of one hour;
$\Delta T(I)$	= change of air temperature under the container;
$\Delta W(I)$	= transpiration including virtual ones at an arbitrary time I; and
$\Delta WD(I)$	= cumulative drainage from the container during one hour.

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