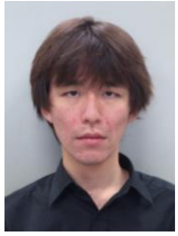

Tomoki KIYONO

Weighing whole tree transpiration rate of urban trees and analysis of trees morpho-physiological effects

Tomoki KIYONO[1], Takashi ASAWA[2], Akira HOYANO[3], Katsuya SHIMIZU[4]
1 Tokyo Institute of Technology, Interdisciplinary Graduate School of Science and Engineering, Yokohama, Japan, kiyono.t.ab@m.titech.ac.jp
2 Tokyo Institute of Technology, Interdisciplinary Graduate School of Science and Engineering, Yokohama, Japan, asawa.t.aa@m.titech.ac.jp
3 Open University of Japan, Chiba, Japan, hoyano@ouj.ac.jp
4 TOYOTA Motor Corporation, Biotechnology & Afforestation Business Division, Aichi, Japan, Katsuya_Shimizu@mta.mx.toyota.co.jp

Abstract

The purpose of this study is to quantify the species variation of whole tree transpiration rates and the sensitivity of single tree's vapor diffusion conductance (G_v) to atmospheric condition, vapor pressure deficit (VPD) and photosynthetic active radiation (PAR). The sample trees are under soil volume restricted (0.5 m^3) and isolated condition which assuming roadside or garden trees in urban area. We developed hanging type gravimeter using S-shape beam load cells and container planted trees, which enables to measure hourly transpiration rate accurately and is convenient to weigh a number of samples in a short period. This paper report the result of the measurement in summer irrigation period and the comparison of parameterization schemes of G_v to reconcile model simplicity and species variation in hourly transpiration rate prediction.

1. Introduction

Transpiration effect is expected to mitigate urban thermal environment but efforts to predict urban trees' transpiration are complicated by our limited knowledge of how much and different whole tree's water use is. The difficulty in understanding urban trees' transpiration is mainly caused by the limitation of measurement method. In previous studies dealt with whole tree transpiration rate of urban tree (e.g. Bush et al. 2008, Peters et al. 2010, Chen et al. 2011), transpiration rate were estimated by sap flow measurement mainly using Granier's thermal dissipation sensor. However, it is well known that Granier's sensor can leads significant systematic error according to xylem porosity (cf. Steppe et al. 2010) and sapflow velocity can lags a few hours behind real transpiration rate (e.g. Saugier et al. 1997). Therefore, the differences in hourly base whole tree transpiration rate among species are uncertain, as is the averaged value of the transpiration rate among species under urban environments.

Stomatal conductance is one of the most important parameter when predicting tree's energy balance and microclimate effect using numerical simulations. Because of the biological process of stomatal openness and water transportation in a tree are extremely complicated and data-intensive, stomatal conductance models used in climate models need empirical or semi-empirical calibration (e.g. Jarvis 1976, Collatz et al. 1991). However, the parameters and microclimate effect of urban tree transpiration is simply evaluated using data from forests and trees under different conditions; reliable and applicable data for urban trees are deficient.

This paper reports the result of the whole tree transpiration rates measurement by use of a gravimeter in summer irrigation period and the comparison of the sensitivities of vapor diffusion conductance of single tree (G_v) which correlates with total leaf area and mean stomatal conductance to VPD and PAR among 11 popular urban tree species in Japan. After that, we evaluated the importance of parameters in conductance model to reconcile model simplicity and species variation in hourly transpiration rate prediction by the comparison of different parameterization schemes.

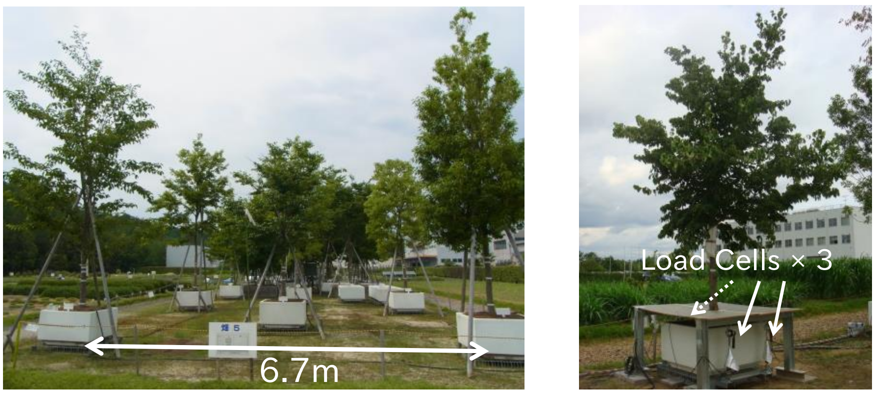

Fig. 1 Photos of farm field (left) and measurement of tree weight using load cells (right).

2. Materials and Methods

2.1 Site Description

The measurement site is an experimental farm field with an area of 8800 m² in Miyoshi city of Aichi prefecture, Japan (35°8′N, 137°6′E). The positions of the trees are shown in Figure 1 and Figure 2. The distances between the trees were greater than 4 m, so that each tree could easily receive solar radiation and air flow. This planting condition was considered for application of the experimental results to urban environmental conditions.

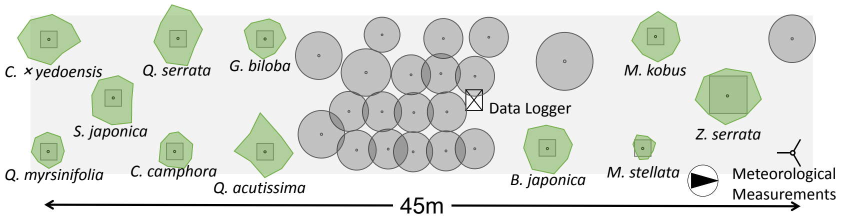

Fig. 2 Plot plan of farm field in summer 2012.

2.2 Tree Materials

Previous works of plant physiology have discussed the effects of leaf life-span (evergreen or deciduous), xylem porosity, trunk diameter (sapwood area) and tree height on transpiration characteristics. In the present study, we selected 11 tree species for the comparison experiment, taking into account leaf life-span and xylem porosity. Table 1 shows the selected trees and their characteristics. The tree heights varied from 3 m to 7 m in the year 2012, during which many of the measurements were conducted. These trees were planted in individual large containers with areas of 1 m² and depths of 0.6 m.

Table 1 Characteristics of sample trees.

	Z. s. 2010	Z. s. 2012	Q. m. 2012	Q. m. 2013	S. j.	C. × y.	G. b.	Q. s.	C. c.	B. j.	M. s.	Q. a.	M. k.
Daily Transpiration [kg/tree/d]	28.1	25	6.8	26.8	10.9	13.7	16.3	32.2	28.1	22.2	11.5	25.1	20.9
Leaf Life-span [month]	8	8	36	36	8	8	8	8	12	8	8	8	8
Xylem Porosity	Ring	Ring	Diffuse	Diffuse	Diffuse	Diffuse	Tracheid	Ring	Diffuse	Diffuse	Diffuse	Ring	Diffuse
Crown Projection Area (8 points) [m^2]	5.5	9.2	3.3	-	6.6	7.8	4.5	7.3	3.6	6.9	1.5	7.5	6.1
Tree Height [m]	6.4	6.4	5.5	-	4.4	5.5	5.4	5.8	4.7	4.5	3	6.7	4.1
Basal Diameter [cm]	-	-	12	12	11	14	13	14	13	12	6	11	13
Trunk Diameter [cm] (below the lowest living branch)	10	11	10	10	9	10	10	9	9	9	5	8	8

2.3 Measurement Devices

The meteorological data was measured at the northern part of the experimental field and the measurement height for wind direction and velocity was 4 m. The trees' morphologies measurements was conducted using terrestrial laser scanner (Asawa et al. 2014). The measurement devices are shown in Table 2.

In order to accurately measure whole tree transpiration, gravimeters were developed using weighing load cells. Whole tree transpiration rates were measured by the weight change of sample trees planted in container. For the long term measurement of *Zelkova serrata*, a platform weighing machine (Sartorius AG, CAPS4-1500LL-I) was used (Asawa et al. 2012). The water balance was also measured, including the amount of supply and drainage water. The evaporation from the soil surface was restricted by a cover, and the soil surface was shielded from rain water by a shed. For short term measurements of the other species, S-shape beam load cells (Minebea, U3S1-100K~5T-NS) were used. The container was hanged by the load cells at three points, and the weight change was measured (Figure 3). We confirmed that the measurement error of whole tree transpiration rates was within 100 g/h when wind velocity was below 1.5 m/s for platform type (Asawa et al. 2012), and the mean relative error (2 S.E.) of all species' hourly transpiration rate of hanging type was about 10% when wind velocity was below 2.0 m/s.

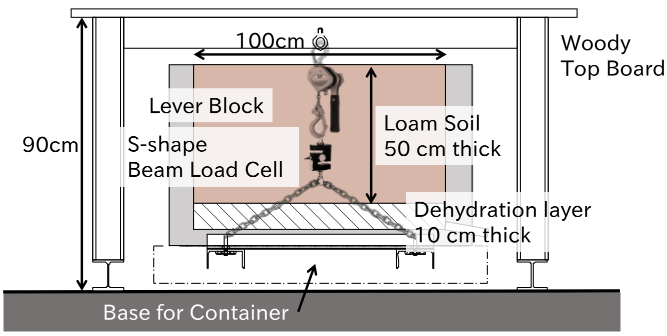

Fig. 3 Hanging type gravimeter for whole-tree transpiration measurements (Short term measurement).

Table 2 Measurement devices.

Measurement item	Device
Weight (Trees + Soil + Container) 1) Zelkova serrata 2) Other species	1) Platform weighinh machine (Load cell type) CAPS4-1500LL-I (Zartorius AG) 2) S-type beamload cells × 3 U3S1-100K ~ 5TNS (Minebea)
Soil water content	ADR soil moisture sensor ThetaProbe ML2x (Delta-T)
Air temperature	Aspirated radiation shield YG-43502 (R.M. Young) Platinum resistance thermometer (Pt100)
Relative humidity	Capacitive humidity sensor
Global solar radiation	Pyranometer (Thermopile type) MS-402 (EKO Instruments) 0.3 ~ 2.8μm
Wind direction and wind velocity	3D ultrasonic anemometer CYG-81000 (R.M. Young)
Phosynthetic photon flux density	Quantum sensor LI190 (Li-COR) 0.4 ~ 0.7μm
Precipitation	Tipping bucket type rain gauges TE525MM (Campbell Scientific)

2.4 Irrigation Scheme and Measurement Period

The water supply volume was fully controlled and the water supply was automatically implemented at midnight on each day. The transpiration rate of *Zelkova serrata* was measured continuously from July 2010 to the end of 2013. The transpiration rates of the other ten species were measured for about two weeks in the summer of 2012 and 2013, and three species were measured at a time. For *Quercus mirsinifolia*, the transpiration rate was measured in both 2012 and 2013, because the tree had been moved from an area enclosed by other trees to an open space before the 2012 measurement.

2.5 Calculation of Vapor Diffusion Conductance

Transpiration from a leaf can be described as a vapor diffusion process and expressed using a series of resistances of stomata and leaf boundary layer. When the plant have small leaf or is susceptible to wind such as tall or isolated tree, boundary layer resistance can be smaller than stomata one-several tenths. In this study, because sample trees are isolated and we confirmed leaf temperatures were nearly equal to air during measurement, G_v is estimated by Eq. (1) using measured whole tree transpiration rates and VPD. The sensitivity of G_v to atmospheric condition is expressed by Eq. (2), multiplicative type conductance model (Jarvis 1976).

$$E = G_v \frac{VPD}{p_a} \tag{1}$$

$$G_v = \left(G_{vref} - b_1 \ln(VPD)\right) \frac{PAR}{PAR + b_2} \tag{2}$$

where p_a is air pressure [kPa], G_{vref}, b_1 and b_2 are fitting parameters. G_{vref} indicates the reference value of G_v when VPD = 1kPa and no light limitation. In general, stomatal conductance decreases exponentially with increasing VPD between leaf and air to prevent critical water loss (cf. Oren et al. 1999, Katul et al. 2009). In this study, PAR value measured on horizontal plane was used in Eq. (2) as a proxy of tree absorption value.

3. Results and Discussion

3.1 Comparison of transpiration rates among species

The results obtained during clear sky days were selected and used for the analysis, so as to select data gathered under identical conditions. Fig. 4 shows the diurnal patterns of transpiration rates and vapor diffusion conductances. *Zelkova serrata* (2010), *Quercus serrata* and *Cinnamomum camphora* transpired over 3 kg/h (2 kW of latent heat) that was the highest value in samples and used the largest daily transpiration amounts, approximately 30 kg/d. The next largest amounts were observed in *Quercus mirsinifolia* (2013), *Quercus acutissima* and *Zelkova serrata* (2012), which showed values of approximately 25 kg/d. In contrast, the smallest transpiration amounts were observed in *Quercus mirsinifolia* (2012), *Styrax japonica* and *Magnolia sellata*, with these species showing values of approximately 10 kg/d. The transpiration amounts of *Zelkova serrata* and *Quercus mirsinifolia* largely varied from year to year. Although the leaf area of *Zelkova serrata* increased from 15.4 m^2 in 2010 to 28.9 m^2 in 2012, the transpiration amount slightly decreased. Water conductance of a tree is restricted by root surface area and cross-sectional area of sapwood, therefore, the maximum transpiration value of *Zelkova serrata* was 30 kg/d under the conditions of soil volume (0.5 m^3) and trunk diameter (0.1 m). In contrast, for *Quercus mirsinifolia*, although the crown shape and leaf area did not change considerably from 2012 to 2013, the transpiration amount increased by a factor of three. These findings indicate that photosynthetic ability largely increased due to the change in tree location from an enclosed space to an open space, which resulted in changes in the surrounding conditions.

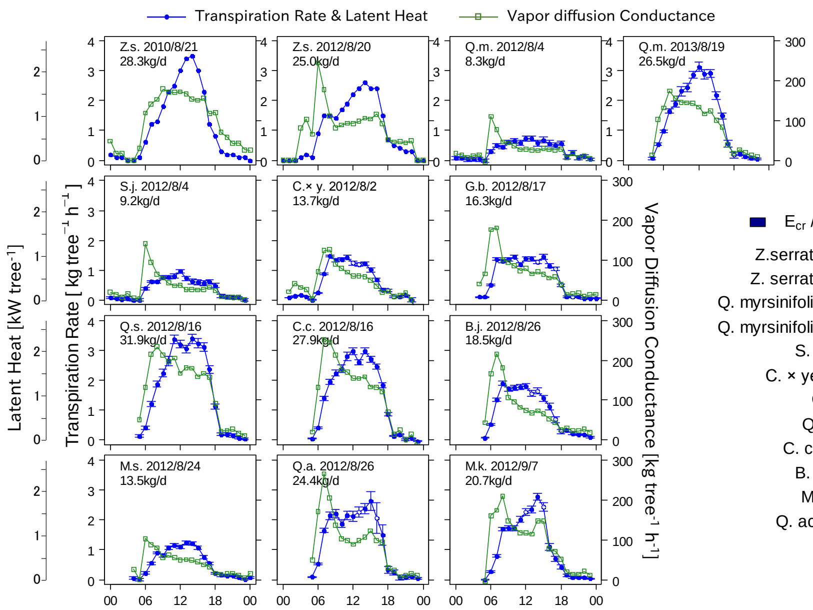

Fig. 4 Diurnal patterns of transpiration rates and vapor diffusion conductances (bars: 2 S.E.).

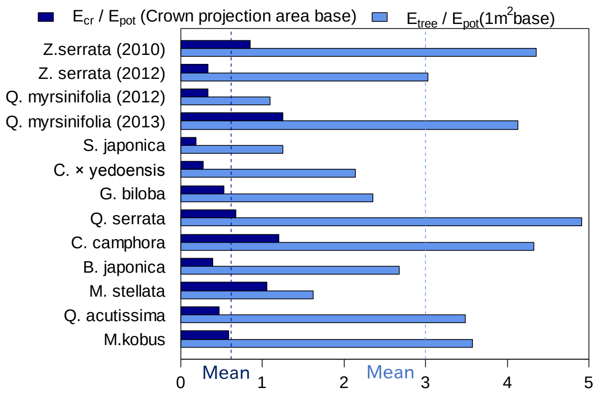

Fig. 5 Ratios of daily transpiration amount to potential evaporation.

3.2 Daily transpiration capacity based on potential evaporation

Transpiration is influenced by meteorological conditions, so in this section we analyze and compare the transpiration characteristics among these tree species based on the standard of potential evaporation (ET_{pot}). ET_{pot} is estimated by simplified Penman equation (Makkink 1957). Figure 5 shows the ratio of the measured transpiration amount to potential evaporation (ET/ET_{pot}) during clear sky and irrigated conditions. In general, crown projection area is used as a standard when comparisons are made with potential evaporation, but in this study, the area of the container ($1m^2$) is also used as a standard as well as the crown projection area. The average and standard deviation of ET/ ET_{pot} was 0.62±0.36 (Mean±S.D.) when using the standard of crown projection area. The mean value of ET/ET_{pot} was not different from previous studies in temperate deciduous forest (in the review of Komatsu 2005), but S.D. and the range was broader. Although ET/ ET_{pot} is smaller than 1.0 on average, *Cinnamomum camphora* showed a value of 1.1 in this experiment. It is considered that the transpiration amount of *Cinnamomum camphora* is large for its crown size, and that the transpiration rate per leaf area and leaf area density is also high.

Focusing on differences in xylem porosity, *Quercus acutissima*, *Zelkova serrata* and *Quercus serrata*, which are ring-porous species and have thick conduit, showed relatively large transpiration amounts ($p = 0.045$ in Welch's t-test). On the other hand, we expected a difference in transpiration amounts based on leaf life-span (evergreen or deciduous) because photosynthetic capacity is inversely proportional to leaf life-span in general and transpiration and photosynthesis rates are simultaneously controlled by the stomata, but any clear differences were not observed.

3.3 Analysis of vapor diffusion conductance responses to VPD and PAR

Fig. 6 shows the tree species variation of estimated G_v responses to VPD and PAR. Fig. 7 shows the relationship between G_{vref}, and b_1. The positive correlation between transpiration capacity of a tree (G_{vref}) and the sensitivity to VPD (b_1) was found and this correlation can be explained by water supplying limitation (Oren et al. 1999) or the stomatal optimization theory derived from gas exchange efficiency of transpiration and photosynthesis (Katul et al. 2009). In previous study, Oren et al. (1999) found the ratio b_1/G_{vref} typically equals 0.6 from large data set (mainly forest data). In this study, the ratio was lower ($b_1/G_{vref} = 0.4$), that indicate less water limitation and it can be considered caused by the effect of every day irrigation.

PAR responses varied widely by tree species (Fig.7), but its effect to daily transpiration amount appear small. Fig. 8 shows the comparison of transpiration rates predicted using (1) the model using the estimated parameters of G_{vref}, b_1 and b_2 for each species, (2) the model using the averaged values of b_1 and b_2 and each estimated value of G_{vref}, (3) the model using all averaged parameters. The result of model (2) is close to model (1) and the error was below 0.4kg/h but model (3) is far worse. Overall, G_{vref} of each trees are the most important parameter when predicting whole tree transpiration rate in hourly basis.

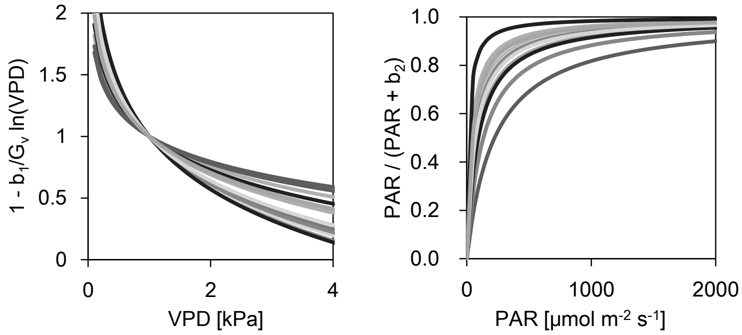

Fig. 6 Responses of vapor diffusion conductance to VPD and PAR.

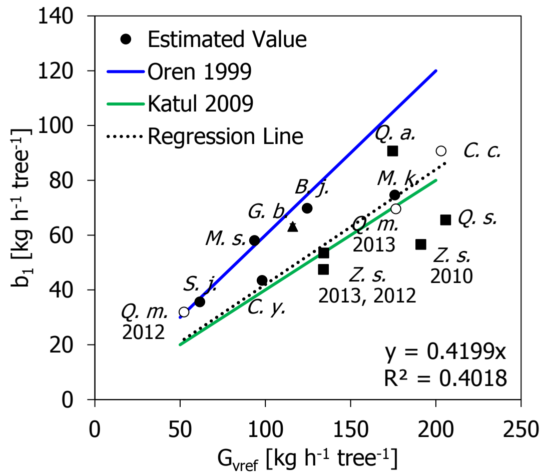

Fig. 7 Relationship between vapor diffusion conductance and sensitivity to VPD.

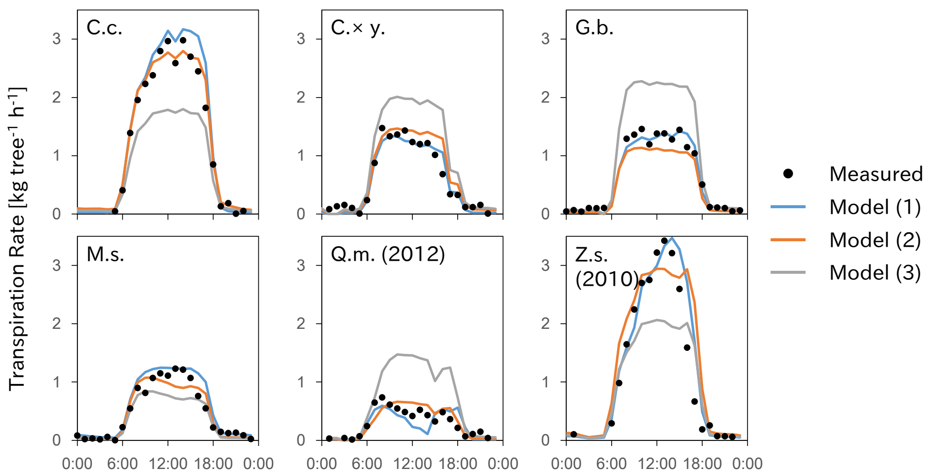

Fig. 8 Comparison of predicted transpiration rates using different parametarization schemes.

4. Conclusion

The daily water use of sample trees ranged 10~30 kg, equivalent to 0.62±0.36 times of water evaporation from the same size of crown projection area. Ring-porous species tend to use much water, which suggest the significance of hydraulic capacity under soil volume restricted condition. We found the sensitivities of G_v to PAR were significantly different from individuals but its effect to transpiration rate was small except early morning and late afternoon, and the sensitivities to VPD were relatively constant. Overall, the maximum (reference) value of G_v of each trees is the most important parameter when predicting whole tree transpiration rate in hourly basis.

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