Granier法によるニホンナシの樹液流測定

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Sap Flow Measurement in Japanese Pear Using the Granier Method

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Abstract

To apply a technique to estimate correctly and easily the long-term water use in Japanese pear under the root zone restriction cultivation for irrigation, the Granier method of sap flow measurement was compared with the measurement of transpiration using a balance. The sap flow rate was calculated by multiplying the sap flow velocity, given by Granier's original equation, by the sapwood area, which was estimated using the dyeing method. The daily sap flow rate, as measured by the Granier method, correlated well with the daily transpiration rate during the growing period. In addition, provided heartwood had not developed, the daily sap flow rate was measured directly using the Granier method by multiplying the sap flow velocity by the cross-sectional area, excluding the bark. This suggests that the Granier method can be used to measure the daily transpiration rate in Japanese pear to produce long-term estimates of daily water use for irrigation throughout the growing period.

Key words: Granier method, Japanese pear, Root zone restriction cultivation, Sap flow, Transpiration.

1. Introduction

Japanese pear [*Pyrus pyrifolia* (Burm. f.) Nakai] is an important deciduous fruit tree in Japan. Although sensitive to drought, it can be adapted to conditions in Japan because of moderate rainfall and the use of cultivation techniques. Recently, a new cultivation system, referred to as "root zone restriction cultivation," has been applied to fruit trees, including Japanese pear. This system involves growth in a limited soil volume with the plant water balance maintained to obtain stable and high-quality fruit production. As a result, the estimation of actual water use is indispensable for this type of irrigation management.

Several techniques have been developed to measure the amount of transpiration and thus control irrigation or elucidate plant/water relations. Two main methods are used: namely, mathematical models and direct measurements. Mathematical models such as the Penman-Monteith methodology (Monteith, 1965) are suitable for calculating the total evapotranspiration over a large area, but require many meteorological elements and transpiration cannot be calculated separately from evapotranspiration. In contrast, direct measurements using the chamber method can measure the transpiration rate per leaf or branch. Direct methods offer good resolution, but require expensive instruments that cannot be used over extended periods, and they are limited in their ability to estimate whole-plant transpiration from measurements collected at a single leaf or branch.

Because transpiration involves water absorption by roots, movement through stem sap, and evaporation from leaf stomata, the sap flow rate can be equated to the transpiration rate. Therefore, it is possible to evaluate transpiration by measuring sap flow. Many of the methods used to measure sap flow have been developed from several principles, all of which have advantages and limitations in terms of the ease of use, cost, and adjustment size (Smith and Allen, 1996). The Granier method (Granier, 1985), which is sometimes called the heat dissipation method or thermal dissipation method,

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uses heat as a tracer to measure sap flow. Compared to other methods, the Granier method is relatively simple, easy to use, and can be used for long-term continuous measurements. Therefore, it has been widely used in measurements of forest tree sap flow (*e.g.* Granier *et al.,* 1996). Like forest trees, fruit trees are woody plants; thus, it should be possible to measure sap flow using the Granier method. However, few studies have addressed sap flow measurement in fruit trees (*e.g.* Braun and Schmid, 1999; Lu, 2002). Moreover, Smith and Allen (1996) advised that the Granier method should be calibrated for individual species. And there are no reports detailing whether the Granier method can be used under special cultivation like root zone restriction cultivation different from natural condition. Thus, as an initial step for future applications, we evaluated the use of the Granier method in Japanese pear by simultaneously comparing sap flow measured by the Granier method to transpiration measured by weighing throughout the growth period.

2. Theory of the Granier method

The Granier method measures sap flow using two cylindrical thermometer probes with a diameter of 2 mm and length of 20 mm. The two probes are inserted radially into the trunk 10 to 15 cm apart. The upper probe contains a heating element that is activated consecutively with a constant power of 0.2 W. The temperature difference between the two probes (ΔT: ℃) is influenced by the sap flow velocity (u: m s^{-1}). During the daytime, ΔT decreases as sap flow transports part of the heat from the upper probe. At night, however, u is low and ΔT increases because the transport of heat occurs mainly by conduction, meaning that most of the heat remains in the upper probe. When there is no sap flow, the temperature of the upper probe increases to the point at which heat conduction through the wood is in equilibrium with the heat energy supplied by the heater, and ΔT peaks (ΔT_0). Granier (1985) developed an empirical relationship (Equation 1) between u, ΔT, and ΔT_0 that has been validated for a number of species:

$$u = 1.19K^{1.231} \tag{1}$$

where K is

$$K = \frac{\Delta T_0 - \Delta T}{\Delta T} \tag{2}$$

The sap flow rate (F, m^3 s^{-1}) can be calculated as follows:

$$F = uS_A \tag{3}$$

where S_A (m^2) is the cross-sectional area of sapwood measured at the upper probe using an increment borer, which is used to distinguish hardwood and sapwood in boring a trunk (Granier, 1987).

3. Materials and Methods

Each experiment was conducted in a glass greenhouse at the National Institute of Fruit Tree Science, Tsukuba, Ibaraki, Japan. To compare the amount of sap flow measured by the Granier method to the amount of transpiration measured by the weighing method, we used two 13-year-old Japanese pear trees (cv. 'Kosui') with trunk diameters of 7.8 cm (defined as n1) and 9.8 cm (n2), respectively, growing in 100-L pots filled with soil. The trees were irrigated on the basis of tree growth and weather conditions; no water was supplied on some weekends. The experiments were run from May to August (n1) and May to September (n2) 2007. The flowering and harvesting dates were 16 April and 17 August, respectively.

We used a sap flow measurement system (Ex618_BAS, Umweltanalytische Produkte GmbH, Germany) consisting of a pair of probes, elongation cables, and a constant current supply device (CCS) to heat one of the probes. Before installing the probes, two 1 cm diameter sections of bark and phloem, one at a height of 50 cm above the pot and the other at 40 cm, were stripped off to prevent the probe from touching the bark and phloem. At each of these locations, 23 mm deep cylindrical radial holes were opened, each with a diameter of 2.1 mm, into which aluminum tubes (20 mm long) were then inserted. The probe with the heater was inserted into the upper tube and the other probe was inserted into the lower tube; the tubes were then sealed with a thermal conductive paste to obtain good thermal contact between probe and tube and the upper probe was connected to the CCS. The probes were installed on the north side of each tree trunk, and the probes and trunk were wrapped in aluminum foil to avoid thermal effects from the sun. The ΔT was measured for both trees every 5 s; the mean values were recorded every 10 min using a data logger (CR23X, Campbell Scientific, USA).

The value of ΔT_0 is essential for the calculation of u, because ΔT_0 is influenced by the thermal characteristics of the wood surrounding the heated probe and must be determined separately for each sensor. The daily maximum ΔT, which was generally recorded at night, is defined as ΔT_M. Granier (1987) estimated ΔT_0 over a 10-day period using linear regression with ΔT_M; the calculation of ΔT_0 is described in detail elsewhere (Lu *et al.,* 2004). In contrast, Iida *et al.* (2003) proposed that it is appropriate to substitute ΔT_M for ΔT_0 for long-term applications. In our case, because the measurements were performed for a period exceeding four months, we used the approach proposed by Iida *et al.* (2003).

In using the Granier method, it is necessary to evaluate S_A in calculating F. To determine S_A, we used the dyeing method of Chaney and Kozlowski (1977). On 27 September, the trunk was cut just above the rootstock union 4 h after sunset, and the cut end was immediately placed in an aqueous solution of 1% acid fuchsin. The following morning, the trunk was cut near the upper probe, and S_A was calculated from the dyed area.

To compare sap flow measured by the Granier method to transpiration, we used the same Japanese pear tree and assessed transpiration simultaneously with sap flow measurements using a balance (maximum weight 300 kg, resolution 2 g). To suppress evaporation from the pot surface, the pot was covered with plastic film. The whole weight, including the tree and pot, was recorded on a PC via an RS-232C link every 5 min, while the transpiration rate was calculated from the amount of weight lost, excluding that of the irrigation water.

Air temperature, solar radiation, and soil water tension were measured in the greenhouse. Air temperature was measured using a ventilated thermocouple at a height of 1.5 m, solar radiation using a pyranometer at a height of 1.8 m and soil water tension using a tensiometer 20 cm below the soil surface. All values were measured every 5 s, with the mean values recorded every 10 min using a data logger. The number of leaves was counted from May to September.

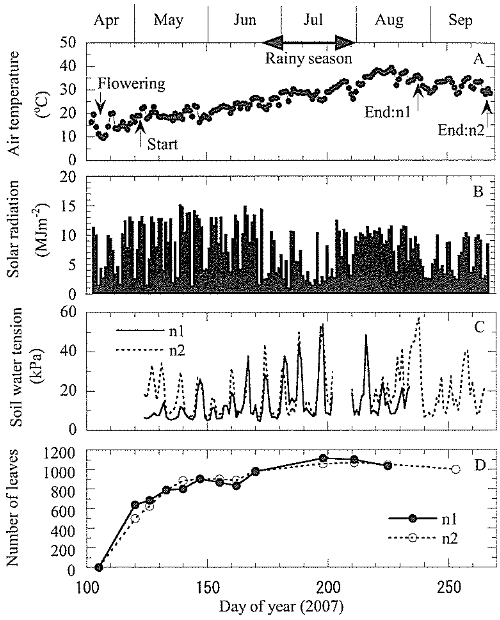

Fig. 1. Time series of daily mean air temperature (A), daily total integrated solar radiation (B), daily mean soil water tension (C), and the number of leaves of Japanese pear (D) growing in a glass greenhouse in 2007. In (A), "Flowering" indicates the time of flowering; "Start" and "End" indicate the beginning and end of measurements of sap flow and transpiration.

4. Results

The seasonal environmental conditions are summarized in Fig. 1. The daily mean air temperature increased gradually from April (16℃) to August (35℃) and then decreased until the end of September. The daily total integrated solar radiation changed in accordance with seasonal and weather conditions. Low values of solar radiation were observed during the rainy season (June and July). The daily mean soil water tension changed weekly and was 5 kPa on weekdays and higher on the weekends. The number of leaves increased rapidly after flowering and plateaued at approximately 1000 in mid-June as the extension of new shoots declined.

To evaluate the sapwood area, the tree was made to absorb a stain solution such that nearly the entire cross-sectional surface of the trunk, excluding part of the center and the bark, was dyed (Fig. 2). Therefore, the sapwood area was assumed to be the cross sectional area, excluding the bark. S_A, which was calculated from the breadth and the length of the trunk excluding the bark thickness, as 39 cm^2 for n1 and 63 cm^2 for n2 respectively.

The hourly sap flow rate (F_h: L h^{-1}) calculated using F and the hourly transpiration rate (TR_h: L h^{-1}) calculated from the amount of weight lost per hour in tree n1 are shown in Fig. 3. Although 26 June was a cloudy day and 27 June was a sunny day, the values for F_h and TR_h correlated well (Fig. 3A). In contrast, 11 August was a sunny day and 12 August was partly

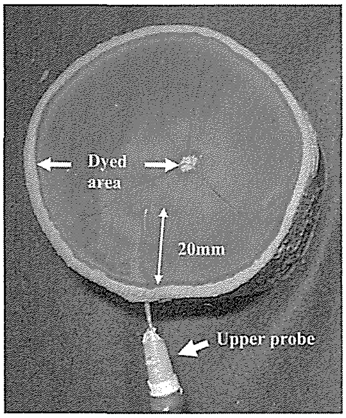

Fig. 2. Representative picture of a dyed cross-section of Japanese pear wood (n1; 1% acid fuchsin) cut near the upper probe. The dark area colored by the stain indicates the sapwood, whereas the undyed areas (parts of the center and bark) indicate areas with no sap flow.

cloudy, F_h and TR_h did not correlate well, especially during the day (Fig. 3B).

The daily sap flow rate (F_d: L day^{-1}) was calculated using F. The daily transpiration rate (TR_d: L day^{-1}) was calculated based on the amount of weight lost from 0 to 24 h. To compare the monthly and long-term relationships between F_d and TR_d, the values were plotted and compared with a 1:1 relationship (Fig. 4). A good relationship between F_d and TR_d was consistently obtained for both trees, independent of the month of measurement (Fig. 4A-E). The root mean square error (RMSE) was 0.21 L day^{-1} in September for n2 and 0.84 L day^{-1} in August for n1. Furthermore, F_d and TR_d corresponded well throughout the measurement period (Fig. 4F); the RMSE was 0.64 L day^{-1} for n1 and 0.65 L day^{-1} for n2.

5. Discussion

Fig. 3A shows F_h and TR_h correlated well. On the other hand, Fig. 3B shows F_h and TR_h did not correlate well, especially during the day. Such disagreements resulted in gaps between F_d and TR_d throughout the measurement period (Fig. 4). The Granier method is very sensitive to the natural thermal gradient in the trunk and to heat storage and conduction within the tissues, which may lead to low accuracy (Köstner *et al.*, 1998). Any thermal effect, for example, high air temperature or significant temperature difference between soil and trunk, may have affected our results because Lu *et al.* (2004) measured the natural thermal gradients in the trunk in mango trees and considered that gradients were inevitable, despite the use of appropriate insulation in case the probes were close to the ground due to trunk length limitations and our examinations were carried out under similar conditions. However, our data were insufficient to detect the type of disagreements. Do and Rocheteau (2002) proposed a correction method; however, it is complicated and impractical (Lu *et al.*, 2004). On the other hand, Braun and Schmid (1999) suggested that the low accuracy was cancelled out by daily integration of the measurements. Therefore, we targeted only F_d calculated by integrating F. Moreover, we intended to assess seasonal deviations in the relationship between F_d and TR_d; thus, measurements were collected from the leafing stage to the full canopy stage under various air temperatures, solar radiation levels, and soil water tension levels (Fig. 1). The RMSE between F_d and TR_d throughout the measurement period for both trees became 0.64 L day^{-1} for n1 and 0.65 L day^{-1} for n2 (Fig. 4F), the relationship between F_d and TR_d was consistent in terms of accuracy. This indicates that F_d obtained by the Granier method could be substituted for TR_d, even for long-term measurements, despite the fluctuations in air temperature, solar radiation, and soil water tension throughout the growing period.

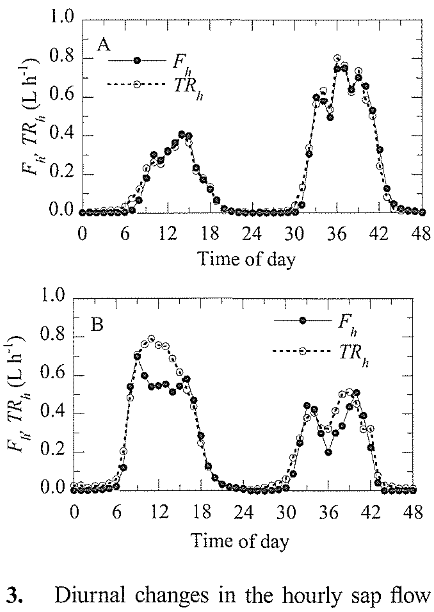

Fig. 3. Diurnal changes in the hourly sap flow (F_h) and hourly transpiration (TR_h) rates for n1 from 26 to 27 June (A) and 11 to 12 August (B).

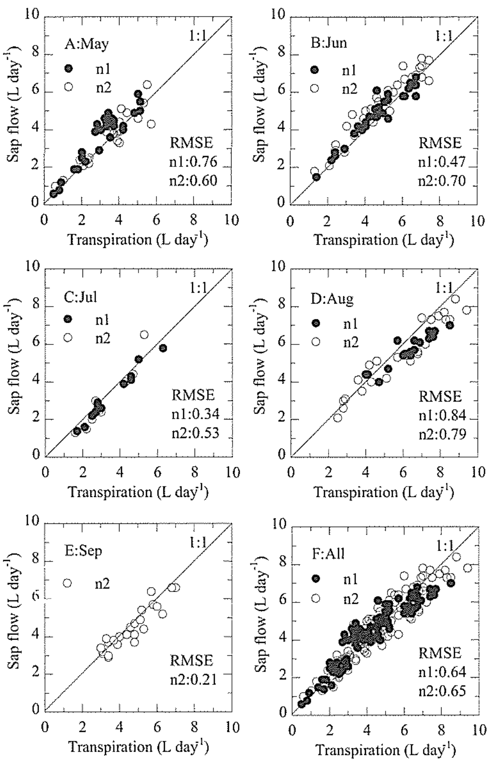

Fig. 4. Relationship between the daily sap flow rate (F_d) measured using the Granier method and the daily transpiration rate (TR_d) measured using a balance in May (A), June (B), July (C), August (D), September (E), and all months (F).

Clearwater *et al.* (1999) pointed out the necessity for correction in cases of uneven distribution of sap flow velocity in the cross-section of sapwood. Lu *et al.* (2004) found that if the probe length was less than the radius of the sapwood cross-section, the calculation of sap flow may contain errors because sap flow velocity in the deeper zones of sapwood is uncertain. 'Yamanashi,' a wild type of Japanese pear, has diffuse-porous wood (Ito, 1997); hence, 'Kosui,' a Japanese pear cultivar, may also have diffuse-porous wood. Indeed, the sapwood portion was evenly dyed by the stain solution (Fig. 2), indicating that the size and array of vessels in Japanese pear were similar throughout the sapwood. Therefore, no correction for u, which was calculated using Granier's original equation, was necessary, and F could be calculated directly by multiplying u by S_A.

Because the 13-year-old Japanese pear trees that we examined were still young, hardwood had not yet developed (Fig. 2). Therefore, it was difficult to visually distinguish sapwood from hardwood by sampling using an increment borer. Thus, the sapwood area was determined by visual observation after the uptake of the stain solution. If Japanese pear trees have little hardwood, as in those trees that we examined, it should be possible to calculate F_d by multiplying u by the cross-sectional area, excluding the bark thickness. In contrast, for Japanese pear trees with well-developed hardwood, an increment borer might be useful to distinguish between the sapwood and hardwood areas.

Compared to the other major sap flow measurement methods (Marshall, 1958; Čermák, 1973; Sakuratani, 1981), the Granier method has several advantages. Some of the other methods are labor intensive because they require the installation of complex apparatus; moreover, they are unsuitable for long-term measurements and require corrections because of the heater. Hence, with only one pair of probes and a simple device to supply a constant current, the Granier method is suitable for long-term daily sap flow measurements thanks to its ease of use and installation; therefore, it is also useful for estimating daily water requirements for irrigation.

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References

Braun, P., and Schmid, J., 1999: Sap flow measurements in grapevines (*Vitis vinifera* L.) 2. Granier measurements. *Plant Soil*, **215**, 47–55.

Čermák, J., Deml, M., and Penka, M., 1973: A new method of sap flow rate determination in trees. *Biol. Plant.*, **15**, 171–178.

Chaney, W. R., and Kozlowski, T. T., 1977: Patterns of water movement in intact and excised stems of *Fraxinus americana* and *Acer saccharum* seedlings. *Ann. Bot.*, **41**, 1093–1100.

Clearwater, M. J., Meinzer, F. C., Andrade, J. L., Goldstein, G., and Holbrook, N. M., 1999: Potential errors in measurement of non-uniform sap flow using heat dissipation probes. *Tree Physiol.*, **19**, 681–687.

Do, F., and Rocheteau, A., 2002: Influence of natural temperature gradients on measurements of xylem sap flow with thermal dissipation probes. 1. Field observations and possible remedies. *Tree Physiol.*, **22**, 641–648.

Iida, S., Kobayashi, Y., and Tanaka, T., 2003: Continuous and long-term measurement of sap flow using Granier method. *J. Jpa. Soc. Hydrol. Water Resour.*, **16**, 13–22.

Ito, T., 1997: Anatomical description of Japanese hardwood III. *Wood Res. Technical Notes*, **33**, 83–201.

Köstner, B., Granier, A., and Cermák, J., 1998: Sap flow measurements in forest stands: methods and uncertainties. *Annu. Sci. For.*, **55**, 13–27.

Granier, A., 1985: Une nouvelle méthode pour la mesure du flux de sève brute dans le tronc des arbres. *Annu. Sci. For.*, **42**, 193–200.

Granier, A., 1987: Evaluation of transpiration in a Douglas fir stand by means of sap flow measurements. *Tree Physiol.*, **3**, 309–320.

Granier, A., Biron, P., Breda, N., Pontailler, J. Y., and Saugier, B., 1996: Transpiration of trees and forest stands: short– and long-term monitoring using sap-flow methods. *Global Change Biol.*, **2**, 265–274.

Lu, P., 2002: Measurement of whole–tree water use of some tropical and subtropical tree crops and its application in irrigation management. *Acta Hortic.*, **575**, 781–789.

Lu, P., Urban, L., and Zhao, P., 2004: Granier's thermal dissipation probe (TDP) method for measuring sap flow in trees: theory and practice. *Acta Bot. Sinica*, **46**, 631–646.

Monteith, J. L., 1965: Evaporation and environment. *Symp. Soc. Exp. Biol.*, **19**, 205–224.

Marshall, D. C., 1958: Measurement of sap flow in conifers by heat transport. *Plant Physiol.*, **33**, 385–396.

Sakuratani, T., 1981: A heat balance method for measuring water flux in the stem of intact plants. *J. Agric. Meteorol.*, **37**, 9–17.

Smith, D. M., and Allen, S. J., 1996: Measurement of sap flow in plant stems. *J. Exp. Bot.*, **47**, 1833–1844.

Granier 法によるニホンナシの樹液流測定

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要　　約

根域制限栽培におけるニホンナシの水利用量を長期間，精度よく簡単に測定する方法を見出すため，樹液流量の測定法であるGranier法を重量法との比較により評価した。Granierのオリジナル式で求めた樹液流速に染色法で測定した辺材面積を乗じて樹液流量の計算をした。Granier法で求めた日樹液流量は日蒸散量と測定期間を通して良く一致した。さらに心材が発達していない場合は，樹液流量の計算に樹皮の厚さを除いた主幹断面積を利用でき，この面積に樹液流速を直接乗じて樹液流量が計算できることを確認した。以上より，Granier法はニホンナシの日蒸散量を長期間精度よく簡単に測定でき，生育期間を通して灌水に必要な水利用の見積りに利用できる。

キーワード： Granier法, 根域制限栽培, 樹液流, 蒸散, ニホンナシ