Measurements of Sap Flow in the Roots, Trunk and Shoots of an Apple Tree Using Heat Pulse and Heat Balance Methods

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Abstract

To understand more deeply water dynamics in an apple tree, we examined diurnal changes in sap flow in the shoots, trunk and roots of a 10-year old apple tree (cv. *Splendor*), using to advantage both the heat balance and heat pulse methods. There was little time lag between sap flow in the trunk and the root, suggesting a high hydraulic conductivity between them. The time lag between the start of shoot sap flow, and that of trunk and root, after sunrise was estimated to be about 30 min. Considering the finding of Schulze *et al.* (1985) that the main water store is located in the tree crown, it appeared here in our experiment that the main storage element of the apple tree was also the crown.

Key words: Apple tree, Heat pulse method, Sap flow, Stem heat balance method, Time lag.

1. Introduction

Deeper understanding of water dynamics in fruit trees is needed to produce fruits of better quality and to develop technologies for more efficient management for sustainable use of water on agricultural land. One means to examine the water dynamics is the thermic method for measuring sap flow in plants, such as heat pulse method and heat balance method. Clothier and Green (1994) have shown that Huber's heat pulse method can be now used in roots with modern technology. In fact Green and Clothier (1995) applied the compensation heat-pulse method (Swanson and Whitfield, 1981) to measure sap flow in intact roots and the trunk of kiwifruit vines. With regard to the constant power heat balance method (Sakuratani, 1981), Steinberg *et al.* (1990a) measured trunk and branch sap flow in pecan using a modified system (Baker and van Bavel, 1987; Steinberg *et al.*, 1990b). Few measurements to characterize the complete root-trunk-shoot system of sap flow have been made. In the present paper, we ex-

amined diurnal dynamics in sap flow in the shoots, trunk and roots of an apple tree under non-limiting soil moisture conditions, taking advantage of both the heat pulse and heat balance methods.

2. Materials and methods

The experiment was carried out in a research orchard near HortResearch Institute in Palmerston North, New Zealand during a period from 22 to 24 November 1995. An apple tree was selected from a block of 10-year old apple (cv. *Splendor*) which was growing on the semi-dwarfing rootstock MM106 and was at a stage of fruit set. The soil in the field was a Manawatu fine sandy loam. Sap flow in the roots and trunk was monitored using the compensation heat-pulse technique (Swanson and Whitfield, 1981) as further developed by Green and Clothier (1988). A heat-pulse probe was installed into the trunk of 12.9 cm in diameter at a height of about 0.7 m above the ground, and into a large root of 7.3 cm in diameter at a depth of around 15 cm below the soil surface. Pulses of heat were initiated once every 30 min. A heat-balance sap flow sensor (Sakuratani, 1984), as modified in wiring of the sensor (Steinberg *et al.*,

Received on December 24, 1996.

Accepted on March 3, 1997.

1990b), was used to measure sap flow in thin shoots. A heat balance sensor was attached to the basal part of a shoot of 0.86 cm diameter with an eastern exposure. And the 0.67 cm-diameter shoot with a western exposure, at a height of about 1.5 m above the ground was also instrumented. Signals were logged every 30 s and averaged over 30 min during measurement on 22 Nov., but over 5 min on 23 and 24 Nov. Campbell 21X data loggers were used in both the heat pulse and balance measurements. The constant of heat-balance sap flow sensor, so called sheath conductance, K , was determined from measurements collected during periods of minimal flow during the predawn hours.

3. Results and discussion

Air temperature and saturation deficit during the measurements ranged from 4.3 to 17.8°C and 0.17 to 1.15 kPa, respectively, on 22 Nov. 1995; 4.2 to 22.0°C and 0.023 to 1.58 kPa on 23 Nov.; and 7.3 to 21.2°C and 0.037 to 1.18 kPa on 24 Nov.

Figure 1 shows the diurnal pattern of sap flow

in the root, trunk and shoots, and also of photosynthetically active radiation, PAR measured by a Li-Cor Li200SB PAR sensor. These lines, except for PAR, were smoothed by computer software. The diurnal pattern of root and trunk sap flow was similar to that of PAR. The sap flow at the root and the trunk started concurrently at around 0600 h, following sunrise (0445 h), except for the sap flow on 24 Nov. They reached a maximum at around noon, and ended at 2000 h about 30 min after sunset (1923 h). The presence of significant, but low, sap flow observed in the early morning and the evening on 24 Nov. may be caused by nocturnal recharge, some transpiration or just noise in the system. We found no evidence of lags between start of sap flow in the trunk and the root. Fichtner and Schulze (1990) suggested that the magnitude of any time lag depends on the conductivity and water storage of the tissue. Thus that lack of time lag we obtained is probably due to the high hydraulic conductivity and low water storage capacity of the roots and trunk.

Sap flow in the eastern shoot peaked between 0900 h and 1000 h, while that in the western shoot

Fig. 1. Diurnal course of sap flow as measured in the shoots (A), trunk (B) and root (C) of an apple tree, and of photosynthetically active radiation PAR (D).

did so between 1300 h and 1500 h, indicating that sap flow in the shoots was strongly influenced by exposure to the sun. The small negative values in sap flow which were observed at night on 23 Nov. were probably due to errors which were caused by a shift of K value. The calculated changes in sap flow for the shoots in the early morning and in the evening were also unreliable and were sometimes negative, especially for the western shoot. These were mainly due to errors in measurements in the heat flow sensing element (Sakuratani, 1984; see Fig. 1) which is a part of the sensor. Such errors, as well as the ones due to K cause large errors in sap flow at low flow rates.

Thus to detect a time when sap flow in the shoots began to increase in the morning, and to cease in the evening, we used the difference in stem temperatures between the down- and upstream points of heated segment, ΔT (Fig. 2). As noted by Senock and Ham (1993), the temperature difference can be assumed to produce an accurate measure of the sap flow. That is, generally ΔT increases with a rise of sap flow under conditions or stems of low flow, and decreases with that under high flow. As can be seen in Fig. 2, the time when ΔT began to increase was 0530 h for

Fig. 2. Diurnal change in difference in shoot temperatures between the down- and upstream points of the heater of a heat balance sap flow sensor attached to the shoots, ΔT .

the eastern shoot, but 0540 h for the western shoot. This indicates that the time lag between the start of shoot sap flow, and that of trunk and root, after sunrise was about 30 min. This time lag is somewhat larger than that found in tropical vines (Fichtner and Schulze, 1990), but much smaller than that in *Larix* and *Picea* trees with diameter of 26–28 cm (Schulze *et al.*, 1985).

Landsberg *et al.* (1976) showed that the transpiration flux can be supplied from stored water in the tree and directly from the root through the conducting tissue. On the basis of experiments using *Larix* and *Picea* trees, Schulze *et al.* (1985) noted that the main water store is located in the tree crown. Very recently, Itani *et al.* (1996) found a significant time lag between upper and lower stem flow in cassava (*Manihot esculenta*), and they concluded that the main storage tissue is the stem. The existence of a time lag between the shoots and trunk in our experiment suggests that main storage tissue is likely to be the crown, including the shoot or branches. It appears that the transpiration flux in the early morning was supplied from such storage tissue.

The rate of sap flow in the trunk and root reached a minimum at around 2000 h, as described above. Even after the time, ΔT continued to decrease for about 1 hour and leveled off at about 2100 h, except for 24 Nov. when measurements of ΔT were disturbed by the permeation of rainwater into the sensor. The result above differs from the response expected from previous findings that canopy transpiration or shoot sap flow ceased rapidly after sunset, while sap flow in trunk or in basal part of stem proceeded at a decreasing rate till water was replenished in storage tissue (e.g. Steinberg, *et al.*, 1990a; Itani, *et al.*, 1996). Since data are limited, it is difficult to document the reverse result. However two causes may be considered. One of them is related to the heat capacity in the sensor-shoot system. When upward sap flow exists, heat is stored more in the upper part of the system, than in the lower part. When the sap flow becomes minimal, the difference in the stored heat between the upper and lower parts should become minimal, after some delay, because of the heat capacity of the system. As a result ΔT does so also. It is reasonable to estimate such a delay from a time constant of the system.

Baker and van Bavel (1987) estimated the time constant of a sensor-stem system for a 10 mm diameter stem to be about 18 min, under a no-flow condition. The diameters of our shoots were smaller by 14–33% than 10 mm, suggesting a smaller time constant for our system. Thus the delay of 1 h in our experiments may be partly, but not wholly, attributable to the heat storage in the system.

Another cause we can consider is related to the water dynamics of the storage elements. Landsberg *et al.* (1976) found that the (apple) tree could be subdivided into a number of storage elements. Considering their view, it is possible in our case that small amount of water proceeded to be supplied to the upper part of storage elements, such as leaves or petioles, from lower part of the storage elements such as branches. Prior to this, water appeared to have been rapidly replenished in the lower storage elements by around 30 min after sunset, because of the low conductivity in the root and trunk. The lower storage elements could supply the upper storage elements with water, without directly taking up water from the roots. The lower elements would probably be filled again with water by sap flow in the root and trunk, which was observed through the night. It is also possible to consider that the delay is due to the two causes described above.

To our knowledge, this study reports the first measurements in which heat pulse and balance techniques were concurrently used for a fruit tree. Both systems performed well, except that the heat balance sap flow sensors for this experiment gave unreliable data in the early morning and around sunset. Further application of heat pulse technique, heat balance technique or both to researches in water dynamics in fruit trees can be expected to provide interesting data on the dynamics of water flow in trees.

Acknowledgments

We acknowledge the assistance of Mr. David J. McLeod in the preparation of the experiments and of Dr. W. R. N. Edwards for providing the meteorological data. This work was supported in part by grants from the Ministry of Education, Science, Sports and Culture in Japan.

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*written in Japanese

ヒートパルス法と茎熱収支法によるリンゴ樹の 根、幹および枝条の蒸散流測定

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要 約

果樹の水分動態の理解を一層深めるために、ヒートパルス法と茎熱収支法を併用して、リンゴ樹 (cv. *Splendor*) の根、幹および枝条における蒸散流の日変化を調べた。日の出後の蒸散流の上昇は、根と幹内の間でほぼ同時に生じ、タイムラグはほとんど認められなかった。これに対し根・幹と枝条の間では約30分のタイムラグが認めら

れた。本実験と既往の研究とから、リンゴ樹体の貯水組織は枝を含む樹冠であることが示唆された。上記2種類の蒸散流測定法の併用は果樹の水分動態研究に有効であることがわかった。

キーワード：茎熱収支法，蒸散流，タイムラグ，ヒートパルス法，リンゴ樹