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NON-DESTRUCTIVE, REAL-TIME, AND AUTOMATIC MEASUREMENT OF TRANSPIRATION FROM A PLANT CANOPY STAND

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ABSTRACT

This study to measure plant canopy stand transpiration was conducted using newly developed sensor units. Transpiration from the tomato stand and by artificial leaves made of towel and paper filters showed good agreement with data measured by weight loss using a weighing device. The problem of sun flecks directly on the back side of the sensor causes malfunction of the energy balance equation, which is the basis of this method when *LAI* is not dense. During the period when a sun fleck was on the sensor, the data were eliminated. Overall measurements of this kind are far superior to measurements taken using a leaf porometer to estimate transpiration from the entire plant canopy stand.

Keywords: flat surface; frame shadow; sun fleck

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INTRODUCTION

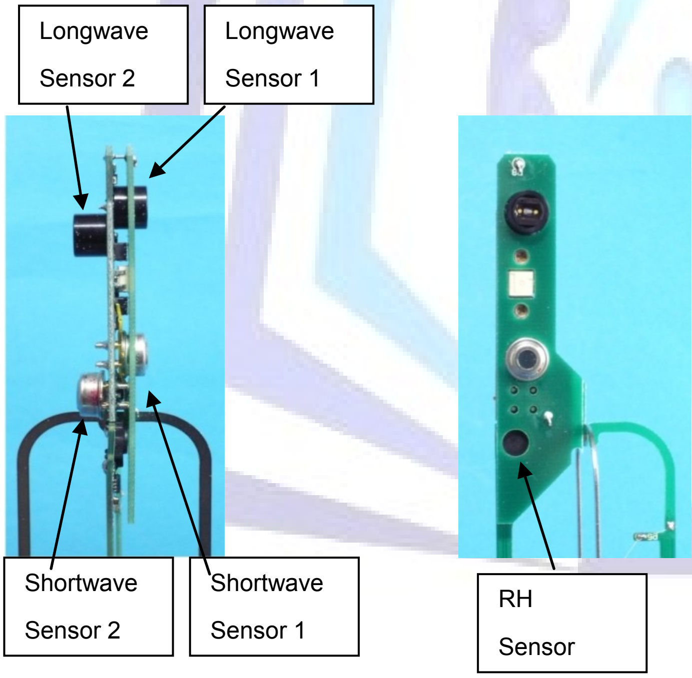
To optimize environmental conditions, growth information such as net photosynthesis was measured directly from plants. The optimization logic was controlled using a digital computer (Takakura *et al.,* 1974; Takakura, 1975). This method, designated by a Dutch researcher as the 'Speaking Plant Approach', became popular (Udink ten Cate *et al*., 1978). To control environmental conditions in a greenhouse, a controller based on leaf temperatures instead of air temperature was commercialized by Priva BV (the Netherlands) but it has not been widely adopted. Monitoring several aspects of single plants was also tested, but it became apparent that the method was insufficient to assess all plants in a greenhouse and that it cannot constitute an important analytical method. However, obtaining direct information from plants is important to control their environments. Some advances in this respect have been reported (*e.g.,* Takakura, 1992; Voogt and van Weel, 2008; Takakura *et al*., 2009).

Monitoring stomatal behavior is expected to be important. Solving the energy balance equations of plant surfaces is one means to investigate its overall situation in a greenhouse. The basic idea was reported by Takakura *et al*. (2009). This study applied the same approach to a plant canopy stand in a single row using newly developed integrated compact sensor units.

EXPERIMENTAL METHOD

Sensor development

All environmental factors to be measured are already defined. The problem is to integrate all sensors to measure them in one unit and to minimize it. The basic components of the sensor unit are an improved hot wire anemometer that measures not only air speed but also air temperature without air aspiration (Okushima *et al*., 2014). In addition to these factors, incoming and outgoing shortwave radiation sensors and longwave radiation sensors are needed. They are attached to the top part of the original unit (see Fig. 1a). Some silicon photodiodes (S1087-01; Hamamatsu Photonics K.K.) are used for shortwave radiation measurement. Others (MLX90614; Melexis NV) are used for longwave radiation measurement. To measure relative humidity, a sensor (SHT21; Sensirion AG) is used. A CO_2 sensor by (0–2000 ppm, K30; SenseAir AB) is also attached. The sensor unit is finalized as a wireless type with some small modifications, mainly to the position of radiation sensors (see Fig. 1b).



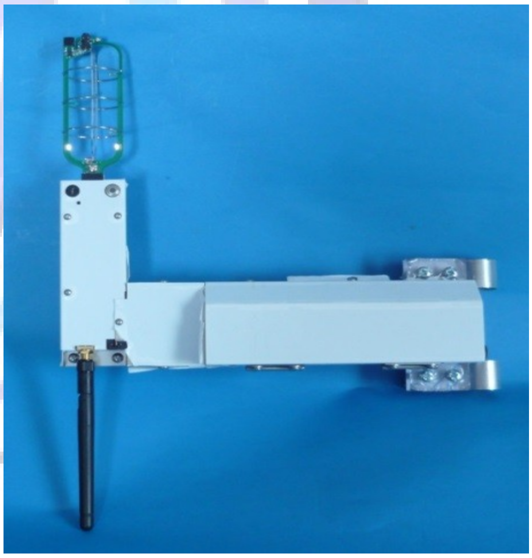


Fig. 1a. Enlarged side and front views of the top part of the original sensor unit where new components are added.

Fig. 1b. Wireless type sensor unit.

Energy balance at the canopy surfaces

All components for the energy balance at both surfaces of a plant stand are presented in Fig. 2 with two sensor units located on both sides. Two energy balance equations are the following.

$$S_o + L_o - E_o \ell + Q_o = 0 \quad (1)$$

$$S_i + L_i - E_i \ell + Q_i = 0 \quad (2)$$

Then, adding Eqs. (1) and (2), the total transpiration from both sides $E = (E_o + E_i)$ (g/m^2/s) is

$$E = \{S_o + S_i + L_o + L_i + Q_o + Q_i\}/\ell \qquad (3)$$

The following are used above or in the text.

S_o: Net solar radiation at one side surface (W/m^2)

S_i: Net solar radiation at the other side surface

L_o: Net longwave radiation at one side surface (W/m^2)

L_i: Net longwave radiation at the other side surface

E: Total transpiration from both sides (g/m^2/s)

ℓ: Latent heat because of vaporization 2501 (J/g)

Q_o: Convective heat transfer at one side surface = $h_o(T_{\ell o} - T_o)$ (W/m^2)

Q_i: Convective heat transfer at the other side surface = $hi(T_{\ell i} - T_i)$

LAI: Leaf area index in a horizontal direction (not used)

$T_{\ell o,i}$: Leaf temperature at each surface (°C)

To: Air temperature at one side

T_i: Air temperature at the other side

h_o: Convective heat transfer coefficient at one side (W/m^2/°C)

h_i: Convective heat transfer coefficient at the other side

v_o: Air speed at one side (m/s)

v_i: Air speed at the other side

rh_o: Relative humidity at one side (%) (not used)

rh_i: Relative humidity at the other side (not used)

$h_{o,i} = 2.8 + 1.2 v_{o.i}$ from Takakura (1993)

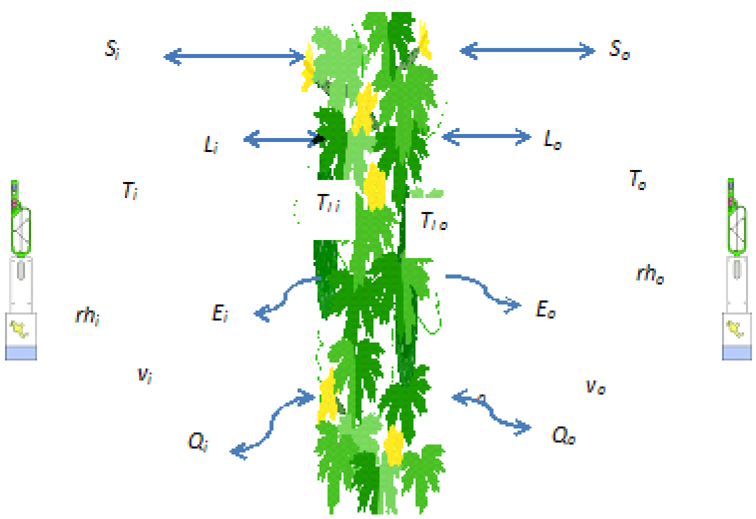


Fig. 2. Diagram to measure all components using the developed sensor units.

Transpiration per unit leaf area which radiation sensors see as view angles of the plant canopy stand is obtainable by eq. (3). It is converted easily to a unit leaf area basis if it is divided by *LAI*, which is in a horizontal direction. The *LAI* in the present study was measured (CI-110 Digital Plant Canopy Imager; CID Bio-Science, Inc.). The device was set horizontally to view the plant canopy horizontally, just as radiative sensors see the plant canopy. Relative humidities were measured, but were not used in this study. However, for monitoring stomata aperture, the calculation of *VPD* is necessary using relative humidity values to extend the study.

SYSTEM CALIBRATION AND RESULTS

Several means exist to calibrate the developed system. To measure actual transpiration, sap-flow meters are useful, although sap-flow is not exactly the same as transpiration. Furthermore, several sample stems are selected to estimate total transpiration from a plant canopy because few sap-flow meters were available. Another shortcoming of sap-flow meters that they are indirect methods. Moreover, they require calibration against an absolute method. Leaf porometers are used if the leaves are few. It is not advisable to use them for a plant canopy. In this study, water loss from plants is measured directly using a weighing machine and a manometer.

Weight reduction using artificial leaves

Artificial leaves, one made of a bath towel and another of filter paper, were used. The green towel area is approximately 1 m^2 (see Fig. 3a). Sheets of filter paper of 10 × 10, each of 110 mm^2, were connected to produce an almost equal area (see Fig. 3b). These sheets were fixed to light rigid frames and were set vertically on an electronic weighing machine to record the weight loss caused by evaporation from these surfaces. It is apparent that *LAI* = 1 in the horizontal direction in both cases. Two units of the developed sensors were set facing normal to these surfaces from both sides. The distance from the surface is approximately 50 cm to catch the whole surface area by the sensor on each side. Both materials, the towel and filter paper, were sprayed. They became wet before measurements started. Then the measurements for all factors related to evaporation were conducted while recording the weight change using a weighing machine. Typical results are presented in Figs. 4 and 5.

Fig. 3a. Artificial leaf made of towel sheet on the weighing machine with one sensor unit and hidden unit on the other side.

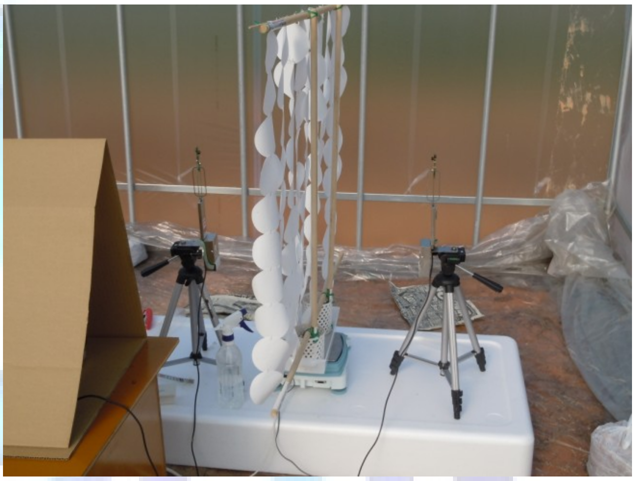


Fig. 3b. Artificial leaves made of paper filters on the weighing machine with two sensor units on both sides.

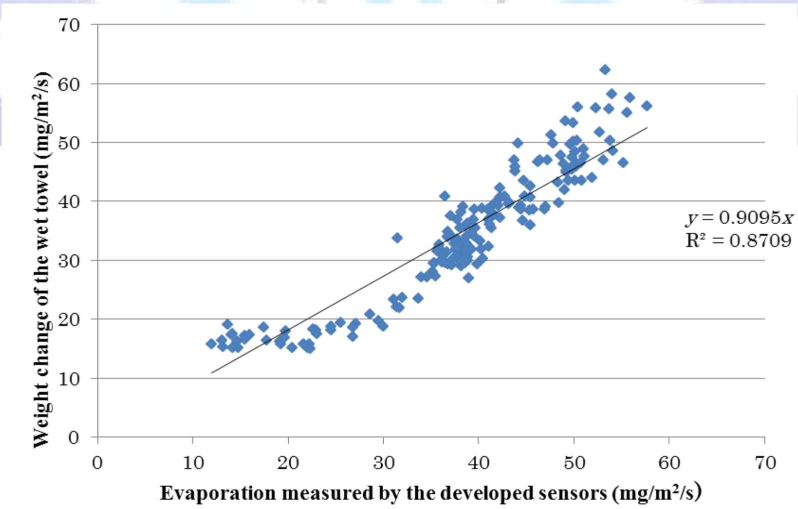


Fig. 4. Comparison of the data obtained by weight change and measured using the developed sensors for a sheet of wet towel as artificial leaves.

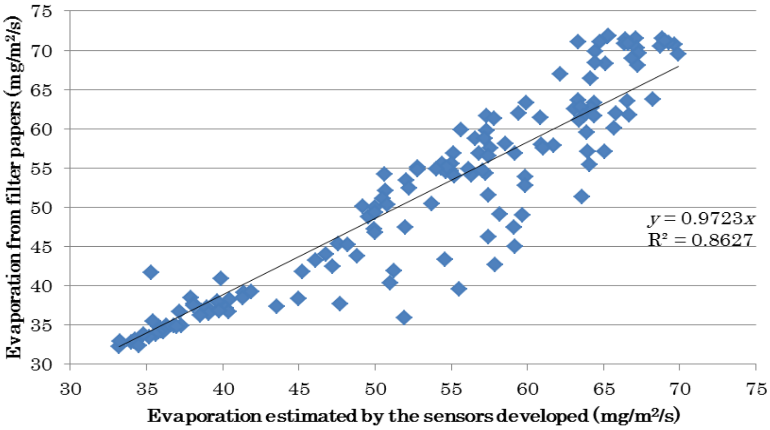


Fig. 5. Comparison of data obtained by weight change and measured using the developed sensors for wet connected paper filters as artificial leaves.

Data measured using the developed sensor units and direct weight change detected using a weighing machine exhibited fairly good agreement in both cases shown in Figs. 4 and 5. One reason that causes deviation is the time lag of the weighing machine and the moving average for 3 min. was calculated. The response of the sensor unit is quick. It catches a wide range of environmental change.

Manometer type method for potted tomato plants

Water depth in an L-shaped glass tube that is connected to each pot and water was refilled to maintain a certain level in the tube every 2 hr. All pots were sealed with plastic films. Water reduction in each tube was monitored. To prepare different *LAI*s, 5 pots of well grown tomatoes in a line give *LAI* of 2.37. The total area is 1 m wide and 1.5 m high. For observations, 11 pots were placed more densely in total area of 1.5 m wide × 1.7 m high give *LAI* of 4.00 and (see Fig. 6).

The results are portrayed in Fig. 7a for the dense canopy and in Fig. 7b for the less dense canopy. Water depth changes were checked at approximately two-hour intervals. Data are shown by straight lines during this time period. Some data were omitted because direct solar radiation through the space among leaves made sun flecks on the small sensor, which causes malfunction of the energy balance equation.

Fig. 6. Two sensor units are set for one side of the tomato stand.

DISCUSSION AND CONCLUSION

How to measure transpiration from a whole canopy

It can be said that the energy balance equation to find transpiration using the measurement conducted by newly developed sensor units is useful for a single row of a plant canopy with high density: *LAI* > 4. Comparison was conducted with weight reduction of artificial leaves made of wet towel and paper filter and manometer type measurement of a potted tomato plant canopy. Because of the time lag of direct methods used to measure transpiration, no exact match could be made in either case. Furthermore, two main surfaces of a canopy stand were measured in this experiment. However, for more accurate measurements, the energy balance of each surface including smaller surfaces of a plant row should be measured.

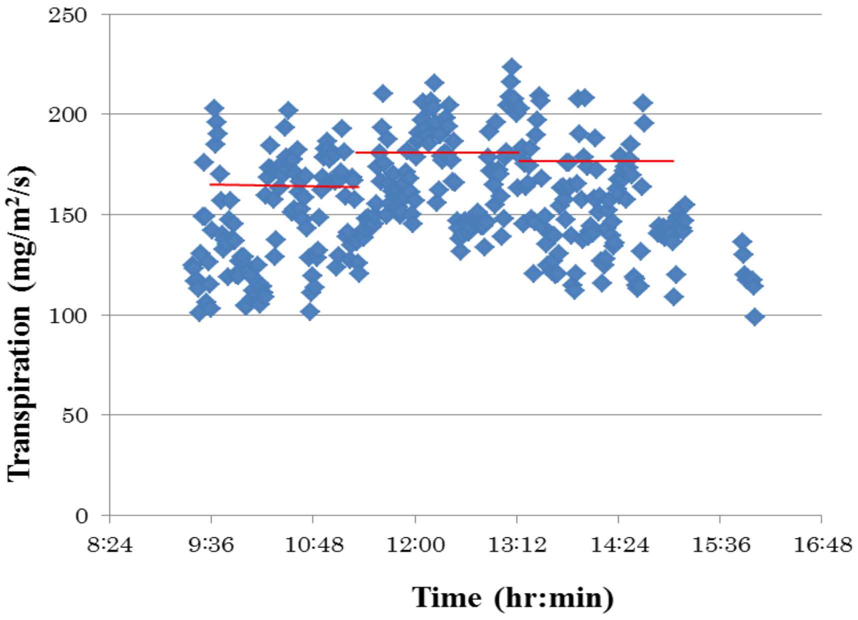


Fig. 7a. Transpiration data by the sensor units developed with water reduction in the time period shown by straight lines for dense row.

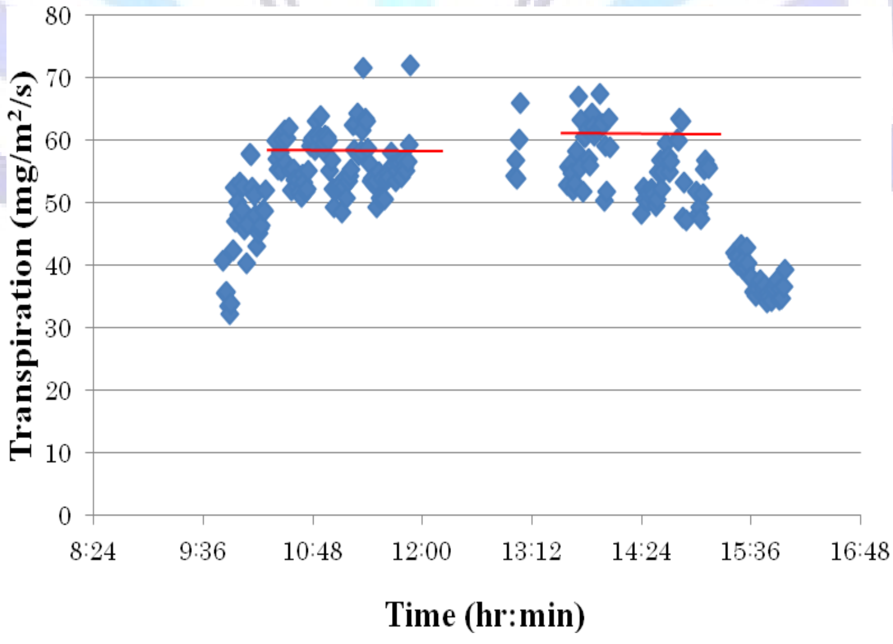


Fig. 7b. Transpiration data by the sensor units developed with water reduction in the time period shown by straight lines for a single row.

Shadow of greenhouse frames on a solar radiation sensor

No reports of the literature describe shadows of a greenhouse frame on a sensor. Actually, sensors are getting smaller. The shadow of direct radiation on a sensor cannot be neglected if environmental control is based on this sensor. Moving the sensor is one solution, but the method and frequency are not clear. Double sensors would help to solve the problem, but cannot do so completely. Recently, diffused covering materials are becoming popular. They might solve the problem to some degree. In this study, experiments have been conducted in a greenhouse covered by diffuse plastic film to minimize the effect of frame shadows. Double sensors are set for one surface (see Fig. 6) of the dense canopy, but no method to select one sensor was conducted because it was not easy to evaluate the difference of the two outputs. Matching is expected to be improved more if this could be done.

Flat surface sensors

In this study, a flat type photodiode was used to measure solar radiation and detect incoming solar radiation to the flat surface of plant canopy stand. When one sensor is used, a spherical type sensor should be used to measure solar radiation at the top of the canopy (Takakura, 2008; Takakura *et al*., 2009; Miyahira *et al*., 2015).

Sun flecks through the canopy

The sensor set behind the canopy stand, i.e., presuming the sun is to the south and that the sensor is to the north side of the canopy stand faces to the canopy sometimes receives sun flecks through the plant canopy. The energy balance equation on this side does not hold because it is based on this measurement. The data period when the net balance of incoming and outgoing solar radiation on the north side is negative: when outgoing radiation from the canopy is greater than incoming radiation, this period was omitted. This seldom occurs if the plant canopy density is high.

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