ISSN XXXX-XXXX
Volume … Number…
Name of the Journal

IN SITE NET PHOTOSYNTHESIS MEASUREMENT OF A PLANT CANOPY IN A SINGLE-SPAN GREENHOUSE

Tadashi Takakura*, Haruki Sunagawa, Maro Tamaki, Takae Usui, Naoki Taniai

Okinawa Agricultural Research Center, Makabe 820, Itoman, Japan;

*Corresponding author: takakura @nagasaki-u.ac.jp

ABSTRACT

Using newly developed sensor units that were more compact and accurate than earlier units (Takakura *et al.*, 2009), this study was conducted to estimate the net photosynthesis of a plant canopy in a practical greenhouse during plant cultivation. Net photosynthesis and the ventilation flow rate are two unknowns in this greenhouse system, with adequate growth of bitter gourd plants. Environmental conditions related to evapotranspiration from the canopy and CO_2 flux from the soil surface were measured respectively using the developed sensor units and a box-type CO_2 concentration sensor. Heat flux from the soil was also measured. Two equations were solved: one for CO_2 balance and one for water vapor balance. On-line monitoring of net photosynthesis is possible using simple and inexpensive sensors, but the obtained data of the canopy photosynthesis were scattered because of frequent changes in the ventilation amount. Furthermore, improved sensor units revealed that the evapotranspiration of the canopy was linearly related to net solar radiation in the greenhouse.

Keywords: CO_2 flux, evapotranspiration, on-line monitoring

INTRODUCTION

On-line monitoring of net photosynthesis of a plant canopy in a greenhouse is crucially important to elucidate and improve plants environments during greenhouse cultivation. Direct measurement of net photosynthesis by plants requires a chamber to measure changes in CO_2 concentration. The method used for this study, using no chamber, calculates net photosynthesis as one unknown factor in the CO_2 balance equation of a greenhouse. However, other unknown factors include the ventilation flow rate of the greenhouse. To ascertain those unknown influences, nitrous oxide (N_2O) and an infrared gas analyser (IRGA) were used (Nederhoff, Gijzen, Veger, and Rijsdijk, 1989; Nederhoff and Vegter, 1994).

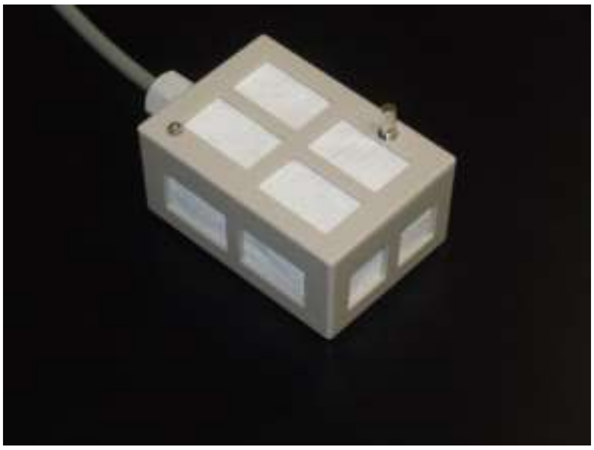
Usually, CO_2 flux from the soil gas flux surface is neglected (Nederhoff and Vegter, 1994). Alternatively, it is measured using expensive devices such as a soil flux chamber (Li-Cor Inc.) and a rather complicated model such as the Penman–Monteith equation (Bontsema et al., 2011). A much simpler method that does not use the Penman–Monteith equation has also been reported (Takakura, 2008; Takakura *et al.*, 2009). The present study uses simple and inexpensive sensors to estimate the net photosynthesis of the plant canopy in a greenhouse by solving two equations: one for CO_2 balance and one for the water vapor balance.

DEVELOPED INSTRUMENT

The basic sensor, a smart sensor, use for this study was developed to measure air temperature, relative humidity, CO_2 concentration, and thermal radiation for both sides of the unit (see Fig. 1a). It is much more compact than the one used for earlier experiments (Takakura et al., 2009). Moreover, it has a CO_2 concentration sensor (CO_2 engine K30; SenseAir AB, Sweden). It is a hot wire type sensor with no aspiration. The same type has been used to measure canopy transpiration (Akutsu et al., 2015). To measure incoming and outgoing shortwave radiation above the canopy, a net solar radiation sensor with two spherical photodiodes was used (Fig. 1b). To eliminate the so-called cosine law effect on the flat sensor, a spherical photodiode was used as described in reports by Miyahira et al. (2014, 2015). The CO_2 gas emitted from the soil surface was measured using a box inside of which a CO_2 detector (CO_2 engine K30; SenseAir AB, Sweden) was installed. The box windows were covered by transparent film for sensing of the soil gas emissions (Fig. 1c). The top surface of the box was level with the soil surface when measurements were conducted (Tamaki, Usui, Inoue, Sunagawa, & Takakura, 2016a).

(a)

(b)



(c)

Fig 1: Instruments developed: a) smart sensor, b) net solar radiometer, and c) CO_2 sensor box (6 cm × 8.5 cm × 4 cm depth).

GREENHOUSE EXPERIMENT

The experiment was conducted in December, 2016 in a single-span greenhouse of the Okinawa Agricultural Research Center, Japan. The greenhouse, which had an arch-shaped roof covered by polyethylene film, was oriented approximately north–south. The greenhouse was 27 m long × 8 m wide, with 2.3 m eaves and 4.2 m ridge height.

The naturally ventilated greenhouse has 2 m tall film vent openings spanning the length of each sidewall. The film was rolled up and down automatically to keep the inside temperature within 2°C of 31°C. The bitter gourd plants were transplanted on November 18. At the time of the experiment, four rows of fully grown bitter guard plants were oriented north–south along the long axis of the greenhouse. After selecting one small 1 m × 1 m area with a frame, the leaf area in the frame was calculated, followed by estimation of the total leaf area and LAI. To prevent disturbances caused by people doing crop management, the door of the greenhouse was closed for one full day. The experiment was repeated intermittently on several days. The arrangement of all sensors is presented in Fig. 2. Three smart sensors were installed in the greenhouse. One smart sensor to measure net thermal radiation and a net solarimeter were set above the canopy. Two sets of smart sensors were also installed, one in the greenhouse at the centre and one at the outside, each at the screen height. The output of the CO_2 sensor in the box buried in the soil was connected to another smart sensor. The output of the heat flux meter (HFP01; Hukseflux Thermal Sensors B.V., Netherlands) was also connected to the same smart sensor. All data from the smart sensors were sent to a microcomputer.

CALCULATION OF NET PHOTOSYNTHESIS OF THE CANOPY

An energy balance equation for the canopy per unit floor area of a greenhouse (Eq. (1)) has been proposed and verified (Takakura *et al.,* 2009; Villarreal-Guerrero *et al*., 2012). It is used here to calculate evapotranspiration.

$$S_i - S_o + L_i - L_o - E\ell + Q_c + Q_s = 0 \quad (1)$$

In Eq. (1), evapotranspiration *E*, the only unknown quantity, is found from the equation.

The carbon dioxide balance equation of the greenhouse is

$$f(C_o - C_i) - 0.5P + K_c(C_s - C_i)/d = 0. \quad (2)$$

The water vapor balance equation of the greenhouse is

$$f(e_o - e_i) + E = 0, \quad (3),$$

The following are used above or in the text.

C_i inside CO_2 concentration, μL L^{-1}

C_o outside CO_2 concentration, μL L^{-1}

C_s CO_2 concentration in the soil surface, μL L^{-1}

d distance between soil surface and a CO_2 sensor 0.5 m above ground level, from Tamaki et al. (2016a)

E evapotranspiration of the canopy and soil, g $m^{-2}s^{-1}$

e_i inside absolute humidity, $mgH_2O\ m^{-3}$

e_o outside absolute humidity, $mgH_2O\ m^{-3}$

f ventilation flow rate, $m^3m^{-2}s^{-1}$

hi convective heat transfer coefficient of the canopy, $Wm^{-2}K^{-1}$

$= 2.8+1.2\ v_i$, from Takakura (1993)

K_c CO_2 diffusion coefficient from the soil surface, m^3h^{-1}

$= 2 \times 10^{-5}\ m^2s^{-1}$, from Tamaki et al. (2016a)

L_i incoming long-wave radiation, Wm^{-2}

L_o outgoing long-wave radiation, Wm^{-2}

ℓ latent heat of vaporization = 2501, J g^{-1}

P total net photosynthesis, $mgCO_2\ m^{-2}\ min^{-1}$

Q_c convective heat transfer, $Wm^{-2} = hi(T_i - T_\ell)$

Q_s heat flux in soil, Wm^{-2}

rh_i relative humidity inside the greenhouse, %

rh_o relative humidity outside the greenhouse, %

S_i incoming solar radiation to the canopy, Wm^{-2}

S_o outgoing solar radiation from the canopy, Wm^{-2}

T_ℓ surface temperature of the canopy, °C

T_o outside air temperature, °C

T_i inside air temperature, °C

v_i wind speed inside the greenhouse, m s^{-1}

where absolute humidity $e = pv \times 100 \times 18/(8.31447 \times (273.15+T)) \times 1000$, saturated vapor pressure $ps=6.11 \times 10^{(7.5\times T/(237.3+T))}$ hPa, and vapor pressure $pv=ps \times rh/100$, hPa, where rh is relative humidity in %.

From Eq. (3), ventilation flow rate f is found. Then using Eq. (2), the net photosynthetic rate P can be calculated.

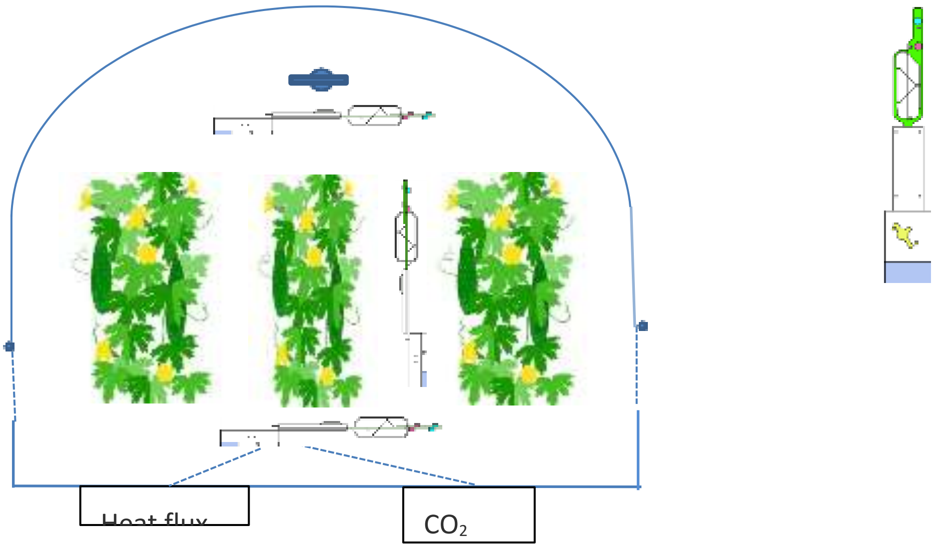


Fig. 2 – Sensor arrangement.

RESULTS

As discussed in an earlier report (Takakura, 2009), the largest term in Eq. (1) is net solar radiation ($S_i - S_o$). The relation between evapotranspiration and net solar radiation is portrayed in Fig.3. They show good agreement.

Then the absolute humidity inside and outside of the greenhouse were calculated using air temperatures and relative humidity inside and outside. Using Eq. (3), the ventilation flow rate was calculated. Substituting this ventilation flow rate for Eq. (2), the net photosynthetic rate was calculated. A typical result is presented in Fig. 4.

The figure shows an increase of net photosynthesis with the increase of net solar radiation, but scattering of the data increases along with increased net solar radiation. A main reason for this scattering is the variation of ventilation flow rate and the time course of the water vapor difference inside and outside of the greenhouse, as depicted in Fig. 5.

From Eq. (3), it is apparent that the large variation of water vapor difference between inside and outside causes variation of the ventilation flow rate, and consequently produces scattering of the net photosynthetic rate.

DISCUSSION

Net photosynthetic rate

In general, verification of the calculation of the net photosynthetic rate can be conducted by comparing measured data and using models. However, only measurements based on a single leaf are available for bitter gourd plants. The calculated results were converted from the greenhouse floor area to leaf area and were compared with single leaf area data (Tamaki *et al*., 2016b). They show good agreement.

Although the main factor affecting net photosynthesis is net solar radiation, other factors such as air temperature, CO_2 concentration and humidity cannot be neglected. No adequate model exists for bitter gourd plants for comparison with the present data.

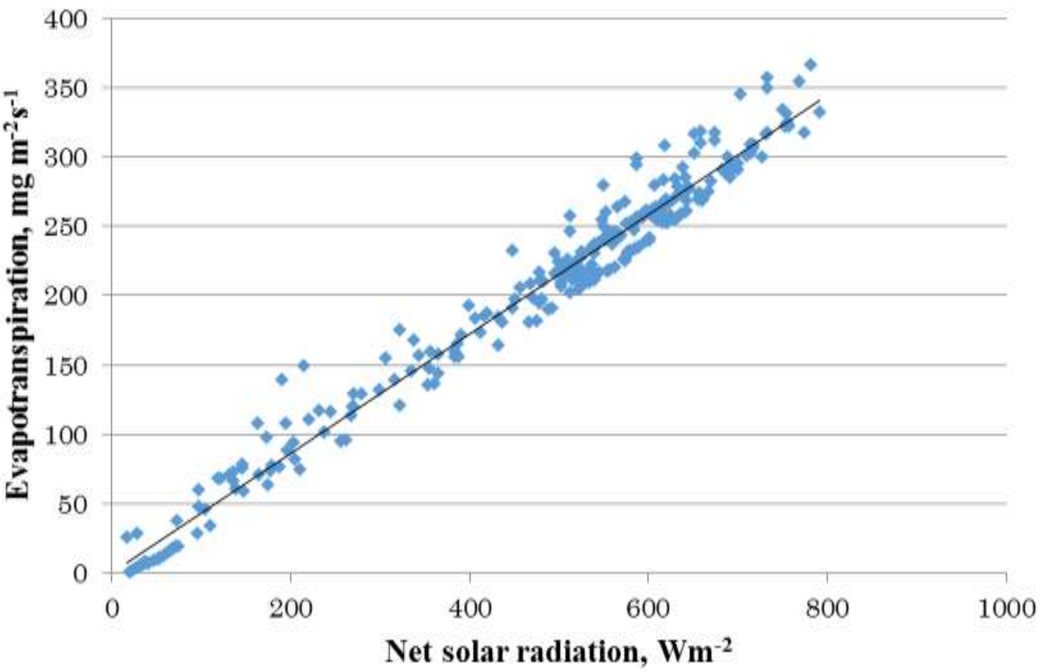


Fig 3: Relation between evapotranspiration and net solar radiation above the canopy, R^2 = 0.972 and y = 0.431x.

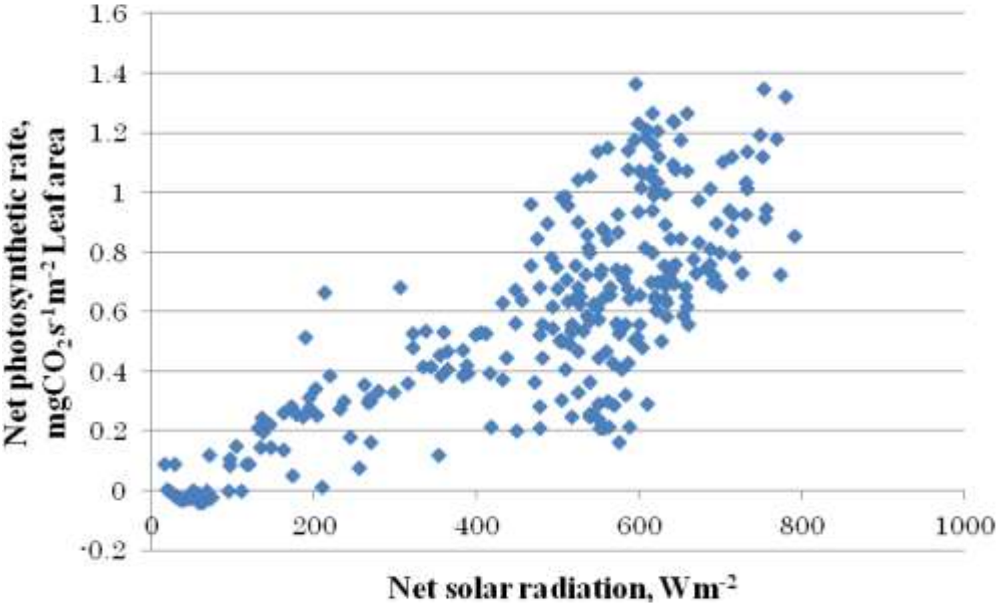


Fig 4: Relation between the net photosynthetic rate and net solar radiation.

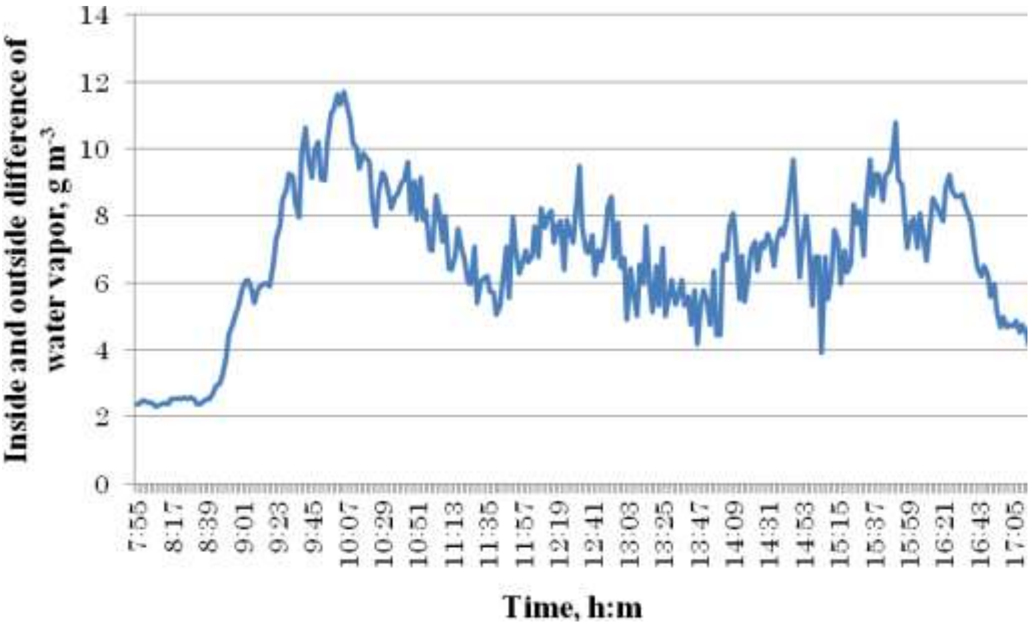


Fig 5: Time course of the inside–outside water vapor difference.

Variation of ventilation flow rate

Comparing Fig. 3 with Fig. 4 clarifies that the variation of evapotranspiration is smooth, but the effect of ventilation flow rate is great because of the fluctuation of the water vapor difference between those prevailing inside and outside. A high ventilation flow rate can be expected to cause great difficulty in estimating the net photosynthetic rate of the canopy in a greenhouse.

Sensor calibration

For this study, sensor calibration is extremely important. Calibration was conducted before each experiment: several sensors were used to measure the same environmental factors; then their differences were noted. CO_2 concentrations inside and outside the greenhouse were the most important terms in the calculations. Differential type sensors are ideal for CO_2 concentration measurements and are commercially available, but they are not only expensive; they were regarded as inadequate for this study.

Number of sensors used

The greenhouse examined in this study is not large. For that reason, one sensor of one environmental condition was adequate. However, a greater size would require more sensors to obtain average values of the respective environmental conditions.

Application of this study

The technique and apparatus for measurement of evapotranspiration of the canopy used in this study are applicable to widely diverse plant cultivation situations in which the canopy is not too small for detection of net photosynthesis. In this study, the canopy of bitter gourd was used, but the methods are applicable to any other plant.

CONCLUSION

Using a single-span greenhouse during normal bitter gourd cultivation, on-line monitoring net photosynthesis can be done using rather simple and inexpensive sensors, although the obtained data were scattered because of the changes in the ventilation amount. In addition, use of these improved sensor units revealed that the canopy evapotranspiration is closely related to net solar radiation in the greenhouse.

ACKNOWLEDGEMENTS

This study was funded by a Specific Government Grant for Okinawa No. 69: Research project to develop sophisticated environmental control techniques for vegetable and flower greenhouses.

REFERENCES

1. Akutsu, M., Sunagawa, H., Usui, T., Tamaki, M., Taniai, N., Hirata, M., Kaiho, A., and Takakura, T. (2015). Non-destructive, real-time, and automatic measurement of transpiration from a plant canopy stand. *J. Adv. Agr., 5*, 677-683.

2. Bontsema, J., Hemming, J., Janssen, H. J. J., Meinen, E., Rispens, S., Steenhuizen, J. W., and de Visser, P. (2011). On-line monitoring van transpiratie en fotosynthese: de praktijk. Rapport GTB-1091, Wageningen UR, 65pp.

3. Miyahira, M., Tamaki, M., Akutsu, M., Usui, T., Okushima, L., Kaiho, A., and Takakura, T. (2015). Calibration device development for spherical solar radiation sensors. *J. Adv. Agr., 4*, 371-376.

4. Miyahira, M., Usui, T., Kaiho, A., Okushima, L., and Takakura, T. (2014). Lightweight, low-cost, automatic monitoring of global and diffused solar radiation. *J. Agr. Met., 70*, 133-138.

5. Nederhoff, E. M., Gijzen, H., Veger, J. G., and Rijsdijk, A. A. (1989). Dynamic model for greenhouse crop photosynthesis: Validation by measurements and application for CO2 optimization. *Acta Hort., 260*, 137-148.

6. Nederhoff, E. M., and Vegter, J. G. (1994). Photosynthesis of stands of tomato, cucumber and sweet pepper measured in greenhouses under various CO_2-concentrations. *Annals of Botany*, *73*, 353-361.

7. Takakura, T. (1993). *Climate Under Cover. Digital Dynamic Simulation in Plant Bio-Engineering*. Kluwer Academic Publishers, 155pp.

8. Takakura, T. (2008). Why Penman–Monteith equation is used yet in the world? *Agriculture and Horticulture*, *83*, 953-957.

9. Takakura, T., Kubota, C., Sase, S., Hayashi, M., Ishii, M., Takayama, K., Nishina, H., Kurata, K., and Giacomelli, G. A. (2009). Measurement of evapotranspiration rate in a single-span greenhouse using the energy-balance equation. *Biosystems Engineering*, *102*, 298-304.

10. Tamaki, M., Usui, T., Inoue, H., Sunagawa, H., and Takakura, T. (2016b). Impact of leaf temperature, vapor pressure deficit, and CO2 concentration on rising photosynthesis rate of Bitter gourd (Shiokaze). ISTHH 2016 International Symposium on Tropical and Temperate Horticulture (Nov. 20-25, 2016), Cairns, Australia.

11. Tamaki, M., Usui, T., Nikawa, T., and Takakura, T. (2016a). Development of a device to measure CO2 concentration in soil and its flux from soil surface. Proc. of Annual Meeting of Agricultural Structures in Kochi, p91-92.

12. Villarreal-Guerrero, F., Kacira, M., Fitz-Rodriguez, E., Kubota, C., Giacomelli, G. A., Linker, R., and Arbel, A. (2012). Comparison of three evapotranspiration models for a greenhouse cooling strategy with natural ventilation and variable high pressure fogging. *Scientia Horticulturae*, *134*, 210-221.