ADVANTAGES OF THE CONTINUOUS AROUND-THE-CLOCK MONITORING OF THE LEAF CO_2 EXCHANGE IN PLANT RESEARCH AND IN CROP GROWING

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ABSTRACT

Continuous recording of the leaf CO_2 exchange, provided by the new photosynthesis monitor with the automatic self-clamping leaf chambers, enables direct evaluation of the daily CO_2 balance as well as the effect of environmental factors on net photosynthesis and night respiration.

INTRODUCTION

Measurement of plant gas exchange with the use of infrared gas analyzers remain at the heart of studies in plant ecophysiology (Coombs et al.) as well as in some practical applications in greenhouse crop growing (Lootens & Vandecasteele 1998, Schmidt 1998). Gas exchange by leaves was in focus of the design of most commercial photosynthesis meters. Almost all of them are portable hand-held instruments of open- or closed system design. In a closed system, a leaf is enclosed in a sealed chamber where the change of CO_2 and H_20 concentration is measured, and their rates are calculated. In an open c system, an air stream with the known concentration passes the chamber with the constant flow rate so the output concentration is the measure of gas exchange. A closed-loop open type system is equipped with the CO_2 and water vapor generators for maintaining the required input gas concentrations. Most of commercial photosynthesis meters are designed for instant measurement and have a limited duration of measurement cycle. However, recently, a new model of the photosynthesis meter (PTM-48M Monitor, Daletown Company Ltd.) with the original automatic self-clamping chambers (Fig.1) becomes commercially available. The chamber is normally open and holds an open leaf in fixed position. In measurement cycle, the leaf is enclosed for 30 seconds only. Typical sampling interval is from 10 to 30 minutes. This monitor enables automatic continuous recording of both CO_2 and H_2O exchange with minimal effect on leaf conditions. The monitor is of true open-type design. It takes ambient air so it has no special requirements for sealing the chamber with the leaf. The main advantage of the monitor is the capability to evaluate daily totals of CO_2 uptake that seems to be more significant than the transitory values of photosynthesis. In addition to that, the continuous recording of gas exchange allows investigating response of photosynthesis to light intensity and to other affecting environmental factors in order to disclose a factor which currently limits productivity.

The paper reported several case studies carried out in laboratory conditions and in commercial greenhouses aimed at demonstration of capabilities and advantages of the continuous around-the clock recording of leaf gas exchange.

MATERIALS AND METHODS

The laboratory tests were done in the Institute of Plant Physiology (Moldova) and were aimed at determination of the extended performance specification of the PTM-48M Photosynthesis Monitor. The tests included determination of the following parameters: leaf boundary resistance inside the leaf chamber by using the wet paper technique; actual range of the photosynthesis measurement; the overall accuracy of the photosynthesis measurements over the measurement range; discrimination between CO_2 and water vapor. Laboratory plants were obtained from the local nursery.

The field experiments were carried out in the commercial greenhouses with the following greenhouse plants: Cucumber (Kazan, Russia), Bell Pepper (The Netherlands), Tomato and Roses (Israel), and Orchids (The Netherlands).

The PTM-48M Photosynthesis Monitor (Daletown Company Ltd.) included four leaf chambers. The standard chamber has a 20 cm^2 aperture suitable for a wide variety of broad-leaf plants. Standard sampling time was 30 seconds for every leaf chamber. Sampling interval was 10 or 15 minutes in most of cases. In addition to leaf chambers, the Monitor included optional sensors for measuring solar radiation (pyranometer), air temperature and humidity, and soil (substrate) moisture.

The Monitor measured and recorded automatically all the data required for calculation of gas exchange such as CO_2 concentration and absolute air humidity in the vicinity of a sample leaf, air flow rate through the leaf chamber, CO_2 concentration and absolute air humidity in the output of the leaf chamber, atmospheric pressure, and air temperature. The data were processed automatically by the meter so that the recorded data represented gas exchange rate in $\mu molCO_2m^{-2}s^{-1}$ and $mgH_20m^{-2}s^{-1}$.

The diurnal variations of the CO_2 exchange rate were analyzed against solar radiation, air CO_2 concentration, air temperature and humidity. The daily CO_2 balance was analyzed componentwise and included the daytime accumulated amount of CO_2, the nighttime loss by respiration, and the surplus of the CO_2 daily budget.

RESULTS AND DISCUSSION

Performance check

Three commercial units of the PTM-48M Photosynthesis monitor with 12 leaf chambers were provided by the manufacturer for performance check in the laboratory conditions.

The standard air flow rate is 0.9±0.1 liter per minute. At this flow rate, the leaf boundary resistance for water vapor inside the leaf chamber was found equal to 200±10 s m^{-1}.

The photosynthesis measurement range depends on the depletion of CO_2 concentration in the chamber’s outlet in relation to the ambient reference concentration. In the manufacturer’s specification, the rated measurement range of 20 $\mu molCO_2m^{-2}s^{-1}$ was found corresponding to 70 ppm depletion that is equivalent to 20% down at 350 ppm reference concentration. At the same time, the reasonable depletion of 130 ppm may extend the range up to 40 $\mu molCO_2m^{-2}s^{-1}$.

The actual accuracy was determined by measuring signal fluctuations of the CO_2 analyzer and the electronic flow meter. The accuracy was found depending on the measurement range. It varied from ±0.3 $\mu molCO_2m^{-2}s^{-1}$ at zero exchange to ±0.94 at 40 $\mu molCO_2m^{-2}s^{-1}$ exchange rate. The overall error E may be well represented (R^2=0.975) by the following linear equation: $E = 0.016x + 0.26$, where x is the measured photosynthesis rate.

The discrimination between CO_2 and water vapor was tested in hot and dry air conditions by replacing the actual leaf with the piece of wet paper, which had the equivalent evaporation rate. The effect of water vapor on CO_2 readings was found almost negligible. If transpiration rate was about 20 $mgH_20m^{-2}s^{-1}$, the equivalent evaporation did not cause any effect above the measurement error. At the maximum level of 50 $mgH_20m^{-2}s^{-1}$, the effect was between +2 and +3 ppm that was equivalent to approximately +0.8 $\mu molCO_2m^{-2}s^{-1}$. This is also comparable with the overall error found for photosynthesis rate between 20 and 40 $\mu molCO_2m^{-2}s^{-1}$.

Basic outcome of the around-the clock records

The daily records allow to determine a net daily amount of accumulated CO_2 which is a good measure of the net dry matter production.

The separate analysis of daytime and nighttime components gives an idea of the production control by using their ratio as a controllable factor. The ratio is the greater a) the greater the photosynthetic rate, which mainly depends on light intensity, CO_2 concentration, temperature, and plant water status, b) the longer the daytime, and c) the shorter and cooler the night that reduce the nighttime respiration loss.

During the daytime, the correlation between hourly evaluated photosynthesis rate and environmental factors may be effectively used for disclosing a factor which currently limits productivity of the plant. In this regard, the special feature of the Monitor, which provides measurements on the same fixed leaves, is critically important for data comparability.

In addition, the presence of four channels for leaf chambers allows to carry out a comparative study of two or more plants under different treatments.

The leaf CO_2 exchange balance

The net yield of carbon assimilation is the positive balance of the CO_2 exchange, which consists of the net photosynthetic yield at daytime and the CO_2 lost by respiration at nighttime. Under favorable conditions, the daily CO_2 consumption of C3 plants is three to five times greater than dissimilation losses. For C_4 plants with no photorespiratory losses, this factor is 10 to 20 (Larcher 1995). In any case, the lower contribution of nighttime respiration seems to be favorable for total daily production. The night/day ratio for greenhouse tomato in wintertime is shown in Fig.2. During 18 days of observation, the nighttime temperature was 21±0.6 °C. The light conditions were fairly variable that resulted in the changing ratio of daytime accumulation and nighttime discharge of CO_2. The ratio shows how great was the nighttime loss in relation to the amount of CO_2 accumulated during previous daytime. On sunny days, the ratio was as low as 13% and reached 30 to 50 % at overcast. It means that a half of accumulated CO_2 was lost so the possible reduction of nighttime temperature should be taken into consideration.

Components of the daily CO_2 balance of greenhouse roses obtained under different solar conditions are shown in Fig.3. In hot days, the grower's feeling was that the plants were suffering from excess of light and high temperature. However, the direct measurement of the leaf production gave the opposite results. Application of the shading screen depressed the total balance to almost one third of the original level.

An alternative example is shown in Fig. 4 where the nighttime component was changed by the controlled nighttime temperature.

The daily values are also useful for disclosing a limiting factor. In most of practical cases, the light is the limiting factor and the linear dependence between light and photosynthesis is observed. The accumulated daily values of both light and photosynthesis allow to eliminate diurnal short-term fluctuations of both values and, thus, to determine when the light is no more limits productivity. An example is shown in Fig. 5. Apparently, when the daily integral of solar radiation reached 7 MJ/m2, the photosynthesis growth ended. It means that there was another factor that became to limit CO_2 assimilation, likely, the shortage of CO_2 in ambient air.

In clear sky conditions, the light curve of the photosynthesis may be easily obtained by drawing the recorded photosynthesis values against the recorded solar radiation. A practical example is shown in Fig.6. It is evident that the photosynthesis was depressed from 12:00 till 16:00. Analysis of other factors showed that the shortage of irrigation water had caused stomatal response and reduction of CO_2 flux into the leaf.

CONCLUSION

Continuous recording of the CO_2 exchange of intact leaves opens up some new possibilities for analysis of plant productivity in controlled environment. It also allows to reveal and to distinguish limitations of the CO_2 uptake inside and outside the plant under study. Those advantages may be effectively used both for plant research and for commercial crop growing.

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Figure 1. Automatic self-clamping leaf chambers.

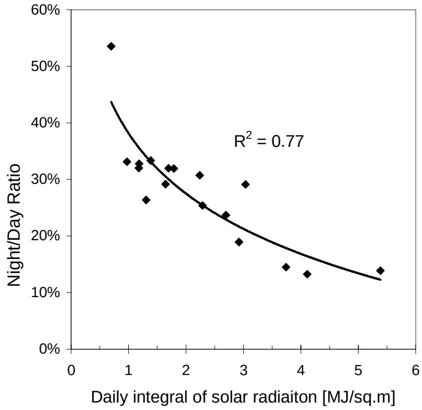

Figure 2. The ratio of daytime accumulation and nighttime discharge of CO2 as a function of the daily integral of solar radiation. (Greenhouse tomato).

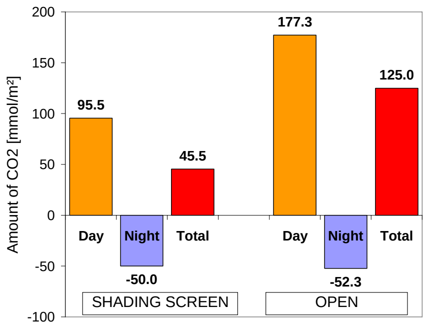

Figure 3. Daily components of CO2 exchange of the leaves with and without the shading screen (Greenhouse roses)

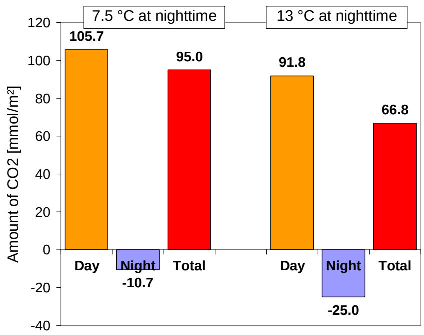

Figure 4. Daily components of CO2 exchange of the leaves under different nighttime temperature (Greenhouse tomato)

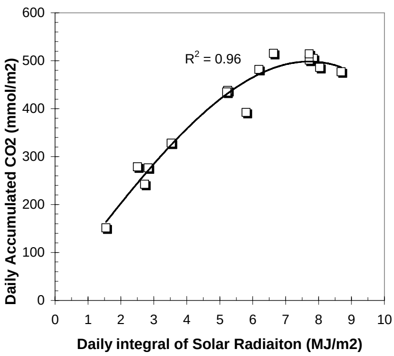

Figure 5. Daily net photosynthesis vs. daily integral of solar radiation (Greenhouse Bell Pepper)

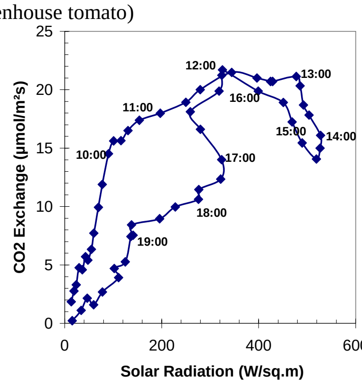

Figure 6. Diurnal loop-like curve of the net photosynthesis (Greenhouse Bell Pepper).