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Measurement of CO_2 Concentration and Leaf Area Index for Crop Photosynthesis Model in Sweet Pepper

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Abstract

This study was aimed to introduce the measurement of CO_2 concentration and leaf area index in the phytotron for predicting the effect of CO_2, light and leaf area index on the instantaneous photosynthetic rate of sweet pepper with the existing ASKAM model. Measurements were made in 2 semi-closed phytotron compartments in which three different CO_2 concentrations were applied at random. Plants were grown on containers with circulating nutrient solution at 21°C and 80-95% relative humidity. The model estimates crop net CO_2 uptake for short time intervals during the day based on short-term data of daily radiation, temperature and CO_2 concentration. During the photosynthesis measurements, CO_2 concentrations in both compartments and in the basement were measured every minute. This was also done for the flow of pure CO_2 into the compartment, global radiation, photosynthetic active radiation inside the compartment, temperature and relative humidity. Crop growth models summarize our knowledge on crop behavior and have as such a wide range of applications in analysis, crop management and thus as a farm management tool.

Key words: ASKAM model, carbon dioxide, global radiation, phytotron

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Introduction

Photosynthesis is a basic process for crop production, as it supplies the assimilates for maintenance and growth. Crop photosynthes is influenced by climatic factors. It shows a saturation-type response to photosynthetic photon flux density (Acock et al., 1978; Hand et al., 1993). Crop photosynthesis increases substantially, albeit less than proportionally, in response to increasing CO_2 concentration (Hand, 1982; Kimball and Idso, 1983). Within a wide range, temperature (Schapendonk and Brouwer, 1985) and relative humidity (Acock et al., 1976) seem to be less important. Hence, as for most greenhouse crops it is not economically feasible to increase irradiance by supplementary lighting, CO_2 concentration is the most important climatic factor, which enables to control the crop photosynthesis in commercial practice.

To reach this aim an experiment will be done to measure the crop gross photosynthesis and to gather the necessary inputs for the model. The model that will be used is the ASKAM model (Gijzen, 1992). The model was modified by Gijzen in such a way that it can be applied under phytotron conditions. With the data collected from the experiment and subsequent simulations the model will be validated for sweet pepper.

The aim of this study therefore is to determine the possibility to predict the influence of light, carbon dioxide (CO_2), and leaf area index on the instantaneous photosynthetic rate of sweet pepper with sufficient accuracy.

Materials and Methods

The ASKAM model

The ASKAM model used in this study is designed for calculating crop CO_2 uptake during the day. Originally the model is designed for a Venlo-type greenhouse. In this study the model is adjusted for the phytotron (Gijzen, 1992). Fig. 1 gives the general structure of the model. The model calculates the instantaneous gross and net crop photosynthesis based on CO_2, radiation and temperature measurements. These data are thus input to the model (Gijzen, 1992). The time step in the model can be equal to any short term interval within the day, and depends in this study on the time resolution of the data (Gijzen, 1992).

Calculated photosynthesis rates can be considered "potential", as no limiting effects like water or nutrient stress, high vapor pressure deficit of the air, or pests, are taken into account (Gijzen, 1992).

The elevation of the sun and the solar constant determine the global radiation outside the atmosphere. Atmospheric transmission is derived from the relation between measured global radiation and global radiation assumed there were no atmosphere present. In the next step the fraction diffuse of global radiation is calculated (Verbeek, 1992).

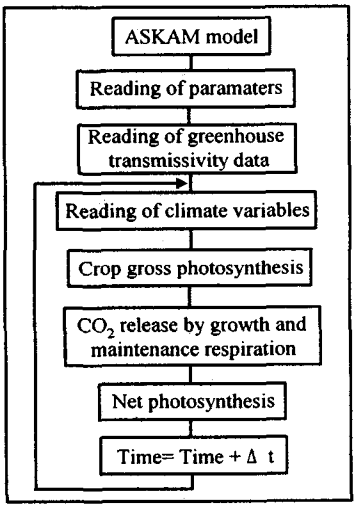

Fig. 1 Diagram of the structure of ASKAM model

Measurement system

Photosynthesis was measured in daylit compartments (4.8 m ×5.1 m floor area) of the phytotron of the department of horticulture, Wageningen Agricultural University, The Netherlands. Two identical compartments in the middle of a row of six compartments were used (Fig. 2 and 3): Compartment I was located at the west side of Compartment 2. The north wall of these compartments reflected light, as it was covered with aluminum foil and the glazing of the cover was of diffusing glass. The compartment cover had a roof slope of 30° to the horizontal facing 27° east of south. Temperature was controlled by electric heating and mechanical cooling. The CO_2 exchange rate of the crop was determined by mass balance and the compartments were operated as semi-closed systems (Sesták et al., 1971; Dutton et al., 1988). Changes in the CO_2 mass in a compartment were caused by CO_2 supply (aiming at a constant CO_2 concentration), air exchange with the outside atmosphere (leakage) and crop CO_2 exchange, including root respiration. CO_2 exchange of the crop (Pnc) was calculated according to Lake (1966) :

$$Pnc = (Ec - L - \rho \times V \times (C_{t2} - C_{t1})/(t_2 - t_1)/A_{crop} \quad \cdots\cdots(1)$$

where Pnc: crop net CO_2 uptake rate ($\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$), Ec: supply rate (flow) of CO_2 into the compartment ($\mu mol\ CO_2 \cdot s^{-1}$ $compartment^{-1}$), L: leakage rate of CO_2 to surroundings ($\mu mol\ CO_2 \cdot s^{-1}$ $compartment^{-1}$), ρ : density of CO_2 ($41.86 mol \cdot m^{-3}$ at 20°C), V: volume of compartment including air treatment system ($110 m^3 \cdot compartment^{-1}$), C_{t1}: carbon dioxide concentration ($\mu mol \cdot mol^{-1}$) at time t_1, C_{t2}: carbon dioxide concentration ($\mu mol \cdot mol^{-1}$) at time t_2, t_1, t_2: time (s), A_{crop}: total ground area occupied by the crop ($m^2 \cdot compartment^{-1}$), measured as length times width of the canopy stand.

It was assumed that the respiration rate during the day was equal to the respiration rate during the following night.

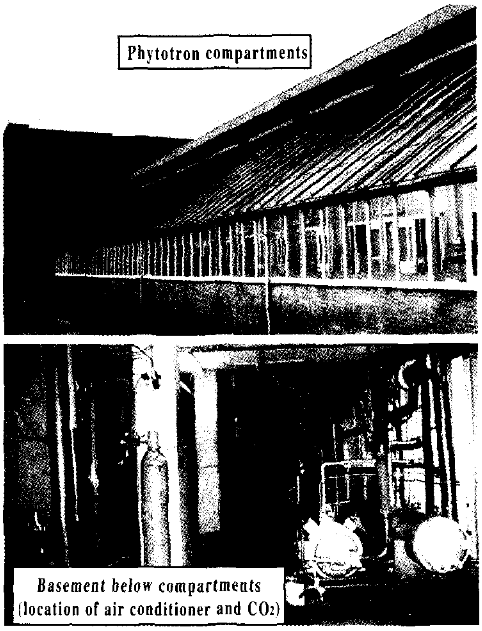

Fig. 2 North-south cross-section of a phytotron compartment used as semi-closed system for crop photosynthesis measurement and a basement below compartments (location of air conditioner)

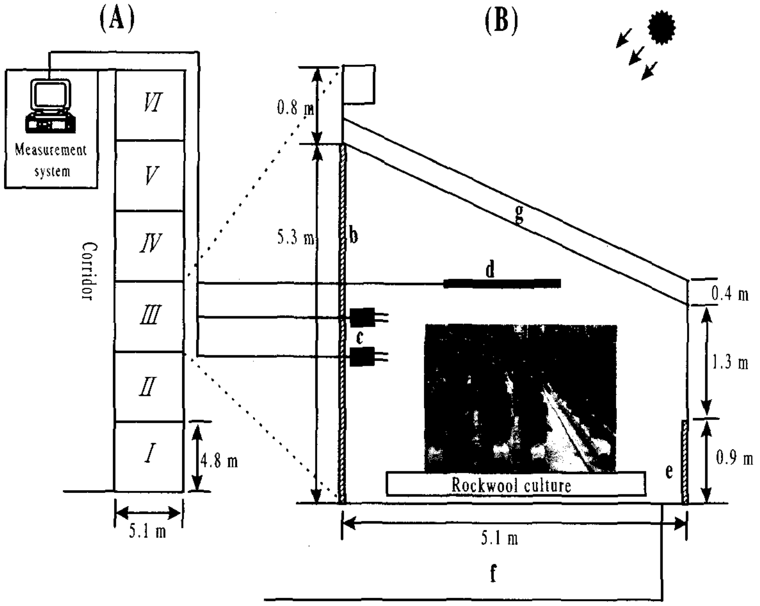

Fig. 3 North-south cross-section of a phytotron compartment used as semi-closed system for crop photosynthesis measurement. Situation of the compartments at the phytotron (A), and the lay out of a compartment in which the photosynthesis measurements were carried out (B).

(a) phytotron building, (b) reflecting north wall, (c) CO_2, temperature and humidity sensors, (d) PAR sensor, (e) brick wall, (f) basement below compartments (location of air conditioner), (g) construction for guidance of a screen (not used during the experiment).

Leakage measurements

Leakage was determined previous to the experiments in empty compartments at several conditions, where CO_2 supply rate in both compartments and CO_2 concentration gradients were at equilibrium. Leakage appeared to be linearly related to the difference in CO_2 concentration between the two compartments and the difference in CO_2 concentration between the compartment and the basement below the compartments, where the air conditioner was situated (Fig. 2). It proved that these were essential pools for exchange of CO_2. Preliminary measurements showed that neither the CO_2 gradient between compartment and outside air, nor the wind speed affected the leakage of CO_2, proving that sealing of the compartment cover had been very effective. Regression formulae resulting from leakage measurements were used to estimate leakage during photosynthesis measurements.

Due to leakage of the compartments it was necessary to quantify the leakage in empty compartments at different CO_2 concentrations. The leakage measurements were carried out after the photosynthesis measurements. When the compartments are empty the CO_2 flow, which has to be closed to keep CO_2 concentration in the compartment constant, equals the leakage of that compartment. Leakage was linearly related to the difference in CO_2 concentration between the compartment and the basement below and the difference in CO_2 concentration between the two compartments. The CO_2 concentration of the outside air was not measured during the experiment and therefore fixed as a constant value of 370 $\mu mol \cdot mol^{-1}$. Formula 2 shows the relationship between the leakage components, according to Heuvelink (1996).

$$L_i = a + b \cdot (C_i - C_b) + c \cdot (C_i - C_o) + d \cdot (C_i - C_{out}) \qquad \cdots\cdots (2)$$

with L_i: leakage rate ($\mu mol\ CO_2 \cdot s^{-1} \cdot compartment^{-1}$), a, b, c and d: regression coefficients, C_i: CO_2 concentration in compartment *III* of *IV* ($\mu mol \cdot mol^{-1}$), C_b: CO_2 concentration in basement ($\mu mol \cdot mol^{-1}$), C_o: CO_2 concentration in other compartment ($\mu mol \cdot mol^{-1}$), C_{out}: outside air.

Carbon dioxide measurements

The carbon dioxide concentrations in both compartments and in the basement below the compartments, were measured every 30 seconds by an infrared gas analyzer (URAS 3G, Hartmann and Braun) connected to a gas handling unit (ADC,WA-161-MK2, Hoddesdon). Gas samples were taken from a perforated tube (4m long) inside each compartment. Pure CO_2 was injected in the system through a thermal mass flow controller (BROOKS 5850 TR, Rosemount). This system regulated the pre-defined CO_2 set-point. The sampler, analyzer and the mass flow controller were controlled and read by a data-acquisition/control unit (HP3825A, Hewlett-Packard). The data-logger was connected to a PC (HP-Vectra) on which the measurement and control system were running (Fig. 4).

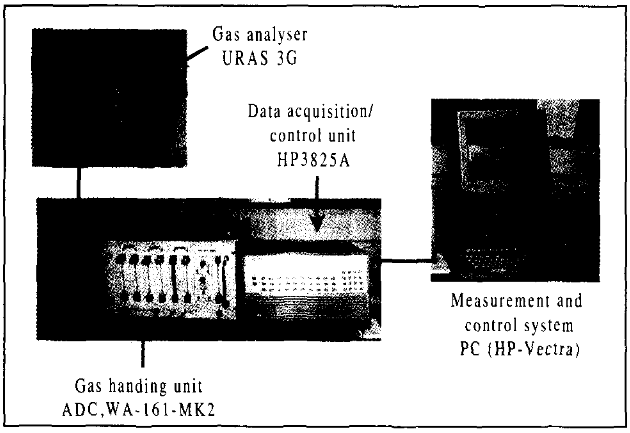

Fig. 4 Carbon dioxide measurement and control systems.

These data were measured every 30 seconds and once every 6 minute the average data over this time period were stored in a file. The measured data were temperature and relative humidity at two positions in each compartment. Outside radiation was measured by two solarimeters (Kipp and Sons) on top of the greenhouse. One solarimeter (type CM11) measured the total global radiation, and the other solarimeter (type CM121) with a shadow ring measured the diffuse component of global radiation. PAR (W·m^2) was measured inside both compartments. PPFD was measured above the canopy by a 75-cm quantum response tube PAR- sensor (TEDL) in the middle of Compartment 2. In the simulation only temperature, total global radiation and CO_2 data were used. The other data were used as control of the climate and the simulation.

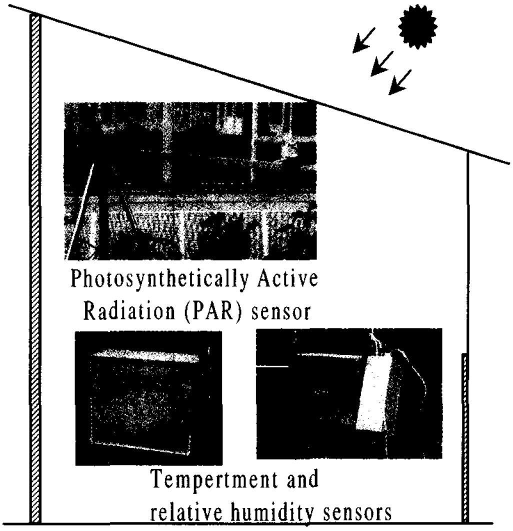

Fig. 5 PAR, temperature and relative humidity sensors.

Leaf area index measurements

The measurements were done to define the leaf area index and height of the crop necessary as inputs for the model. Once a week the compartments were opened to replenish the containers with the nutrient solution in the containers and to carry out destructive measurements. In each compartment 7 plants were selected at random. After removal of compartment IV from the experiment 7 plants were taken from compartment III. Measurements consisted of determination of the leaf area (LICOR 3100), determination of the length of the plants, fresh and dry weight and a distinction was made between roots, stem and leaves. After experiment leaves and stems of the shoots were measured separately.

Photosynthesis measurements

The compartments in which the photosynthesis measurement was carried out, were closed and the doors were sealed with aluminum tape in order of reduce CO_2 losses. The photosynthesis measurements were performed from 24 September until 20 October 1998.

In both compartments the set points for the CO_2 concentrations were adjusted. The CO_2 set points were either 400, 700 or 1000μmol·mol^{-1}. Everyday the set points were adjusted to one of these three CO_2 concentrations.

Results and Discussion

This report fits into the modeling research of the department of horticulture, Wageningen Agricultural University, Wageningen, The Netherlands. Crop growth models summarize our knowledge on crop behavior and can be widely applied to e.g. scientific analysis, crop management as a farm management tool.

Photosynthesis plays a major role in crop growth models. This research aims at predicting the effect of CO_2, light and leaf area index on the instantaneous photosynthetic rate of sweet pepper with ASKAM model. As the compartments are semi-closed CO_2 is leaking to the surroundings. To calculate the CO_2 losses, not by uptake of the plants, a leakage formula is determined. This is done in empty compartments.

Except days with a smooth course of global radiation, crop gross photosynthesis in general followed the course of diurnal global radiation. On days with a smooth course of global radiation crop gross photosynthesis was unstable. In the afternoon crop gross photosynthesis was falling behind on global radiation. As PAR increases, crop gross photosynthesis increased to certain point for which crop gross photosynthesis stabilizes. For higher leaf area indexes crop gross photosynthesis increases.

In all the graphs, the simulation and measurement of crop gross photosynthesis was clearly depicted (Fig. 6). The reason of this underestimation is not really answered in this report. It is not likely that the underestimation is caused by errors in the functioning of the model. It appeared that the model was functioning well for higher leaf area indexes as found in this research and also for a small block as used in this study.

The objective of the present work was to establish relationships between climatic factors and sweet pepper crop photosynthesis for validation of an explanatory crop photosynthesis model. Emphasis was on the qualification of the influence of CO_2 on sweet pepper crop photosynthesis at different PPFD and leaf area index. Only short-term influence of CO_2 on photosynthesis was studied. The present work also aimed at the investigation of hysteresis in sweet pepper crop photosynthesis.

To enable crop photosynthesis measurements at a combination of high CO_2 concentration and high PPFD at normal temperatures, the present work was conducted in summer in daylit phytotron compartments on small stands of sweet pepper. Hence, measurements were conducted over a range of natural

PPFD's Estimation of the response of crop photosynthesis to CO_2, was based on measurements at three CO_2 concentrations. Crop gross photosynthesis rates could be calculated by measuring net CO_2 exchange rates during day and night and assuming equal day and night time respiration rate. Variation in leaf area index was achieved by removal of plants from the crop stand. It was recognized on forehand, that in the afternoon shadow of a building fell over the compartments and therefore the crop photosynthesis model had to be used to investigate hysteresis in photosynthesis.

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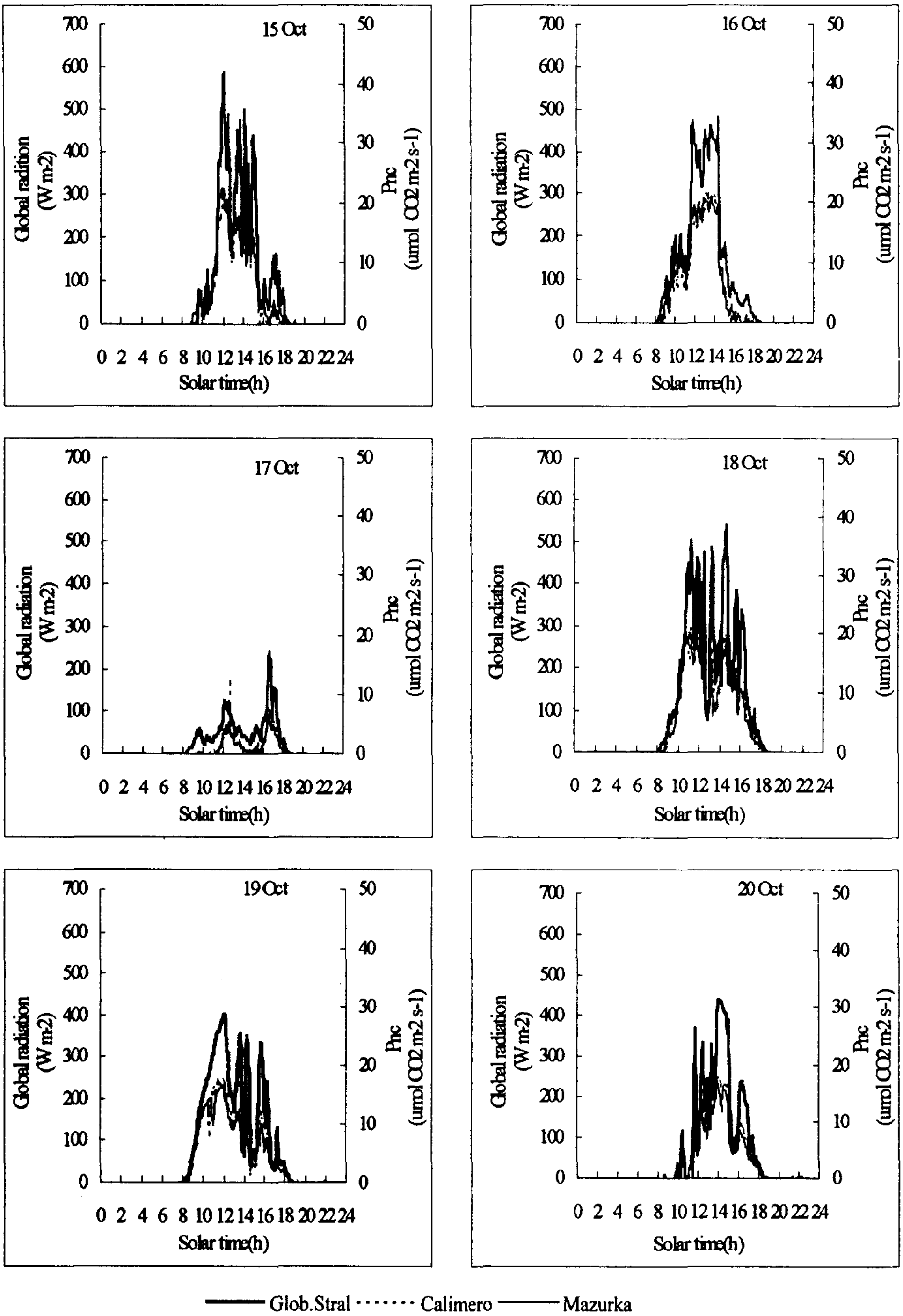

Fig. 6 Diurnal course of global radiation outside and measured and simulated Pnc in compartment for six days.

단고추의 작물 광합성 모델을 위한 CO_2 농도와 엽면적지수 측정

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적요

본 연구는 ASKAM모델로 CO_2, 광 및 엽면적지수가 단고추의 동적 광합성율에 추정가능성을 평가하기 위하여 수행되었다.

CO_2 농도는 2구획으로 구분된 반밀폐된 생장상에서 3수준 (400, 700 or 1000μmol mol^{-1})으로 조절하였다. 온도와 습도는 21℃ 및 80-95%로 조절하였고, 양액이 순환되는 용기내에서 재배하였다. 일태양복사, 온도 및 CO_2농도의 단기 자료를 기초로 하여 일중 단기간격에 대한 작물 순CO_2흡수량를 ASKAM모델로 추정하였고, 광합성 측정중 각 구획과 기부에서의 CO_2농도를 매분마다 측정하였다. 순수 CO_2의 구획으로의 흐름, 지상방사, 구획내의 광합성유효방사, 온도 및 상대습도를 측정하였다.

본 작물생장모델은 작물의 광합성율을 적절하게 추정할 수 있는 것으로 평가되므로 생장해석, 작물관리 및 온실관리에 광범위하게 적용될 수 있을 것으로 판단되었다.

주요어 : ASKAM모델, 이산화탄소, 일태양복사량, 생장상