On-line optimization of intensity and configuration of supplementary lighting using fluorescence sensor technology

A.H.C.M. Schapendonk[1], C.S. Pot,[2] X. Yin[3] and U. Schreiber[4]

[1] Plant Dynamics BV, Englaan 8, 6703EW Wageningen, The Netherlands
[2] Philips Lighting BV, P.O box 90050, 5600PB Eindhoven, The Netherlands
[3] CWE, Wagening University and Research Center, Haarweg 333, 6709RZ Wageningen, The Netherlands
[4] Universität Würzburg Mittlerer Dallenbergweg 64 Würzburg D-97082 , Germany
mail@plant-dynamics.nl

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Abstract

To estimate the impact of different applications of supplemental light in greenhouses, laborious and time consuming experiments are required to measure and verify differences in crop productivity. Especially when the expected differences are small, it will be difficult to prove that a given lighting application outperforms others in that test. Random variation and interaction of numerous environmental factors in a greenhouse environment limit differences that can be determined accurately enough to 5%, at least in an experimental setup. Still effects of less than 5% are of very high economic importance and it would be a big advantage if these small effects could be made visible in an earlier stage than at the time of harvest. Therefore it is important, that effects are not only made visible by comparison of integrated yield, but also by comparison of the dynamics of the responses at different developmental stages and seasons. We tested a modulated fluorescence monitoring system that was specially adapted for horticultural practice, in combination with a sensor system (Growlab) to study photosynthesis responses under 2 different lighting configurations in roses. Comparison of the yield data, based on fluorescence measurements with data based on photosynthesis measurements gave strong support that fluorescence signals, after species-specific calibration, are a sound basis for optimization of light intensity and lamp configuration in roses, with good perspectives for application in other horticultural crops.

INTRODUCTION

Supplementary assimilation light is in practice placed above the canopy, blocking a small percentage of incident radiation, and adding 50 to 250 μmol m^{-2} s^{-1} to the top of the canopy (Bredmose-Niels, 1994). This is added in periods of low irradiance, e.g. in winter or heavy clouded skies, but mostly early in the morning or at night to prolong total daily radiation. The incident light however, is mainly intercepted by the top layer of the canopy. By applying light at different altitudes the light quantity in the lower layers of the canopy would increase, thereby altering the composition of the photosynthetic machinery in the leaves in order to cope with this new light environment (Schapendonk et al., 1999).

It is well feasible that this will enhance the efficiency of light in lower layers of the canopy. Moreover the applied supplementary light is more evenly distributed over the canopy which may increase the overall efficiency of the absorbed radiation (Mortensen and Gislerød, 1994). We compared the effects of mobile lamps close to the canopy, generating light that penetrated deep into the canopy with fixed lamps at a high position in the greenhouse, generating light that is mainly absorbed by the top of the canopy. To study both the dynamics of daily light fluctuations and long-term adaptation, a fluorescence apparatus was developed for horticultural purposes, based on non-contact, non-destructive biophysical techniques. Fluorescence quenching results are interpreted as a reflection of the regulation of photosynthesis and they provide useful information on the important issue of the fluctuation of light-use efficiency both within the canopy and over the growth period (Schreiber et al., 1994; 2000). The estimated electron flow rates, determined with the fluorescence measuring equipment and the measured CO_2 assimilation rates, determined with the LICOR 6400, were used in a photosynthesis model to calculate the dry matter yields, predicted by both methods (Schapendonk et al., 1999; Yin et al., 2004).

MATERIAL AND METHODS

During the months December 2004 and January 2005 we recorded physiological responses of rose production parameters in 2 commonly used lighting treatments.
Treatment 1: lamps fixed at an altitude of 2.15 meter above the top of the canopy.
Treatment 2: a combination of this lamps (50%) with a mobile lighting system (50%) moving back and forth at the an altitude of 1.10 meter above the canopy.
The total PAR emitted by the two lighting applications was equal (125 μmol m^{-2} s^{-1}, 24 hours duration), though there were noticeable differences in light distribution both in the horizontal plane at the top of the canopy and within the canopy. The influence of the lighting treatments was monitored by recording the photosynthetic light- and CO_2 responses in both treatments at different heights in the canopy with a LICOR 6400. CO_2 and H_2O exchange were recorded simultaneously with fluorescence measurements. These data were correlated and used as a calibration to translate the obtained electron transport rates from the special fluorescence probe (fig. 1) into rates of CO_2 fixation. Continuous fluorescence recordings with this probe were combined with leaf temperature, sap flow and PAR measurements. The online registration of the fluorescence was done with a specially developed chlorophyll fluorescence apparatus (Growlab Plantivity meter, Fig. 1). Measurements continued for 2 months at a measuring interval of 8 minutes.

RESULTS AND DISCUSSION

It was confirmed by actual light measurements that the light absorption in the mobile light system was 10% higher, mainly due to deeper penetration in the lower canopy region. This was not due to the fact that the lamps were mobile but due to the associated lower position of the lamps, leading to more scatter in the canopy leaf layers and a smaller upward reflection. In order to harvest the beneficial effects of mobile light, the physiological status of the crop should meet some important prerequisites because mobile light reaches the canopy at regular intervals with a high intensity, whereas fixed lighting reaches the canopy continuously with a relatively low intensity. It is unlikely that the claim that mobile lighting is successful, brought forward by a large number of growers, would be due to increased photosynthesis since by all theories photosynthetic efficiency is expected to decline at higher light intensities or at best remains equal up to a certain

level. On the long run, however, the altered light distribution might improve photosynthetic capacity, by which the canopy profits more from sudden changes in the daily natural irradiance. Indeed we observed a higher photosynthetic capacity in the lower leaves of the mobile light treatment (Fig. 2). The elevated photosynthetic capacity however, did not lead to much higher canopy photosynthesis because the winter light conditions were still too low to profit from the elevated maximum photosynthetic capacity. In addition, the small increase in photosynthetic capacity was compensated by a simultaneous increase in respiration. The parallel upward shift of the highly significant correlation between ETR and photosynthesis is probably due to a higher respiration rate in the mobile light treatment (Fig. 3). In conclusion it became evident that the supposed positive effect of mobile lighting would be entirely due to the increased light absorption rather than to an increased photosynthesis under mobile lighting. This is conclusive with fundamentals on light-photosynthesis interaction. At best we would expect equal daily rates of assimilation, provided that the maximum light intensity on the leaf surface during passage of the lamp is relatively far from the deflection of the linear phase of the light response curve, which is about 200-300 μmol PAR for roses. In Figure 4a we depict simultaneous recordings of measured PAR and photosynthesis during two subsequent light pulses of 160 and 320 μmol PAR respectively. The small decrease of the proportionality between PAR and photosynthesis during the second peak with a higher intensity indicates a first sign of saturation.

Instead of time consuming and expensive photosynthesis measurements, chlorophyll fluorescence measurements can be applied to estimate photosynthetic optimal light conditions. On line measurements are essential because photosynthetic capacity varies over the day and over the season. The relation between photosynthesis and electron transport rate (ETR) for various conditions of temperature, light and CO_2, derived from the fluorescence measurements (Genty et al., 1989) is shown in figure 3. A highly significant correlation was observed. The displacement between the lines is caused by the higher dark respiration rates of the leaves under mobile light, indicative for higher growth activities.

A second prerequisite for optimal utilization of mobile light is the condition of open stomata between subsequent light peaks to prevent CO_2 limitation of photosynthesis during the next lamp passage. In fact it is required that stomatal conductance remains high in the low light or even dark condition between two subsequent light peaks to prevent stomatal dynamics to be too slow to follow the light intensity fluctuations that are implicit to mobile lighting. For roses this prerequisite is met, as shown in figure 4. When roses are exposed to light for more than 20 hours stomatal control seems to be deregulated and stomatal closure is postponed long after the light decreases. Complete darkening for 1 hour or more did not induce stomatal closure (Fig 4 b , c). Therefore roses are capable of taking optimal advantage of all the light that reaches the leaf. During the relative high irradiance peaks when the mobile light passes, additional CO_2 will be more profitable than for the fixed light treatment.

To estimate the relevance of chlorophyll fluorescence measurements in relation to yield we evaluated the predicted yields derived from photosynthesis measurements and fluorescence after converting the gas exchange data and the estimated electron transport rates into total daily dry matter yield with a mechanistic simulation model (Yin et al., 2005). The comparison between both methods is depicted in Fig. 5. The dotted line presents the line for the ideal situation that both methods give a complete match. Apparently this is not completely the case. For low yield conditions the fluorescence

measurements underestimate yield somewhat compared with the simulated yields that were based on photosynthesis measurements. Despite this controversy, that still has to be solved, we conclude that there is sufficient agreement between both techniques to support the conclusion that chlorophyll fluorescence measurements are an appropriate method for on line optimization of dry matter production. With respect to the particular case study on roses we conclude that, during the winter period, the effect of mobile light apparently is not based on direct photosynthetic effects nor on adaptation of photosynthetic characteristics. The positive effect of mobile light is mainly associated with the increase in light absorption. However, it is expected that the higher photosynthetic capacity of the lower leaves (Fig. 2), may have beneficial effects later in the year when lower leaves will profit from increasing natural day light conditions. Of course there are many other processes that are directly influenced by light intensity. In addition to the 10% increase in light absorption, irrespective of the absence of a net effect on photosynthesis, the high light conditions lower in the canopy may have additional positive effects on bud brake and shoot formation (Roberts et al., 1993).

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Figures

Fig. 1 Fluorescence measuring apparatus with clamped leaf.

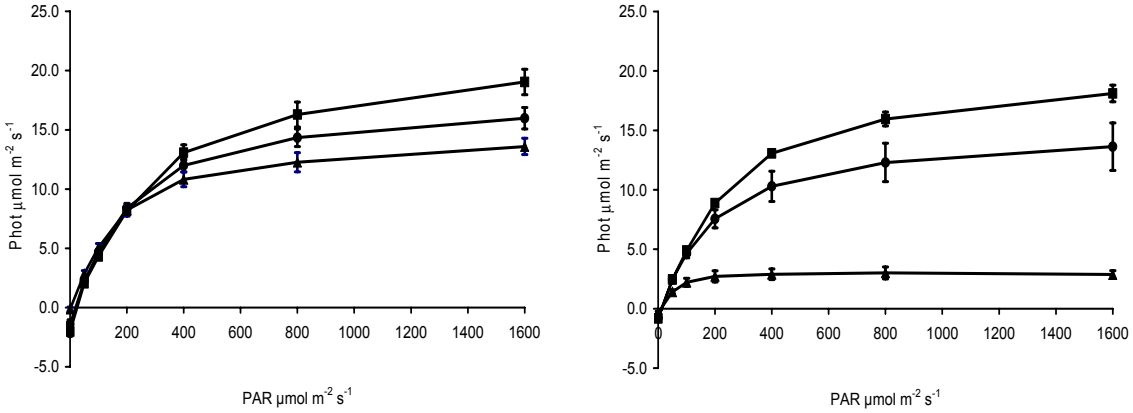


Fig. 2 CO_2 exchange by the leaves at 3 different layers in the canopy from top (squares) to middle (dots) to bottom (triangles). Mobile+fixed treatment (left) and Fixed only (right).

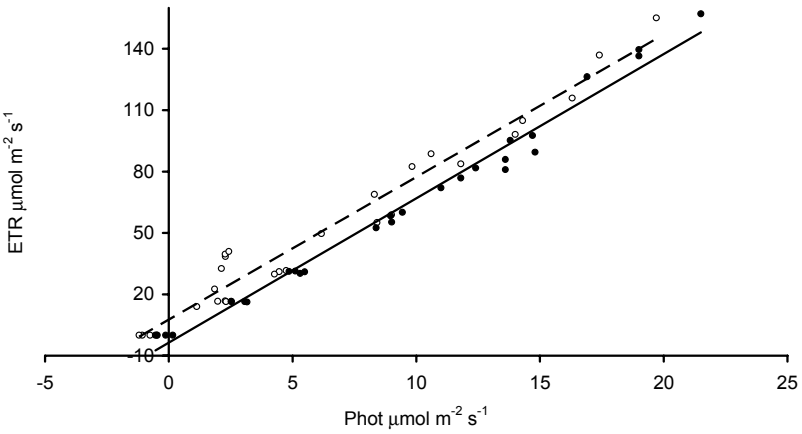
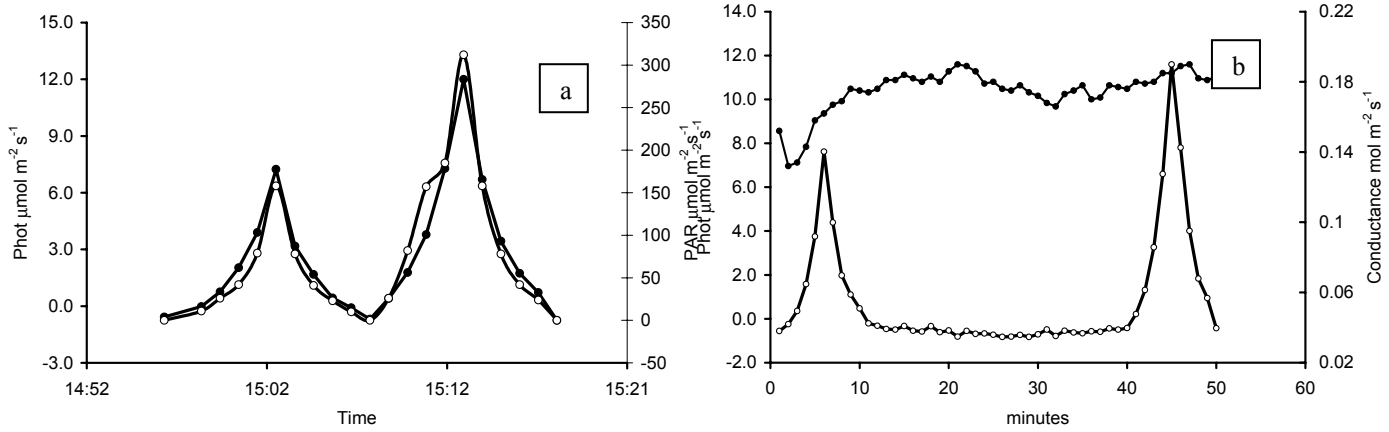


Fig. 3 Relation between photosynthesis and electron transport rate for fixed (closed circles) and mobile lighting (open circles).



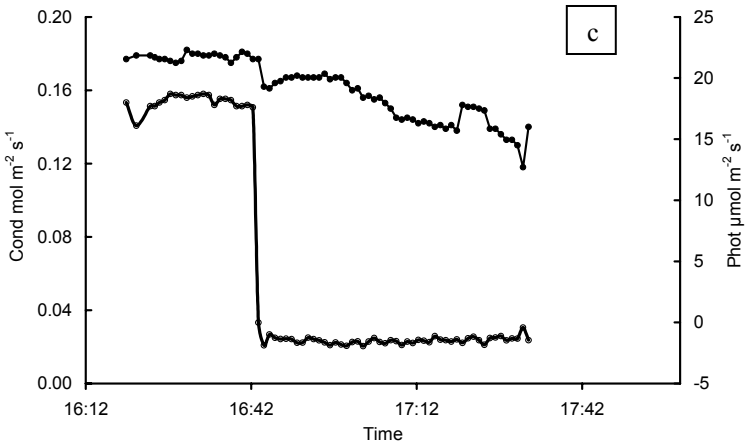


Fig. 4
a) PAR (open symbols) and photosynthetic rates (closed symbols) during two subsequent lamp passings at intensities of 320 and 160 µmol m^{-2} s^{-1} PAR.
b) Stomatal conductance (closed symbols) and photosynthetic rates (open symbols) during two subsequent lamp passings of 320 and 160 µmol m^{-2} s^{-1} PAR.
c) Stomatal conductance (closed symbols) and photosynthesis (open symbols) after shutting down the light at 16:42 h.

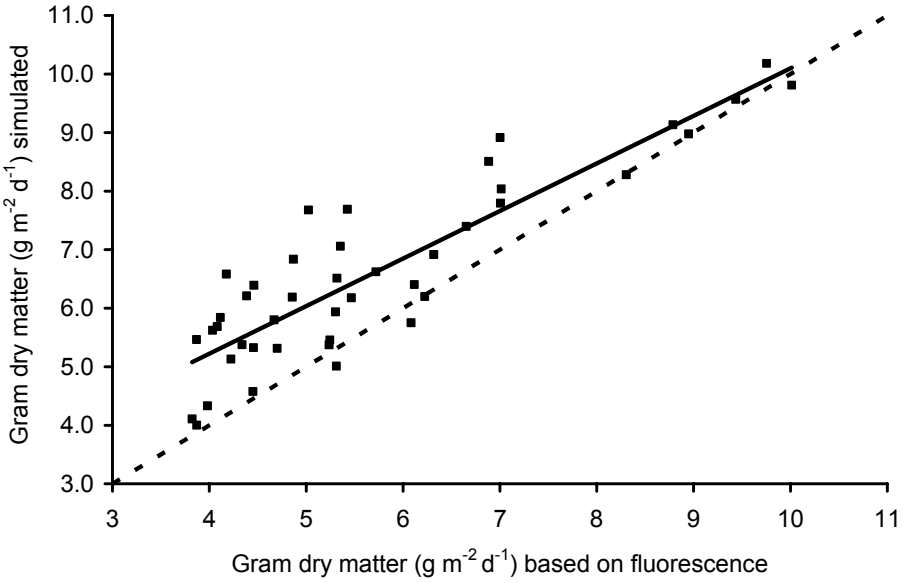


Fig. 5 Relation between dry matter yields calculated either from fluorescence measurements or from gas exchange measurements