The Application of LEDs as Assimilation Light Source in Greenhouse Horticulture: a Simulation Study

W. van Ieperen and G. Trouwborst
Wageningen University
Horticultural Production Chains Group
Marijkeweg 22, 6709PG Wageningen
The Netherlands

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Abstract

The application of light-emitting diodes (LED's) as potential source for assimilation lighting in greenhouse production systems opens up a range of new possibilities. LED's produce light in a very narrow wavelength range and do not directly emit heat radiation. The heat which is produced by LED's due to their limited energy conversion efficiency, can be drawn away via convective (water)cooling. As a result, LED's can be applied at relative dark places within the crop to increase leaf photosynthesis at locations where assimilation light normally doesn't penetrate. In theory this type of intercrop lighting could significantly increase crop photosynthesis. Existing simulation models for greenhouse/crop systems can be used to simulate the potential effects this intercrop lighting on crop photosynthesis. It is unclear however, whether the assumptions and simplifications that are justified in present crop models cause problems in simulations of growth systems with intercrop lighting. It may be anticipated that photosynthetic capacity of leaves that are subjected to intercrop lighting adapt different than leaves that are subjected to top lighting by natural light and assimilation light only. In this simulation study we investigated the sensitivity of leaf photosynthesis to adaptation of leaf photosynthetic components at different CO_2/light combinations, using the widely used steady-state model of Farquhar et al. (Planta 149: 78–90, 1980) for photosynthesis. The results are used to discuss limitations of current crop photosynthesis models to simulate production in greenhouse systems with intercrop lighting.

INTRODUCTION

For decades, supplemental assimilation light (AL) has been applied in greenhouses for commercial production at latitudes where natural light (intensity and/or day length) limits plant production (Heuvelink et al., 2006). Supplemental AL positively influences production via increased crop photosynthesis and in many crops also via a positive effect on product quality (Marcelis et al., 2002). The commercial application of AL started in ornamental crops, but nowadays also increasing area's of vegetable crops are supplied with supplemental AL (Knijff et al., 2004). For long, the economic advantages of AL overruled its inherent disadvantages. Important drawbacks of the use of AL are the energy use and concomitant CO_2 emission, while often supplemental AL from greenhouses significantly also adds to light pollution. With increasing energy prices and increasing societal demands to reduce energy use, CO_2-emission and light pollution (Tibbitts, 2002), this situations quickly changes.

Today, High Pressure Sodium (HPS) lamps are the most commonly used sources for supplemental AL in greenhouse horticulture. At the moment, HPS-lamps are still the most energy efficient AL sources available for commercial plant production, but they have certain characteristics that may limit their application in future. Due to the technology of light production (gas discharge) HPS-lamps operate at a high temperature (>200^{o}C), which results in significant radiant heat emission (infrared) towards their direct environment. HPS-lamps emit radiation in a broad band spectrum, including heat radiation. As a result HPS-lamps cannot be applied at close distance from leaves, and sufficient ventilation or cooling capacity should be available to avoid too high greenhouse temperatures. This may restricts the possibilities for future use of HPS lamps in future energy saving greenhouse concepts, where cooling is a major issue (Opdam et al., 2005).

The search for energy efficient alternatives for HPS-lamps led to Light-Emitting Diodes (LEDs) as possible candidate. At this moment, the most efficient LED's are still less efficient than HPS lamps (Fig. 1), but the PAR efficiency of LEDs developed very fast last decade. HPS-lamps, on the other hand, are at the end of their developmental cycle and no significant further progress in PAR efficiency is expected (de Ruijter, 2004). The current 'inefficiency' of LED's implies that a major part of the electrical energy input is still lost for photosynthesis and converted into heat. However, in contrast to heat from HPS lamps, heat from LED's can be dissipated via convective (water)cooling systems, and therefore removed from the crop environment. As a consequence, LED's can well be applied at relative dark places within a canopy to increase photosynthesis at locations in the canopy where supplemental AL applied at the top of the canopy normally hardly penetrates. In theory, this type of intercrop AL could significantly increase crop photosynthesis, while at the same time light pollution might be reduced due to reduced light reflection from the upper canopy surface. LED's emit radiation in a relative narrow band of wavelengths of only several nm's. The exact wavelength depends on the materials used in the LED. LED's are available in a broad range of wavelengths broadly covering the PAR spectrum (400-700 nm). This in principle enables the possibility to optimize the wavelength output of future LED-based AL sources for the photosynthesis process and related physiological responses such as opening of the stomata (stimulated by blue light), by choosing the right (combination of) colored LED's (Brazaitytė et al., 2006; Hogewoning et al., 2007; Kim et al., 2006).

Both, from greenhouse systems and from plant physiological point of view the application of LED's within the crop as supplemental intercrop assimilation lighting open new and challenging opportunities, especially in rather dense canopies such as for instance 'high wire' tomato, sweet pepper and cucumber. Unfortunately, crop physiological consequences of intercrop AL are largely unknown. Significant changes in leaf photosynthetic capacity at different depths in a canopy can be expected (Schapendonk et al., 1999). Intercrop AL will probably interact with the normal adaptation process of mature leaves that usually move from a high light environment towards a relative low light environment when they age. The quantitative effects of the adaptation are not known yet, while disturbances in the natural light environment with canopy depth may influence the instantaneous efficiency as well as the long term efficiency of the application of AL.

Simulation models are often used to predict the effect of AL scenario's in interactions with other environmental factors (e.g. CO_2 and temperature) on crop production. Until now, these simulation models do not, or hardly account for adaptations and vertical gradients in (decreasing) photosynthetic capacity within a canopy. These gradients may especially be relevant when intercrop AL is applied and may negatively influence crop photosynthesis under all light circumstances (no AL, top AL and intercrop AL). In this paper we investigate the potential effect of supplemental AL (applied either from the top (top AL) or within the canopy (intercrop AL)) on crop photosynthesis with a conventional simulation model (without a vertical gradient in photosynthetic capacity) and with a new model that includes vertical gradients in photosynthetic capacity.

MATERIALS AND METHODS

The simulation models used in this study are multi-layer derivates from SUCROS (Goudriaan and van Laar, 1994). Within these models, the canopy is vertically divided in 10 layers of equal leaf area (Cavazzoni et al., 2002), equally distributed over plant height. Absorbed light is calculated per individual crop layer following the method of Spitters (1986). Absorbed light is used as input for a photosynthesis module, which calculates photosynthesis per crop layer according to the biochemical model for steady state photosynthesis of Farquhar et al. (1980). Values for all parameters of the biochemical photosynthesis model are from Bernacchi (2001). Other inputs of the photosynthesis model, the internal CO_2-concentration and leaf temperature are mostly kept constant. Total absorbed radiation and crop photosynthesis are the cumulative totals over all leaf layers.

Top AL is simulated by adding it to the natural radiation above the canopy and assumed to be 100% diffuse. Intercrop AL can be added in all leaf layers and is also assumed to be 100% diffuse. A second simulation model (new model) includes vertical gradients in photosynthetic capacity. The simulated gradients are simulated via differences in Rubisco and Chlorophyll content between leaf layers, which are assumed to influence the maximal carboxylase activity and maximal electron transport rate in the photosynthetic systems, respectively (Schapendonk et al., 1999). In both models, total absorbed radiation and crop photosynthesis are the cumulative totals over all leaf layers.

Simulations are done with the conventional model (without vertical profiles of photosynthetic capacity) to investigate the theoretical maximal effect of intercrop AL on crop photosynthesis compared to top AL. Similar simulations were done with the new model (including a linear vertical gradient in photosynthetic capacity). In these simulations a static vertical gradient in photosynthetic capacity was assumed. RuBP- and Chlorophyll contents in the lowest canopy layer were assumed to be 50% of the contents in the top canopy layer.

RESULTS AND DISCUSSION

To check the performance of the multilayer models, their basic output (total absorbed radiation and crop photosynthesis) was compared with the output of a model, which calculates absorbed radiation and crop photosynthesis over canopy depth by a 3-point Gaussian integration method (Goudriaan and van Laar, 1994). Simulations with similar input resulted in similar output (not shown), which implies that the simulation of light absorption in the multilayer model functioned well. The multilayer models enabled the possibility to increase absorbed light in a defined leaf layer, which was used to simulate intercrop AL. The incorporation of adaptation of the photosynthetic system to decreasing light intensity with canopy depth in the model (via decreasing chlorophyll content and decreasing RuBP content) was done in the photosynthesis module of the model. Figure 2 shows the simulated sensitivity of output of the photosynthesis module (Gross Photosynthesis rate; F_g) to leaf internal CO_2 concentrations and Light Intensity at different degrees of photosynthetic capacity (Fig. 2A-D). These figures show that the simulated light-response curve for photosynthesis strongly depends on the degree of adaptation: slope as well as the maximal photosynthesis decreased with decreasing photosynthetic capacity. Figure 3 shows that adaptation of the photosynthetic capacity altered the calculated efficiency of the application of AL in adapted leaves already at low natural light intensity (compare length of the solid arrows with length of the dashed arrows). The simulated negative effect of adaptation on AL efficiency was larger at higher leaf internal CO_2 (Fig. 3A versus B).

Comparison of top AL with intercrop AL (160 μmol $m^{-2}s^{-1}$ AL upon 500 μmol $m^{-2}s^{-1}$ natural PAR at ambient CO_2 (350 ppm)) resulted in an simulated increase in crop photosynthesis of approximately 25% (with top AL) and 35% (with intercrop AL), in case a conventional simulation model (without a vertical gradient in Photosynthetic Capacity) was used. The simulated extra increase in crop photosynthesis at intercrop AL was due to more efficient use of the extra light in lower canopy layers (steeper part of the light response curve), and due to the absence of direct reflection of PAR to the sky at the canopy surface. However, after adaptation of photosynthetic capacity was included in the model, the positive effect of intercrop AL compared to top AL decreased from 10% to 5% (Fig. 5), mainly due to a lower increase in photosynthesis in the lower canopy layers (Fig. 4). The effect of including vertical gradients of photosynthetic capacity on simulations with natural and top AL was small, probably because most of the extra light by top AL was absorbed by the upper canopy layers with the lowest decrease in photosynthetic capacity.

From present simulation results it can be concluded that the absence of vertical gradients in photosynthetic capacity within a crop, do not cause very large overestimations of crop photosynthesis for as long as natural light (PAR) and top AL are considered. However, adaptation will significantly influence crop photosynthesis in case light intensity in lower canopy layers strongly increases, as will be the case with intercrop AL. Conventional simulation models perform well under conventional light conditions, but need to be updated when non-conventional light regimes are employed such as intercrop AL.

These simulations also show that the process of adaptation of the photosynthetic system to either light environment and or leaf age might be of high relevance for the actual performance of a crop with intercrop AL. Research on adaptation dynamics of photosynthetic capacity (how fast does adaptation occur, what is the role of light intensity/quality during leaf development on photosynthetic capacity and on the adaptability to changing light conditions?) is necessary to make simulation models suitable for future light systems in greenhouse horticulture and to be able to optimally control intercrop AL.

ACKNOWLEDGEMENTS

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Figures

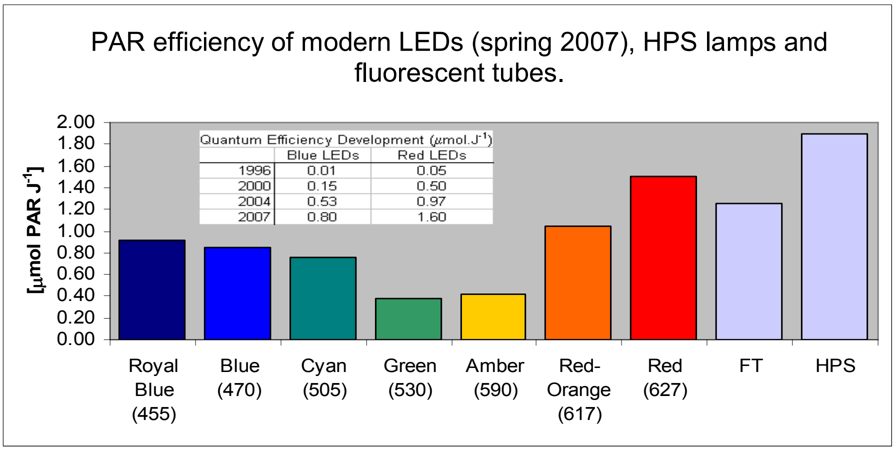

Fig. 1. Calculated PAR efficiency of modern high intensity Light Emitting Diodes (LEDs: Luxeon K2-Lumileds 2007)[1] compared with PAR efficiencies of HPS-lamps and Fluorescent Tubes. Insert: Development of PAR efficiency of blue and red LEDs during the last decade. [1]PAR efficiency of LEDs calculated from Lumen efficiency according to factory datasheets (www.lumileds.com) and the CIE 1988 'Photopic luminous efficiency' function for conversion.

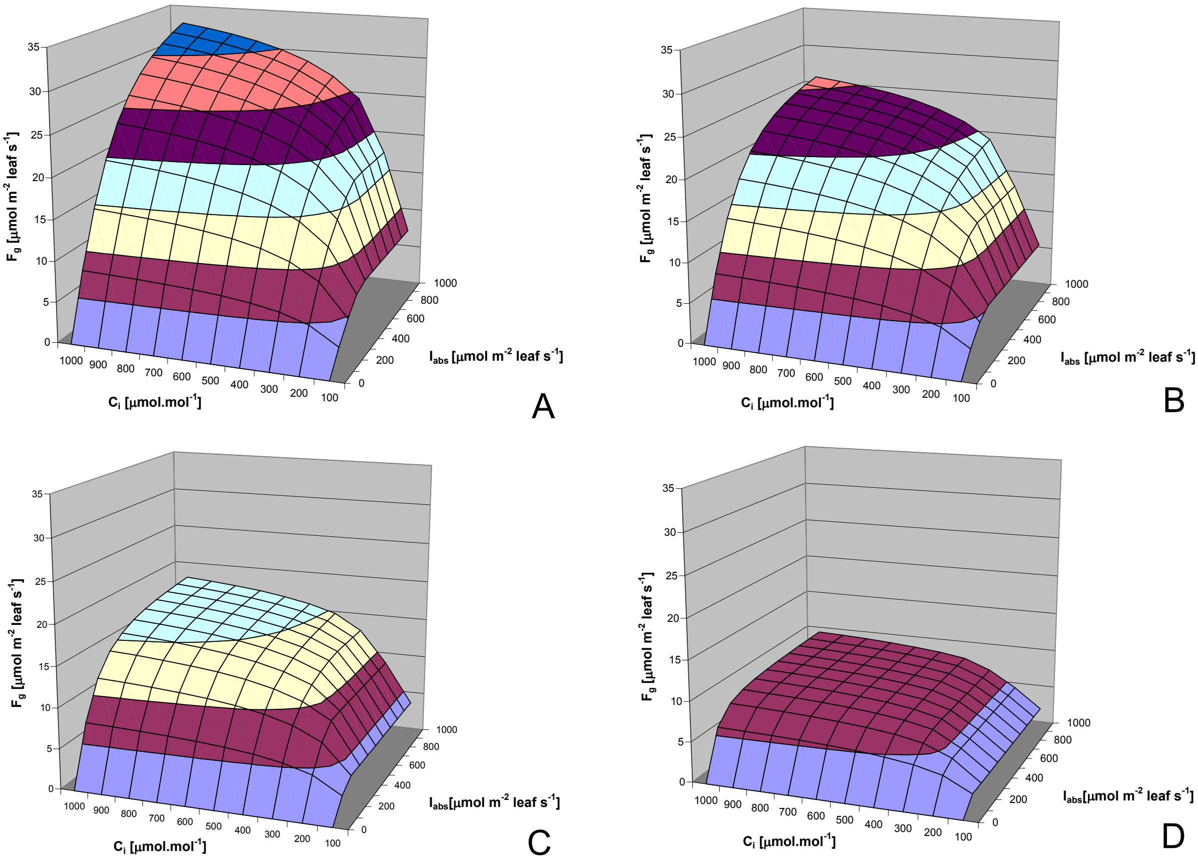

Fig. 2. Sensitivity of leaf photosynthesis (F_g) to chlorophyll (Chl) and ribulose-1,5-biphosphate (RuBP) content at combinations of different absorbed light intensities (I_{abs}) and intercellular CO_2 concentrations (C_i). A: Chl 500 µmol.m^{-2} leaf, RuBP 5 µmol.m^{-2} leaf; B: Chl and RuBP 75% of A; C: Chl and RuBP 50% of A; D: Chl and RuBP 25% of A.

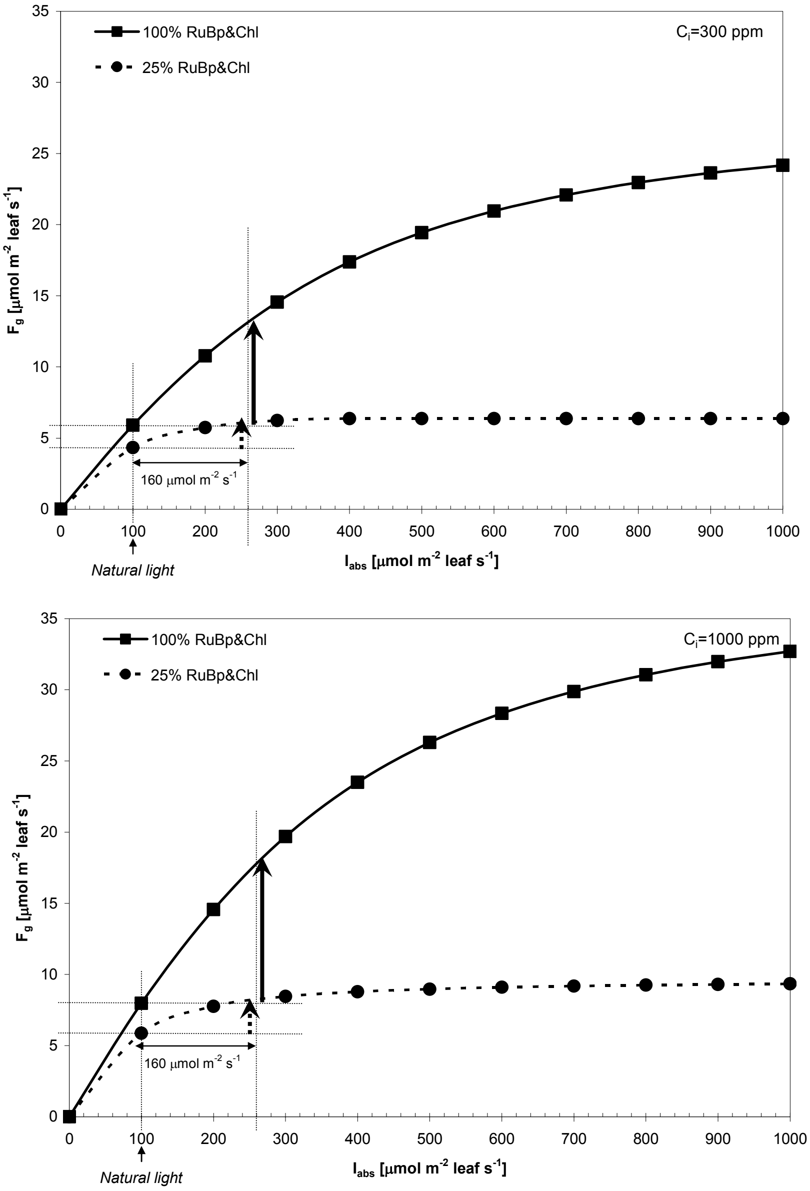

Fig. 3. Simulated light-response curve at normal (100%) and reduced (25%) RuBp and Chlorophyll content at two CO_2 levels (A: 300 ppm; B: 1000 ppm). The arrows indicates the increase in photosynthesis rate after the application AL (160 µmol m^{-2} leaf s^{-1}) on a mature leaf. A: C_i=300 ppm; B: C_i=1000 ppm.

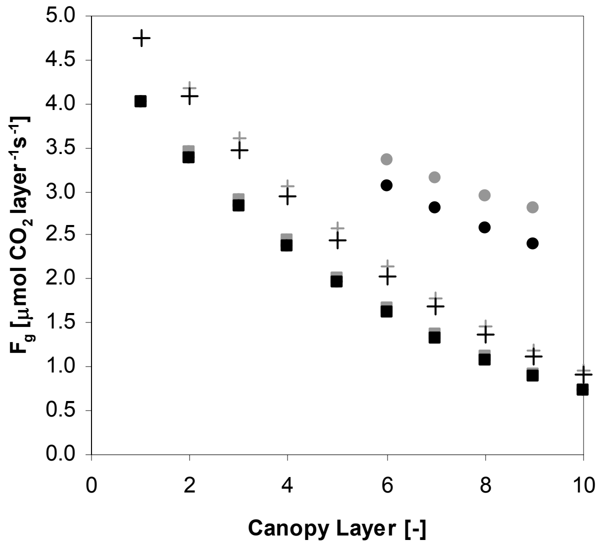

Fig. 4. Simulated Rate of Gross Photosynthesis (F_g) per canopy layer (0 = top layer) at different types of AL (without AL (■); top AL (+) and intercrop AL (●)). Natural PAR: 500 µmol $m^{-2}s^{-1}$; Top AL: 160 µmol $m^{-2}s^{-1}$; Intercrop A: 4 x 40 µmol $m^{-2}s^{-1}$ in canopy layer 6,7,8,9 (out of 10 equal layers, counting layers start at top); LAI 3 m^2m^{-2}. CO_2 350 ppm); black symbols: model with adaptation; grey symbols: model without adaptation.

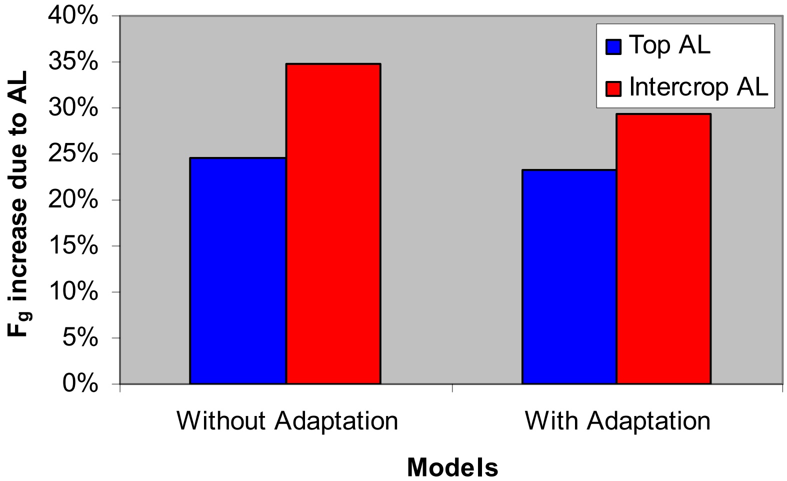

Fig. 5. Simulated increase in total Crop Photosynthesis due to Top AL and Intercrop AL, calculated with models without and with adaptation of photosynthetic capacity with canopy depth included. See further legend Figure 4.