

A 3D greenhouse model to determine the optimal lighting strategy and crop structure for light capture and photosynthesis in tomato

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Introduction

Light interception in high-growing row crops like tomato and cucumber is of great importance for crop production and economic profit. The spatial distribution of sun light (direct and diffuse component), assimilation lamps (HPS, LED) and reflecting surfaces of greenhouse structure is difficult to measure. Moreover, photosynthesis is seldom measured synchronously at several places in the whole canopy, but is generally determined only at the leaf scale, so that crop photosynthesis is hard to predict.

For determination of optimal lamp, screen and crop configuration in 3D space, the recently developed 3D greenhouse model (Buck-Sorlin et al. 2009), constructed within the GroIMP platform (Kniemeyer 2008), is very well suited. This model is a suite of modules comprising multiple diffuse and/or direct light sources, the position and optical properties of greenhouse components, and various absorbing and perceiving light sensors. These elements constitute a 3D scene for which the distribution of light is computed using the built-in radiation model of GroIMP. Importantly, the model is coupled to a photosynthesis rate model which allows the computation of assimilate production as a function of absorbed light. Thus, the model principally allows to evaluate effects of different strategies of lamp configuration, row structure and reflecting walls and screens on overall crop assimilate production.

Methods

The virtual greenhouse is constructed by explicitly considering the position, shape and optical properties of all objects in the 3D scene. The light distribution is then computed by the GroIMP radiation model, which is based on an inversed Monte Carlo path tracer, similar to the one used by Cieslak et al (2008). Sunlight is modelled as a direct and a diffuse component, depending on the recorded outside light level. Diffuse light comes from a sky object consisting of 72 directional lights arranged in a hemisphere around the greenhouse, whilst direct sun light is provided by a single directional light. The power of both light sources, as well as the position of the sun are a function of latitude, day of year, and time of day (Goudriaan and van Laar 1994). Optical properties of all greenhouse objects entail reflection, transmission and absorption of photosynthetic radiation (PAR), and were measured on subsamples with a Perkin-Elmer spectrometer coupled to a light sensing sphere. The virtual greenhouse consisted of a glass roof, side walls, floor, energy-saving screen, gutters, assimilation lamps, and a crop consisting of static virtual plants (Fig. 1). The light pattern emitted by the lamps matched that of a SON-T in a wide angle reflector (data from Hortilux ©), see Buck-Sorlin et al (2009) for details. The tomato crop was represented as a static mockup, corresponding to the crop on Jan 27th in 2009 at the Improvement Centre, Bleiswijk, The Netherlands. This mockup was created in GroIMP by a growth rule that created 30 phytomers per plant, of which 8 were trusses and the rest consisted of leaves. Each leaf was composed of 15 leaflets of a fixed geometry, yet their size increased in proportion to length of the terminal leaflet of the composite leaf. Crop density was 2.27 plants per m² ground floor, the top of the canopy was situated at ca. 4.2 m above the floor.

The model components were individually calibrated (lamps, leaf optical properties, etc). The light model was validated to observed light distribution in two grids of 24 point sensors perpendicular to the rows in the mockup crop. The validated model was used to calculate the effects of lamp configurations and row structures on light interception and crop photosynthesis.

Results and discussion

Measurement of the optical properties of the tomato leaves showed an average reflection and transmittance of PAR of 8.3 and 3.3% of incoming light, respectively. The properties of the leaf shader in GroIMP were adjusted accordingly (see the light pathways in Fig. 2). Validation of the light model on the crop mock-up, using calibrated leaf optical properties, lamp light distribution and light sensors simulated at the measured heights in the crop, showed good resemblance with observed light distribution ($R^2 = 0.96$).

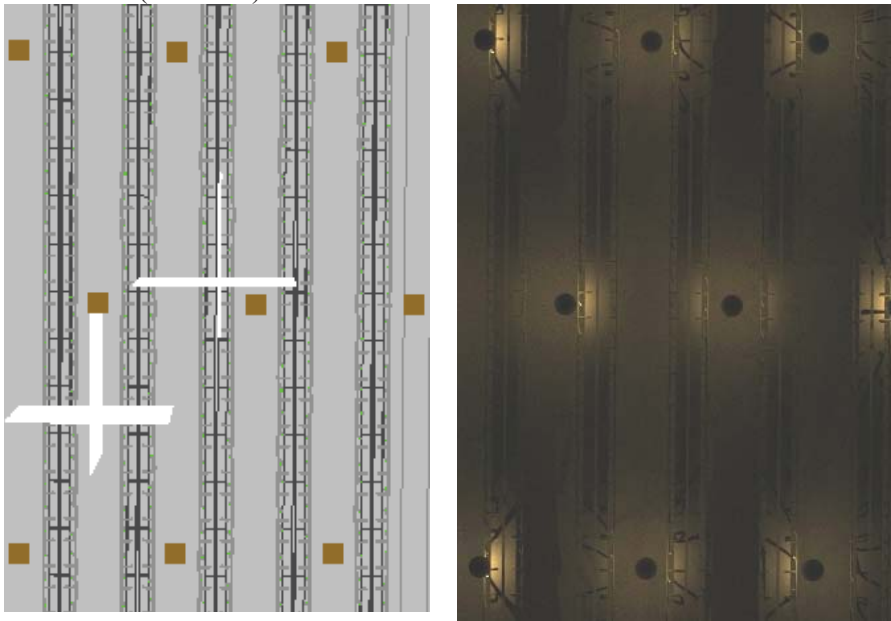


Fig. 1. Top view of the greenhouse compartment. Left, wireframe display with gutter rows that carry the plants, SON-T lamps (brown squares) light sensors (white lines); right, rendered floor with slabs and lamps (spheres)

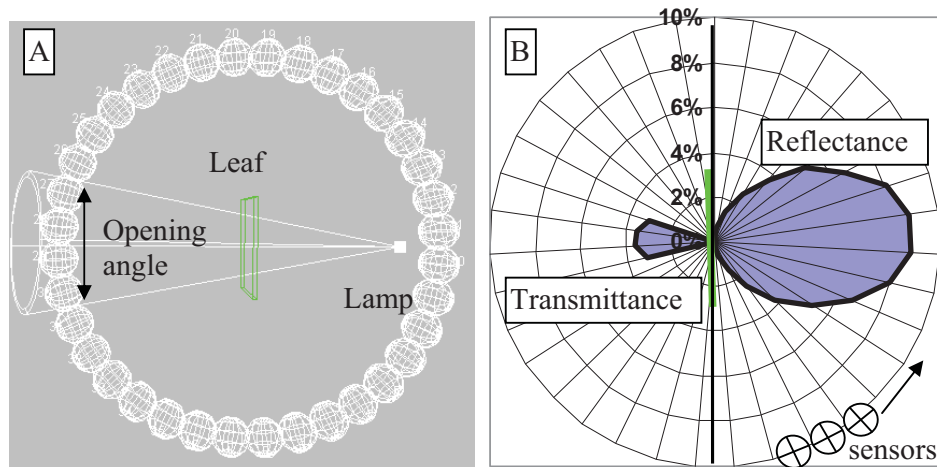


Fig. 2. Light reflected and transmitted by a leaf. A, model setup with light source, green leaf surface and 36 sensors; B, simulated light level per sensor as percentage of incident light intensity

Table 1. Simulated light absorption and perceived light level ($\mu\text{mol PAR m}^{-2} \text{s}^{-1}$) for some scenarios

Scenario	Absorbed light	Light level below crop
	% of input	$\mu\text{mol m}^{-2} \text{s}^{-1}$
0. Default [#]	92.7	9.00
1. Wide reflector	93.3	8.16
2. Lamp height 5.3m	95.2	7.95
3. Wider path (2.0m), pd 1.83	89.7	13.07
4. Idem, pd as default	91.3	10.96

[#]default: Small reflector, lamp height 6.3m, path width 1.6 m, plant density (pd in plants m^{-2}) 2.27

Simulated light absorption by the crop increased as a result of widening the opening angle of the lamp reflector or decreasing the lamp height. The absorption decreased by widening the path (scenario 3), even when simultaneously the plant distance in the row was decreased to correct the plant density again to default (scenario 4). A wider path permits light to reach lower leaves at higher light intensities. However, such measures may result in a decreased efficiency of lamp light by light loss to the floor. Further studies are planned to incorporate effects of lighting scenarios on photosynthesis and crop growth.

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Modeling photo-modulated internode elongation in growing greenhouse cucumber canopies

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Introduction

Light quantity and quality are major determinants in regulating internode growth. Reductions in both, PAR and R:FR, result in similar shade avoidance responses, such as increased internode elongation. In this context, however, the R:FR ratio seems to act as an early competition signal, while at higher leaf area indices, the light quantity signal becomes more crucial (Ballaré 2009). The main part of knowledge about the patterns that control plant response to light signals is derived from analysing hypocotyls or, in case of density effects, even-aged seeding stands. Different organs are sites of light signal perception (Morgan *et al.*, 1980), but to which extent the various signals from the different organs contribute to internode elongation in a cucumber canopy grown under naturally varying PAR conditions is unclear. This also refers to the question of timing and duration of the PAR-sensitive time window for the growth of the individual internode and the contribution of the R:FR signal to final internode length. Functional-structural plant modeling was already shown to be useful for coping with the feedback processes between canopy architecture, light distribution and canopy growth (e.g., Prusinkiewicz & Rolland-Lagan, 2006). Especially, with respect to irradiances and photo-signaling in canopies, Chelle *et al.* (2007) concluded that three-dimensional plant modeling is superior to the currently used experimental approaches. The objective of this work is to find out whether consideration of both, light quantity and quality signals, is essential for an accurate prediction of internode lengths in a growing cucumber canopy.

Materials and Methods

Due to the large number of possibly relevant sites of perception and duration of the light signals, we consider PAR above the canopy and the R:FR ratios at the level of the individual internode and the whole stem. To provide the R:FR data, the growing canopy will be modelled based on the L-system for cucumber growth, L-Cucumber, presented previously (Kahlen *et al.*, 2008). In L-Cucumber, internodes simply elongate from a minimum value at internode appearance to a final internode length (FIL). The increase in internode length per day equals 50% of the difference between actual internode length and FIL (Kahlen *et al.*, 2008). The extended model will use the original approach for internode elongation, except that the FILs will be determined based on the prevailing PAR and R:FR conditions. For model conceptualization and parameterization, we stepwise analyse FILs measured in two greenhouse experiments. At first, we try to evaluate the effect of PAR on FILs (1st experiment) resulting in a PAR-sensitive model approach for prediction of FIL, MA1. Then, we analyse the R:FR ratio perceived at the stem level using L-Cucumber. In this step, measured FILs of the 2nd experiment are used as input data, and MA1 is modified by adding a R:FR-sensitive term resulting in model approach 2, MA2, for FILs. For model evaluation, we extend the internode growth model used in L-Cucumber by the light-sensitive FIL-prediction model based on MA2 and compare simulated FILs using L-Cucumber with measured data from a 3rd experiment.

PAR-sensitive model approach

The hypothesis underlying the first step is that mainly light quantity, PAR, controls FILs of isolated plants. Therefore, we analyzed the relationship between daily PAR or mean PAR above the canopy of up to four days and FILs for internodes 5 - 9 grown in a sparse isometric cucumber canopy (exp. 1) by means of linear regression considering periods of up to 10 days before the individual internode has reached its maximum growth rate (cm day^{-1}), which is assumed to be at an internode length of ca. 3 cm.