A 3D Model of Illumination, Light Distribution and Crop Photosynthesis to Simulate Lighting Strategies in Greenhouses

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Abstract

A functional-structural model for a tomato crop, situated in a greenhouse, was developed to calculate the most efficient lamp (HPS, LED) positions and crop structure, with the objective to reduce energy consumption and improve light use efficiency. The model was built within the GroIMP platform and written using the dedicated modelling language XL. The entire production system is described as a 3D scene including a virtual greenhouse with the crop and light sources (natural light and lamps). The pathways of individual light rays were modelled multi-spectrally with an inversed path tracer. Plant organs (leaves, internodes, flowers, fruits) are the basic units of the multi-scaled, fully object-oriented model. Surface textures and colours were included for all 3D objects. For the current objective a static 3D mock-up of an existing crop was used. Measured 3D distribution pattern and spectrum of light emitted by the lamps were fed into the model. The modelled horizontal light distribution agreed well with measurements. Effects of different positions, reflector types, and spectra of lamps, and plant architectural and optical properties on light distribution and photosynthesis were evaluated. In total 10 illumination scenarios were simulated to quantify crop absorption and loss of light. In summary, a more efficient illumination strategy was predicted when the light was more focused on the crop by lamp reflectors, at inter-lighting (LEDs), and with a reflecting screen above the lamps. The inter-lighting strategy also resulted in a relative increase of light intercepted by fruit and stems relative to lighting from the top of the crop.

INTRODUCTION

In greenhouse horticulture there is much debate on the spatial distribution of assimilation light (Hovi-Pekkanen and Tahvonen, 2008; Trouwborst et al., 2010; De Visser and Buck-Sorlin, 2011). If positioned correctly, lamps can illuminate the crop more efficiently and thus save energy costs. It is time-consuming and costly to find experimentally an energy-efficient design in practice. A more rapid approach would be to use a computer aided design, to simulate possible lamp configurations in the greenhouse. For more than a decade, software tools (e.g., CAD-CAM) exist that enable 3D visualization of objects in a 3D scene including simulation of the trajectories of light rays. The accompanying light model usually uses a Monte Carlo ray tracer (Veach, 1997) or a radiosity approach (Chelle and Andrieu, 1998) to calculate the fate of light rays. The rapid innovations in information technology also enhanced the development of more elaborate models for crops, so-called functional-structural plant models (FSPM) that integrate both structure and function (Vos et al., 2010). For greenhouse crops nowadays FSPMs exist for tomato (Sarlikioti et al., 2011a,b), cut rose (Buck-Sorlin et al., 2009) cucumber (Wiechers et al., 2011) and chrysanthemum (De Visser et al., 2007). Although in greenhouse practice a few 3D models on greenhouses including lamps are being used, to our knowledge no model also incorporates the 3D structure of the plants. Therefore a 3D model has been developed that simulates the light distribution of natural and artificial light within a realistic 3D representation of a crop in a greenhouse. Subsequently, the model can be used to calculate effects of lamp positions, properties of HPS or LED lamps, leaf angles and row structure on light distribution, absorption and photosynthesis.

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In this paper, a selection of lamp positioning scenarios are being simulated for a tomato crop, with the aim to find the most efficient lighting strategy.

MATERIAL AND METHODS

The virtual greenhouse is constructed by explicitly considering the position, shape and optical properties of all objects in the 3D scene. The distribution of light in the scene 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 was modelled using a sky object consisting of 72 directional lights arranged in a hemisphere around the greenhouse, whilst direct sun light was modelled by a single directional light object which was able to change its orientation. The power of both light sources, as well as the position of the sun, is a function of latitude, day of year, and time of day (Goudriaan and van Laar, 1994). The objects in 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). Optical properties of these 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 light pattern emitted by the modelled lamps were taken from a HPS (High Pressure Sodium) lamp (1000W, HS2000 deep reflector, Hortilux), see Buck-Sorlin et al. (2009) for details. The HPS grid, at 6.3 m above the floor, generated 130 µmol m^{-2} s^{-1} PAR at the top of the canopy. The LEDs (95% red, 5% blue) generated 60 µmol m^{-2} s^{-1} PAR, both for top- and inter-lighting. Each LED module was simulated as a spotlight with an opening angle of 60°.

A functional-structural plant model (FSPM) of tomato was used. This is a further extension of the model of Sarlikioti et al. (2011a,b). This FSPM described the structure of the crop down to the organ level (internode, leaflet) explicitly in 3D using the rewriting rules in XL grammar within the GroIMP platform (Kniemeyer, 2008). The function used in the current FSPM consisted of a mechanistic photosynthesis model derived from Kim and Lieth (2003). The maximum photosynthetic capacity of leaves decreased with canopy depth following a logistic curve (Sarlikioti et al., 2011a). For the light simulations, the tomato crop was represented as a static mock-up, corresponding to a full grown crop (cultivar 'Komeett') measured in 3D on 27 January 2009 in a greenhouse at Bleiswijk, The Netherlands. This mock-up was created by a set of growth rules that created 30 phytomers per plant, of which 8 consisted of an internode and a fruiting truss and the others representing 11 internodes with attached leaf. 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. 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. Leaf area index was 2.8 m^2 m^{-2}. Stem density was 3.4 stems per m^2 ground floor, path width was 0.9 m and crop row width 0.6 m, and the top of the canopy was situated at ca. 4.2 m above the floor. The observed floor PAR reflection of 40% was incorporated in the model.

The modelled light emission from the lamps and the reflection and transmission from leaves were individually calibrated by matching modelled and measured sensed light distribution in a sphere around the objects. The simulation of light distribution in the canopy was validated by comparing simulated and observed light distribution in two grids of 24 cosine corrected PAR sensors perpendicular to the rows in the mock-up crop. The validated model was used to calculate the effects of lamp configurations and row structures on light interception and crop photosynthesis. The following lighting scenarios were computed with regards to emitted power, crop absorption, crop photosynthesis, crop reflection and light loss to floor and greenhouse cover:

0. HPS lamps evenly distributed above the crop rows and path (default).
1. As 0, but HPS lamps with 20% wider opening angle.

2. As 0, but HPS lamps at a height of 5.3 instead of 6.3 m.
3. As 0 and increased distance between plant rows (1.5 m instead of 0.9 m) and decreased stem density (2.7 instead of 3.4 stems m^{-2}).
4. as 3, yet stem density (stems m^{-2}) corrected to default (3.4 stems m^{-2}).
5. HPS (as 0) + LED grid above crop rows.
6. As 5, where LEDs have a 50% smaller opening angle (90° instead of 180°).
7. As 6, including a screen above the lamp grid that reflects 50% of PAR.
8. HPS + LED strings within the crop (inter lighting): strings at 2.5 and 2.85 m height.
9. As 8, now 2nd string at 3.20 m high.
10. As 9, and no leaf age related decrease of maximum photosynthetic capacity.

Simulations were always carried out with the same crop structure, yet for scenario 3 plant density was changed.

RESULTS AND DISCUSSION

Validation of the modelled light distribution in the crop mock-up, using calibrated leaf optical properties, emission pattern of the lamp and light sensors showed that the simulated vertical light distribution in the canopy matched well with observed light distribution (R^2=0.96).

Simulated light absorption by the crop only slightly increased by decreasing the lamp height compared to the reference (Table 1). The small effect is due to the increased loss to the floor from 4.5 to 5.1% of light input, which almost counteracts the reduction in reflection loss to the roof. The absorption decreased by widening the opening angle of the lamp reflector, giving more reflection losses, and by widening the path, even when the plant density was corrected to default (scenario 4). A wider path permitted light to reach lower leaves at higher light intensities. However, such measures did result in a decreased efficiency of lamp light by light loss to the floor. The tomato FSPM of Sarlikioti et al. (2011a) also simulated higher light levels on the floor combined with lower crop absorbance when the path widened. Beneficial effects of increased light levels at lower leaves on their photosynthetic maximum have been claimed to enhance crop growth, yet these possible benefits might be overshadowed by the reduction in light absorption of the crop.

In the HPS+LED top lighting, where both HPS and LED lamps were installed above the rows of the crop and shined downwards, light absorption by floor and slabs (reflection not included) was very low (Scenario 5, Table 2). However, a significant amount of incoming light was reflected by the canopy (Scenario 5, Table 2) as compared to the reference situation with 100% HPS-illumination (Table 1). As an alternative for this HPS+LED system, we narrowed the light bundle from the LEDs by decreasing their opening angle by factor 2 (Scenario 6, Table 2). This led to 10% higher crop absorption, but also to more light being cast (and lost) on the greenhouse floor. The narrower opening angle caused a more focused light bundle with a higher light level per surface unit. Given a similar fraction of lit ground area, more light is thus lost to the floor as compared to scenario 5.

Simulation of the vertical light distribution within the crop when two LED strings were installed at 2.5 and 3.2 m above the floor, showed a drastic decrease of light level to almost 0 at ca. 70 cm above or below the LEDs (Fig. 2). Without a crop the light level gradually decreased with distance as could be expected from a light source with Lambertian emission pattern.

The simulated LED inter-lighting showed that absorption increased and loss of light decreased compared to LED top lighting, due to reduced canopy reflection (Table 3). Surprisingly, light absorption slightly increased by a higher placement of the 2nd LED string (scenario 9) relative to scenario 8. Scenario 9 showed less light absorption by stems and fruit and more by leaves (data not shown) because the string was in the denser part of the crop canopy relative to scenario 8, thus explaining the reduced loss of light. Fixing modelled photosynthetic properties for all leaf ages resulted in a strong increase in growth and therefore efficiency of light conversion into biomass (Table 3, compare Scenario 10 and 9). This strong response to exclusion of the aging effect is mainly due to the increased photosynthesis at light saturation, in leaves (very) close to the LED light. We therefore recommend to always determine age-related photosynthetic properties in experiments that study the effects of local light on photosynthesis and growth. This effect shows that a possible maintenance of maximum photosynthetic capacity to light adapted leaf level due to illumination by LEDs may increase light use and crop productivity. This promising effect of LED inter-lighting was also observed for cucumber by inter-lighting with HPS lamps of older leaves (Hovi-Pekkanen and Tahvonen, 2008; Trouwborst et al., 2010). The inter-lighting showed ca. 8% of the light being absorbed by fruit and stems, while at top lighting only 2% was modelled (for details, see De Visser and Buck-Sorlin, 2011). This presumed loss to fruit absorption may be a relevant drawback of inter-lighting.

The model is capable to compute the fate of light and the resulting crop photosynthesis for different lamp and canopy configurations. It is a powerful tool to estimate prospects of new illumination strategies without costs of elaborate measurements and experimentation. Further innovative illumination strategies are sought to be tested for possible implementation in horticultural practice.

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Literature Cited

Buck-Sorlin, G.H., Hemmerling, R., Vos, J. and de Visser, P.H.B. 2009. Modelling of spatial light distribution in the greenhouse: description of the model. Proceedings of the Third International Symposium on Plant Growth Modeling, Simulation, Visualization and Applications - Beijing (China), 9-13 Nov. 2009.

Chelle, M. and Andrieu, B. 1998. The nested radiosity model for the distribution of light within plant canopies. Ecological Modeling 111(1):75-91.

Cieslak, M., Lemieux, C., Hanan, J. and Prusinkiewicz, P. 2008. Quasi-Monte Carlo simulation of the light environment of plants. Functional Plant Biology 35:837-849.

de Visser, P.H.B. and Buck-Sorlin, G.H. 2011. Modellering ruimtelijke lichtverdeling in gewassen. GTB report 1104, Wageningen UR Greenhouse Horticulture, The Netherlands.

de Visser, P.H.B., van der Heijden, G.W.A.M., Heuvelink, E. and Carvalho, S.M.P. 2007. Functional-structural modelling of chrysanthemum. p.199-208. In: J. Vos, L.FM. Marcelis, P.H.B. de Visser, P.C. Struik and J.B. Evers (eds.), Functional-Structural Plant Modelling in Crop Production. Dordrecht, the Netherlands: Springer.

Delepoulle, S., Renaud, C. and Chelle, M. 2008. Improving light position in a growth chamber through the use of a genetic algorithm. Artificial Intelligence techniques for Computer Graphics, Studies in Computational Intelligence, Volume 159/2008, Springer Berlin, p.67-82.

Goudriaan, J. and van Laar, H.H. 1994. Modelling Potential Crop Growth Processes. The Netherlands, Dordrecht: Kluwer Academic Publishers.

Hovi-Pekkanen, T. and Tahvonen, R. 2008. Effects of interlighting on yield and external fruit quality in year-round cultivated cucumber. Scientia Hortic. 761:183-191.

Kim, S.-H. and Lieth, J.H. 2003. A coupled model of photosynthesis, stomatal conductance and transpiration for a rose leaf (*Rosa hybrida* L.). Annals of Botany 91:771-781.

Kniemeyer, O. 2008. Design and Implementation of a Graph Grammar Based Language for Functional-Structural Plant Modelling. Doctoral dissertation, University of Technology at Cottbus, Fakultät für Mathematik, Naturwissenschaften und Informatik.

Sarlikioti, V., de Visser, P.H.B. and Marcelis, L.F.M. 2011a. Exploring the spatial distribution of light absorption and photosynthesis of canopies by means of a functional-structural plant model. Annals of Botany 107:875-883.

Sarlikioti, V., de Visser, P.H.B., Buck-Sorlin, G.H. and Marcelis, L.F.M. 2011b. How plant architecture affects light absorption and photosynthesis in tomato: towards an ideotype for plant architecture using a functional-structural plant model. Annals of Botany 108(6):1065-1073.

Trouwborst, G., Oosterkamp, J., Hogewoning, S.W., Harbinson, J. and van Ieperen, W. 2010. The responses of light interception, photosynthesis and fruit yield of cucumber to LED-lighting within the canopy. Physiologia Plantarum 138(3):289-300.

Veach, E. 1997. Robust Monte Carlo Methods for Light Transport Simulation. Ph.D. Dissertation, Stanford University, http://graphics.stanford.edu/papers/veach thesis.

Vos, J., Evers, J.B., Buck-Sorlin, G.H., Andrieu, B., Chelle, M. and de Visser, P.H.B. 2010. Functional-structural plant modelling: a new versatile tool in crop science. Journal of Experimental Botany 107(5):723-727.

Wiechers, D., Kahlen, K. and Stützel, H. 2011. Dry matter partitioning models for the simulation of individual fruit growth in greenhouse cucumber canopies. Annals of Botany 108(6):1075-1084.

Tables

Table 1. Simulated light absorption by crop and floor+slab for some scenarios with HPS lamps.

Scenario	Absorbed light (% of input)	
	Crop	Floor and slab
0. Default[#]	87.5	4.5
1. Wide reflector	86.0	3.6
2. Lamp height 5.3 m	87.8	5.1
3. Wider path (1.5 m)	80.0	9.0
4. Path 1.5m, sd 3.4 m^{-2}	81.0	9.0

[#] default: deep reflector, lamp height 6.3 m, path width 0.9 m, stem density (sd) 3.4 m^{-2}.

Table 2. Illumination by HPS+LED situated above the crop. See main text for explanation on the scenarios.

HPS+LED top lighting	Scenario		
	5	6	7
Light distribution (% of input)			
Light absorption crop	78.8	87.7	89.3
Light on floor and slab	2.8	6.3	6.7
Canopy reflection	18.0	5.7	4.0
Crop growth (mg DM s^{-1} m^{-2})	5.59	6.29	6.68
Light use (g DM MJ^{-1} PAR)	4.71	4.53	4.53

Table 3. Simulated light distribution and light use for the inter-lighting scenarios. See main text for explanation on the scenarios.

HPS+ LED inter-lighting	Scenario		
	8	9	10
Light distribution (% of input)			
Light absorption crop	87.7	87.9	87.9
Light on floor and slabs	5.9	5.7	5.7
Canopy reflection	6.2	5.4	5.4
Crop growth (mg DM s^{-1} m^{-2})	4.78	4.95	6.33
Light use (g DM MJ^{-1} PAR)	3.93	4.03	5.16

Figures

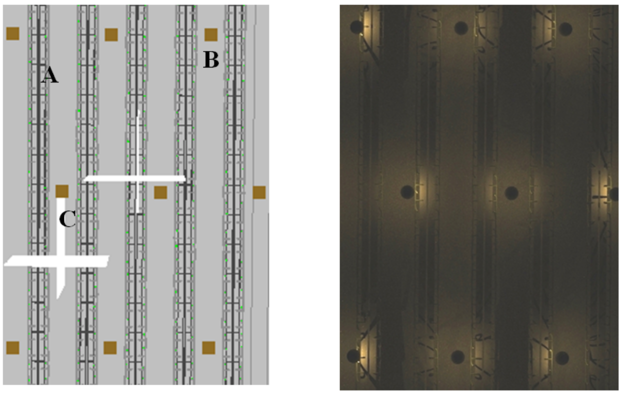

Fig. 1. Top view of the greenhouse compartment. Left, wireframe display with gutter rows (A) that carry the plants, HPS lamps (B, brown squares) light sensors (C, white lines); right, rendered floor with slabs and lamps (black spheres).

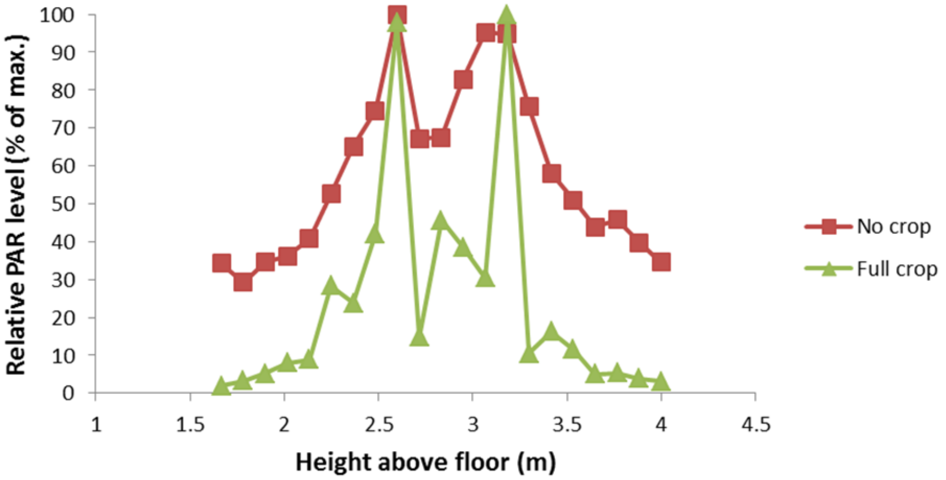

Fig. 2. Simulated relative PAR intensity summed for up and down side of sensors at fixed intervals, averaged in the horizontal plane, for scenario 9 having 2 LED strings (2.5 and 3.2 m above floor) with or without a crop.