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Deliverable 4.425

D4.425 - Optimisation of spectral distribution of SSL lighting in the crop plant based on Functional structural plant modelling

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D4.425 – Optimisation of spectral distribution of SSL lighting in the crop plant based on Functional structural plant modelling

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CONTENTS

List of abbreviations

FSPM	Functional Structural Plant Model
GroIMP	Growth Interactive Modelling Platform
HPS lamps	High pressure sodium lamps
LAI	Total crop Leaf Area Index
LED	Light emitting diode
PAR	Photosynthetically active radiation

SECTION 1 – INTRODUCTION

The introduction of assimilation light in horticulture has made it possible for Northern-European climates to grow greenhouse vegetables year-round, instead of being limited to the summer season. Up to now, most greenhouse systems use high pressure sodium (HPS) lamps for assimilation light. In the last decades, these lamps have been somewhat improved in terms of energy efficiency, but still the conversion of electric energy to light energy is around 25% only. Over the last years, the use of LEDs as assimilation light has increased considerably, mainly due to their claimed higher efficiency in the conversion of energy to light. Two other essential advantages will be studied in this research: (1) the spatial distribution of assimilation light in the greenhouse crop can be improved by positioning the LED lamps within the crop without burning the leaves since the LEDs produce less heat than conventional light sources such as HPS lamps, (2) the spectrum of the LEDs can be adjusted as such that plant photosynthesis is optimal. Here we present the outcomes of model calculations with a 3D functional-structural plant model that can both simulate the 3D structure of plants and spatial light distribution, and simulate the light in its full spectral composition realistically. The intriguing question to address is whether a specific position and colour (spectrum) of the LEDs will optimize the performance of the crop with respect to quality and level of production, given a specific 3D plant architecture.

Different parts of the visible light spectrum are perceived by plants and trigger plant responses, resulting in changes in plant morphology and physiology. This light-driven morphogenesis determines plant architecture, flower colour and complex processes such as flowering. In general, a light spectrum similar to that of sunlight supposedly guarantees a normal plant development. When expressed as a percentage of all photons between 400 and 800 nm, sunlight is composed of 21% blue light (400-500 nm), 26% green (500-600 nm), 27% red (600-700 nm) and 26% far red radiation (700-800 nm). These spectral compositions of the light vary in their efficiency in the process of photosynthesis as was reported by McCree (1972), and these mechanisms were incorporated in the FSPM.

In order to simulate spatial light distribution in a greenhouse crop, a 3D model of the crop, consisting of leaves, internodes, stems and fruits, is required. In the last decade state-of-the-art 3D models of plants were constructed within an international scientific community of biologists, physicists and computer experts, and were called Functional Structural Plant Models (FSPM, see e.g. Vos et al., 2010). These FSPM are able to simulate each individual light ray in an engineered 3D scene. In model-wise predicting the effects of LED light in an existing tomato crop, a new model of LED lighting in a greenhouse crop showed promising results (De Visser et al., 2014). The model of De Visser et al. (2014) was used here and was extended to enable multispectral calculations, i.e. the transport of light was made dependent on its spectral composition. This state-of-the-art model was used to simulate a number of scenarios that are expected to be possibly realized in the near future of tomato production under LED light. The scenarios addressed the questions of the crop, (1) which colours most favour crop photosynthesis, and thus, crop yield, (2) what is the impact of plant morphological changes - due to plant photomorphological responses to a certain LED colour - on light interception and growth. Question 1 was already partly addressed in the modelling work of deliverable 4.424b with a 2D crop growth model. In deliverable 4.424b, the results of the experiments of sub-tasks 4.2.1 and 4.2.2 (described in Deliverables 4.421 and 4.422) were used to calculate the effects of spectral composition on the crop photosynthesis and thereby production. In this deliverable (4.425), this will be extended by using a 3D model that can simulate the light distribution of various spectral compositions through the canopy, given the crop characteristics such as leaf length and leaf position. Question 2 has not been addressed in recent studies as far as we know, except in our own work with a preliminary model (De Visser et al., 2014) that has been improved considerably for this deliverable.

SECTION 2 – Materials & Methods

Functional Structural Plant Model (FSPM) approach

The Functional Structural Plant Model (FSPM) was developed within the GroIMP interactive modelling platform, which was initially developed and described by Kniemeyer (2008) and now serviced by the University of Göttingen (Germany). The scenarios (see paragraph below) for testing the crop response on LED lighting should be simulated for a realistic 3D scene, incorporating the essential objects, apart from the FSPM mimicking the crop, as present in a standard greenhouse, Thus, a virtual greenhouse compartment was constructed within GroIMP on basis of an existing compartment by explicitly considering the positions, shapes and optical properties of all the objects (roof, walls, lamps, gutter, plants) in a 3D scene. The light distribution was 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).

Optical properties of all greenhouse objects as well as leaves entailed reflection, transmission and absorption of the fraction of photosynthetic radiation (PAR) generated by a light source, and were measured on subsamples with a Lambda 1050 spectrophotometer (Perkin-Elmer Inc) coupled to a snap-in light integrating sphere.

Net photosynthesis was simulated for each leaflet on the basis of absorbed light, air temperature and CO_2 according to Kim and Lieth (2003), with a leaf-age-depended value for Jmax, the potential rate of electron transport (in μmol electrons m^{-2} s^{-1}), a value that could be estimated based on chlorophyll fluorescence characteristics as determined in deliverable 4.424a. Default light response curves for tomato leaves, as measured on many occasions in Dutch greenhouses, were used to calibrate the photosynthesis module. Differences in light response between colours were quantified following the approach of McCree (1972), by correcting α, i.e. the slope of the light-response curve for photosynthesis, expressing the conversion of a micromole of light to a micromole of assimilated CO_2. Thus , the value for the parameter α was spectrally corrected as based on the relative quantum efficiency per light colour of a measured McCree curve for tomato leaves. The maximum photosynthesis in the model depends on Vcmax, the maximum carboxylation capacity, which is in principal not depending on the light spectrum but on the enzyme rate of CO_2 carboxylation. Such a model will allow to simulate spectral photosynthesis of light originating from differently coloured LEDs, and is a substantial improvement compared to model set-up of deliverable 4.424b.

The virtual greenhouse compartment that was used for 3D model calculations[i] consisted of a glass roof, side walls, floor, assimilation LED lamps, and a crop consisting of static virtual plants (Fig. 1). The emission pattern of LED light, placed as top light above the plant rows, concisely matched (per 10 degree interval) that of an existing, 250 cm long, commercially available LED lamp, and emitted PAR was calibrated to 110 μmol m^{-2} s^{-1}. For the mathematical approach to calculate the 3D emission pattern, see Buck-Sorlin et al. (2009). The strings with LEDs were at a height of 4.75 m above the ground, above each double row of plants and placed in row direction. The crop was represented as a static structure, corresponding to measurements on a tomato crop cv. Komeet in our DLO research facilities in Bleiswijk, The Netherlands, as measured on plants on Jan 11th in 2011 (see De Visser et al., 2014). Each plant consisted of 8 trusses and 21 leaves. Each leaf was composed of 15 leaflets of a fixed geometry. The modelled scene of 3 by 3.2 m ground area consisted of 32 plants. Plants were placed on slabs at 0.8 m above the floor, and pairs of slabs, with internal distance 0.4 m, were divided by a path, giving 1.6 m distance from centre to centre between slab pairs. The tops of the plants were situated at 3.5 m above the floor. An infinite canopy was simulated by placing perfect mirrors around the scene.

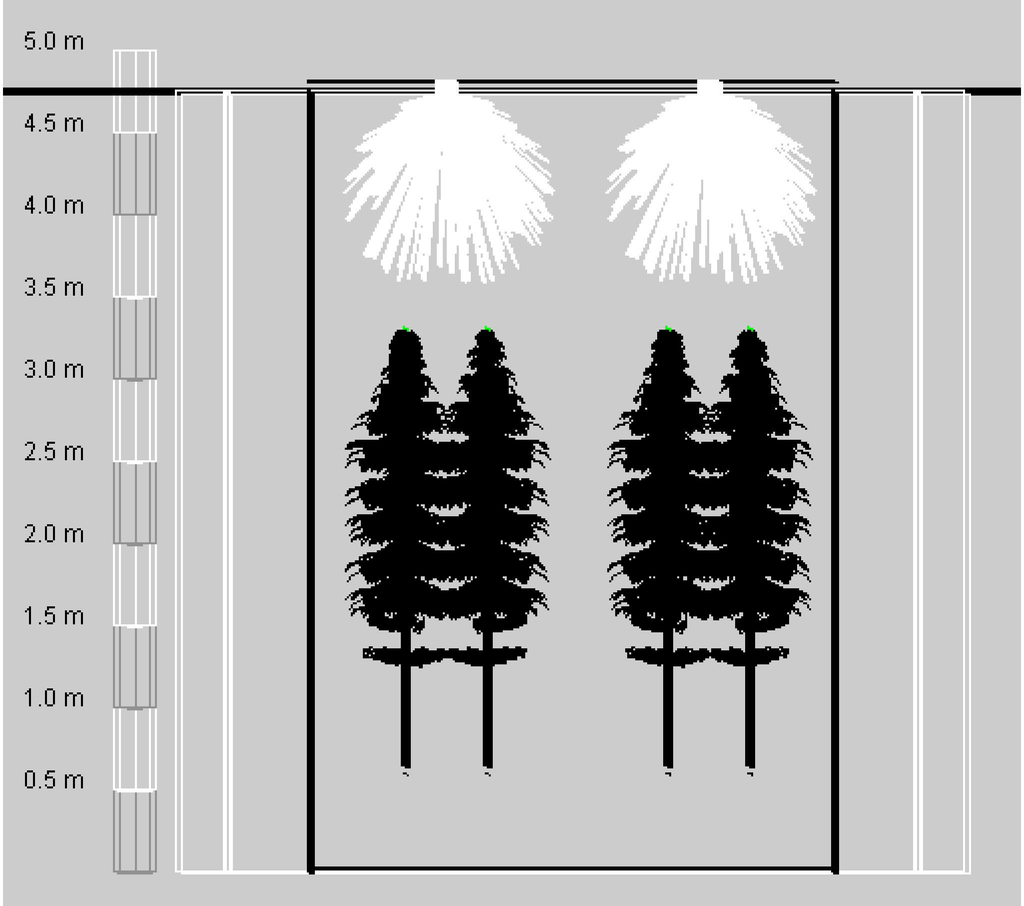

Fig. 1. The 3D scene, as seen in the direction of the plant rows, consisted of 2 double plant rows and two strings of LEDs above the crop.

Model scenarios

The scenarios comprised (1) the spectral composition of the LED light, and (2) plant architecture. For each scenario the total crop absorption of light and the crop photosynthesis was calculated by aggregation of light absorption and photosynthesis of each individual leaflet of the crop. In the scene ca. 500.000 leaflets were present, illustrating the complexity of the simulation.

Ad 1: spectral composition of the LED light:

For blue (400-480 nm), green (500-550 nm) and red (600-700 nm) LEDs the spatial light distribution, reflection and absorption by the tomato crop was simulated. The output level of the blue LEDs was 100 μmol m^{-2} s^{-1} for each colour separately.

For each of these three colours, simulations were done for plants with one, seven or twenty-one leaves (full crop with a Leaf Area Index (LAI) of 3 m^2 m^{-2} ground floor). The reason to take these three leaf numbers is that the effect of an enlarging crop on the utilization of each colour can be shown. We expect that the differences as observed at leaf scale will almost totally average out at the crop scale, as was suggested by Paradiso et al. (2011) who used a rather simple model that was possibly not allowed for addressing such research questions.

Ad 2: Interaction between LED colour and plant architecture:

The colour of the assimilation light has been shown to change the 3D shape or morphology of the plant, her further referred to as 'plant architecture'. As was shown in task 4.2.1 (Deliverable 4.422), blue light causes a plant to grow more compact, with shorter leaves and internodes, while green light does the opposite and creates a taller plant. For the scenarios, the observed plant architecture of constant illumination with blue, green and red light respectively were incorporated in the FSPM. Subsequently, the effect of the plant architecture on light interception and photosynthesis were modelled. The number of scenarios was 9, i.e. architecture at red, green or blue light, combined with illumination of red, green or blue, i.e. 3 x 3. So, for example, the consequences of a blue adapted plant architecture is simulated under a subsequent illumination by green (or red or blue).

Each scenario was carried out using 20 million light rays in the ray tracer and 40 recursions (light bounces).

SECTION 3 – RESULTS

The incorporation of observed data on leaf angles, leaf shapes, internode lengths and fruit sizes enabled the simulation of realistic crop (Fig. 2). The rendering in Figure 2 shows that not all the light was intercepted by the crop. This was confirmed by the calculated amounts of absorbed photons in Fig. 3, showing light absorption of maximally 84% of incoming light.

Scenarios of illumination with different colors on light interception and photosynthesis:
Despite the fact that green light is reflected more than blue or red light, the absorption of green light by the crop carrying either 1, 7 or all (21) leaves was only slightly lower than for red and blue illumination (Fig. 3). This shows that the reflection properties of a single leaf, indicating ca. 10% less absorption of green versus red, has less impact on a crop scale.

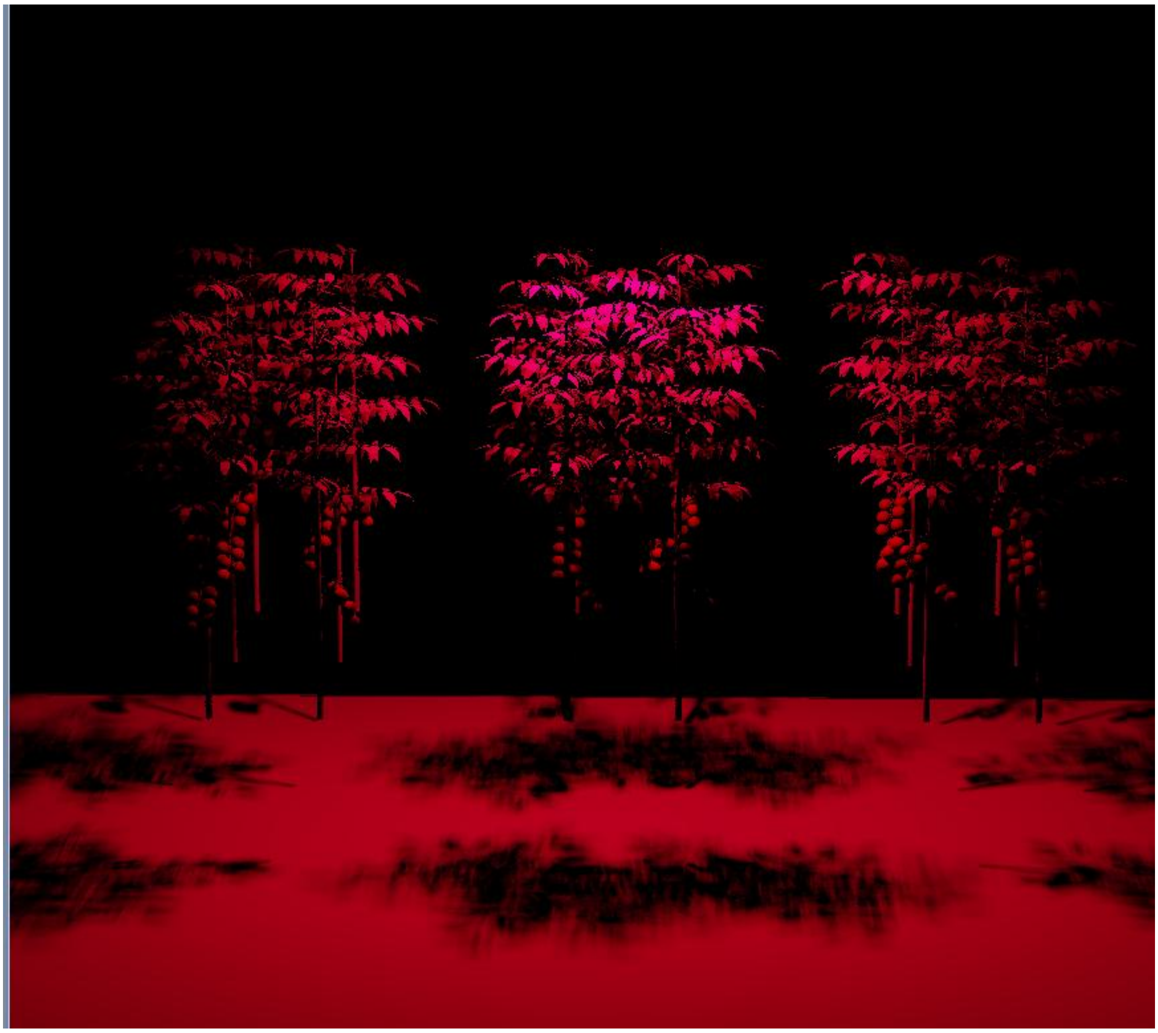

Fig. 2. Rendered image of the 3D crop, illustrating the lighting effects of 95% red and 5% blue LEDs placed above the middle row of plants.

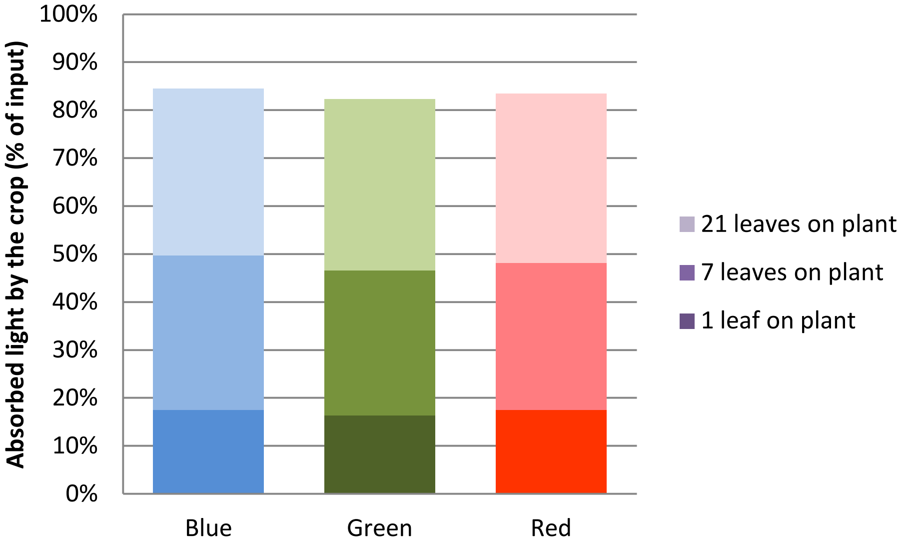

Fig. 3. Absorbance by the crop of either blue, green or red light, simulated for 1, 7 and 21 leaves on each plant.

The lower crop absorbance of green over red light was almost alleviated when the plant carried more leaves, from -7% to only ca. -1% at 21 leaves (Fig.4). This result shows that the somewhat higher numbers of reflected light rays of green over red per leaf are again absorbed by other leaves after several bounces within the crop, as was also found by Paradiso et al. (2011).

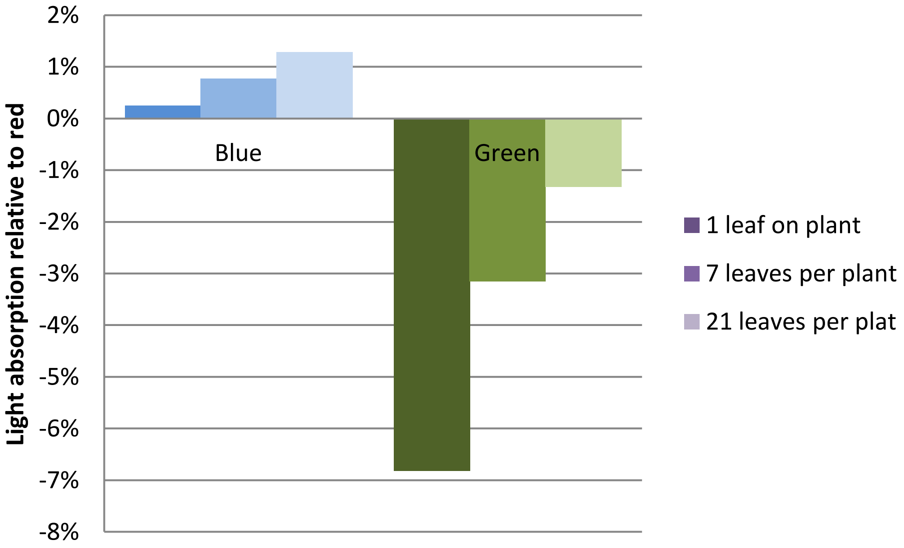

Fig. 4. Crop absorbance of blue or green relative to red light, simulated for 1, 7 and 21 leaves on each plant.

The actual photosynthetic response on a given amount of a specific light color, expressed in moles of assimilated CO_2, is the result of both absorption and quantum efficiency. This response is highest for red light and lowest for blue light (Fig. 5). Blue light performs less than green light since the used bandwidth for green allows for a higher quantum efficiency and thus higher photosynthetic performance (102% relative to PAR light) relative to blue (91% relative to PAR light), according to McCree (1972).

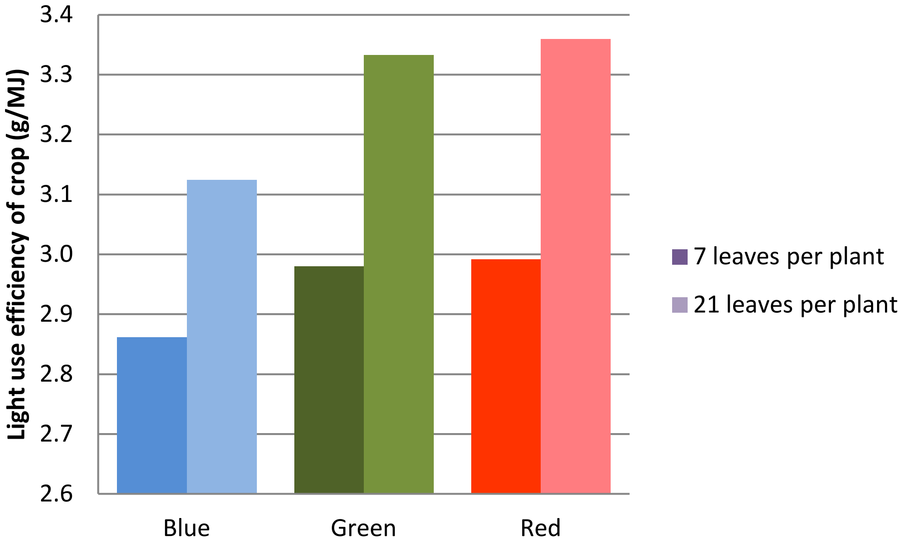

Fig. 5. Conversion of absorbed light to assimilates for blue, green and red, for 7 and 21 leaves per plant.

Scenarios on the effect of plant architecture on light interception and photosynthesis:

The green, red or blue adapted plant architectures showed almost similar light absorption between the three colors, but the effect of morphology on light absorption was big (Fig. 6).

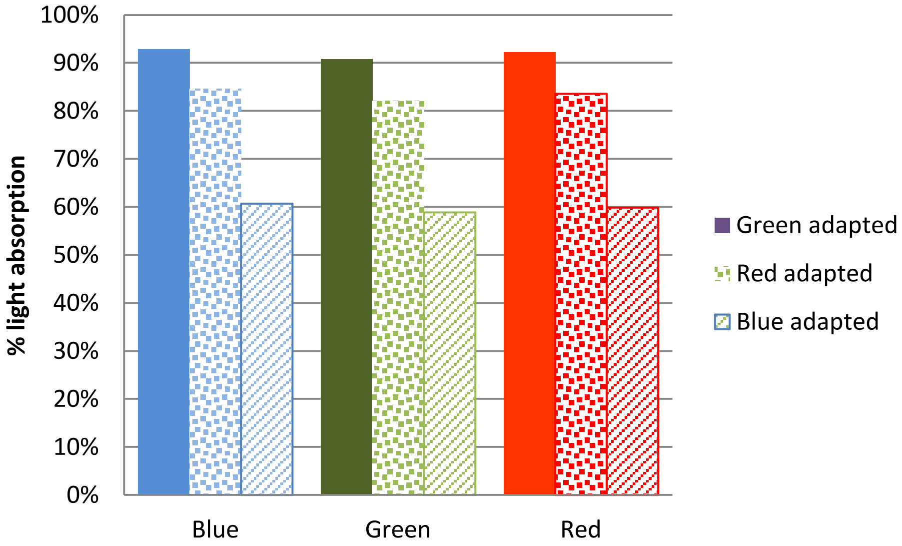

Fig. 6. Absorption of blue, green or red light (X axis) for green (solid fill), red (grained fill) or blue (striped fill) adapted plant architecture.

The green adapted plants had a much larger plant length and a slightly bigger leaf area (10% more) than red, resulting in the highest light absorption, even for the somewhat more reflected green light. Blue adapted plants were, contrary to green, very compact due to shorter leaves, internodes and upward leaves, thus intercepting almost 30% less blue, green or red light relative to red adapted plants.

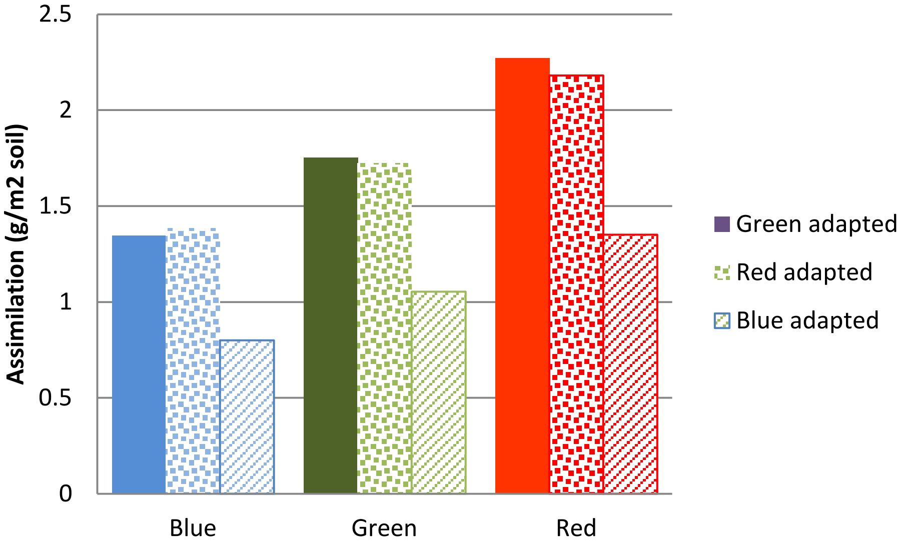

Fig. 7. Produced assimilates following absorbance and photosynthesis of blue, green or red light (X axis) for green (solid fill), red (grained fill) or blue (striped fill) adapted plant architecture.

The FSPM model was able to convert the absorbed light colors into assimilates following the action spectrum of McCree. This action spectrum resulted in higher photosynthesis and assimilate production per photon absorbed red light, which increased assimilate output for the scenarios with red (at the right in Fig. 7) relative to blue and green light. Interestingly, the differences in absorption between green and red adapted plants were almost fully reversed by McCree photosynthesis, thus showing almost no differences anymore between these two plant architectures at each color (e.g. assimilation is ca. 1.4 g m^{-2} at blue light for both green and red adapted plants (at the left in Fig. 7).

SECTION 4 – CONCLUSIONS

The tomato crop absorbed relatively more of the emitted red light compared to blue and green light. This result agrees to previous findings (Deliverable 4.424a, Paradiso et al., 2011). Blue light performed the poorest, mainly due to its lower quantum efficiency relative to green and red. The relatively low absorption rates for green on a leaf basis have only a low impact on the crop scale.

The FSPM was capable of reproducing a realistic crop in 3D space, allowing for an accurate prediction of light distribution in crop canopies. The change in plant architecture, caused by illumination by blue light, resulted in 30% less light interception relative to red adapted plants, showing the importance of plant shape on yield. A possible effect of blue light on photosynthesis, by promotion of chlorophyll content and stomatal conductance (Deliverable 4.422), cannot compensate for this major reduction of light interception. Plants with a green adapted shape performed intercepted much more light than red or blue adapted plants. Although the molecular basis of photomorphogenesis is only partly understood (see e.g. Laxmi et al., 2008), the plant shapes following green or blue light have been commonly found in experiments lately (Folta and Maruhnich, 2007; Kim et al., 2004; Cope and Bugbee, 2013). The effects of these different shapes on photosynthesis and growth are not yet fully examined. Thus, a predictive plant model incorporating the plant shapes, like the FSPM used in this study, is very welcome to explore these effects.

The simulation results indicate that the crop performs best under red light. The lamp manufacturer (Hortilux) can easily modify their LED systems to generate only red light, so a successful implementation of the results in horticultural practice is expected.

SECTION 5 – REFERENCES

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[i] In the trials of Tasks 4.2.1 and 4.2.2, we used greenhouse compartments of 24 m^2. The demonstration trial (task 5.3) was done in two greenhouse compartments of 144 m^2. However, 3D model calculations were done based on a cut-out of a greenhouse, to prevent extremely long processing time of the calculations (if a full greenhouse would be used).