Vertical lamellae highly diffusive for light: effect on growth of young tomato plants in a climate chamber

Bram van Breugel, Esther Meinen, Johan Steenhuizen, Esteban J. Baeza, Cecilia Stanghellini and Silke Hemming

Report WPR-936

WAGENINGEN
UNIVERSITY & RESEARCH

TOPSECTOR

Holland High Tech
Global Challenges, Smart Solutions

Ministerie van Landbouw, Natuur en Voedselkwaliteit

Abstract
Experiments done in the past have shown a clear advantage for many crops of receiving more diffuse light in relation to direct light. However, in these experiments, extremely high light scattering levels were never tested, and therefore, we do not know whether such results could be extrapolated, and how. The scattering is quantified by means of the Hortiscatter (0-100%) parameter as defined in norm NEN2675. In this trial an innovative material in the form of rectangular lamellae has been used, that when positioned vertically above the crop and below the source of light, can generate a very high Hortiscatter (>90%). These highly diffusive vertical lamellae were tested in three trials in a climate chamber using young tomato plants, with both direct light and a conventional Hortiscatter (50%) as reference treatments. Light interception, leaf photosynthetic capacity of different layers and dry matter (and other related production values) were compared. Despite the efforts in optimizing the set up, it was not possible to maintain a homogeneous horizontal PAR intensity distribution. However, results indicate that, regardless of the light intensity, young tomato plants under a very high Hortiscatter intercepted more PAR light in the three trials. On the other hand, both top and bottom leaves under this treatment did not show a higher photosynthetic capacity than under a direct light treatment. Finally, results indicate a trend to higher total dry matter production under the very high Hortiscatter. However, more research, if possible under sunlight conditions and trying to minimize the sources of variation are needed in the future.

Reportinfo

Report WPR-936
Projectnumber: 3742233900
Doi: https://doi.org/10.18174/563067
Theme: Energy and Climate

This project/research has been carried out within the PPS project Smart Materials with support of the topsectors Horticulture & Starting Materials, Agri & Food and High-tech Systems and Materials, financed by the Dutch Ministry of Economic Affairs, LTO Glaskracht and above mentioned industrial partners.

Disclaimer

© 2020 Wageningen, Stichting Wageningen Research, Wageningen Plant Research, Business Unit Greenhouse Horticulture, P.O. Box 20, 2665 MV Bleiswijk, The Netherlands; T +31 (0)317 48 56 06; www.wur.eu/plant-research.
Chamber of Commerce no. 09098104 at Arnhem
VAT no. NL 8065.11.618.B01
Stichting Wageningen Research. All rights reserved. No part of this publication may be reproduced, stored in an automated database, or transmitted, in any form or by any means, whether electronically, mechanically, through photocopying, recording or otherwise, without the prior written consent of the Stichting Wageningen Research. Stichting Wageningen Research is not liable for any adverse consequences resulting from the use of data from this publication.

Address

Wageningen University & Research, BU Greenhouse Horticulture
Violierenweg 1, 2665 MV Bleiswijk
P.O. Box 20, 2665 ZG Bleiswijk
The Netherlands
+31 (0) 317 - 48 56 06
glastuinbouw@wur.nl
www.wur@glastuinbouw.nl

Table of contents

1 Introduction

Many studies suggest that plants use diffuse light more efficiently than direct light (Cohan *et al.* 2002; Farquhar and Roderick, 2003; Gu *et al.* 2003; Alton *et al.* 2007; Mercado *et al.* 2009; Li *et al.* 2014). Li *et al.* (2014) reported increased production for tomato (cv. 'Komeett') with diffuse light than with direct light, comparing clear glass and diffuse glass with different scatter properties but comparable light transmittance in experimental greenhouses. He also quantified the importance of different contributing factors. Conclusion was that crop photosynthesis was increased resulting in more production due to (1) a more homogeneous horizontal PPFD distribution, (2) a more uniform vertical PPFD distribution, (3) a higher leaf photosynthetic capacity in the middle leaves of the crop and (4) a higher LAI (more light interception).

However, it is well-known that the amount of light is directly linked to yield (Marcelis *et al.* 2006). Therefore, producers of greenhouse covering materials have been aiming to combine high diffusiveness and high hemispherical light transmittance. Since diffusing light also increases backscattering and therefore decreases hemispherical light transmittance, this is a clear trade-off.

The concept proposed in this research to overcome this trade-off is to use a geometrical set-up that conveys light (incoming from the upper hemisphere) towards the crop, thus with negligible back-scattering, that is: vertical "curtains" of non-absorbing, highly diffusive materials.

In the present work, we have tested the hypothesis that a high level of light diffusion (Hortiscatter), obtained by using vertical lamellae of a very high diffusive material, increases the growth of young tomato plants. The experiment was performed in a climate room, using a single high-intensity light source, whereby the very high diffusive treatment was compared to both direct light and to a moderate level of diffusiveness, generated with a conventional diffusive material.

2 Hypothesis

Plant growth (dry matter production and development rate) is increased by more diffuse light compared to direct light, due to

1. More homogeneous horizontal PPFD distribution.
2. More uniform vertical PPFD distribution.
3. Higher leaf photosynthetic capacity.
4. Higher LAI.

Experiments done so far for different greenhouse crops have proven that the higher the light diffusion of the covering material (light diffusion measured as Hortiscatter, as described in NEN2675:2018), the higher the plant growth and crop productivity (Hemming *et al.* 2007; Li *et al.* 2014) (Figure 1).

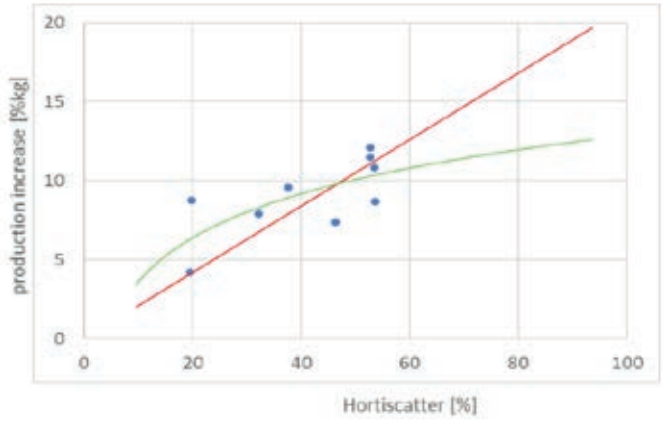


Figure 1 *Effect of the Hortiscatter of the greenhouse cover (%) on production increase (%) for different crops tested in different trials at WUR Greenhouse Horticulture facilities in Bleiswijk.*

However, experiments reported in the literature never tested covering materials with the extremely high Hortiscatter values that can be achieved by e.g. using the vertical lamellae. Our hypothesis is that the effects will be even higher using vertical lamellae (Hortiscatter >90%) with a higher scattering angle making the light more diffuse compared to direct light and also compared to a 'conventional diffusive material' (Hortiscatter=50%).

3 Material and methods

3.1 Experimental set-up

All the trials previously referenced (Figure 1) were done in multiple greenhouse compartments performing full growing seasons. This type of experimental set up is out of the scope of the present project and for that reason, we have chosen for a smaller scale experiment in a climate cell, using young plants which will not be grown to generative stage, therefore, limiting the duration of the experiment. In order to mimic a high LAI a high density of young plants will be selected for the experiment.

Therefore, the experiments were carried out in a climate chamber of 9 m^2 (C9 in Wageningen KLIMA) with 2 opposite tables of 3.36 x 0.85 meter (2.86 m^2) as in the sketch (Figure 2). The height of the table can be adapted.

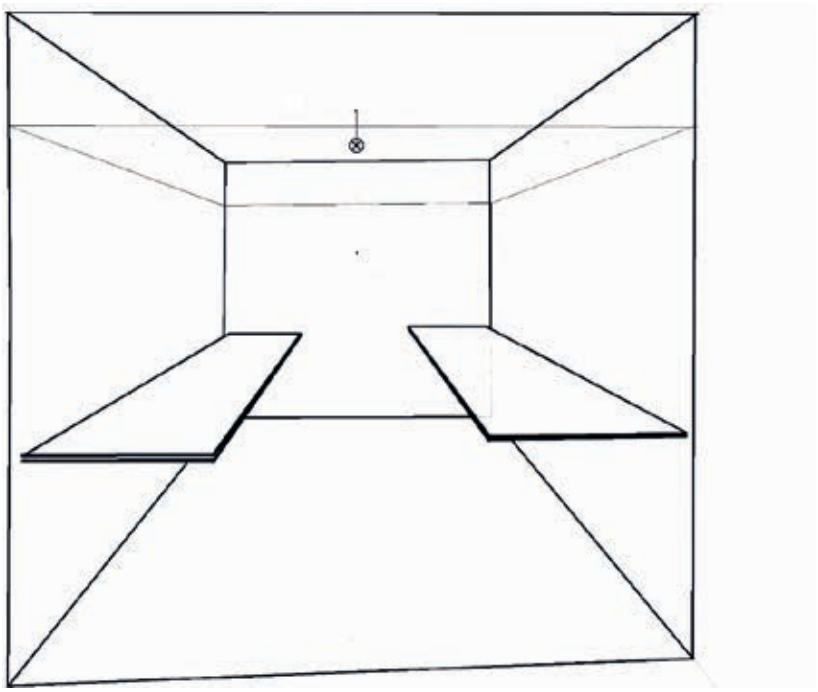


Figure 2 *Sketch of the climate chamber with the two opposite tables where each treatment will be located.*

To test the hypothesis 3 treatments were carried out:

1. Direct light; scattering angle is 0.
2. Highly diffuse light by vertical lamellae; scattering angle up to 40°, Hortiscatter = 90%.
3. Diffuse light by conventional diffusive glass; scattering is around 15°, Hortiscatter = 50%.

In the middle of the climate chamber 1 lamp (Figure 3) was positioned so that 2 treatments could be realised at the same time. Only direct light is needed as a reference. For this, all the light was generated from a single point source, since the use of multiple light sources would have resulted in light coming from multiple directions and therefore diffuse in effect. The light source selected (Figure 4) is a Osram HMI 9000W SE XS daylight source with an arc length of ~40 mm driven by an ARRI electronic ballast 6/9 HS autoscan and operated in a custom made M90 armature from ARRI consisting of only the body and lamp holder so the light source could operate unprotected. A mirror attached to a heatsink and 6 fans was placed above the lightbulb in order to increase the light intensity at the crop level. The walls of the climate cell were also made black so that only the direct light remained. Below the lamp a glass pane was positioned to allow the heat from light source to be removed separately from the growing compartment and to protect the crop managers and researchers below from UVB and for the small chance of catastrophic lamp failure from an exploding glass bulb. For safety reasons the bulbs were not used until failure but replaced after their nominal life time of 400 hours.

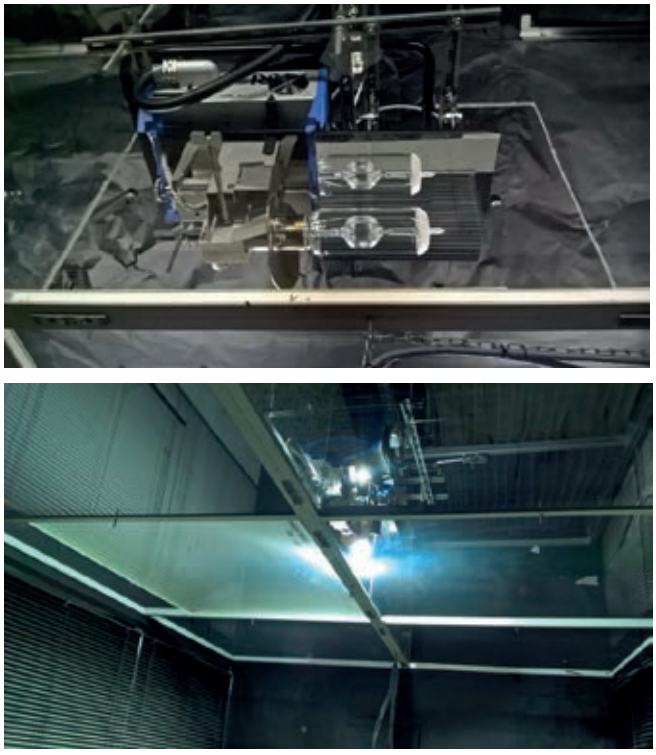


Figure 3 *Detail of the lamp used in the experiments: the light source burning.*

The lamellae were placed in such a way that light from the lamp past through at least one lamella before hitting the table with the plants.

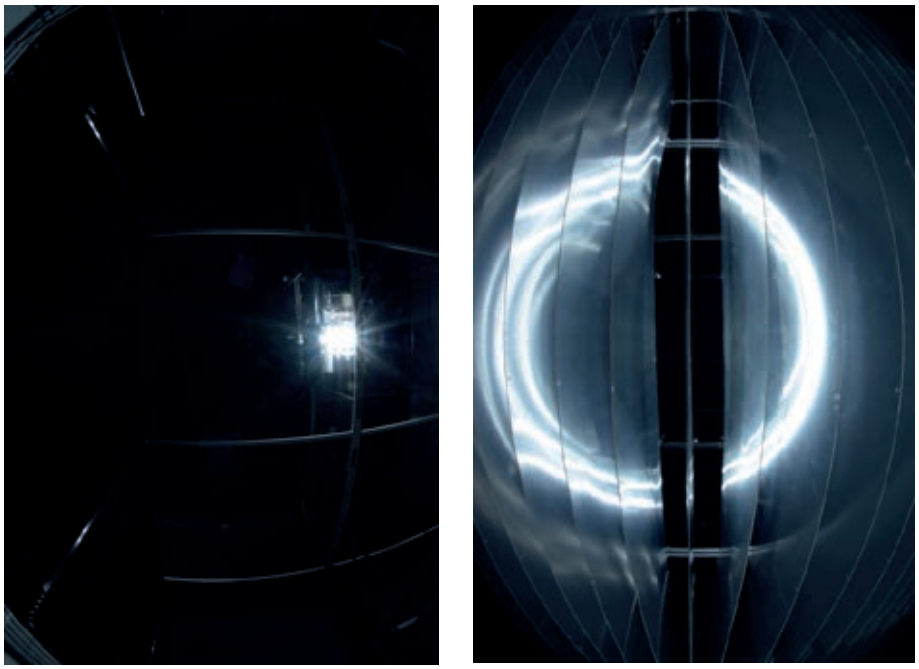


Figure 4 *Irradiance from the light source for direct light at the left and through the lamella at the right. Both images were captured by a Nikon D5300 camera equipped with a 10 mm, 1:2.8 DC FishEye HSM lens using a f/22 aperture and 1/200 s shutter speed.*

The spectrum distribution of the direct light treatment and the highly diffusive vertical lamellae treatment is shown in Table 1.

Table 1

Spectrum of the direct light treatment and the highly diffusive vertical lamellae treatment from 300-800 nm.

	Direct light treatment	Vertical lamellae
UV (301 - 400nm)	8%	5%
Blue (401 - 500nm)	27%	26%
Green (501 - 600nm)	29%	30%
Red (601 - 700nm)	21%	23%
PAR (401 - 700nm)	77%	79%
Far red (701 - 800nm)	15%	16%

Three experiments were carried out successively.
Trial 1: direct light (1) and vertical lamellae (2) (pilot 1 to determine optimal climate conditions and plant density) (Table 2)
Trial 2: direct light (1) and vertical lamellae (2) (pilot 2 to determine optimal climate conditions and plant density) (Table 2)
Trial 3: conventional diffusive glass (3) and highly diffusive vertical lamellae (2) using the optimal climate conditions and plant density determined in one of the previous experiments (Table 2)
The extremely high scattering of the light that the lamellae generate was clearly observed in the absence of shade generate by the tomato young plants, contraposed to the clear shade generated below the direct light treatment (Figure 5).

Figure 5 *Tomato young plants casting a sharp shadow under direct light (left) and total absence of shade under the highly diffusive light created by the vertical lamellae (right).*

Table 2

Climate and other relevant set points used during the three experiments.

	Trial 1 (Pilot 1)	Trial 2 (Pilot 2)	Trial 3
Plant density	100/m^2	50/m^2	50/m^2
CO_2	800 ppm	400 ppm	400 ppm
Temperature day/night [°C]	23/20	21/19	21/19
Light table 1	Direct (HS=0)	Direct (HS=0)	Conventional diffuse (HS=50)
Light table 2	Vertical lamellae (HS=90)	Vertical lamellae (HS=90)	Vertical lamellae (HS=90)
RH	75%	75%	75%
Day length	12 h	12 h	12 h
Light intensity	To be measured	To be measured	To be measured

The motivation behind the choice of the settings in trial 1 was:

- If the effect of diffuse light is to reduce the extent to which plants cast mutual shadow on each others leaves a dense canopy should show a more pronounced effect compared to the sparser canopy.
- To see the effect of light other parameters should not be limiting so a high CO_2 concentration of 800 ppm was chosen.

On the other hand, the motivation for parameter choice on trial 2 was:

- If the effect of diffuse light is to reduce the extent of self-shadowing a sparser canopy should give a similar effect.
- If the mechanism of action of diffuse light versus direct light lays in the vertical photon flux density being more homogeneous resulting in less saturation of the directly illuminated leaves and consequently overall a more efficient photosynthesis, the effect should be more pronounced at lower CO_2 concentration, which would cause the photosynthesis apparatus to show saturation at relatively low light levels.

3.2 Plant material

Experiments were carried with young tomato plants cv "Komeett'. Two weeks after sowing in rock wool plugs the plants were transplanted to rockwool blocks (10 x 10 cm) and placed in the climate chamber at the maximum possible density of 100 plants/m^2, to achieve a high LAI in the shortest possible time. That was necessary to ensure that light penetration in the canopy would be limiting, as it would in a well-developed tomato crop (Figure 6).

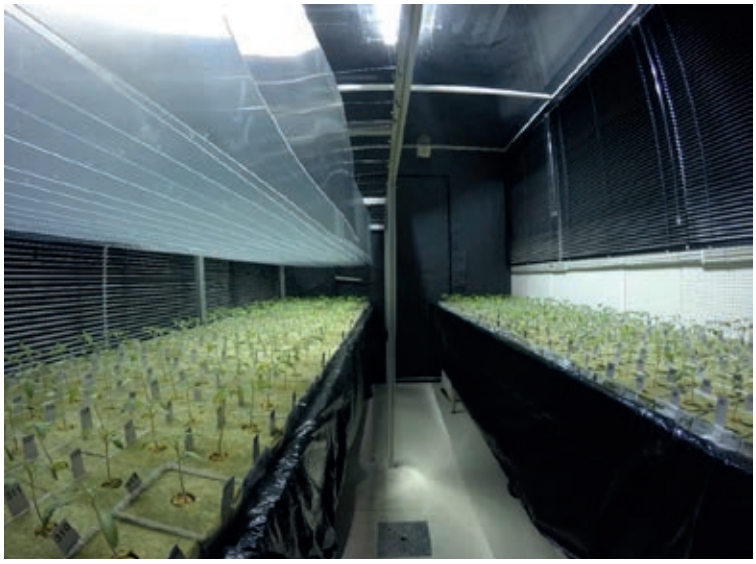


Figure 6 *Detail of the setup including tomato plants just after been transplanted to the climate chamber for the experiment.*

At the start of Trial 1, 264 plants were positioned per table (100 plants/m^2) (Figure 6) to create a crop in a young stage, but with a LAI of 0.5. Plants were growing towards a LAI of 3. Plants were removed during the trial (spacing) to maintain this LAI of 3 On Trials 2 and 3, half of that number of plants (50 plants/m^2)were positioned per table by removing 1 in of every 2 plants (Figure 7) to obtain a desired LAI of 1.5.

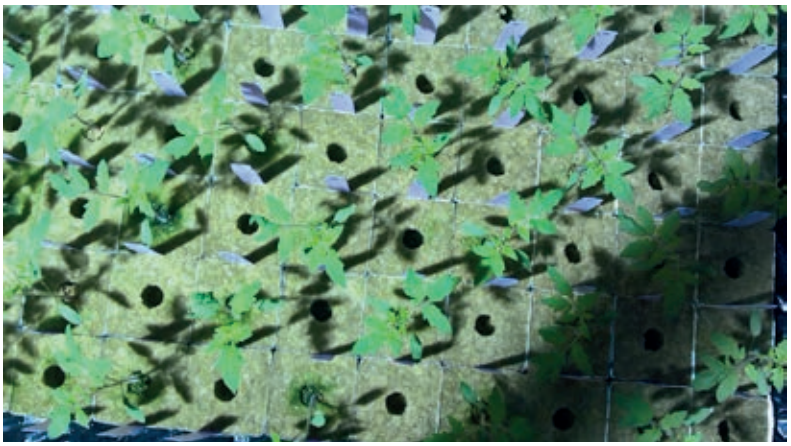


Figure 7 *Tomato young plants positioned on a density of 50 plants/m^2.*

3.3 Measurements

3.3.1 Light measurements (average light intensity)

The horizontal light distribution at the top of the crop was measured both before and during the experiment.
Before the experiment
The pre-experimental measurements were aimed at making sure that the desired average level of PAR light intensity was achieved and that it was comparable on each treatment. The horizontal light distribution was measured with a Licor LI 190 QUANTUM PAR sensor in a grid of cm (10x10 cm) for all treatments.
It was also checked that the average light intensity of the treatments was the same
During the experiment
Every week it was measured using the Sunscan sensor and the same grid used in the pre-experimental measurements.

3.3.2 Light interception crop (vertical light distribution)

Using a SS1 Sunscan sensor (Delta-T Devices Ltd) the light interception by the crop is measured at 2 heights by using a light stick.

3.3.3 Photosynthesis

A Licor-6800 (Li-Cor Inc.) was used to measure the maximum photosynthetic capacity at intensities of - 1500 and 2000 µmol/m^2/s using the internal light source of the LI-6800 (90% red, 10% blue LED) for 23 plants at both treatments during trial 1 at two different heights: the 2nd and 5th leaf. In total, 92 values were obtained. The measurements were performed on day 36 to 38 of trial 1.

3.3.4 Destructive harvests

In order to determine the plant dry matter, 3 destructive harvests of a number of plants was performed (Table 3): 25 at the start, 120 and 47 per treatment after plant spacing and 60 and 46 at the end of each experiment. In the first two harvests the total dry weight of the aerial part of the plants was determined, whereas in the final one the number of leaves, the leaf area and fresh- and dry weight of leaves and stem separately was performed.

Table 3

Number of plants for destructive harvest.

	At start	After plant spacing	End of trial
Trial 1	25	120/treatment	60/treatment
Trial 2	25	47/treatment	46/treatment
Trial 3	25	47/treatment	46/treatment

3.3.5 Summary of measurements

Table 4 summarizes the dates in which the most relevant measurements were performed during the 3 trials, as well as other important milestones. It is very important to mention that plants grew to a certain height that their heads were in contact with the lamellae, thus, it was decided first to lower the tables, and afterwards, the lamellae had to be moved upwards.

Table 4

Summary of main crop measurements, their dates and other relevant milestones during the three trials (D=day).

	Trial 1	Trial 2	Trial 3
sowing of 600 tomato seeds (Komeet)	D1, Mo, 7th Jan.	D1, Tu, 19th Feb.	D1, Tu, 2nd April
transplant to cubes	D15, Tu. 22nd Jan.	D15, Tu, 4th March	D15, Tu, 16th April
light interception without plants	D16, We, 23rd Jan.	D16, We, 6th March	D16, We, 17th April
plants moved to C9	D16, We, 23rd Jan.	D16, We, 6th March	D16, We, 17th April
start harvest	D16, We, 23rd Jan.	D16, We, 6th March	D17, Th, 18th April
light intercept & level			D22, Tu, 23rd April
light source set to full power	D18, Fr, 25th Jan. (13:00)	D19, Sa, 9th March (9:00)	D22, Tu, 23rd April
light intercept & level	-	D21, Mo, 11th March	D23, We, 24th April
light intercept & level		-	D28, Mo, 29th April
tables lowered	D28, Mo, 4th Feb.	D28, Mo, 18th March	D29, We, 1st May (9:00)
light intercept & level	D28, Mo, 4th Feb.	D28, Mo, 18th March	D29, We, 1st May
light intercept	D29, Tu 5th Feb.	D30, We, 20th March	
first harvest	D29, Tu 5th Feb.	D30, We, 20th March	D29, We, 1st May
light intercept & level			D29, We, 1st May
lamellae moved upwards	D29, Tu 5th Feb.		D30, Th, 2nd May (10:00)
light level	D29, Tu 5th Feb.	-	
light intercept & level	D31, Th 7th Feb.		
light intercept & level		D35, Mo, 25th March	D35, Tu, 7th May
photosynthesis (Amax)	D36-38. Tu, We & Th, 12th, 13th, 14th Feb.		
end harvest	D36-38. Tu, We & Th, 12th, 13th, 14th Feb.	D36, Tu 26th March	D35, Tu, 7th May

4 Results

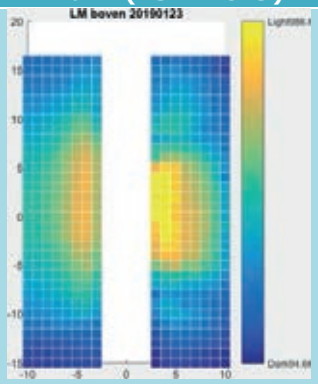
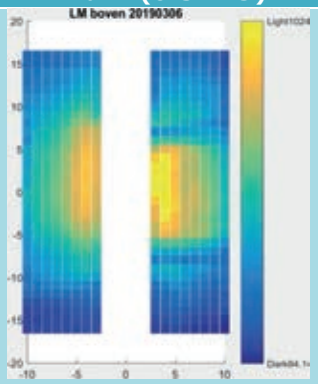
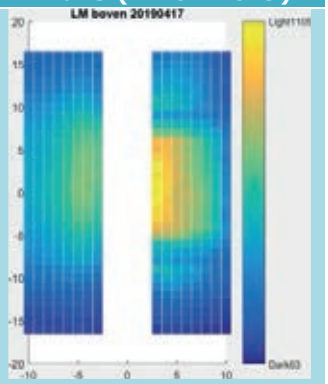
4.1 Light measurements

4.1.1 Before the trials (before plants were moved in)

For trial 1 and 2 it was possible to obtain an almost similar light intensity for each treatment, but on trial 3, the presence of the conventional diffusive glass caused a slightly lower average light intensity (Table 5) of this treatment compared to the highly diffusive vertical lamellae treatment. However, in all treatments, it was not possible to achieve the desired level of homogeneity, since the standard deviation values were not very similar; it was thus carefully thought if anything could be done in the experimental arrangement to improve the homogeneity in light intensity distribution. However, that was not possible. PAR light intensities are consistently higher in the area which is directly below the perpendicular of the lamp in both treatments.

Table 5

Light intensity values (µmol/m²/s) measured on a 10 cm x 10 cm grid above each one of the treatments before moving plants in.

	Trial 1 (23-1-2019)		Trial 2 (6-3-219)		Trial 3 (17-04-2019)	
Top of canopy						
	Direct	Lamellae	Direct	Lamellae	Direct	Lamellae
Average PAR (std) [µmol/m²/s]	502 (178)	507 (225)	495 (199)	501 (234)	424 (161)	499 (230)

The light intensity distribution shown in Table 5 is certainly counterintuitive when compared to the fish-eye photos in Figure 4. Actually what we have in each pixel of the light distribution, is the sum of all light that would appear in a fish-eye photo taken at that spot.
Anyhow, there is little doubt that in the present, limited set-up, high hortiscatter did not result in homogeneous distribution of light intensity. However, as the absence of shadows in Fig. 5 makes clear, it did result in a homogeneous "sky".

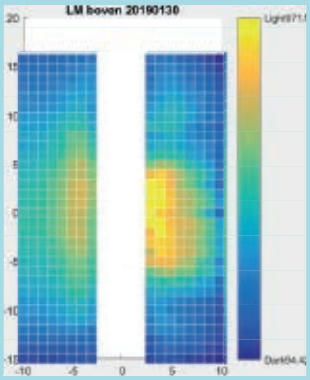
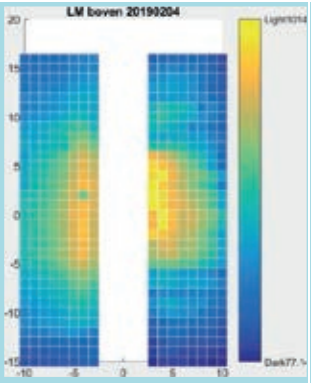
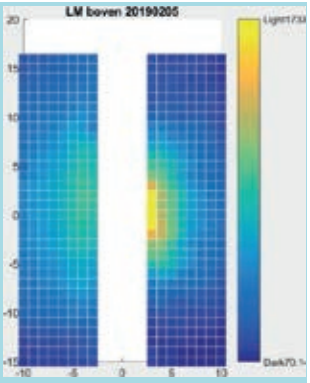
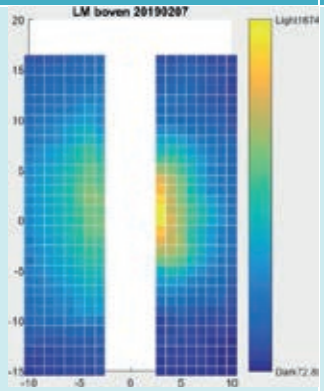
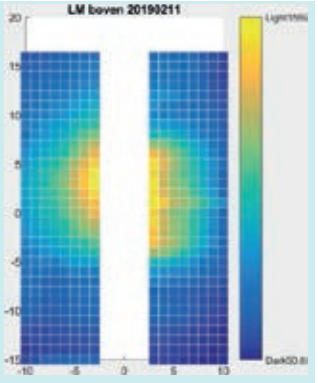
4.1.2 During the trials

During trial 1, it was possible to maintain the average PAR light intensity above each treatment on values which did not differ very substantially (Table 6). The maximum percentage difference between the average PAR light intensity on both treatments was 16.8%, on the February 5th, being the average percentage difference of the average values during the trial of only 7.8%.

The standard deviation is consistently higher under the vertical lamellae treatment, which is in contradiction of the assumption made by different authors that higher light diffusion involves a more homogeneous horizontal light distribution (Hemming *et al.* 2007; Dueck *et al.* 2012). However, these authors considered the effect of a diffuse greenhouse cover under sunlight conditions, which is different from this experiment, where we have used a single light source in a climate chamber and a low distance between light source and treatment. A greenhouse has construction elements creating shadows and the climate cell doesn't. Besides, variation in light intensity is determined by the varying distance to the light source and in the case of the chamber, scattering will not reduce this.

Table 6

Light intensity values (µmol/m²/s) measured on a 10 cm x 10 cm grid above each one of the treatments during different moments in Trial 1.

Date	30-01-2019		04-02-2019		05-02-2019	
Top of canopy	 DiDirect	Lamellae	 DirDirect	Lamellae	 DirDirect	Lamellae
Average PAR (std) [µmol/m²/s]	477 (210)	476 (146)	508 (176)	482 (220)	516 (200)	429 (297)
Date	**07-02-2019**		**11-02-2019**			
Top of canopy	 DDiffuse	Lamellae	 DirDiffuse	Lamellae		
Average PAR (std) [µmol/m²/s]	556 (227)	483 (318)	531 (301)	511 (330)		

On trial 2, less measurements of light intensity distribution were performed. However, results indicate also that average values of PAR light intensity were similar to those measured in Trial 1 and that average differences between average direct and highly diffusive PAR light intensity were never higher than 15% and 5.7% on average (Table 7). The standard deviation is also consistently higher under the vertical lamellae, just as it was measured on Trial 1.

Finally, in Trial 3, in which a conventional diffusive glass was located above treatment 1, we observe the largest differences in PAR light intensity (Table 8), which average 12.4%, with a maximum percentage difference of 18%. The standard deviation is also higher below the highly diffusive vertical lamellae than under the conventional diffusive glass.

Table 7

Light intensity values (µmol/m²/s) measured on a 10 cm x 10 cm grid above each one of the treatments during different moments in Trial 2.

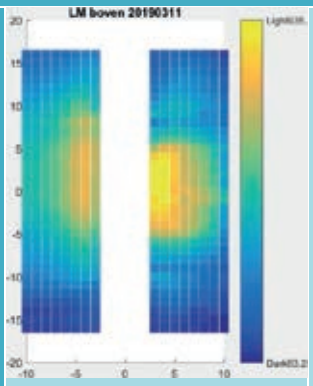
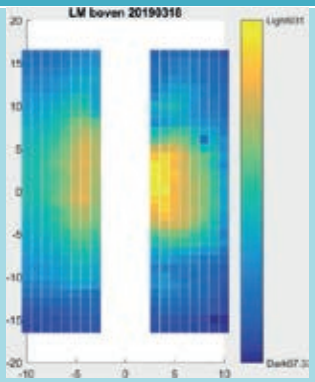
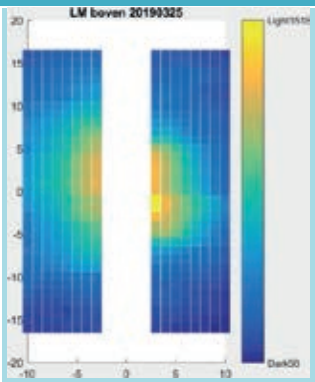
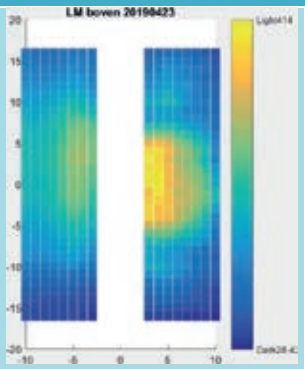
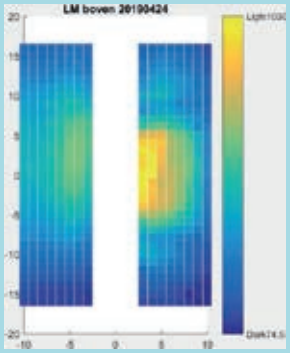
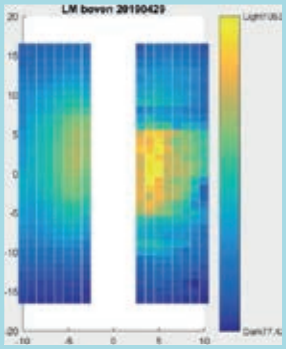
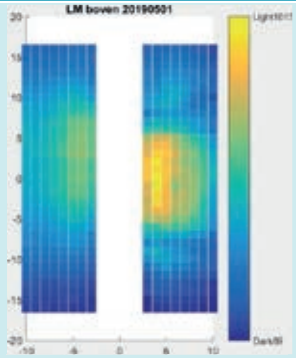
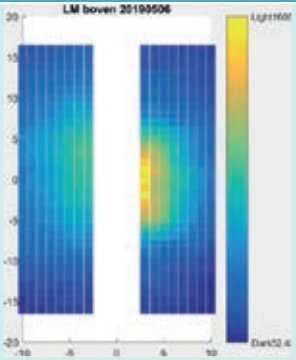
Date	11-03-2019		18-03-2019		25-03-2019	
Top of canopy						
	Diffuse	Lamellae	Diffuse	Lamellae	Diffuse	Lamellae
Average PAR (std) [µmol/m²/s]	450 (170)	452 (213)	437 (157)	428 (208)	534 (250)	456 (293)

Table 8

Light intensity values (µmol/m²/s) measured on a 10 cm x 10 cm grid above each one of the treatments during different moments in Trial 3.

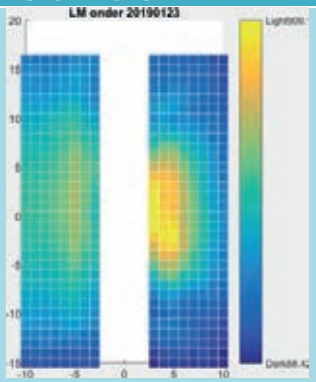
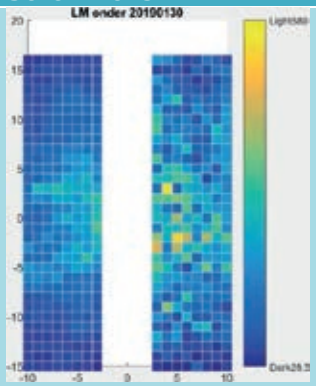
Date	23-04-2019		24-04-2019		29-04-2019	
Top of canopy	 Diffuse	Lamellae	 Diffuse	Lamellae	 Diffuse	Lamellae
Average PAR (std) [µmol/m²/s]	172 (62)	193 (92)	402 (146)	462 (224)	420 (168)	494 (238)
Date	01-05-2019		06-05-2019			
Top of canopy	 Diffuse	Lamellae	 Diffuse	Lamellae		
Average PAR (std) [µmol/m²/s]	400 (147)	472 (226)	448 (199)	456 (308)		

4.2 Light interception crop

During the experiments, light interception was measured by measuring the PAR light intensity on top and at the bottom of the plants (Table 9). Since we were using young plants it was not possible to add more intermediate measuring points. Table 9 shows and example of the grid of PAR light distribution in both treatments, in this case, at the bottom of the crop, on Trial 1. On the first date, since the plants were just transplanted and were quite small, both the average light intensity and the standard deviation are quite similar to the values measured above (Table 6). Only one week later, the plant growth has been such that most of the PAR light is already intercepted by the crop. In both cases, we also see that the light homogeneity is still higher below the direct light treatment, also after light has been intercepted partially by the plants.

Table 9

Light intensity values (µmol/m²/s) measured on a 10 cm x 10 cm grid at the bottom of the plants in both treatments during different moments in Trial 1.

Date	**23-01-2019**		**30-01-2019**	
Below the canopy				
Average PAR (std) [µmol/m²/s]	400 (147)	408 (201)	128 (60)	171 (98)

Results of Trial 1 indicate clearly that the high scattering of the incident PAR induced by the presence of the vertical lamellae translated in a higher interception of light into the canopy (Figure 8). This caused the plants on this treatment to consistently intercept more PAR than under the direct light. From moment of transplant to the chamber until 5-2-2019, as the plants grew and their head became closer to the lamellae, the difference in intercepted radiation decreased by a factor of 10 (from 10.4% points more intercepted PAR to only 1.4% points). On that same day (5-2-2019) the lamellae where moved upwards, but also the first harvest was done, so more light was available coming from the sides and this difference increased again to 7.2%; as the head of the plants grew again closer to the lamellae, the difference decreased again to 2.4%. This might indicate that in order to achieve a better light penetration in the crop, the top of the plants must be at a minimum distance from the lamellae, but it is not conclusive, because on the same day, plants were removed (1st harvest), which also affected the light interception.

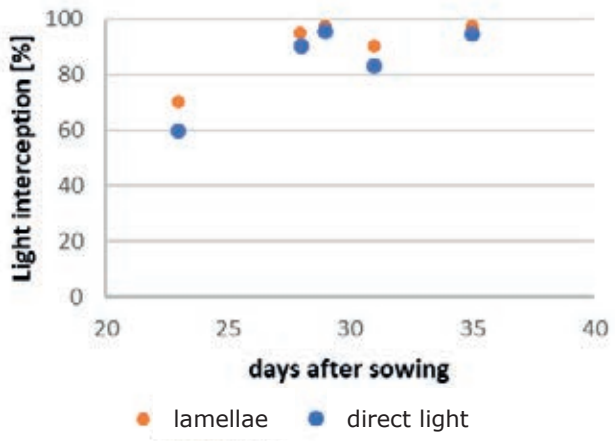


Figure 8 *Intercepted PAR light (%) by the plants on different stages of development on Trial 1.*

In Trial 2, with half of the plant density of Trial 1, the PAR intercepted under the highly diffusive vertical lamellae treatment is also consistently higher along the trial than under the direct light treatment. Differences range between 4.6 % and 5.1 % (Figure 9). Thus, differences were lower and more constant than under Trial 1. In this experiment, we did not observe a clear decrement of the difference as the plants grew closer to the lamellae. Thus, the hypothesis that distance from plants to lamellae may affect negatively light interception does not hold in this case. However, the trend of higher light interception under the highly diffusive vertical lamellae treatment is the same in Trial 1 and Trial 2.

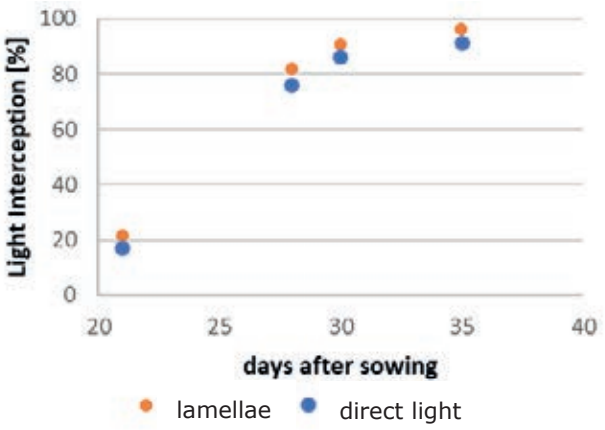


Figure 9 *Intercepted PAR light (%) by the plants on different stages of development on Trial 2.*

In Trial 3 the highly diffusive vertical lamellae where tested against a conventional diffusive glass, also here a higher PAR interception was still observed for the highly diffusive vertical lamellae treatment (Figure 10). The differences between the highly and the conventional diffuse treatment ranged from 9.6% points just after transplant to differences of only 3% points. Again, it is not possible to establish a relation between distance of the top of the plants to the lamellae and the light interception, rejecting the hypothesis observed in Trial 1.

Summarizing, the highly diffuse vertical lamellae did indeed increase the PAR light interception both in relation to the direct light treatment (with higher and lower plant density) and in relation to the conventional diffuse treatment (with low plant density). The question that remains to answer is, did this increase in intercepted PAR light translate in an increased photosynthesis and/or increased dry matter production? We answer this question in the next sections.

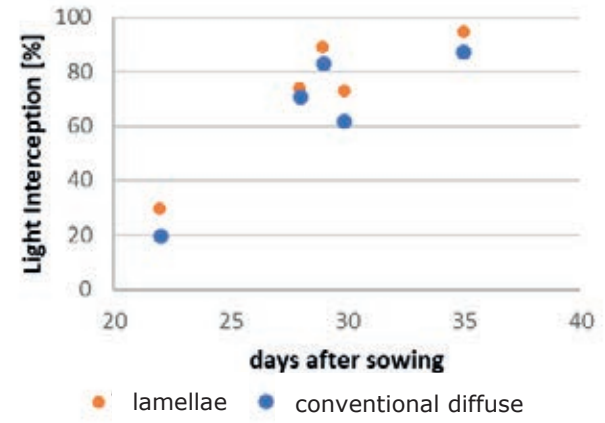


Figure 10 *Intercepted PAR light (%) by the plants on different stages of development on Trial 3.*

4.3 Leaf photosynthesis

The photosynthesis measurements both in leaf position 2 and 5 (counting from below to top) and at the two tested maximum PAR light intensities (1500 and 2000 mmol/m^2 s), indicate a higher maximum assimilation under direct light than under the highly diffusive light of the lamellae treatment (Figure 11). The difference in maximum assimilation between treatment is slightly larger for the lower leaf (2) than for the upper leaf (5). As a matter of fact, the differences in maximum assimilation between the two treatments are only statistically significant for the lower leaf (2) at the two maximum tested intensities (Table 11).

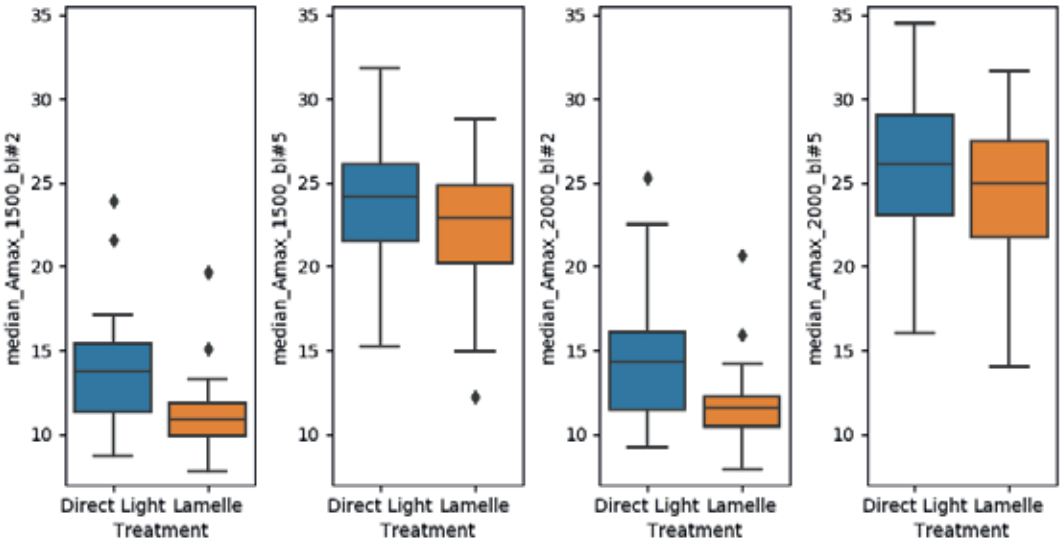


Figure 11 *Maximum CO_2 assimilation for leaves 2 and 5 under two PAR light intensities (1500 and 2000 µmol/m²/s) for plants under both the direct light and highly diffuse light (vertical lamellae) treatments in Trial 1.*

The means by which homogeneous vertical distribution should increase productivity are: 1. that light is re-distributed from top leaves (that could be saturated) to lower leaves that can use it more efficiently; 2. since this results in an average higher light level in the lower layers in the canopy the leaves there maintain a higher photosynthetic capacity "while getting older" in a diffuse environment.
The fact that for leaf 2 the numbers are the same for 1500 and 2000 umol shows that saturation is reached (probably at even lower intensities than 1500), whereas the upper leaves are not saturated at 1500. This means that the principle of efficient redistribution of light cannot be proven (nor disproven) in our set-up, since the intensity of 1500 µmol/(m² s) is hardly exceeded. Similarly, as the results about photosynthetic capacity of "old" leaves relate to mature crops, it is debatable whether any difference in photosynthetic capacity among leaves in a relatively young crop could be measured at all.

4.4 Dry matter production

The dry matter production was higher under the highly diffusive vertical lamellae compared to the direct light treatment and also compared to the conventional diffusive treatment. As we already saw in section 4.1., the average light intensity and its horizontal homogeneity was not equal under both treatments (in any of the trials). Therefore, we cannot directly conclude that the consistently higher dry matter production (for both harvests, H1 and H2) under the vertical lamellae could be attributed to the higher level of diffusion. This difference in average light intensity was statistically significant in Trials 1 and 2, during the period that went from harvest 1 (H1) to harvest 2 (H2), when there was less light underneath the vertical lamella relative to the direct light treatment and in Trial 3, during the period until harvest 1 (H1) there was more light underneath the vertical lamella relative to the conventional diffusive treatment.

Statistically significant differences were found in favour of the highly diffusive treatment on Trial 1 and on Trial 3, for total dry weight on H1, but never on H2. Also, in Trial 3, dry stem weight in H2 was statically higher for the highly diffusive vertical lamellae. Finally, the plants under the vertical lamellae were significantly taller than the plants on the other treatments in the three trials, as well as fresh stem weight and leaf area, which were also statistically higher on Trial 2 and Trial 3 (Table 11).

The increased total average dry matter was not the result of an increased number of leaves, but mostly the result of a higher light interception which can be caused by wider leaves as we can observe in the values of total leaf area. Longer internodes also contribute to a higher light interception (Sarlikioti, 2011). A higher light interception can result in a higher crop photosynthesis which can then lead to a higher dry matter production.

Since there are statistically significant differences in the explanatory variables it is necessary to carry out a more detailed regression analysis, to identify if the light intensity and the harvest are statistically affecting the dry matter values. Light intensity is a major confounding variable in this experiment. Since there is an inhomogeneous light intensity within each treatment and the aim is to figure out the effect coming forth from the diffusiveness. In order to disentangle the results multiple regression has been applied to the data, the results are shown in Table 10.

By applying a multiple regression (Table 10) we get a better fitting of the data in all three trials, which shows that light intensity also has an important explanatory effect in the differences in dry matter between the two treatments and in all 3 trials the p-values show a larger confidence in the predicting parameters for the combined model relative to each of the separate models evaluated. Likewise, the proportion of explained variance is also highest for the combined model.

Table 10

Multiple regression parameters relating dry matter production with the treatment (light diffusion) and the light intensity for the three trials.

	Trial 1		
	Treatment	Light	r^2
Treatment	0.305 ($7e^{-4}$)	-	0.047
Light intensity		0.00215 ($1e^{-26}$)	0.384
Combined	0.292 ($4e^{-5}$)	0.00214 ($7e^{-28}$)	0.427
	Trial 2		
	Treatment	Light	r^2
Treatment	0.150 (0.209)	-	0.0171
Light intensity		0.00238 ($6e^{-24}$)	0.671
Combined	0.149 (0.03)	0.00238 ($2e^{-24}$)	0.688
	Trial 3		
	Treatment	Light	r^2
Treatment	-0.376 ($8e^{-4}$)	-	0.116
Light intensity		0.00246 ($2e^{-30}$)	0.763
Combined	-0.211 ($1e^{-4}$)	0.00236 ($6e^{-31}$)	0.798

Since the light intensity distribution changed between the first and second harvest the light sum is used instead of the intensity. When doing so, and combining results from Trial 2 and Trial 3 (Figure 12), results indicate trend for only slightly higher dry weight under the highly diffusive vertical lamellae in relation to the conventional diffusive treatment, whereas both show a clear trend of higher dry matter accumulation than the plants under the direct light treatment.

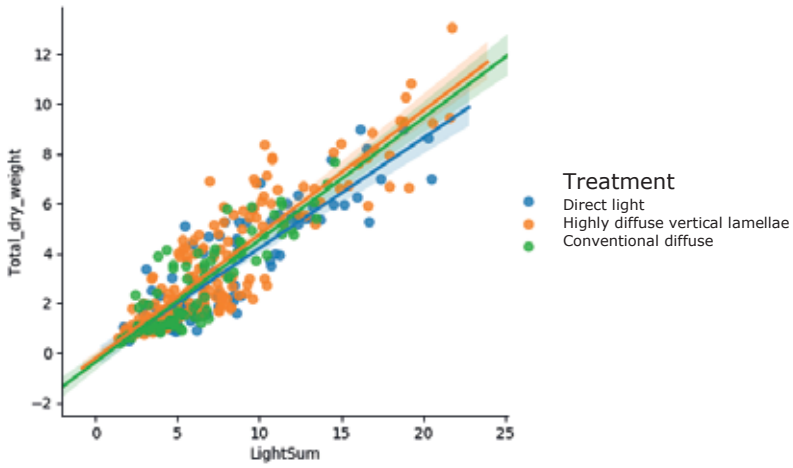


Figure 12 *Total dry weight of the young tomato plants (both harvests H1 and H2) vs. the accumulated light sum for different treatments of direct light, conventional diffuse and highly diffuse vertical lamellae (in trials T2 and T3).*

Table 11

Summary of the results (average values) of dry matter determinations in the three trials.

	Trial 1			Trial 2			Trial 3		
	Direct Light mean (std)	Vertical lamellae mean (std)	Difference P-value (effect size)	Direct Light mean (std)	Vertical lamellae mean (std)	Difference P-value (effect size)	Conventional Diffuse mean (std)	Vertical lamellae mean (std)	Difference P-value (effect size)
PAR Light Sum [mol/plant]	4.50 (2.92)	4.29 (3.13)	0.503 (-4.9%)	8.00 (4.45)	7.59 (4.74)	0.542 (-5.3%)	6.11 (3.16)	6.83 (4.23)	0.192 (11%)
Light to H1 [µmol/m²/s]	502 (178)	507 (225)	0.821 (1.0%)	460 (176)	461 (217)	0.993 (0.1%)	411 (156)	482 (227)	0.014 (16%)
Light to H2 [µmol/m²/s]	536 (213)	456 (307)	0.004 (-16%)	533 (252)	456 (294)	0.054 (-16%)	448 (199)	457 (310)	0.808 (2.0%)
Total dry weight [g]	3.40 (3.16)	3.68 (3.37)	0.420 (7.9%)	3.33 (2.23)	3.65 (2.72)	0.375 (9.3%)	2.63 (1.76)	3.10 (2.26)	0.118 (16%)
Total dry weight H1 [g]	1.53 (0.583)	1.83 (0.780)	0.001 (18%)	1.51 (0.548)	1.66 (0.596)	0.209 (9.4%)	1.17 (0.384)	1.55 (0.634)	0.001 (28%)
Total dry weight H2 [g]	7.11 (2.89)	7.37 (3.53)	0.665 (3.5%)	5.18 (1.70)	5.68 (2.53)	0.267 (9.2%)	4.12 (1.32)	4.68 (2.24)	0.146 (13%)
Dry leaf weight H2 [g]	4.45 (1.89)	4.82 (2.86)	0.557 (8.0%)	3.51 (1.29)	3.80 (1.90)	0.399 (7.9%)	2.89 (0.98)	3.21 (1.70)	0.267 (11%)
Dry stem weight H2 [g]	2.58 (1.91)	2.43 (0.91)	0.690 (-6.1%)	1.67 (0.51)	1.88 (0.63)	0.078 (12%)	1.23 (0.34)	1.47 (0.55)	0.014 (18%)
Amax @1500 µmol/m²/s L#2	13.8 (3.71)	11.1 (2.67)	0.006 (-22%)						
Amax @2000 µmol/m²/s L#2	14.5 (3.96)	11.7 (2.77)	0.009 (-21%)						
Amax @1500 µmol/m²/s L#5	24.3 (4.33)	22.3 (4.21)	0.117 (-8.6%)						
Amax @2000 µmol/m²/s L#5	26.4 (4.74)	24.1 (4.61)	0.112 (-8.9%)						
Length [cm]	77.0 (5.95)	81.8 (7.10)	0.006 (6.1%)	58.8 (4.98)	63.8 (3.29)	0.000 (8.1%)	48.5 (4.85)	55.3 (3.79)	0.000 (13%)
Fresh leaf weight [g]	41.8 (12.9)	39.7 (15.3)	0.565 (-5.2%)	36.7 (9.3)	38.9 (13.5)	0.384 (5.6%)	30.7 (9.0)	33.5 (13.0)	0.228 (8.8%)
Fresh stem weight [g]	43.3 (10.1)	43.0 (11.0)	0.920 (-0.6%)	33.1 (6.4)	37.2 (7.9)	0.008 (12%)	26.0 (6.0)	31.0 (7.6)	0.001 (18%)
Number of leaves	9.57 (1.01)	9.74 (1.09)	0.518 (1.8%)	8.80 (0.81)	8.76 (1.06)	0.825 (-0.5%)	8.30 (0.84)	8.37 (0.83)	0.708 (0.8%)
Total Leaf Area [cm²]	1178 (259)	1193 (308)	0.834 (1.3%)	977 (164)	1105 (252)	0.005 (12%)	871 (177)	986 (242)	0.011 (12%)

In addition, we must also take into account the fact that plants were harvested twice for dry matter determination, which also determined a change in light interception, which was increased after the first harvest, as we saw in the previous section. Indeed, when results of dry matter production are plotted separately for the first and second harvest (combined data for T2 and T3) we see clearly different trends for both harvests (Figure 13). Therefore, a new multiple regression is done, including harvest as a factor (Table 12). Results indicate that including harvest in addition to the other two factors (light intensity and treatment) in the regression analysis provides the best fitting for the estimation of the total dry matter production. From Table 12 we can conclude that the average dry weight of 3.18 grams can be explained for 88.8% by 0.365*LightSum+1.77*harvest. If we include the treatment 89.3% of the 3.18 average dry weight can be explained by 0.364*LightSum+1.77*harvest for the clear treatment and 0.364*LightSum+1.77*harvest+0.337 for the lamellae and the treatment conventional diffusive treatment is not significantly different from the clear treatment. So, the lamellae caused a 10.6% increase in dry weight relative to the clear treatment while the standard diffusive treatment caused a not statistically significant 0.234% decrease in dry weight.

Table 12

Multiple regression parameters relating dry matter production with the treatment (light diffusion), light sum and harvest for the Trials 2 and 3.

	Light	Harvest	Treatment		r^2
			Conventional Diffuse	Vertical lamellae	
Light	0.478*	-	-	-	0.782
Harvest	-	3.44*	-	-	0.566
Treatment	-	-	-0.696 (0.037)	0.0478 (0.869)	0.019
Light + Harvest	0.365*	1.77*	-	-	0.888
Light + Treatment	0.480*	-	0.213 (0.175)	0.429 (0.002)	0.788
Harvest + Treatment	-	3.44*	-0.696 (0.001)	0.0478 (0.799)	0.585
Light + Harvest + Treatment	0.364*	1.77*	-7.43e-3 (0.947)	0.337*	0.893

*means p value is smaller than 0.001

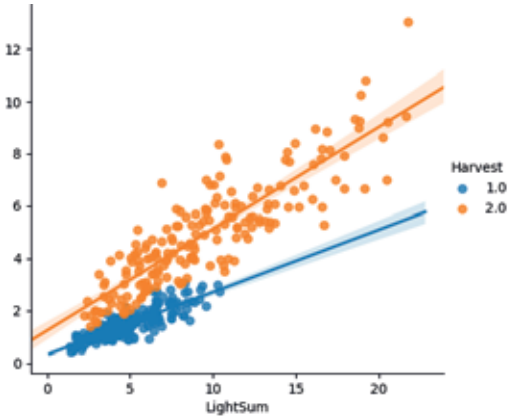


Figure 13 *Total dry weight of the young plants of harvest H1 and H2 of all treatments vs. the accumulated light sum in T2 and T3.*

In order to check if trial 2 and 3 can be compared in this way the same multiple regression model was applied with 'trial' as additional categorical explaining variable to a subset of the data with only the highly diffusive lamellae treatment. If there would be no confounding differences between the 2nd and 3rd trial this additional variable should show no statistical significance in explaining the variation dry weight (Table 13).

Table 13

Multiple regression parameters relating total dry weight production with the light sum, harvest and trial for the lamellae treatment in trial 2 and 3.

	Light	Harvest	Trial	r^2
			T3	
Light + Harvest + trial	0.394*	1.84*	-0.252 (0.037)	0.896

Table 13 shows that the total dry weight of the plants underneath the lamellae treatment was significantly less in the 3rd trial compared to the 2nd trial even when compensated for the light sum and harvest. This shows there is an unknown confounding variable causing a difference between the 2nd and 3rd trial.
If we assume that the difference observed between trial 2 and 3 for the lamellae treatment had a similar impact on both treatments in each trial we can correct for this difference by taking it into account in the regression analysis (Table 14). It must be noted that it is unknown if this is a valid assumption or not.

Table 14

Multiple regression parameters relating total dry weight production with the light sum, harvest, trial and treatment in trial 2 and 3

	Light	Harvest	Trial	Treatment		r^2
			T3	Conventional Diffuse	Vertical lamellae	
Light + Harvest + trial + Treatment	0.362*	1.78*	-0.276 (0.012)	0.265 (0.090)	0.473*	0.895

The unknown influence causing a difference between trial 2 and 3 for the lamellae treatment is now taken into account for the treatments direct light and conventional diffusive treatment as well. These results suggest that conventional diffusive treatment explains +8.3% dry matter production and the extremely high diffusive lamellae treatment explains +14.9% dry matter production relative to direct light treatment.

It is important to note that the statistical power of this study is not very high and these results are consequently better expressed using the 95% confidence interval of the model resulting from the regression analysis, these results than really show that conventional diffusive treatment explains between -1.3% and +17.9% of dry matter production and the extremely high diffusive lamellae treatment explains between +8.1% and +21.6% of dry matter production.

5 Conclusions

- A climate chamber experiment was conducted comparing a direct light treatment, a conventional diffusive treatment and a highly diffusive lamellae treatment and their effect on growth and development of young tomato plants.
- The climate chamber experiment should give an answer on the research question if a highly diffusive light environment has additional benefit against a conventional diffusive light environment on the production of young tomato seedlings.
- Despite of the efforts in making the best possible experimental set up in a climate chamber using a single lamp, it was not possible to maintain statistically equal average PAR values under the highly diffusive vertical lamellae and the direct light and conventional diffusive light treatments in the three climate chamber trials. The distribution of PAR was also more heterogenous than desired both under diffuse light and direct light conditions in the three trials.
- The amount of PAR light intercepted by the young tomato seedlings was significantly higher under the highly diffusive vertical lamellae than in the other treatments in three trials.
- Measurements did not find an advantage in higher maximum photosynthetic capacity neither from top nor bottom leaves under the highly diffusive vertical lamellae in relation to those under direct light.
- The best fitting between treatment and dry matter production was obtained by including the average light intensity and the harvest as independent factors in a multiple regression. Results indicate a trend to higher total dry matter production under the high diffusive treatment (vertical lamellae) in relation to both the direct light and the conventional diffusive treatments.
- The increased total dry matter seems to be the result of the plants under the highly diffusive vertical lamellae producing wider leaves (leaf area) and a taller stem which are both favourable factors for light interception.
- In a next step an additional trial should be conducted under natural light conditions in a greenhouse, ensuring comparable average light intensity in all treatments and harvests. The additional trial should include natural light conditions in which cloudy and sunny periods both occur. Such a trial will be performed in 2020.

References

Alton PB, North PR, Los SO. 2007.
The impact of diffuse sunlight on canopy light-use efficiency, gross photosynthetic product and net ecosystem exchange in three forest biomes. Global Change Biology, 13: 776-787

Cohan DS, Xu J, Greenwald R, Bergin MH, Chameides WL. 2002.
Impact of atmospheric aerosol light scattering and absorption on terrestrial net primary productivity. Global Biogeochemical Cycles, 16: 37-1

Farquhar GD, Roderick ML. 2003.
Pinatubo, diffuse light, and the carbon cycle. Science, 299: 1997-1998

Gu L, Baldocchi D, Verma SB, Black TA, Vesala T, Falge EM, Dowty PR. 2002.
Advantages of diffuse radiation for terrestrial ecosystem productivity. Journal of Geophysical Research D: Atmospheres, 107: 2-1

Hemming S, Dueck TA, Janse J, van Noort F. 2007.
The effect of diffuse light on crops. Acta Horticulturae, 801: 1293-1300

Li L, Heuvelink E, Dueck TA, Janse J, Gort G, Marcelis LFM. 2014.
Enhancement of crop photosynthesis by diffuse light: quantifying the contributing factors, Annals of Botany, 114 (1): 145–156, https://doi.org/10.1093/aob/mcu071

Marcelis, L.F.M., Broekhuijsen, A.G.M., Nijs, E.M.F.M., Raaphorst, M.G.M. 2006.
Quantification of the growth response of light quantity of greenhouse grown crops. Acta Hortic. 711.9. http://doi.org/10.17660/ActaHortic.2006.711.9

Mercado LM, Bellouin N, Sitch S *et al.* 2009.
Impact of changes in diffuse radiation on the global land carbon sink. Nature, 458: 1014-1017

Sarlikioti, V. 2011.
Modelling and Remote Sensing of Canopy Light Interception and Plant Stress in Greenhouses. Phd thesis Wageningen University, The Netherlands.

To explore the potential of nature to improve the quality of life

Wageningen University & Research,
BU Greenhouse Horticulture
P.O. Box 20
2665 ZG Bleiswijk
Violierenweg 1
2665 MV Bleiswijk
The Netherlands
T +31 (0)317 48 56 06
www.wur.nl/glastuinbouw

Report WPR-936

The mission of Wageningen University and Research is "To explore the potential of nature to improve the quality of life". Under the banner Wageningen University & Research, Wageningen University and the specialised research institutes of the Wageningen Research Foundation have joined forces in contributing to finding solutions to important questions in the domain of healthy food and living environment. With its roughly 30 branches, 5,000 employees and 12,000 students, Wageningen University & Research is one of the leading organisations in its domain. The unique Wageningen approach lies in its integrated approach to issues and the collaboration between different disciplines.