Effect of high scattering lamellae on growth and photosynthesis of young tomato plants

Smart materials crop experiments

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Abstract
To investigate the effect of very high hortiscatter (extreme light diffusion) on the growth of a young tomato crop, an experiment was conducted at Wageningen UR Greenhouse Horticulture in Bleiswijk. Three levels of light diffusion were compared: high diffusion (hortiscatter=0.9), medium light diffusion (hortiscatter = 0.65) and direct light or no light diffusion (hortiscatter~0). The plants were placed on elevated growing tables and grown at a high density to simulate the high LAI values of a grown-up crop. The materials allowing for the differences in light diffusion were placed on metal frames above the plants. Each material was used on two tables. Despite a careful set up, the PAR sum was not equal for all tables. This was due to position effects in the greenhouse as well as small differences in light transmission of the covering materials. When both diffusion factor and PAR sum are considered in the analysis of the results of the successive destructive harvests, the plants grown under the high diffusing lamellae showed increased leaf area and higher fresh and dry weight compared to the other two treatments. The light use efficiency, expressed as grams of dry matter produced per mol PAR, increased with increasing Hortiscatter for the last two destructive harvests. Net photosynthesis increased also with the increase of scattering. A larger trial in separate compartments would be desirable to verify these results in real growing conditions and evaluate the effects on fruit production during a longer experiment.

Referaat
Bij Wageningen UR Glastuinbouw in Bleiswijk is het effect van zeer hoge hortiscatter (extreme lichtdiffusie) op de groei van jonge tomatenplantjes onderzocht. Drie niveaus van lichtverstrooiing zijn vergeleken: hoge diffusie (hortiscatter = 0.9), gemiddelde lichtdiffusie (hortiscatter = 0.65) en geen lichtdiffusie (hortiscatter~0). De planten zijn op potplantentafels geplaatst op hoge dichtheid om LAI-waarden van een volwassen gewas te simuleren. De materialen met verschillende lichtverstrooiing zijn op metalen frames boven de planten geplaatst. Elk materiaal is op twee tafels gebruikt. Ondanks de zorgvuldige opzet, waren verschillen in ontvangen PAR som tussen behandelingen, door positie effecten en kleine verschillen in transmissie van de gebruikte materialen. Als zowel de lichtverstrooing als de PAR som worden meegenomen in de analyse van de resultaten van de opeenvolgende gewas oogsten, blijken de planten geteeld onder de hoog diffussie lamellen, een hogere bladoppervlakte en hoger vers en droog gewicht te hebben dan de planten geteeld onder de andere twee behandelingen. De lichtbenuttingsefficientie uitgedrukt in gram droge stof per mol PAR nam toe met toenemende lichtverstrooiing. De netto fotosynthese nam ook toe met toenemende lichtverstrooiing. Een grotere proef in aparte compartimenten zou wenselijk zijn om deze resultaten in reële teeltomstandigheden te verifiëren en de effecten op productie tijdens een volledige teeltcyclus te evalueren.

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Disclaimer

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Summary

During the last decade, different research works have clearly proved that diffuse light is preferred over direct light for a wide range of horticultural species. The benefits range from increased crop growth and productivity in edible crops to improved quality in many ornamental crops. Until recently, the diffusiveness of a greenhouse cover was mostly characterized by the haze parameters. However, the haze parameter does not capture well the angular distribution of the scattered light. The hortiscatter parameter (0-1, being 1 the perfect Lambertian diffuser) has been proposed as to indicate the angular distribution of the scattered light. To the extent of our knowledge, no research has been done to investigate very high hortiscatter levels, mostly because achieving such high diffusion in the cover material would involve an rather large decrease in PAR transmission due to back scattering.

The present report describes an experiment that was performed at the Wageningen UR Greenhouse Horticulture facilities in Bleiswijk between August and half October 2020. The aim was to investigate the effect of a very high hortiscatter (extreme light diffusion) on the growth of a young tomato crop. A lenticular material (diffusing vertical lamellae) was used below a very clear cover (clear ETFE) to generate extreme light diffusion (hortiscatter = 0.9) without light loss. The extreme light diffusion was compared with both medium light diffusion (diffuse ETFE, hortiscatter = 0.65) and direct light (clear ETFE, hortiscatter~0). The plants were placed on elevated growing tables and grown at a high density to simulate the high LAI values of a grown up crop. A metal frame was built above the tables to support the covering materials. Each material was used on two tables. Despite a careful set up, the PAR sum was not equal for all tables. This was due to position effects in the greenhouse as well as differences in transmission of the covering materials. When both diffusion factor and PAR sum are considered in the analysis of the results of the successive destructive harvests, the plants grown under the high diffusing lamellae showed increased leaf area and higher fresh and dry weight compared to the other two treatments.

The light use efficiency, expressed as grams of dry matter produced per mol PAR, increased with increasing hortiscatter for the last two destructive harvests, as it happened with the net photosynthesis, which was also clearly increased with increasing hortiscatter in both the top and the middel leaves of the canopy.

Light interception measurements carried out on a sunny day showed a higher interception for the two scattering treatments in the whole canopy depth compared to the clear light interception treatment. The higher percentage of light interception at each level under the scattering treatments is in agreement with the higher photosynthetic capacities observed in the middle leaves of the crop and with earlier research results found on mature plants (Dueck *et al.* 2012).

As the incident natural radiation was diffuse during most of the daytime hours (diffuse PAR sum of 283 mol/m^2), whereas the sum of direct PAR radiation was 212 mol/m^2 only, there was less chance for the scattering treatments to propitiate larger differential levels of scattered light to the plants.

The results confirm those of previous experiments in a climate chamber (Van Breugel *et al.* 2020).

In the future a larger trial in separate compartments would be desirable to verify these results in real growing conditions and during a full production cycle, and so be able to evaluate if the higher scattering leads through the improved photosynthesis, plant leaf area and higher biomass production per unit light, also results in higher fruit production.

1 Introduction

Until a year ago, no research was done to analyze the effect of a very high light scattering (hortiscatter>90%) on greenhouse crops. Last year a first experiment was conducted with highly diffusive vertical lamellae in a climate chamber with small tomato plants (Figure 1) (Van Breugel *et al.* 2020). The 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.

The recommendation of the report from the test in the climate chamber (Van Breugel *et al.* 2020) was to continue the research under natural light conditions in a greenhouse.

The present report describes a trial that was conducted following these recommendations, from the beginning of August 2020 to beginning of October 2020. The experiment was held in a greenhouse compartment covered with a clear glass, to ensure comparable average light intensity in all treatments, while allowing both cloudy and sunny periods.

Figure 1 *Image of the first test performed last year in a climate chamber.*

1.1 Project objective

The objective was to perform a small test in a greenhouse compartment in our greenhouse research facilities in the location of Bleiswijk to evaluate the effect very high light scattering on a young tomato crop under natural light conditions. The high scattering (hortiscatter >90%) is achieved by hanging a new design of lamellae developed by Sabic which scatter downwards virtually all intercepted light above the crop.

1.2 Hypothesis

The hypothesis are:

1. That plant growth (dry matter production and development rate) are increased by diffuse light compared to direct light for an equal light sum. The factors contributing to this enhanced plant growth and development are:
   i. More homogeneous horizontal PPFD distribution
   ii. More uniform vertical PPFD distribution
   iii. Higher leaf photosynthetic capacity
   iv. Higher LAI.
2. That the effect will be larger for highly diffused light (hortiscatter≈90%).

1.3 Research questions

The formulated research questions are:

- Does a very high hortiscatter (≈90%) induce a faster and higher crop growth than a medium hortiscatter (≈65%) in young tomato plants?
- If so, what are the factors that have induced that advantage?

2 Materials and methods

The experiment was conducted in greenhouse compartment 9.04 in our greenhouse complex in Bleiswijk (Figure 2). It has a size of 144 m^2. The greenhouse is equipped with eb/flood irrigation tables where the plants have been cultivated.

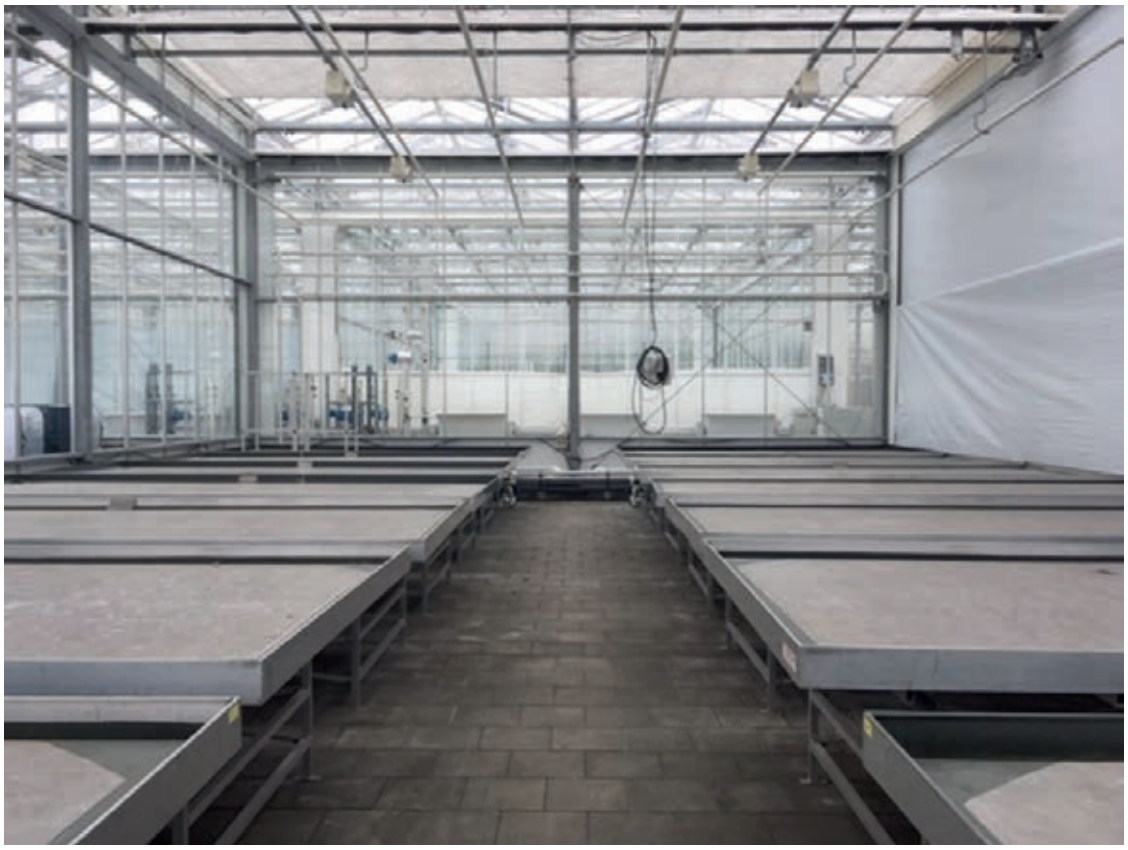

Figure 2 *The experimental greenhouse.*

2.1 Treatments

Three different scattering levels (treatments) schematically represented in (Figure 3) were compared:

1. High scattering (HS), achieved by hanging the lamellae in parallel from the top of a metal frame. For an optimum light distribution, the lamellae should always maintain a minimum height in relation to the top of the plant of 20 cm (see later section 2.2.1.). Above the lamellae, a clear ETFE film was placed, to ensure that average light intensity below the lamellae is similar to that in the other two treatments.
2. Medium scattering (MS), achieved by placing a diffusive ETFE film on the frame above the crop (Figure 3).
3. Direct light, achieved by placing a clear ETFE film on the frame above the crop (Figure 3).

The EFTE films were hanging partially (15-20 cm) on three of the four sides (north side open) to minimize unfiltered light penetration.

The properties of the material used for the treatments are summarized in Table 1.

Table 1
Materials used for the treatments and their optical properties.

Treatment	code	material	Hemispherical transmission	Hortiscatter
High scattering (High diffusion light)	HS	Lamellae, under ETFE clear	86	90
Medium scattering (Medium diffusion light)	MS	ETFE diffuse film	80.5	65
Low Scattering (Direct light)	LS	ETFE clear film	86	0

All treatments were carried out in duplo (two tables per treatment).

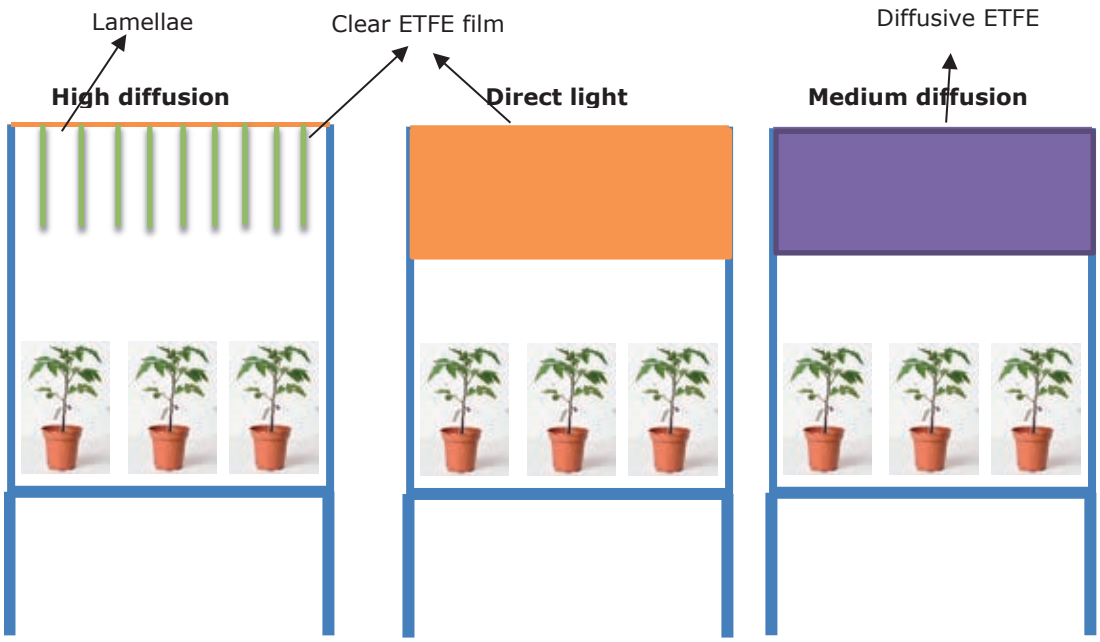

Figure 3 *Side view of the experimental set up with the treatments on tables, plants, supporting material (metal frames) and the different films used to generate the desired light conditions above the plants.*

2.2 Treatment set up

Lamellae and films need to be supported above the crop. This was achieved by the construction of a rectangular aluminum frames as big as the table with high legs resting on the four corners of the table (Figure 5).
By placing the different films on top of the frame and hang the lamellae on wires attached to this frame, the desired light scattering was created for each treatment ensuring as well that the average light intensity above the crop on each table is also equal.

Figure 7 shows the final set up of the different treatments once the young crop had started to grow on the tables.

2.2.1 Solar ray tracing simulations

To determine the best way to place the lamellae on the frames and in relation to the crop, ray tracing simulations were conducted (Figure 4). The information needed was:

a. Ratio between lamellae height and the distance between them.
b. Orientation of the lamellae.
c. Distance from lamellae to crop.

The main conclusions were:

a. The ratio between lamellae height and distance between them should be 3 or higher.
b. Orientation must be East-West.
c. Crop should not be closer than 20 cm to the lamellae, and not further away than 50 cm from them.

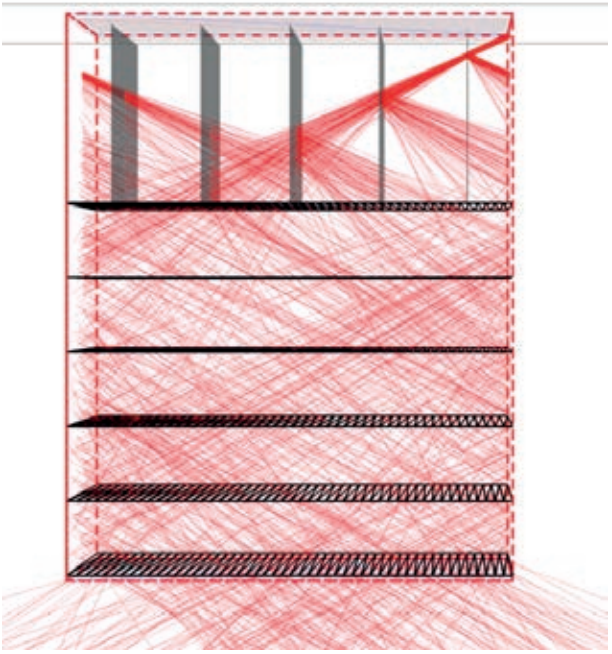

Figure 4 *Solar ray tracing simulations used to calculate how to place the lamellae.*

The calculation results show that the frame needed to be mobile, so that films and lamellae can be moved upwards as the crop growths. In the HS tables, the frame needed to be able to support without bending the weight of both the film and the lamellae. The films are very thin and light; the lamellae have a weight of 360 gram each; for a 2.4 meter width we need 2 lamellae, so 720 gram per wire. With one per 15 cm along 4.5 meters (30 wires), the total weight of the lamellae is 21.6 kg.
The final result of the frames as constructed and with the lamellae in their final position is shown in Figure 5.

Figure 5 *The constructed frames with the lamellae in their final position.*

2.2.2 Spatial distribution of the treatments.

Every treatment was placed on two tables to have a spatial replicate, to compensate for possible position effects on light availability due to shades generated by the neighbouring greenhouse compartments. The final distribution of the treatments and replications on the tables is shown in Figure 6.

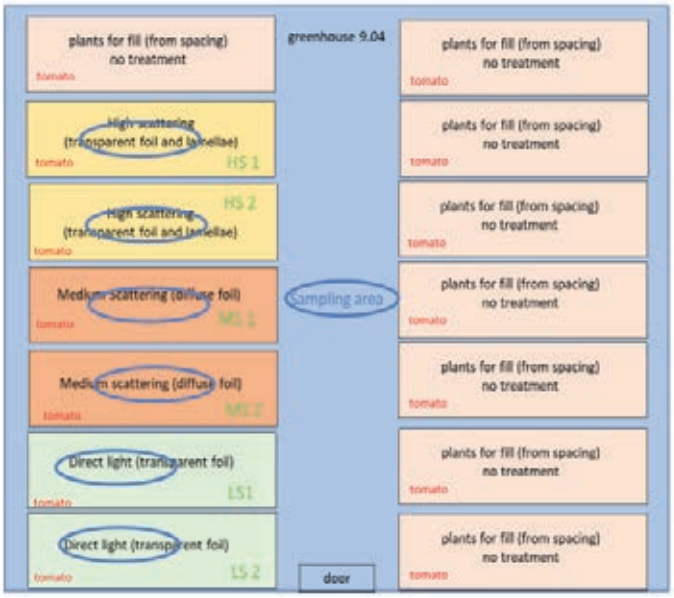

Figure 6 *Treatments distribution in the greenhouse.*

2.3 Crop

Young tomato plants (cv. Komeett) were sown in rock wool plugs (240 plugs per m^2, 3000 seeds) on August 6, 2020. Ten days after sowing the seedlings were transplanted to rockwool blocks (10 x 10 cm) to the tables in the greenhouse compartment at a high density of 100 plants per m^2.

With a high density, it is possible to achieve in short time a high LAI so that light penetration in the canopy becomes limiting, as in a fully developed tomato crop.

2.3.1 Plant management

Plant density was adapted by spacing the crop in time to maintain a LAI of 3 as target. For the first development stages, however, this target needed to be adapted to avoid the plants to elongate too quickly. Lowering the air temperatures in the greenhouse to a day average of 16°C, provided the outside temperature allowed for it, was the first strategy to keep the plants short.

As the light became limiting, the plants started to push each other upwards. This would mean that length growth would be soon limiting, making impossible to maintain the targeted distance to the lamellae, so lowering the LAI target was considered an appropriate decision.

Figure 7 *Final set up of the different treatments once the young crop had started to grow on the tables. Left: LS (direct light); Middle: MS (medium scattering); Right: HS (high scattering lamellae).*

At first flowering truss, the plants were already that high that the maximum height of the movable frames was almost reached. Then the head was removed (topping) to stop the stem elongation. Some plants developed side shoots.

The young plants were supported with 30 cm wooden sticks; after the plants reached a height of 80 cm, 1 m wooden sticks were used to prevent them from falling.

The final plant density was 9 plants per m^2, at which the plants were over 150 cm. To keep them in position it was necessary to suspend them with elastic ropes from the supporting frame.

The spacing schedule with the corresponding LAI after each spacing and other plant management activities are detailed in Table 2. The aspect of the plants at the successive plant densities is shown in Annex 1

Table 2. Spacing schedule including plant management actions

date	activity	density (pl/m^2)	LAI before spacing	LAI after spacing
6 Aug	sowing (plug)	240		
17 Aug	transplant (blocks)	100		
25 Aug	start measurement	100		0.7
1 Sep	spacing 1	75	1.9	1.5
9 Sep	spacing 2	37.5	3.8	1.9
16 Sep	first truss flowering	37.5		
18 Sep	topping	37.5		
21 Sep	spacing 3	18	3.8	1.8
1 Oct	spacing 4	9	3.6	1.8
10 Oct	end of experiment	9		2.6

2.3.2 Water and nutrients

Water and nutrients have been supplied by eb-flow irrigation. The composition of the nutrient solution (Table 3) was the "start solution till the flowering of the first truss" of the "Bemestings Advies Basis substraten" (De Kreij *et al.* 1999).

Table 3
Nutrient solution tomato (start solution till first truss flowering).

Main elements (mmol/l)								Trace elements (µmol/l)						
EC	pH	NH_4	K	Ca	Mg	NO_3	SO_4	P	Fe	Mn	Zn	B	Cu	Mo
2.8	5.5	1.2	8.3	5.7	2.7	16.0	4.4	1.5	15	10	5	30	0.75	0.5

2.4 Measurements

Both climate and plant parameters were measured during the whole duration of the experiment.

2.4.1 Climate and PAR light

The greenhouse compartment climate was monitored at 5 minute intervals with sensors for temperature, RH, CO_2, water pH and EC. One PAR sensor in the center of the greenhouse monitored the light inside the greenhouse. Six additional PAR sensors (one per table /per treatment or repetition) were installed at a fixed height from the frame to monitor the light levels available for the plant throughout the season.

2.4.2 Plant development and growth: destructive harvests

Six destructive harvests of 10 plants per table (treatment replicate) were performed. A start harvest (8 days after transplanting), one harvest at every plant spacing and one harvest at the end of the experiment.
At every harvest, fresh and dry weight of the aerial part of the plants (leaves and stem separately) was determined, as well as the plant length, the number of leaves and the leaf area using a Leaf area meter (LI-3100C, Li-Cor Inc., Lincoln, USA), Figure 8 (right).


Figure 8 *Destructive measurements were carried out several times during the experiment.*

2.4.3 Light interception by the crop (vertical light distribution)

Using a SS1 Sunscan sensor (Sunscan, Delta-T, Cambridge, UK) the light interception by the crop was measured at 2 heights (young plants) or more (as the plants become taller) by using a light stick.

These measurements (Figure 9) were carried out just before every spacing episode (4 times) and at the end of the experiment.

Figure 9 *Measurements of light interception at the top of the canopy (left) and inside the canopy (right).*

2.4.4 Photosynthesis

A Licor-6800 (Li-Cor Inc.) was used to measure the maximum photosynthetic capacity at intensities of 0-50-100-250-500-750 and 1000 µmol/m^2 s using the internal light source of the LI-6800 (90% red, 10% blue LED). Photosynthesis was measured twice: between the first and second spacing, and at the end of the experiment.

The first measurement took place on the 3rd and 4th September. Plants were about 40 cm high and had a maximum of 7 leaves, of which the top ones not yet fully expanded; therefore, only the uppermost first fully expanded undamaged leaf was measured on three plants per treatment.

Conditions in the measuring chamber were chosen taking the average conditions on the last three days between 8-12h (the time in which the photosynthesis was measured). These were: 18.5°C, a CO_2 concentration of 450 ppm and a RH of 60-65%.

The second measurement took place in the last week of the experiment, on the 5 and 6 October.
Plants were about 125 cm high and had on average 9 fully expanded leaves below the first truss (when they were topped). This made possible to measure at two canopy depths: the uppermost first fully expanded undamaged leaf below the truss and the third fully expanded undamaged leaf.

Conditions in the measuring chamber (taking the last three days conditions between 8-12 h) were 15.5°C, a CO_2 concentration of 450 ppm and a RH of 75-80%.

2.5 Statistics

Results of the relevant plant values as measured according to the methods indicated in the previous chapter, have been statistically analysed by means of one factor ANOVA with the Statistics package Genstat. The mean values of the plant parameters obtained were compared using the least significant difference (l.s.d.). The PAR light received by the plants in the different treatments was compared using the Fp value (the probability that the test statistic can take a value greater than the value of the computed test statistics).

Because the light sum in the different treatments interacts with the light scattering treatments for the plant parameters, a REML analysis was performed. REML is suited to analyze unbalanced designs. Treatment and PAR light sum till harvest, (as a covariate) were taken as fixed factors. Treatment effects are analyzed with the Wald-test and are significant when they are smaller than 0.05.

3 Results

3.1 Climate and PAR light

3.1.1 Temperature, Relative Humidity, CO_2

The conditions in the greenhouse are shown for the different periods of the experiment in Table 4. The periods have been chosen in between measurements which corresponded, except for the first period, with plant spacing moments. The average temperature of the greenhouse during the full duration of the experiment (54 days) was 17.5°C. The experiment started in summer with warmer days; that made the first week of the experiment the warmest (Table 4) on average of the whole experiment. The highest greenhouse temperature (30.5°C) was reached on the 20th of August; the second highest (30°C) on the 15th of September. The heating setpoint was set on 10°C at night, in order to use the colder nights to compensate for the high day temperatures. The lowest temperature reached was 10.3°C which means that the heating system did not switch on.

Table 4

Average temperature, relative humidity and CO_2 concentration during the duration of the experiment, shown by periods between the spacing episodes / measurements.

Period From - to	density (pl/m²)	Avg. T	Avg. RH	Avg. CO_2 (day time hours)
17 Aug- 25 Aug	100	22.0 °C	71 %	438
5 Aug- 1 Sept	100	18.2 °C	74 %	426
1 Sep – 9 Sept	75	17.5 °C	77 %	435
9 Sep – 21 Sept	37.5	18.0 °C	76 %	454
21 Sep – 1 Oct	18	16.6 °C	83 %	451
1 Oct - 10 Oct	9	14.2 °C	86 %	455

CO_2 was supplied during daytime to achieve a concentration of 650 ppm. On average, however, the day concentration was only 445 ppm because of the large ventilation needed to keep the temperature as low as possible, to avoid the plants from growing too tall due to the reduced light intensities below the "roof". During colder days the concentration was about 500 ppm.

3.1.2 PAR light

The experiment was designed to maintain PAR levels as similar as possible on each treatment and repetition.

This was done by assuming that the lamellae do not cause any reduction in the PAR available for the crop below (as indicated by previous solar ray tracing simulations) and choosing both clear and medium diffusivity foils which do not differ much in their hemispherical PAR transmission. From detailed transmission measurements in this greenhouse, we know that the position of each table can affect the PAR available for each treatment. Results indicate periods in which mean daily values are more similar and periods in which there are higher differences in favour of some treatments in relation to others (Figure 10). The differences may respond to differential shading of structural elements on the sensors, position differences with respect to the side walls and the neighbouring greenhouses, and to small differences in the light transmission properties of the foils used. The differences are not consistent in time, and in some periods the higher mean values correspond to some repetitions (MS2 shows the highest values around September 6th) and in other periods these same sensors are the ones that exhibit a lower value (MS2 around September 13th). In the moments of maximum PAR, around noon, the differences are more stable (Figure 11) and PAR intensity values below the two HS repetitions are consistently the lowest while values below the LS repetitions, with the exception of some short periods, are the highest.

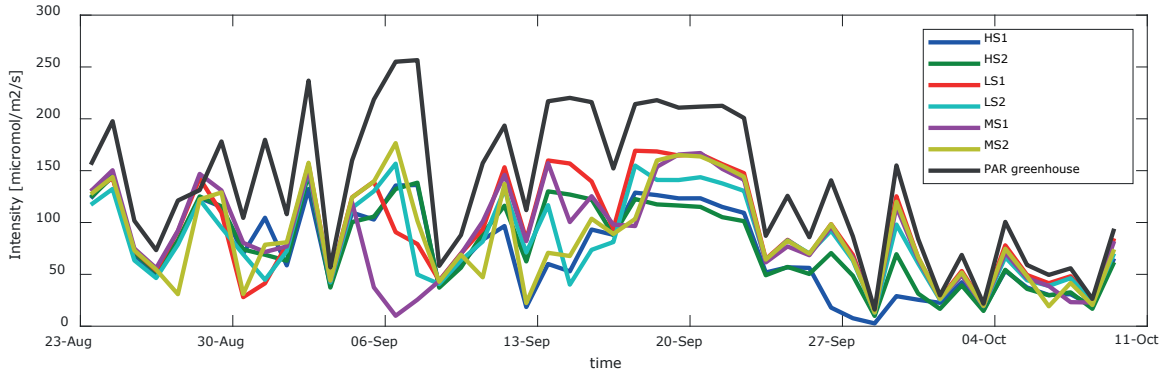

Figure 10 *Average daily PAR intensity (micromols/m^{2}s) below the six repetitions of the three different light diffusion treatments and inside the greenhouse compartment.*

The daily cyclic mean of PAR values (Figure 11) gives more insight and confirms that on an average day of the cycle, the PAR intensities were not equal under all treatments, with substantial differences observed mostly around noon, which penalize particularly the high diffusion (HS) repetitions and favour mostly the low diffusion (LS) repetitions. In the afternoon the HS repetitions change from being the darkest to becoming the ones with more PAR; however, in the afternoon and morning hours the differences are lower.

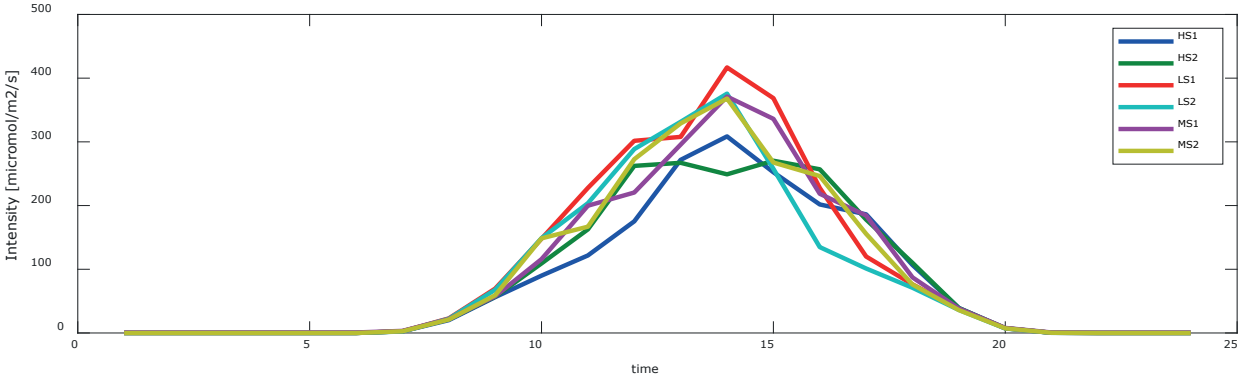

Figure 11 *Daily cyclic mean of PAR intensity (micromol/m^{2}s) below the six repetitions of the three different light diffusion treatments.*

The final sum of PAR indicates some advantage in terms of light available for LS1 and some disadvantage for HS1. The rest of treatments do not differ significantly (Figure 12).

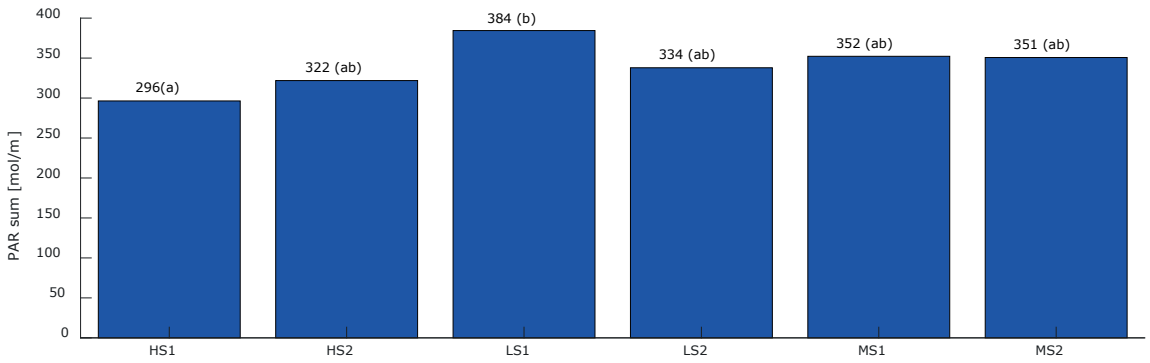

Figure 12 *PAR sum measured below the repetitions of the three treatments. Different letters indicate significant differences.*

As the light sum is the most important factor for the dry matter production, these differences, however small, interfere with possible differences between the treatments beyond those caused by the actual treatments: the level of light scattering.

Therefore, the dry matter production will also be expressed as Light use efficiency (LUE, g/mol) in order to correct for the observed differences in light sum.

3.1.3 Outside radiation: direct and diffuse

An analysis of values of outside direct and diffuse radiation during the duration of the trial is very relevant, because the advantage of scattering direct incoming solar radiation is lost in periods when most of the radiation is already diffused by the cloud cover.

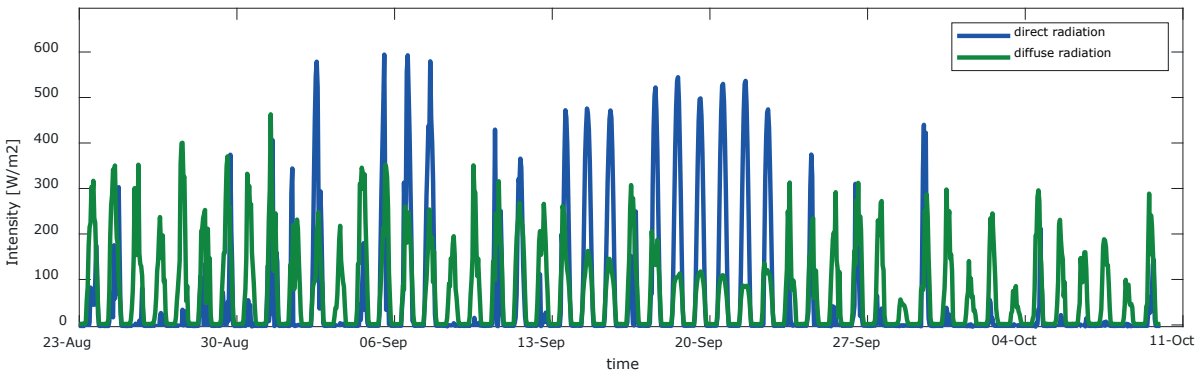

Figure 13 *Direct and diffuse radiation values (W/m²) during the trial.*

During the trial, cloudy days dominated over clear days (Figure 13), that is, conditions in which outside radiation is already highly diffuse, equalizing the light scattering conditions between the different treatments. Only in moments in which direct radiation dominates over diffuse radiation, can the different treatments generate differential levels of scattered light. During the trial, outside diffuse PAR radiation sum was 283 mol/m², whereas the sum of direct PAR radiation was 212 mol/m². The percentage of time in which direct radiation levels were higher than the diffuse radiation levels (dominant clear conditions) was only 14% of the total daytime hours.

3.2 Plant development and growth: destructive harvests

Plant development and growth parameters at the successive plant densities is shown in pictures in Annex 1.

The results of the destructive measurements of the successive harvests (plant length, leaf surface, total fresh weight and total dry weight) are shown in Figure 14 to Figure 17. The histograms show the average of all plants in the two replications (20 plants is total) and are not corrected for the light amount received by each treatment and replication.

A table detailing all mean values per harvest date including the statistical analysis is included in Annex 2.

The differences in plant length between plants from the different treatments are almost negligible. Plant length was measured till the apex in the first three harvests, and till the set of the first truss in the next three destructive harvests (from 21-09).

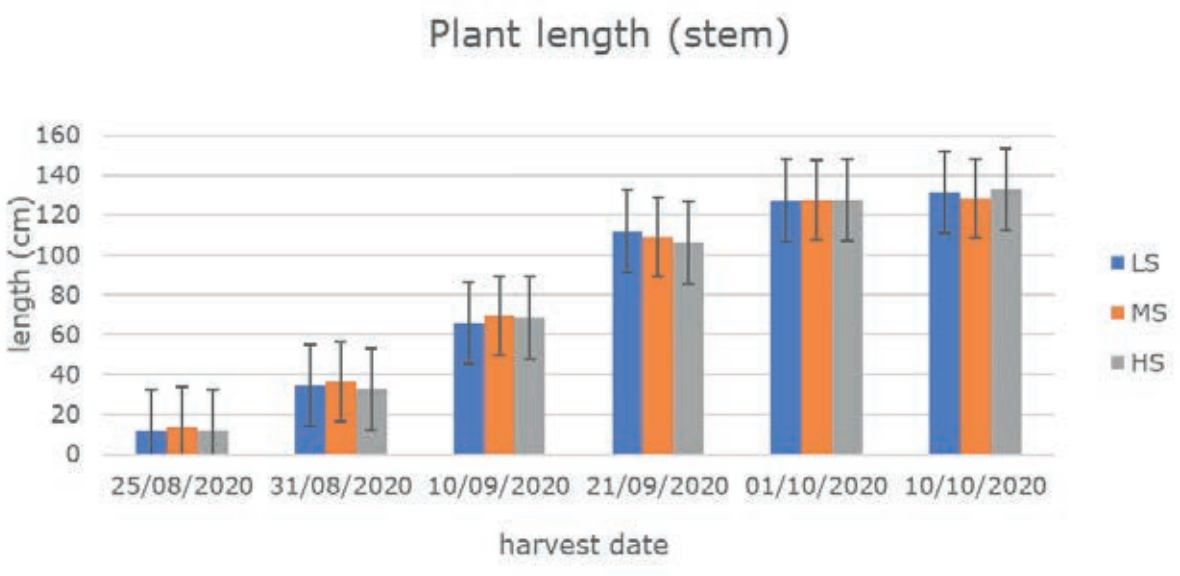

Figure 14 *Average plant length (cm) as measured in the successive destructive harvests for all treatments.*

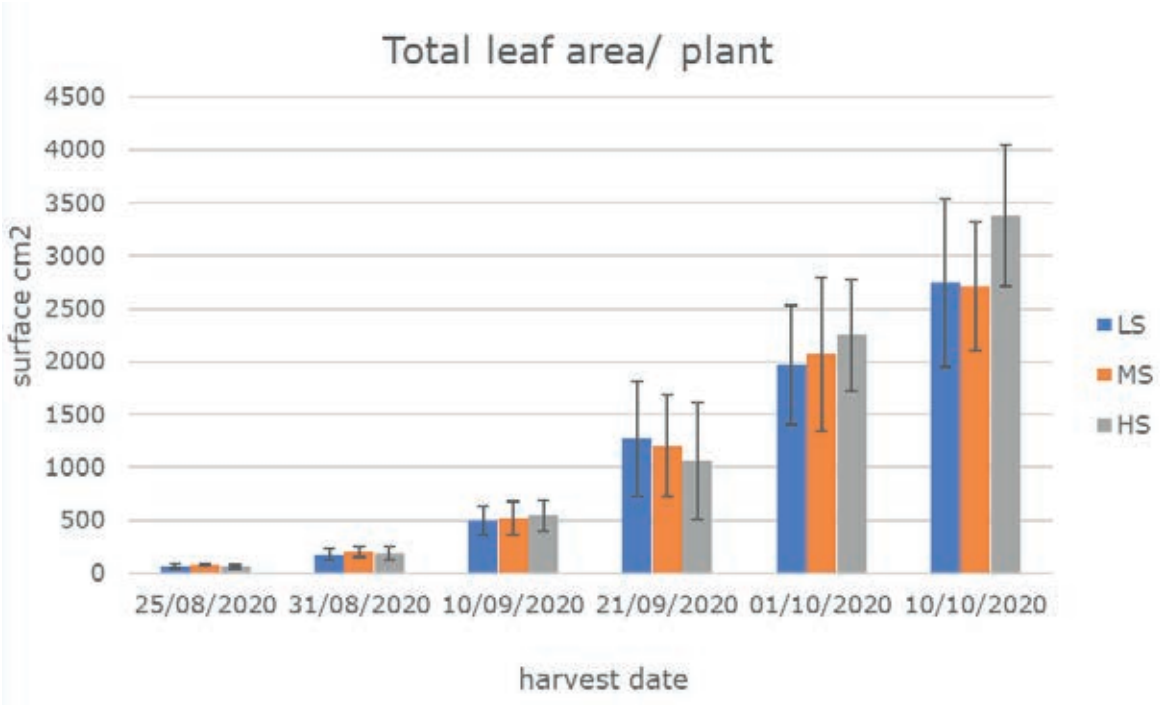

Figure 15 *Average total leaf surface (cm²) of the plants as measured in the successive destructive harvests for all treatments.*

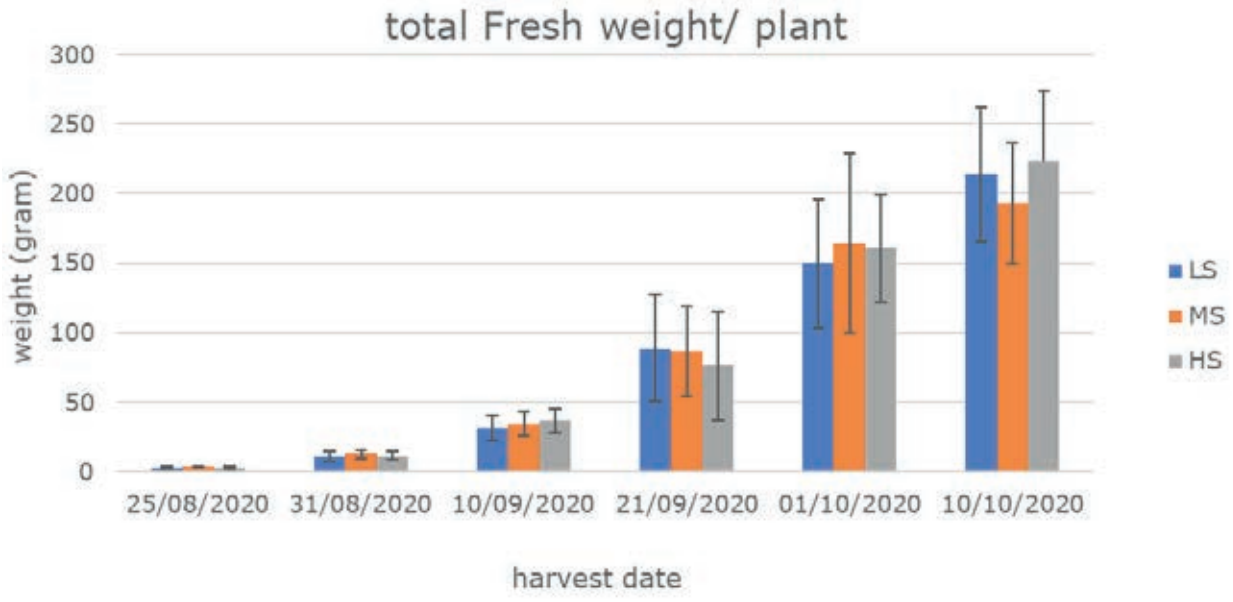

Figure 16 *Average total fresh weight of the plants (g), as measured in the successive destructive harvests for all treatments.*

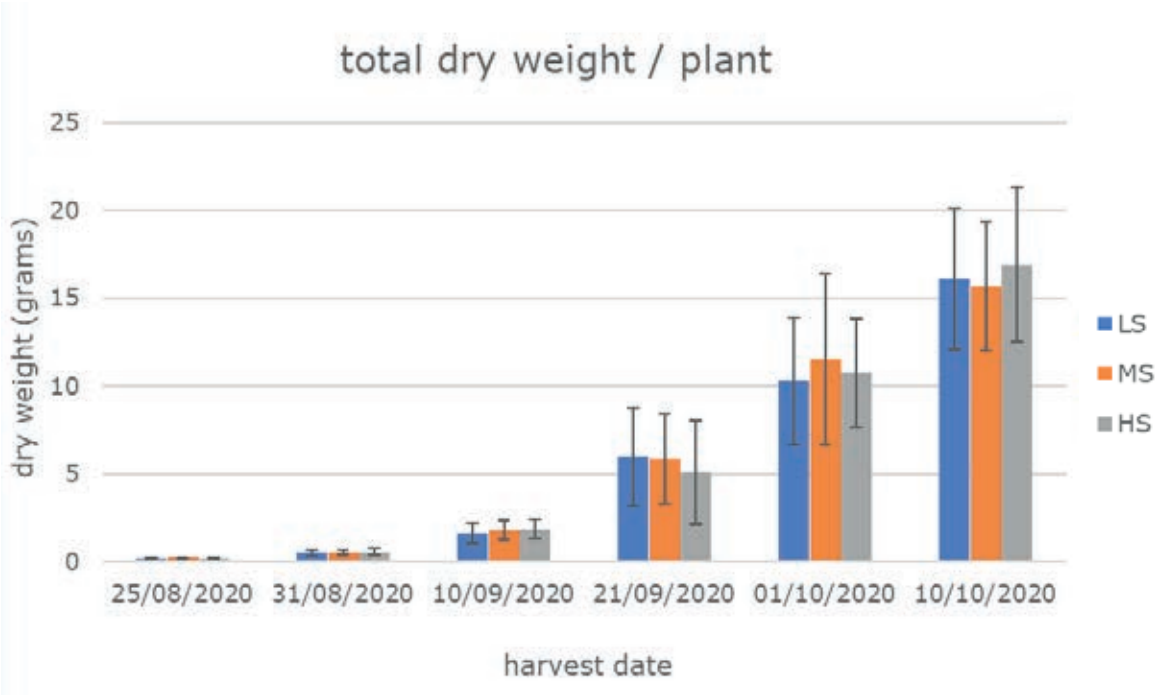

Figure 17 *Average total dry weight of the plants (g), in the successive destructive harvests for all treatments after drying during 48 hours in a ventilated oven at 80°C.*

The leaf surface per plant was very similar for plants of all treatments during the first three harvests before topping the plants. After the topping, the plants in the treatment with direct light (LS in the legend) showed a higher average leaf surface of the plants, but this difference in the treatments is small compared to the plant variability. In the last two harvests, the plants from the high scattering treatment (HS in legend) have a higher leaf surface (8% higher at harvest 1-10, and 25% higher at the end of the experiment) than the plants in both the medium and low scattering (MS and LS in legend). The within treatment differences are still rather big.

The differences in plant weight (fresh and dry) are also small between treatments, but are maximized at the end harvest, with a trend to higher biomass (both fresh and dry matter production) in the plants of the High scattering treatment.

3.3 Interaction plant growth with PAR sum / treatment

3.3.1 Light Use Efficiency

The Light Use Efficiency (expressed as grams – dry matter- produced per m^2 per mol/m^2 PAR light received, unit g/mol) has been calculated for all treatments at the destructive measurement. This value "corrects" the results for the light sum received at each of the moments when plants were measured.
The results are shown in Figure 18. The normalization of the dry matter values per light sum shows a higher LUE for the HS treatment in all the destructive measurements, except for one of the harvests (21/09). The MS treatment has the second largest LUE (as would be expected) for the majority of the determinations, followed by the LS treatment, which showed consistently the lowest LUE for all dates except for the already mentioned measurement on 21/09.

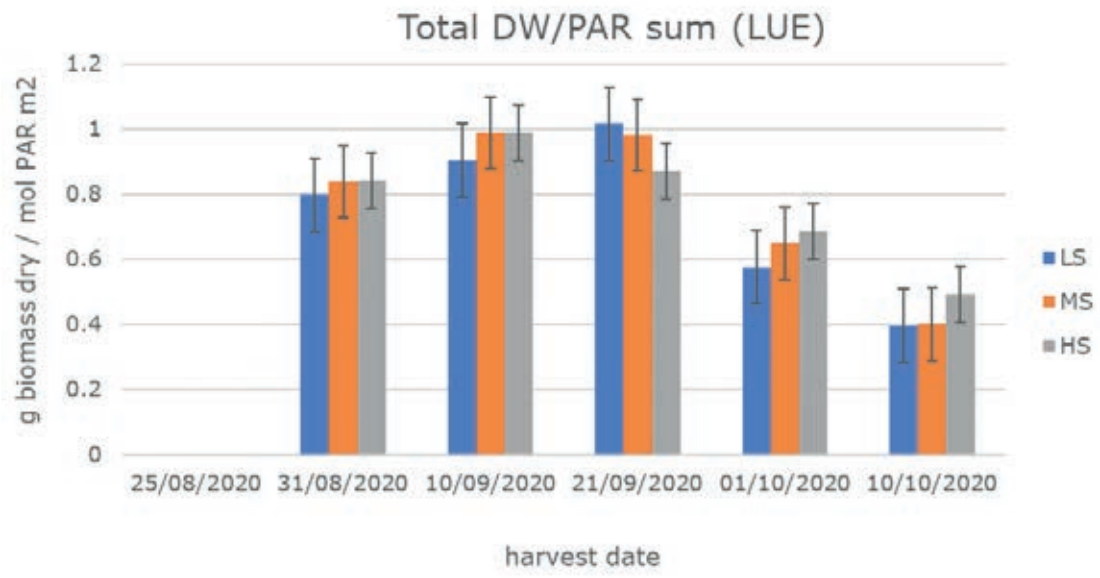

Figure 18 *Light Use Efficiency of the plants in grams dry biomass per mol PAR (g/mol PAR), as calculated for the successive destructive harvests for all treatments.*

3.3.2 Results of the REML variance component analysis

Another way to analyze the results per harvest data in interaction of the treatments with the light sum till harvest for each treatment and repetition is given by the REML variance component analysis.

The results of this analysis show significant differences between the High Scattering treatment (HS) and the other two treatments (LS and MS) for the variables "Total plant fresh weight", "Fresh weight of the stem", "Fresh weight of the leaves", "Total leaf area of the plant" and "Total plant dry weight".

The variables "Plant length", "Number of leaves per plant" and "Dry matter percentage" do not differ significantly between treatments in interaction with the PAR light sum received till harvest (5% level).

The results of the Wald test as well as predictions based on the regression model fitted in REML for some of these variables are shown in Annex 3.

3.4 Light interception

Light interception was measured just before each spacing and at the end. However, we show in this chapter only the results of the last two measurements when plants were more developed and more points could be sampled (Figure 19 and Figure 20). These results illustrate as well the differences in light interception between a sunny and a cloudy day. All the measurements and the conditions in which they were measured, are shown in Annex 4.

For the last light interception measurement, at the end of the trial and just before the measurement, the film roofs and the lamella were removed, so the light probe could measure the reference light above the canopy.

On September 22nd (Figure 19) the light intercepted was consistently higher for the HS treatment at any measured plant height. Values of intercepted light were slightly lower for the MS treatment in the lower half of the plant, and significantly higher that under the LS treatment. Unlike the other measurements, measurements of September 22nd were done under dominant direct light conditions, in which the differences in scattered light and how this affected the amount of it intercepted at each crop level could be observed more clearly than in a cloudy day, when light is already scattered and therefore, the differences between treatments, minimized.

Indeed, to highlight this, in the final measurement (Figure 20), which was performed under dominant diffuse light, the light intercepted by HS in the top 20% length of the crop is higher under HS, but from there to the bottom, slightly more light is intercepted by the MS and LS treatments. On a cloudy day, these differences can be attributed mostly to differences in plant architecture (as we have seen in Figure 15, the plants in the HS treatment had a bigger leaf surface), rather than caused by the scattering.

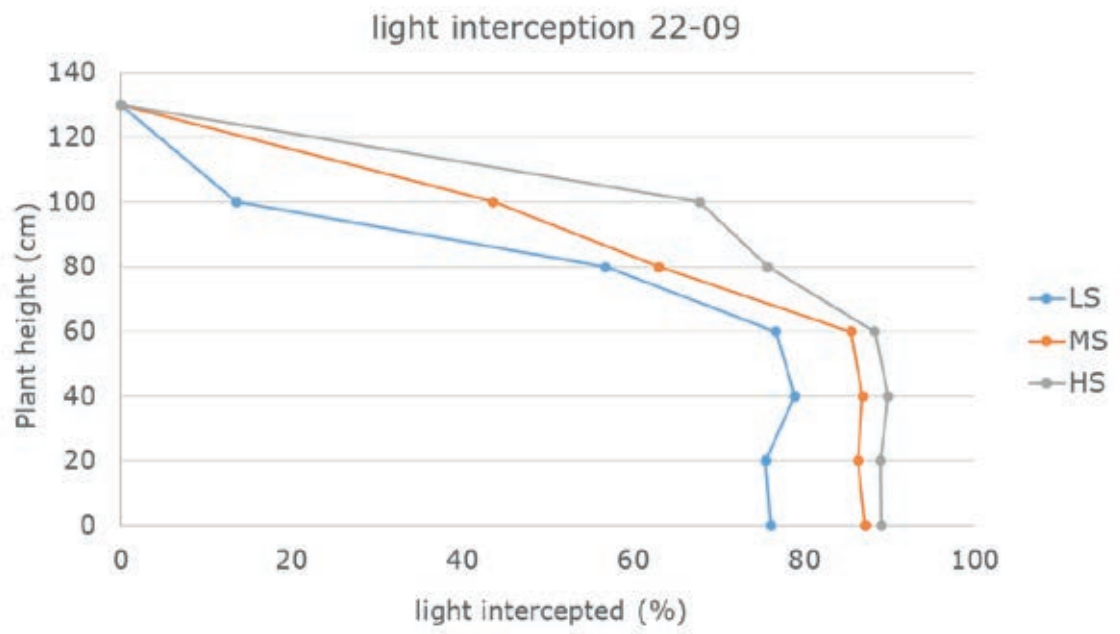

Figure 19 *Light interception measured three days after topping; the plants were at a density of 37.5 plants per m². The length of the plants allowed for measuring at six depth levels. Measurements done under dominant direct light conditions.*

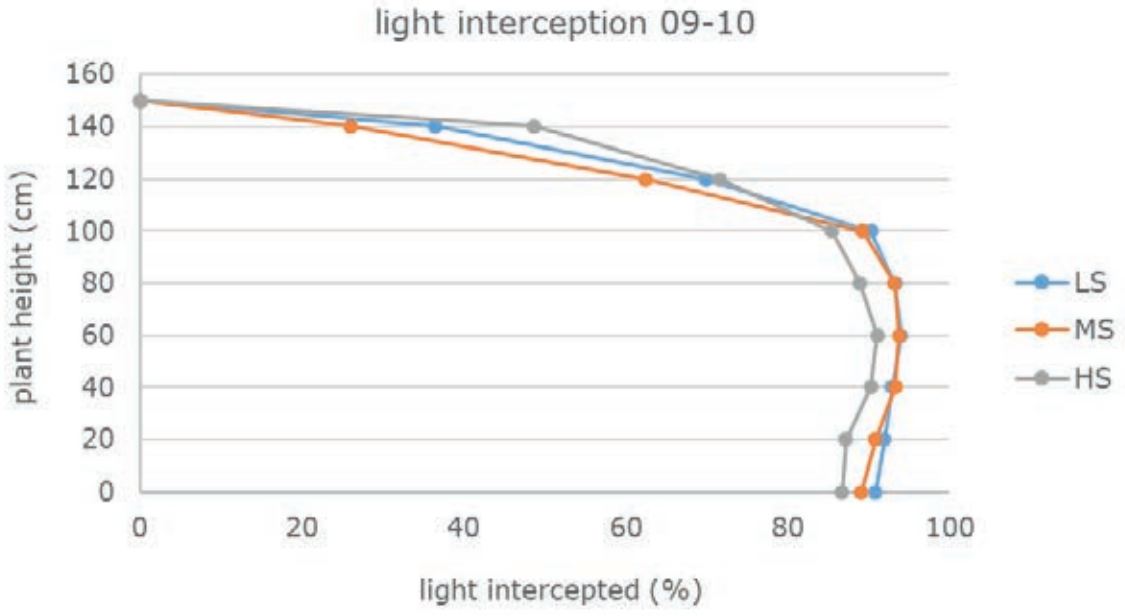

Figure 20 *Light interception at the end of the experiment; the plants were at the final density of 9 plants per m². The length of the plants allowed for measuring at seven depth levels. Measurements done under dominant diffuse light conditions.*

3.5 Photosynthesis

The light response of the photosynthesis as measured with the young plants (only the first fully developed leaf) in September is shown in Figure 21. At the higher light levels, the plants that were kept under direct light (Low Scattering, LS in legend) showed a lower photosynthetic capacity. There was no difference between the photosynthetic capacity of the treatments with diffuse light (medium and high scattering lamellae, MS and HS respectively in the legend).

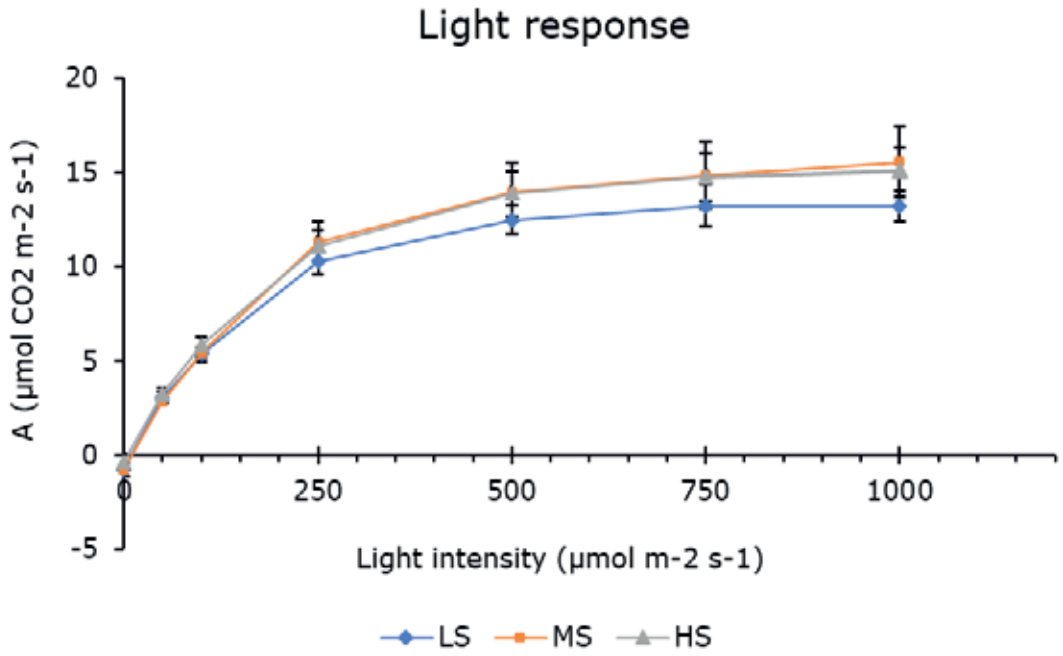

Figure 21 *Light response of the photosynthesis as measured in September (one canopy level, first fully expanded leaf).*

The light response of the photosynthesis was measured again with the flowering plants at the beginning of October, close to the end of the experiment. This time, the size of the plants allowed for a good measurement of two leaves per plant: the first fully developed leaf of each plant below the truss (above it the plants had been topped), and the third leave downwards from the truss.

Already at the low light levels of 250 µmol PAR/m^2 s there was a clear difference in photosynthesis capacity of all treatments, with increasing photosynthetic response for increasing light scattering.

The differences increase with the light level received, and are present at both measured leaves representing two depths in the canopy.

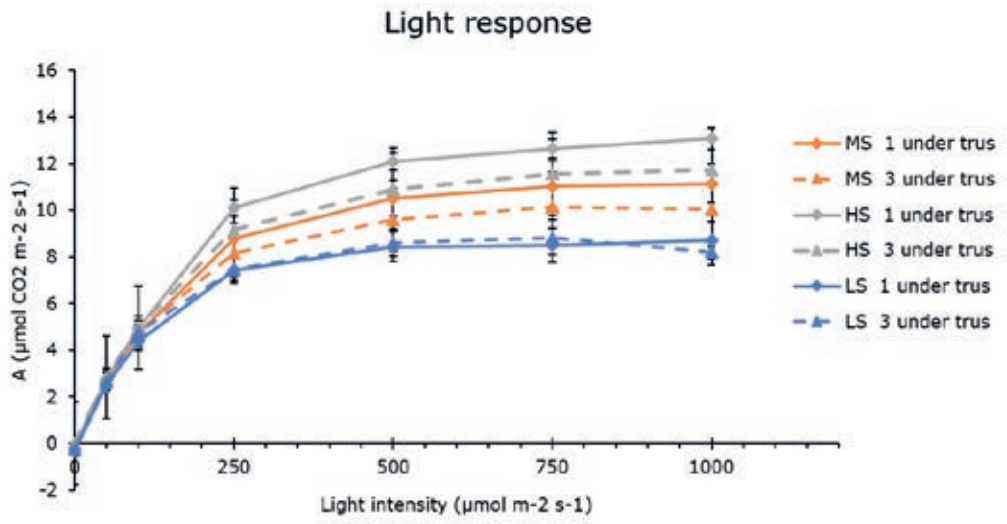

Figure 22 *Light response of the photosynthesis as measured in October (two heights in the canopy: the first fully expanded leaf under the truss, and the third leaf).*

4 Discussion and conclusions

The photosynthesis measurements conducted are doubtless as to the fact that increasing hortiscatter increases the photosynthetic capacity of the plants, even at very high hortiscatter values, 65% and 90%, for which no measurements had been conducted until this research. This effect was stronger for the plants at the end of the experiment than when the plants were very young.

Light interception measurements carried out on a sunny day showed a higher interception of light for the two scattering treatments in the whole canopy depth compared to the clear light treatment. The higher percentage of light interception at each level under the scattering treatments is in agreement with the higher photosynthetic capacities observed in the middle leaves of the crop and with earlier research results found on mature plants (Dueck *et al.* 2012).

Despite the very careful set up, two of the six tables received a significant different amount of PAR than the other four. Sources of difference in PAR light sum are the position of the tables in the greenhouse (selectively shaded by the neighbouring compartments and construction effects) and small transmission differences of the covering materials used (Table 1). The result over time is small accumulated differences in PAR radiation. Which means that PAR sum became a covariant in the analysis of the results.

When analyzing the effects of both Hortiscatter and PAR sum, results showed that the higher light interception in sunny days and the higher photosynthesis capacity of the plants, translate into a higher plant growth rate, so a higher leaf surface and more fresh and dry biomass. Indeed, the plants of the high scattering treatment showed a higher leaf area and higher total biomass (both fresh and dry) than both the plants of the medium and low scattering treatments. They also showed a higher Light Use Efficiency (expressed in g dry weight/mol PAR available).

During the trial it was cloudy during the majority of the time, so direct light sum was smaller than the diffuse light sum (283 mol/m^2 of diffuse light vs 212 mol/m^2 of direct light) with higher instantaneous diffuse light values than direct light values on 83% of the daylight hours. The advantage of increasing levels of scattering should be better observed the higher the amount of direct light, since then more direct light can be transformed into (different amounts of) diffuse light. Such an advantage we observed also in the light interception measurement on a sunny day (Figure 23) and the photosynthetic capacities measured.

The question remains whether a very high hortiscatter will also translate in a higher fruit production, which could not be studied in this experiment but what could be studied when plants are cultivated during a full productive cycle. This indicates the need to do a trial in a larger greenhouse compartment under real plant density conditions, and a longer growing cycle up to mature crop including the summer period, where the advantage of the increasing levels of scattering can be observed better.

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Diffus licht bij tomaat. Rapport GTB-1158, Wageningen UR Greenhouse Horticulture.

Annex 1 The plants during development

Left: Plantlets after transplanting to rockwool cubes at 100 pl/m^2, 17-08-2020.
Middle: on the day of the start measurement, at 100 pl/m^2, 25-08, LAI 0.7.
Right: plants directly after the first spacing to 75 pl/m^2; 1-09, LAI 1.5.

Left: plants to 37.5 pl/m^2, 9-09-2020, LAI 1.7.
Middle: 16-09 1st truss flowering, 18-09 topping.
Right: plants to 18 pl/m^2, 21-09, LAI 1.8.

Plants at the final density of 9 pl/m^2, 9-10-2020 supported with ropes to the frames. LAI 1.8.
Left: Table HS 1.
Middle: Table MS 1.
Right: Table LS 1.

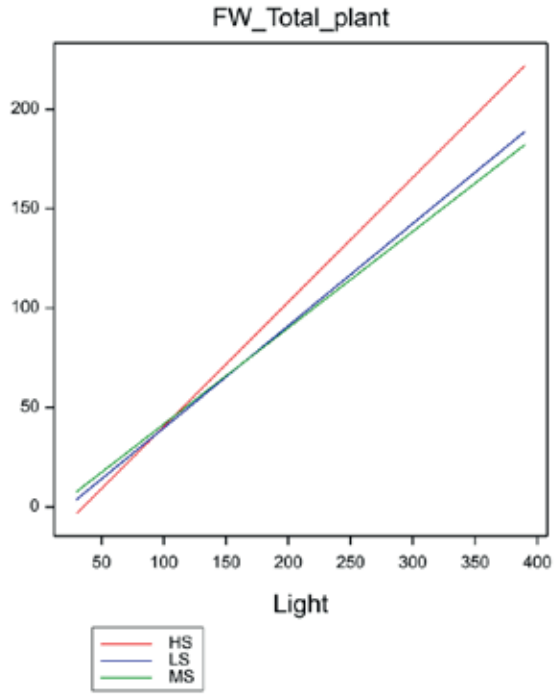
Annex 2 Summary of plant measurements

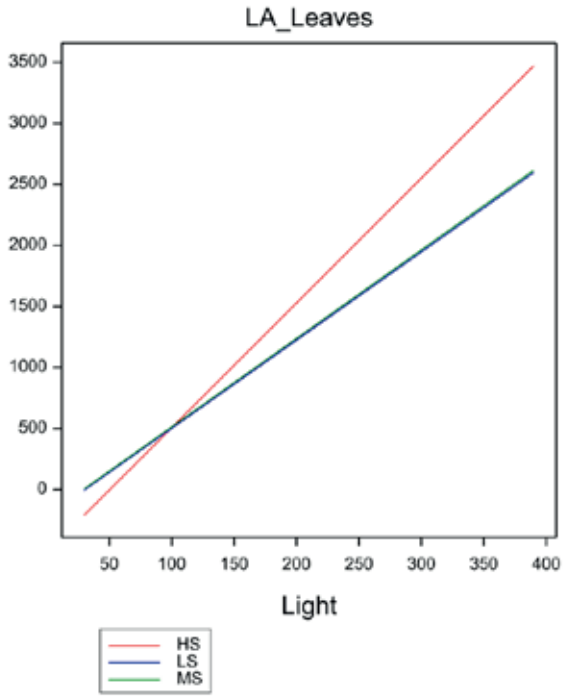
The Table below shows the results of all plant measurements at every destructive harvest. Values are means of 20 plants (10 per replicate). Different letters indicate significant differences (l.s.d. 5% level), one factor ANOVA (not corrected for light sum differences).

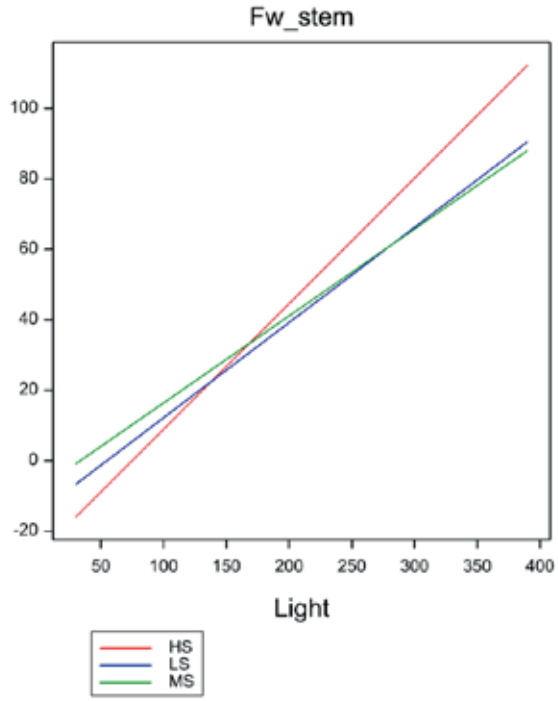
date	treatment	N leaves (#)	Length (cm)	Leaf Area (cm^2)	Fresh weight total (g)	Dry weight total (g)	Dry matter content (%)
31-08	*l.s.d.(5%)*	*0.35*	*2.09*	*35.7*	*2.07*	*0.12*	*0.36*
	LS	7.6 a	34.3 ab	187 a	11.29 a	0.49 a	4.29 ab
	MS	7.7 a	36.4 b	207 a	12.81 a	0.53 a	4.07 a
	HS	7.9 a	32.5 a	196 a	11.58 a	0.53 a	4.51 b
10-09	*l.s.d. (5%)*	*0.76*	*8.0*	*309.2*	*21.5*	*1.66*	*0.46*
	LS	8.6 a	111.9 a	1276 a	89.1 a	5.98 a	6.47 a
	MS	8.3 a	108.6 a	1197 a	86.6 a	5.81 a	6.47 a
	HS	8.1 a	105.8 a	1049 a	75.8 a	5.04 a	6.41 a
21-09	*l.s.d.(5%)*	*0.96*	*7.06*	*377*	*31.4*	*2.43*	*0.33*
	LS	9.5 b	127.5 a	1971 a	149.8 a	10.27 a	6.69 a
	MS	8.3 a	127.7 a	2070 a	164.0 a	11.50 a	6.94 b
	HS	8.9 ab	127.7 a	2248 a	160.9 a	10.76 a	6.59 ab
1-10	*l.s.d. (5%)*	*0.95*	*5.6*	*272.7*	*20.9*	*1.7*	*0.26*
	LS	8.6 a	131 a	2258 a	176 a	12.2 a	6.93 b
	MS	9.4 a	130 a	2204 a	175 a	12.4 a	7.03 b
	HS	8.9 a	129 a	2321 a	167 a	11.2 a	6.65 a
10-10	*l.s.d. (5%)*	*2.83*	*6.9*	*438*	*30.3*	*2.57*	*0.67*
	LS	18.4 a	131.1 a	2737 a	213.6 ab	16.02 a	7.46 a
	MS	17.6 a	128.3 a	2713 a	193.3 a	15.67 a	8.18 b
	HS	20.3 a	132.8 a	3378 b	223.9 b	16.91 a	7.52 a

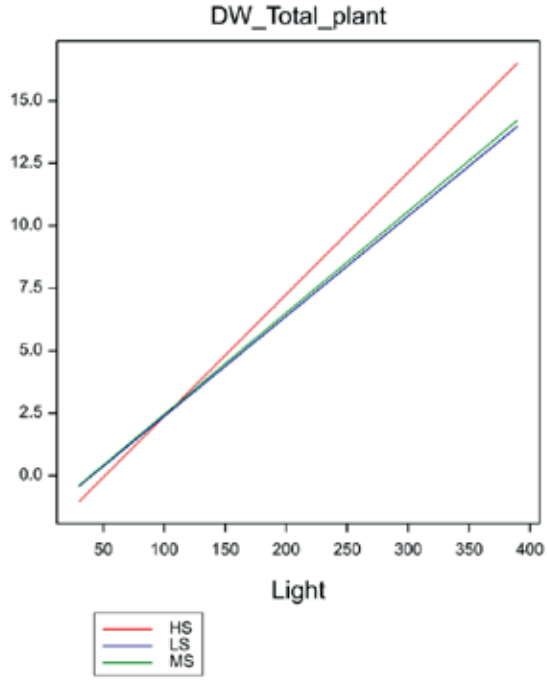
Annex 3 Wald test results and predictions of the regression model

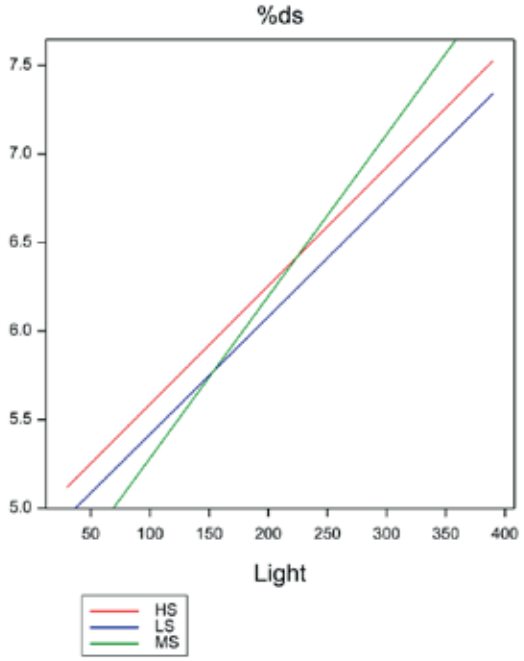
The Figures below show the predicted results (REML) of the plant variables "Total plant fresh weight", "Leaf area of all the leaves", "Fresh weight of the stem", "Total plant dry weight" and "Dry matter percentage" per treatment as function of the PAR sum.











The Table 6 below shows the comparison between treatment means for relevant plant parameters. The significant differences have been bold printed.

Table 6

Comparison between treatment means, Fisher's unprotected least significant difference test.

treatment	N leaves (#)	Length (cm)	Leaf Area (cm^2)	Fresh weight total (g)	Fresh weight leaves (g)	Fresh weight stem (g)	Dry weight total (g)	Dry matter content (%)
LS	10.05 a	81.24 a	1217 a	90.57 a	57.03 ab	54.17 a	6.338 a	6.074 a
MS	9 .92 a	81.79 a	1229 a	89.55 a	53.72 a	54.77 a	6.466 a	6.186 a
HS	10.77 a	81.50 a	**1518 b**	**102.40 b**	60.23 b	**64.33 b**	**7.198 b**	6.248 a

Annex 4 Light interception measurements, all data

The results of these successive measurements are shown in Figure 23 to Figure 26, as well as the distribution of diffuse and direct natural light at the day of the measurements. The arrow indicates the time of the measurement.

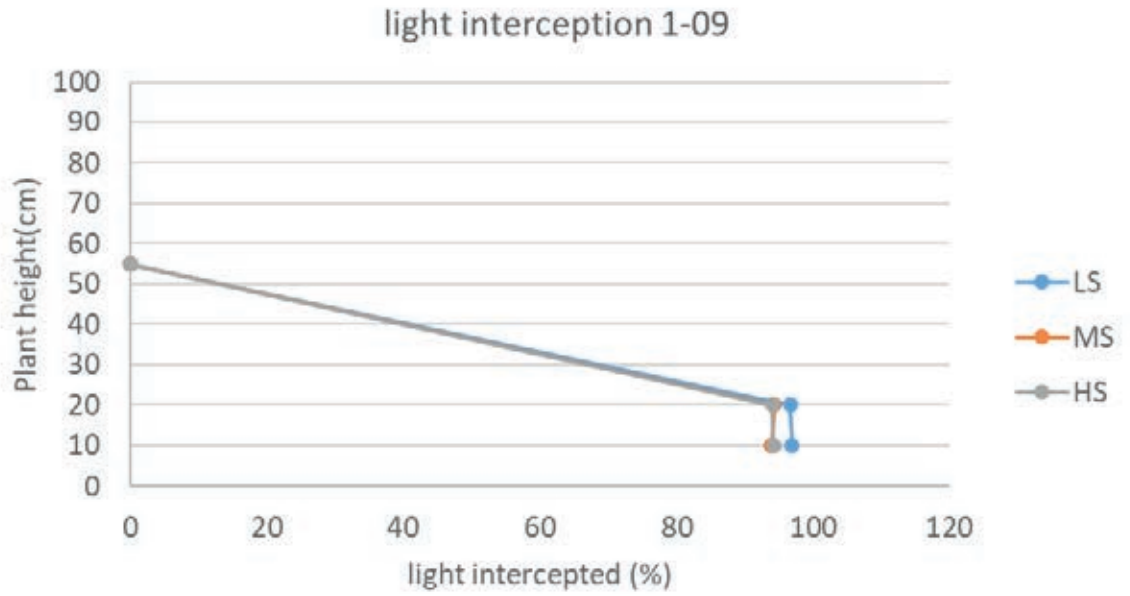
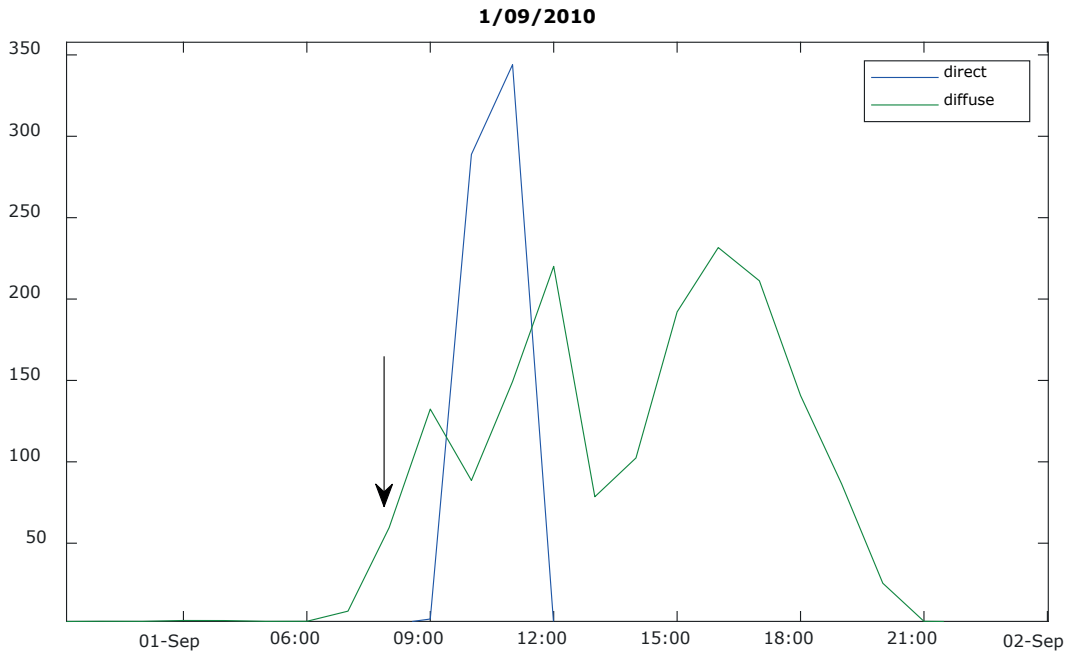


Figure 23 *Light interception measured two weeks after transplanting; the plants were at a maximum density of 100 plants per m². Because the plants were small, only two canopy depths were measured: top (reference), middle of the canopy, and on top of the rockwool block. Measured under diffuse light conditions (Figure below).*



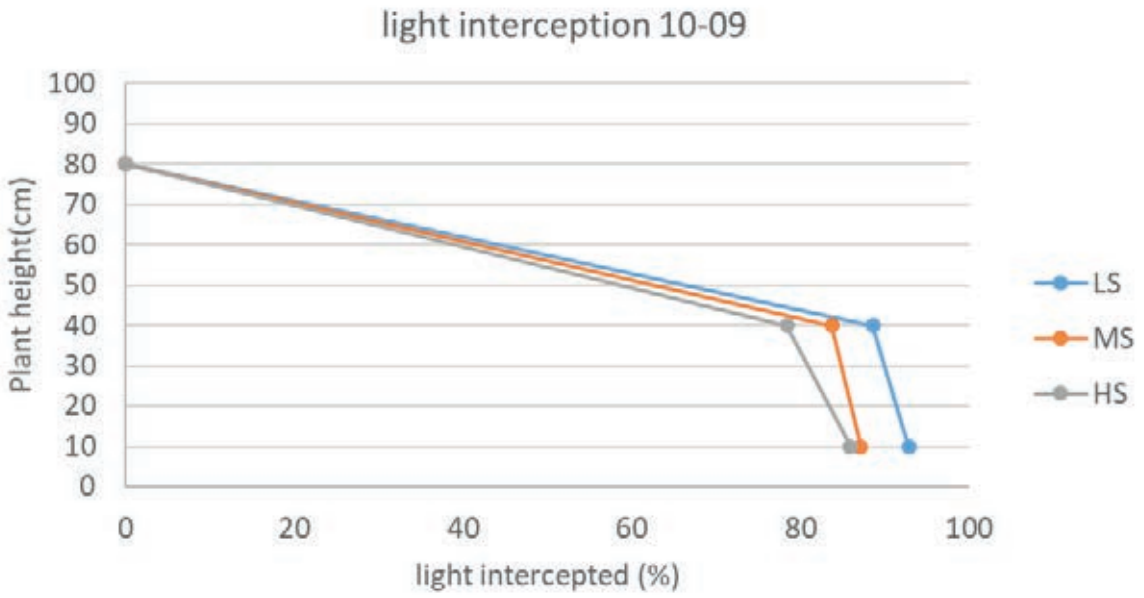
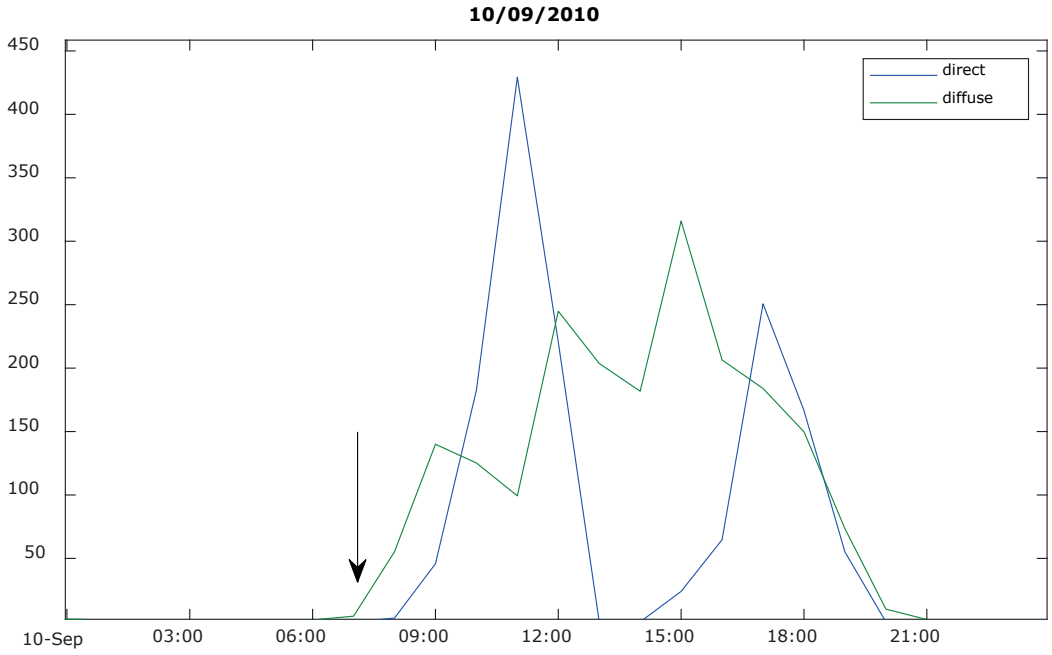


Figure 24 *Light interception measured two weeks after planting; the plants were at a density of 75 plants per m². Two canopy depths were measured: top (reference), middle of the canopy, and on top of the rockwool block. Measured under diffuse light conditions (Figure below).*



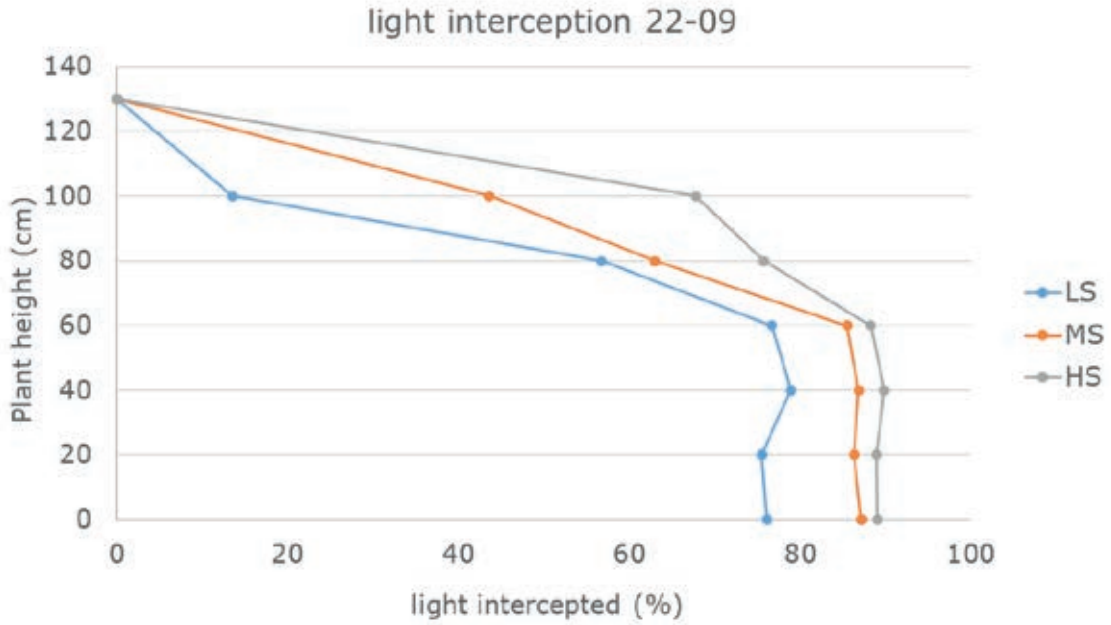
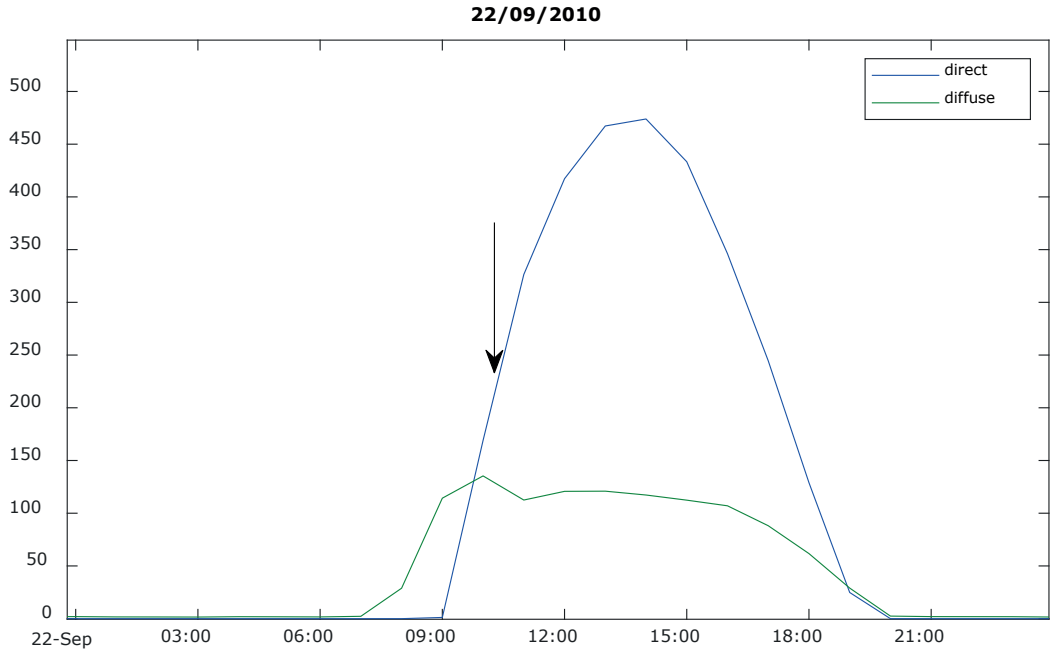


Figure 25 *Light interception measured three days after topping; the plants were at a density of 37.5 plants per m². The length of the plants allowed for measuring at six depth levels. Measured under direct light conditions (Figure below).*



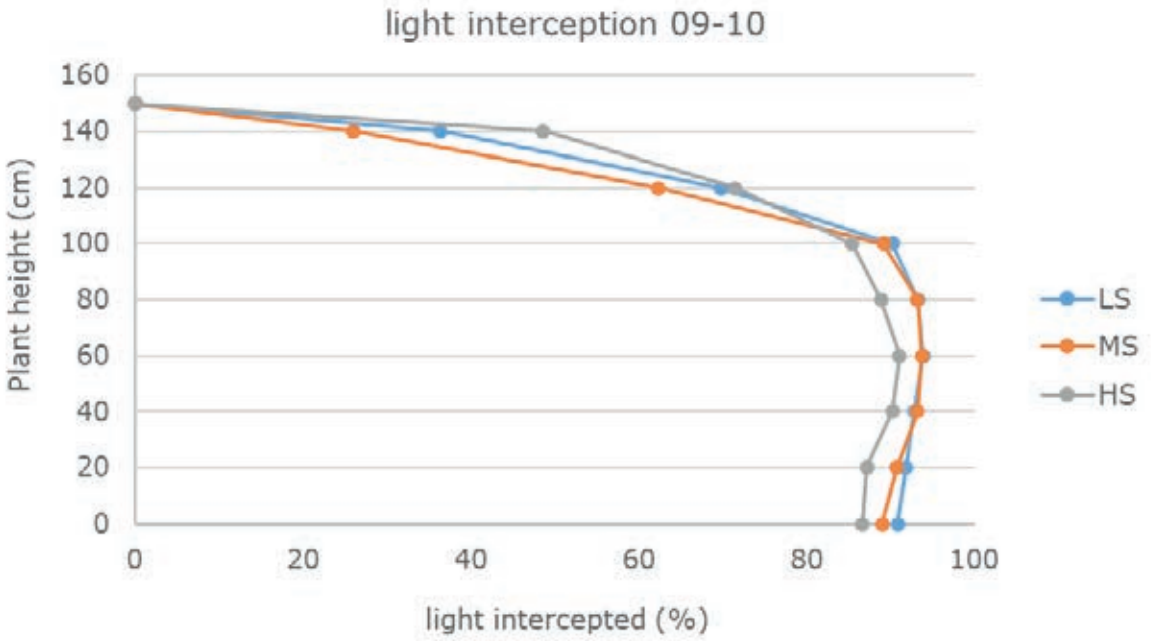
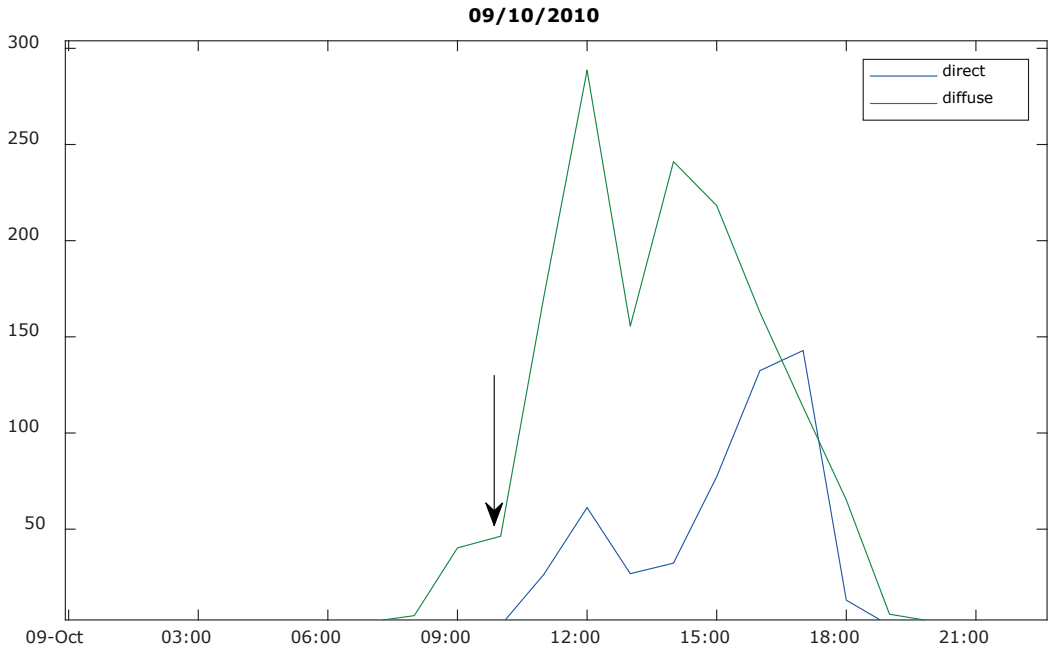


Figure 26 *Light interception at the end of the experiment; the plants were at the final density of 9 plants per m². The length of the plants allowed for measuring at seven depth levels. Measured under diffuse light conditions (Figure below).*



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