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Effect of shading on photosynthesis of greenhouse hydroponic cucumber crops

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Abstract. In this work an attempt was made to investigate the effect of shading on photosynthesis rate, transpiration rate and stomatal conductance of a cucumber cultivation in a greenhouse. To this end, autumnal hydroponic cultivation of cucumbers was installed in three same arched greenhouses with lateral ventilation openings at the University of Thessaly experimental farm in Velestino, Greece. One of the greenhouses was used as a control (without shading), the other two were shaded using two different shading nets (shading intensity of 35% and 50%). In the hydroponic cucumber cultivation, a series of crop photosynthesis measurements were performed for two months on leaves of randomly selected plants per greenhouse under natural illumination and using artificial illumination conditions of 1000 μmol m^{-2} s^{-1} with the LCpro+ instrument. Statistical processing of the results showed that shading reduced photosynthesis of the cucumber leaf almost linearly. Furthermore, artificial illumination measurements allowed us to conclude that shaded plants do not acclimate to shade conditions and respond directly to lighting conditions which practically enhances the usefulness of periodic shading as a tool for improving the microclimate in greenhouses.

Keywords. Photosynthesis, greenhouse, shading, hydroponic crops, cucumber.

INTRODUCTION

Various methods can be used to cool the greenhouse. The use of nets or screens is a typical practice in the whole Mediterranean basin. It is considered a low-cost method of decreasing radiation and the concomitant energy load during warm periods (Kitta, 2014). Mobile shading allows improvement of greenhouse climate, especially during the noon hour. It reduces canopy transpiration and water uptake, and increases remarkably water use efficiency (Lorenzo *et al*., 2006). The use of shading screens in greenhouses became a common practice during the last decade (Cohen *et al*., 2005; Castellano *et al*., 2008) because it is a flexible and efficient method of reducing the energy load inside the greenhouse (Teitel and Segal, 1995), especially in climates characterized by high evaporative demand and limited water resources (Lorenzo *et al*., 2006). The optical properties of the screens (mainly shade factor) can modify the diffuse-to direct radiation ratio (Baille *et al*., 2001; Raveh *et al*., 2003; Cohen *et al*., 2005) and cooling performance (Willits, 2001), while reducing air and crop temperature (Smith *et al*., 1984; Fernandez-Rodriguez *et al*., 2000). The modifications arising from the optical properties of the screens can affect radiation absorbed by the crop, stomatal conductance, and net CO_2 assimilation, and consequently crop growth and productivity. Nevertheless, adaptation of plants to light conditions depends also on the specific behavior of the plant species grown in greenhouses (Raveh *et al*., 2003; Barradas *et al*., 2005; Romacho *et al*., 2006). Shade can increase total and marketable yield of tomato grown in hot climates. Depression of crop yield is frequently observed under Mediterranean conditions when high solar radiation and low air humidity conditions prevail. El-Gizawy *et al.* (1993) mention that the highest tomato crop production was obtained under 35% shading, while increasing shading intensity decreased by up to 100% the incidence of sunscald on fruit. Concerning the effect of shading on cucumber crop, Naraghi and Lofti (2010) observed that increasing shading density up to 35% led to an increase in the number of fruits per plant. However, the number of fruits tended to decrease as shading density increased to 60%. Furthermore, the above authors mention that shading intensity greatly influenced the physiological disorders like sun-scald of cucumber fruits.

A better understanding of plant responses to shading is of great interest for greenhouse crops. With respect to the Mediterranean greenhouses, more information is needed mainly on plant responses to the time of application, including both commencement and termination of shading dates. So, an important issue not yet fully investigated in shaded greenhouses concerns plant acclimation to the light regime imposed by the screen.

Therefore, in this paper we are trying to investigate the effect of shading on photosynthesis rate and plant acclimation of a hydroponic cucumber crop, which is of great economic interest for the Mediterranean countries.

MATERIAL AND METHODS

Greenhouses and plant material

The experiments have been performed in three similar arched roof greenhouses, with vertical side walls, covered with a single sheet of 180 μm thick PE film, N-S oriented, located at the University of Thessaly near Volos, (Velestino: Latitude 39º 22′, longitude 22º 44′, altitude 85 m), Eastern Greece. The geometrical characteristics of the greenhouses were as follows: eaves height of 2.4 m; ridge height of 4.1 m; total width of 8 m; total length of 20 m; ground area of 160 m^2, and volume of 572 m^3. The soil of each greenhouse was totally covered by double-side coloured plastic mulch. The greenhouses were equipped with two side roll-up vents controlled automatically and ventilation set point temperature was set at 23ºC. An autumn hydroponic cultivation of cucumber (*Cucumis sativus cv. Stamina*) was planted, which was transplanted on September 1 and expired on November 12. The plants were grown in slabs (1 m long, 0.3 m wide) filled with perlite sacks (1 m long, 0.3 m wide, 0.2 m high) and planting density was 2.4 plants / m^2.

Plants were arranged in four duplicate rows, spaced between the lines 0.33 m and 0.80 m apart. . The supply of a standard nutrition solution for cucumber (Sonneveld, 2002) was automatically controlled by a fertigation computer and pH set point was at 5.6 with small fluctuations aimed to maintain the pH between 5.5 and 6.5 in the drainage solution. The plants were pruned according to the umbrella training system (Klieber et al., 1993) and all other cultural practices inside the greenhouse (plant protection, harvesting, etc.) were similar to those practiced commonly by local greenhouse cucumber producers.

Three levels of greenhouse shading were tested in the greenhouses, obtained using no net in one of the greenhouses and shade nets made by polypropylene strips (C. Vellis S.A., Piraeus, Greece) differing in hole size. The fixed nets were installed over the external surface of the cover in the two shaded greenhouse. In particular, the three shading treatments were as follows:

- 0% shading ($Gr_{o\%}$), greenhouse transmission to solar radiation approximately 79%).

- 35% shading ($Gr_{35\%}$) (net hole size 2X 8 mm), greenhouse with 35% shading intensity (SI) and transmission to solar radiation of approximately 50% and
- 50% shading ($Gr_{50\%}$) (net hole size 2 X 8 mm), greenhouse with 50% shading intensity (SI) and transmission to solar radiation of approximately 38%.
- The values of greenhouse transmission to solar radiation are the mean values calculated using the ratio of inside to outside solar radiation during the experimental period.

Shading was installed immediately after transplanting and maintained up to the end of the experiment.

Measurements

Climate measurements

For the purpose of the experiment total solar radiation (W/m^2) was recorded by means of pyranometers (model Middleton EP08-E, Brunswick Victoria, Australia), located 2 m above the ground in the center of each of the three greenhouses (Control greenhouse $Gr_{0\%}$, 35% shaded greenhouse $Gr_{35\%}$, and 50% shaded greenhouse $Gr_{50\%}$) and outside (Out) 15 m away from the greenhouse on a mast 3.5 m above the ground.

Photosynthesis Parameters Measurements

For the photosynthesis measurements in the experiment, a closed type LCpro+ photosynthesis system (model LCpro+, ADC BioScientific Ltd., Hertfordshire, England) was used, and the photosynthesis rate (A, $\mu mol.m^{-2}.s^{-1}$), transpiration rate (E, $mmol.m^{-2}.s^{-1}$) and stomatal conductance (gc, $mol.m^{-2}.s^{-1}$) were measured. The photosynthesis measurements were done for two months, October and November. For photosynthesis measurements, 16 plants/greenhouse were randomly selected. The photosynthesis measurements were carried out approximately every 10 days on a random healthy, well-developed leaf that was about the middle of the total plant height each time. A total of 48 photosynthesis measurements were made every ten days. Two sets of measurements were made. The first series was in sunny days under natural light conditions inside the greenhouses. The second one was made over cloudy days, with artificial constant illumination conditions to evaluate whether cultures in different shading conditions (control, 35% shading and 50% shading) were adapted (acclimated) and reacted differently or not. Constant irradiation measurements, were performed with the use of the integrated PAR control and adjustment mechanism using LED diodes provided by the LCpro+ measuring device. The illumination intensity was set at the intensity level of 1000 $\mu mol.m^{-2}.s^{-1}$ for both the control greenhouse and the two shaded greenhouses in the PAR area.

Six (6) complete sets of measurements were made during the experiment, four (4) in sunshine conditions and two (2) in cloudy conditions.

Calculation of Vapor pressure deficit

Furthermore, Vapor Pressure Deficit (VPD_C) in the leaf chamber air of the LCpro+ device can be calculated from (Allen et al., 2005):

$$VPD_C = e_{sat,c} - e_{ref} \quad (1)$$

Where:

VPD_C = Vapor Pressure Deficit in leaf chamber, kPa

$e_{sat,c}$ = saturation vapor pressure in air temperature, kPa

e_{ref} = partial pressure of the water vapor in the air in leaf chamber, kPa

$e_{sat,c}$ and e_{ref} can be calculated from the following relations (Howell and Dusek, 1995):

$$e_{sat,c} = 0.611 * e^{\frac{(17,27*T_{a,c})}{((T_{a,c}+73)-36)}} \quad (2)$$

$$e_{ref} = \frac{RH}{100} * e_{sat,c} \quad (3)$$

where: $T_{a,c}$= air temperature in the leaf chamber (°C) and RH= relative humidity of the air in the leaf chamber.

Collection, storage and processing of measurements

Solar radiation measurements were collected on four (4) data loggers (ZEN0®3200, Coastal Environmental Systems, Inc., Seattle, Wash.) Measurements were taken every 30 s and averaged 10 min.

With regard to photosynthesis, transpiration and stomatal conductance measurements, the closed type LCpro+ photosynthesis measurement system had its own recording and storage system.

Descriptive and inferential statistics were performed with SPSS 25.0. One way ANOVA was used for comparisons, along with Fisher's Least Significant Difference (LSD) test for post-hoc analysis. Level of statistical significance was set at p=0.05.

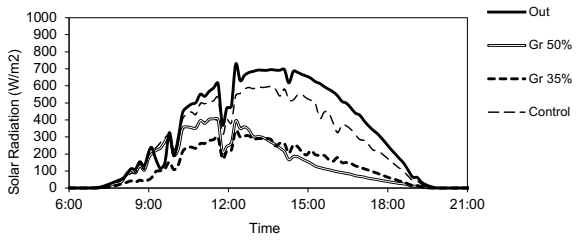

Fig 1. Daily sunlight outside the greenhouses, in the control greenhouse ($Gr_{0\%}$), in the 35% shaded greenhouse ($Gr_{35\%}$) and in the 50% shaded greenhouse ($Gr_{50\%}$), on 19 September.

RESULTS

Solar radiation measurements

Fig. 1 shows the daily course on 19th September of the incident and incoming solar radiation in the three greenhouses. The mean values of solar radiation are 275 W.m^{-2}, 231 W.m^{-2}, 129 W.m^{-2} and 111 W.m^{-2} for the external environment, the control greenhouse, the 35% greenhouse and the 50% greenhouse respectively. Similar results were found throughout the experiment.

Photosynthesis parameters measurements

As already described, photosynthesis rate (A), transpiration rate (E) and stomatal conductance (g_c) measurements concerned leaf measurements of plants exposed to different shading conditions.

Measurements in natural solar radiation conditions

Processing of measurements made during September- November in natural conditions, gave the following results.

Tab. 1. Results of Analysis of Variance (ANOVA) for Photosynthesis Rate A measurements in $Gr_{0\%}$, $Gr_{35\%}$ and $Gr_{50\%}$ during September-November.

Greenhouse	Mean μmol.m^{-2}.s^{-1}	SD μmol.m^{-2}.s^{-1}	F	p
Control	14.50	3.76		
Shading 35%	11.74	4.06	12.54	0.000
Shading 50%	9.51	2.87		

SD= Standard Deviation.

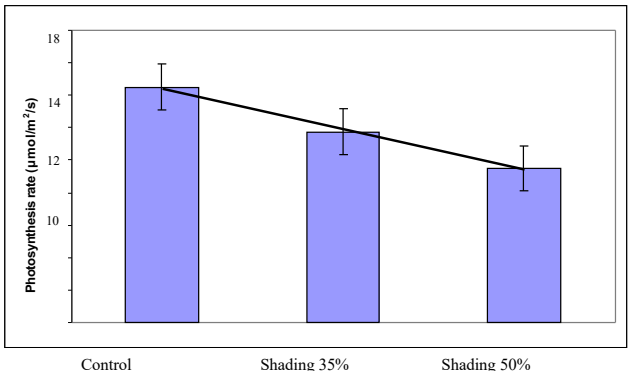

Fig 2. Mean values of Leaf Photosynthesis Rate in greenhouses $Gr_{0\%}$, $Gr_{35\%}$ and $Gr_{50\%}$.

Effect of shading on photosynthesis rate

One- way ANOVA results for the photosynthesis rate A in greenhouses appear in Table 1. From this Table is concluded that photosynthesis rate A differ statistically between the 3 greenhouses.

Fig. 2 shows, also, the descriptive statistics of photosynthesis rate A for the three greenhouses. It can be seen from this Figure that photosynthesis rate decreases as shading intensity increases.

Furthermore, Post Hoc analysis with LSD test for the dependent variable A, showed that the three greenhouses differ statistically from each other, for a significance level of 0.05, with the control greenhouse having the highest photosynthesis rate and the greenhouse with the highest 50% shading having the least photosynthesis (Table 2).

Effect of shading on leaf transpiration rate

Table 3 shows the results of ANOVA analysis of the leaf transpiration rate E in greenhouses.

Tab. 2. Results of multiple comparisons for the depended variable Photosynthesis Rate A in $Gr_{0\%}$, $Gr_{35\%}$ and $Gr_{50\%}$ according to Least Significant Difference (LSD) test for significant level 0.05 for measurements during September- November period

	Greenhouse (I)	Greenhouse (II)	Mean Difference (I-II)	p
LSD	Control	Shading 35%	2.75	0.007
		Shading 50%	4.98	0.000
	Shading 35%	Control	-2.75	0.007
		Shading 50%	2.23	0.028
	Shading 50%	Control	-4.98	0.000
		Shading 35%	-2.23	0.028

Tab. 3. Results of Analysis of Variance (ANOVA) for Transpiration Rate E measurements in $Gr_{0\%}$, $Gr_{35\%}$ and $Gr_{50\%}$ during September-November.

Greenhouse	Mean mmol.m^{-2}.s^{-1}	SD mmol.m^{-2}.s^{-1}	F	p
Control	6.29	1.74		
Shading 35%	4.64	1.55	8.29	0.001
Shading 50%	5.12	1.05		

SD= Standard Deviation.

Tab. 4. Results of multiple comparisons for the depended variable Transpiration Rate E in $Gr_{0\%}$, $Gr_{35\%}$ and $Gr_{50\%}$ according to Least Significant Difference (LSD) test for significant level 0.05 for measurements during September- November period.

	Greenhouse (I)	Grenhouse (II)	Mean Difference (I-II)	p
LSD	Control	Shading 35%	1.65	0.000
		Shading 50%	1.17	0.006
	Shading 35%	Control	-1.65	0.000
		Shading 50%	-0.48	0.253
	Shading 50%	Control	-1.17	0.006
		Shading 35%	0.48	0.253

Tab. 5. Results of Analysis of Variance (ANOVA) for Vapor Pressure Deficit, VPDc in the leaf chamber at the three greenhouses $Gr_{0\%}$, $Gr_{35\%}$ and $Gr_{50\%}$ during September-November.

Greenhouse	Mean mol.m^{-2}.s^{-1}	SD mol.m^{-2}.s^{-1}	F	p
Control	3.32	0.46		
Shading 35%	2.73	0.85	6.39	0.003
Shading 50%	3.19	0.48		

SD= Standard Deviation.

Tab. 6. Results of multiple comparisons for the depended variable Vapor Pressure Deficit, VPDc in the leaf chamber at $Gr_{0\%}$, $Gr_{35\%}$ and $Gr_{50\%}$ according to Least Significant Difference (LSD) test for significant level 0.05 for measurements during September- November period.

	Greenhouse (I)	Grenhouse (II)	Mean Difference (I-II)	p
LSD	Control	Shading 35%	0.59	0.001
		Shading 50%	0,13	0.462
	Shading 35%	Control	-0.59	0.001
		Shading 50%	-0.46	0.006
	Shading 50%	Control	-0.13	0.462
		Shading 35%	0.46	0.006

It can be seen that there are statistically significant differences between the E averages. Post Hoc analysis with LSD test (Table 4) found that the unshaded greenhouse had a statistically greater transpiration rate than shaded greenhouses.

For no statistical differences in transpiration E between 35% and 50% shading greenhouses it should be considered whether there were differences in the air saturation deficit in the leaf chamber between 35% and 50% greenhouses.

Calculating from the experimental measurements data, vapor pressure deficit (VPDc) in the leaf chamber according to the previous equations (1), (2) and (3), we performed an ANOVA analysis for the dependent variable VPDc to determine if there were differences in the three greenhouses. The results are presented in the following Tables 5 and 6.

Vapor pressure deficit appears to be lower in the greenhouse with 35% shading than the 50% shaded greenhouse and the control. Given that cucumber leaves were in good condition, out of stress, the greater vapor pressure deficit in the leaf chamber under the 50% shaded greenhouse chamber probably explains the higher transpiration values in this greenhouse in relation to the corresponding transpiration values in the 35% shaded greenhouse, despite the greater intensity of the incoming radiation load in this greenhouse.

Effect of shading on leaf stomatal conductance

Concerning the values of stomatal conductance g_c for the three greenhouses, it was found that the mean g_c values of the hydroponic cucumber leaves were almost similar for the three greenhouses and there are no statistically significant differences between the greenhouses (Table 7).

Measurements in artificial lighting conditions. Effect of shading on photosynthesis rate

The purpose of these measurements was to investigate how plants in the three greenhouses exposed to

Tab. 7. Results of Analysis of Variance (ANOVA) for leaf Stomatal Conductance g_c measurements in $Gr_{0\%}$, $Gr_{35\%}$ and $Gr_{50\%}$ during September-November.

Greenhouse	Mean mol.m^{-2}.s^{-1}	SD mol.m^{-2}.s^{-1}	F	p
Control	0.97	0.46	0.51	0.950
Shading 35%	1.04	0.82		
Shading 50%	0.98	1.02		

SD= Standard Deviation.

Tab. 8. Results of Analysis of Variance (ANOVA) for photosynthesis rate A measurements under constant illumination conditions in $Gr_{0\%}$, $Gr_{35\%}$ and $Gr_{50\%}$ during September-November.

Greenhouse	Mean μmol.m^{-2}.s^{-1}	SD μmol.m^{-2}.s^{-1}	F	p
Control	11.58	4.29	1.43	0.245
Shading 35%	12.09	2.81		
Shading 50%	10.58	2.79		

SD= Standard Deviation.

different shading conditions responded to the same incident light intensity of 1000 μmol.m^{-2}.s^{-1}. That is, whether they were adapted or not to shading conditions.

The following Table 8 shows the ANOVA results for photosynthesis rate A with constant illumination in the three greenhouses.

From this Table it appears that no statistical differences exist for photosynthesis rate between the three greenhouses. So, under constant illumination conditions of 1000 μmol m^{-2} s^{-1} the photosynthesis of cucumber leaves grown on a perlite substrate is not affected by shading for a significance level of 0.05.

DISCUSSION

Photosynthesis rate

The value of the photosynthesis rate in the control greenhouse (Table 1) is almost the same as this found by Mavrogiannopoulos et al. (1999) for melon cultivation in a greenhouse in Heraklion, Crete, Greece and by Lykoskoufis et al. (2005) on hydroponic greenhouse pepper cultivation in Athens area. The results of the experiments on the effect of shading on photosynthesis rate showed that shading affects almost linearly the photosynthesis of cucumber leaves (Figure 1). Thus from A = 14.5 μmol m^{-2}s^{-1} in the control greenhouse it fell to A = 11.7 μmol.m^{-2}.s^{-1} in the 35% shading greenhouse and to A = 9.5 μmol.m^{-2}.s^{-1} in the 50% shading greenhouse It, therefore, appears that 35% shading reduces the rate of photosynthesis by 20% and 50% shading reduces it by 34%. Thus the ratio of photosynthesis-shading is almost linear, which allows us to conclude that a 10% increase in shading induces a decrease in the rate of photosynthesis by 0.80 μmol.m^{-2}.s^{-1}. Similar results were also found by Schwartz et al. (2002) when they made photosynthesis measurements in a hydroponic tomato culture in a growth chamber at the University of Georgia, USA, and found that a reduction in radiation level of 35% resulted in a decrease in leaf photosynthesis by 0.84 μmol.m^{-2}.s^{-1}.

Furthermore, although photosynthesis rate measurements showed a clear difference between the three greenhouses, at the same time leaf stomatal conductance was statistically the same in all three greenhouses. The reduction in the rate of A under shading is reasonable, since the radiation regime inside the non-shaded greenhouse during September and October was relatively high but below the saturation point for cucumber crop, which ranges between 800-1000 μmol.s^{-1}.m^{-2} (Turcotte and Gosselin, 1989; Drew et al., 1990). The restriction of net photosynthesis in the shaded greenhouses was not due to limitations in the diffusion of CO_2 to the mesophyll through the stomata aperture, as indicated by the lack of any effect of shading on g_c. Hence, it is reasonable to conclude that in the shaded greenhouses net photosynthesis was inhibited at the chloroplast level due to limitations in light energy perception by the photosystem I. A similar response on net photosynthesis owing to suboptimal light availability was also reported by Robbins and Pharr (1987) and by Hao and Papadopoulos (1999).

Transpiration rate and stomatal conductance

The leaf transpiration values presented in Table 3 are greater than the values found by Lykoskoufis et al., 2005, for pepper cultivation. These values, however, are very close to the values found by Medrano et al., 2005, who found transpiration values per m^2 of leaf in a greenhouse with autumn cucumber cultivation in perlite, from 10:00 to 14:00 of the order of 250-300 g.m^{-2}.h^{-1}, corresponding to a transpiration rate of 4.6 - 5.6 mmol.m^{-2}.s^{-1}, which are similar to our values from Table 3. The same researchers found that transpiration rate

values were linearly affected by the levels of incoming solar radiation, thus confirming the effect of shading on the transpiration rate found in our experiment. Also, close to the values of Table 4 are the results of Nederhof et al., 1992, who found for sweet pepper cultivation mean leaf transpiration rate values around 200 $W.m^{-2}$, that is, about 4.5 $mmol.m^{-2}.s^{-1}$ (Hanan, 1998).

For stomatal conductance g_c the values found in the greenhouses of our experiment are similar to those found by Mavrogiannopoulos et al, (1999) in hydroponic melon culture and higher than those found by Lykoskoufis et al. (2005) in pepper cultivation.

The values in Table 7 show leaf stomatal conductance values for our experiment conditions of the order of 1 $mol.m^{-2}.s^{-1}$, corresponding to stomatal conductance of about 22.3 $mm.s^{-1}$ (Rosenberg et al., 1983). This value is close to the values of Katsoulas et al. (2001), who found values for the stomatal conductance of the order of 20 $mm.s^{-1}$ for rose cultivation in a shaded roof greenhouse in Volos-Greece region. Similar values were given by Nederhof et al. (1992) who gave values for stomatal conductance of 15-20 $mm.s^{-1}$ for hydroponic sweet pepper cultivation in a greenhouse in the Netherlands.

It is well known that stomatal conductance values above 20 $mm.s^{-1}$, such as g_c values for cucumber leaves in our three experimental greenhouses in autumn, correspond to normal state of free transpiring plants that are outside stress and their stomata are open (Hanan, 1998). Since, in such conditions their transpiration rate is a function of the incident solar radiation on the leaves and the air vapor pressure deficit in the leaf chamber (Katsoulas, 2002), greater transpiration in the control greenhouse is justified by the higher solar radiation intensity.

Photosynthesis acclimation

Finally, the lack of any difference in photosynthesis rates A between plants from the three shading treatments when the measurements were conducted at light saturation with a constant illumination conditions of 1000 $\mu mol.m^{-2}.s^{-1}$, despite the long term exposure to different light conditions shows that shading up to 50% does not affect permanently the leaf photosynthetic apparatus (Table 8). These results indicate that greenhouse cucumber does not adapt to reductions in light up to 50%. Hence, automated application of intermittent shading depending on current solar radiation intensity does not seem to affect the photosynthetic potential of greenhouse cucumber due to acclimation. This is in accordance with the results of Smith et al. (1993) for tomato crop who found that leaf photosynthetic capacity along a fruit-bearing shoot is mainly driven by the sink demand of the most proximal fruit, and not by light acclimation.

CONCLUSIONS

The analysis of photosynthesis measurements made during autumn hydroponic cucumber cultivation showed that photosynthesis rate is reduced proportionally by shading while, shading does not seem to have a permanent effect on leaves and this illustrates the usefulness of the periodic shading by placing shading for periods of high solar radiation (summer) and removing shading when the intensity of solar radiation decreases (mid-autumn-winter) without photosynthetic cost.

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