# The Effect of Diffuse Light on Crops

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## Abstract

**Light is not evenly distributed in Dutch glass greenhouses, but this can be improved with diffuse light. Modern greenhouse coverings are able to transform most of the light entering the greenhouse into diffuse light. Wageningen UR Greenhouse Horticulture has studied the effect of diffuse light on crops for several years. Modelling and experimental studies showed that crops such as fruit vegetables with a high plant canopy as well as ornamentals with a small plant canopy can utilize diffuse light better than direct light. Diffuse light penetrates the middle layers of a high-grown crop and results in a better horizontal light distribution in the greenhouse. Diffuse light is absorbed to a better degree by the middle leaf layers of cucumber, resulting in a higher photosynthesis. The actual photosynthesis of four pot plant species was found to be increased and crop temperatures were lower during high irradiation. The yield of cucumbers was increased, and the growth rate of several potted plants was increased. These investigations have resulted in a quantitative foundation for the potentials of diffuse light in Dutch horticultural greenhouses and the selection and verification of technological methods to convert direct sunlight into diffuse light.**

## INTRODUCTION

Light is not evenly distributed in Dutch glass greenhouses. Fruit vegetables like cucumber have a high leaf area index and intercept a large quantity of light with the upper leaves, while the middle and lower leaves receive much less light and contribute very little to photosynthesis, growth and in the end, production. The crop would benefit if upper leaves would intercept less incident light and the middle and lower leaves a greater proportion, in order to realize a more uniform light interception over the foliage. Hovi et al. (2004) showed that a higher amount of artificial light within a crop achieved by inter-lighting significantly increased photosynthesis of the lower leaves of cucumber. The same effect can be realized by diffuse light. From earlier investigations in forests (Farquhar and Roderick, 2003; Gu et al., 2003), apple trees (Lakso and Mussleman, 1976) and grass canopies (Sheehy and Chapas, 1976) it is known that diffuse light is able to penetrate deeper into a plant canopy in comparison to direct light and that photosynthesis in forests is increased by diffuse light. There are also indications that plants have developed mechanisms to use diffuse light more efficiently (DeLucia et al., 1996; Vogelmann, 1996). In young plants and small plants like pot plants the horizontal light distribution is not optimal. Shadows cast from the greenhouse construction have a negative influence on the plant production. In order to realize a uniform production, the light distribution has to be uniform over the whole canopy. This can be achieved by diffuse light. Light can be made diffuse by modern covering materials (Hemming et al., 2004). Such materials contain pigments, macro- or microstructures, which are able to transform all incoming direct light into diffuse light. Depending on the design of the structure the incoming light scatters, the angle of incidence is changed. Efficient structures make the light diffuse without a significant reduction in light transmission.

During the past four years Wageningen UR has investigated the potential of diffuse covering materials used in Dutch greenhouses (Hemming et al., 2004). The suitability of several greenhouse covering materials and their optical properties (PAR transmission $\tau_{direct}$ and $\tau_{diffuse}$, haze) was investigated in laboratories as well as in practice. On the basis of light and crop models (Goudriaan, 1988; Marcelis et al., 2000) the effect of diffuse light on crop photosynthesis was studied (Hemming, 2006). In this paper the effect of diffuse covering materials on light distribution, plant photosynthesis, plant growth and development will be elaborated. The results are based on crop experiments with cucumbers and four different types of potted plants.

## MATERIALS AND METHODS

In four greenhouse compartments, each 150 $m^2$, experiments were conducted first with cucumbers and later with four pot plant species. In two compartments the crops received mainly diffuse light, in the other two compartments they received natural light. To change the light conditions inside the greenhouse, roof and side-walls of the glass greenhouses were covered with either a diffuse plastic film "F-Clean diffuse" or with a clear plastic film "F-Clean", both 100 µm from Asahi Glass Europe bv. The optical properties of both materials are described in Figure 1. The diffuse material had a haze of 50%.

Cucumbers 'Shakira' were planted on April, 18th 2006. They were grown in 18 rows with 3.5 plants per $m^2$. Rockwool was used as substrate with an average pH of 5.3 and an average EC of 3. On May, 9th, the crop reached the wire, the top was removed, and two shoots remained. The first flower appeared in the sixth bud after 10 days, and the first flower in the sixteenth bud appeared after 16 days. First harvest took place on May, 9th and crop ended on July, 26th 2006. Cuttings of pot chrysanthemum 'Danielson' and kalanchoe 'Kerinci' and young plants of *Ficus benajmina* 'Exotica' and *Schefflera* 'Compacta' were potted on August, 30th 2006 in a 13 cm pot filled with substrate flush fine from TrefEgo. Plants were grown in natural short day. *Schefflera* and *Ficus* were fertilized with N-P-K 9-2-4, an EC of 1.7 and a pH of 5.6, chrysanthemum and kalanchoe were fertilized with NPK 4-2-4, an EC of 2.0 and a pH of 5.6. Plants were grown with 50 plants per $m^2$ and 20 plants per $m^2$ at the end of the growing period. Chrysanthemum tops were removed after 14 days.

In all compartments greenhouse climate was regulated and monitored: dry and wet bulb temperature [$^oC$], relative humidity [%], $CO_2$-concentration [ppm], ventilation opening [%], global radiation [W $m^{-2}$], PAR [µmol $m^{-2}$ $s^{-1}$]. Crop temperature was monitored with four IR-camera's of Growlab Hogendoorn bv, The Netherlands. PAR Lite sensors and pyranometers CM10 from Kipp & Zonen bv, The Netherlands, were installed above the crop for permanent measurements. Additionally, light distribution within the crop, with different heights, on diffuse and clear days, in young and full-grown crops was measured vertically and horizontally with a Sunscan system from Delta-T Ltd., U.K.

The photosynthetic capacity was measured with an advanced mobile photosynthesis system (LCpro+, ADC Bioscientific Ltd., U.K.) with a leave chamber of 6.25 $cm^2$. Measurements were carried out in different crop layers of cucumber at two light levels (465 µmol $m^{-2}$ $s^{-1}$ and 1250 µmol $m^{-2}$ $s^{-1}$) on fully-grown leaves at a $CO_2$-concentration of 700 ppm, a temperature of 21°C and a relative humidity of 85%. Moreover full light response curves were measured for the four pot plants. The amount of chlorophyll was estimated with a SPAD 50 meter from Minolta. For cucumber the amount of protein content [µg $g^{-1}$] and the RuBisCo-content [µg $g^{-1}$] was determined.

Destructive measurements were carried out to examine possible changes in crop morphology of cucumber every second week. Cucumbers were analyzed in four different leaf layers, e.g. amount of leaves per layer [-], fresh weight of leaves, stems and fruits per layer [g], dry weight of leaves, stems and fruits per layer [g], dry matter content, leave area per layer [$m^2$], LAI per plant [-], SLA per plant [g $m^{-2}$]. Destructive measurements of the four pot plants were carried out after six weeks and at the end of the crop growth period. Next to the parameters mentioned above, the length of the plant [cm], the amount of lateral shoots [-], dry weight and fresh weight of buds and flowers [g] and the time of flowering [date] were measured for the flowering pot plants. Leave orientation was determined with 2D and 3D image analysis techniques.

## RESULTS AND DISCUSSION

To estimate the potential of diffuse greenhouse covering materials, the amount of natural global radiation has to be known. The Dutch climate is characterised by 3650 MJ $m^{-2}$ global radiation per year, of which 1081 MJ $m^{-2}$ direct light. This amount can be potentially transformed into diffuse light, the rest is already diffuse. Only 200 MJ $m^{-2}$ of the direct light occurs during the winter month, 880 W/$m^2$ during the summer month. It can be assumed that a diffuse covering material will give the most advantages during spring, summer and autumn months. However, as long as no light losses appear under the covering, no disadvantages are to be expected during the winter months.

During the experiments, the greenhouse climate in the different treatments (diffuse or natural) was comparable (Table 1**Error! Reference source not found.**). Measurements in cucumber showed that crop temperature in higher leaf layers in the crop was 0.2-0.8°C lower in the diffuse treatment, but was 0.4°C higher in the lower layers on days with high irradiation (data not shown). The amount of PAR light under the diffuse covering was about 4% less than under the other treatment (Fig. 2). However, the horizontal light distribution was much more equally under the diffuse covering (Fig. 3). Measurements of light distribution inside the cucumber crop showed that after three weeks of growth, more than 85% of the light was being intercepted by the crop and a difference in light interception between treatments could be observed. More light was intercepted in the diffuse treatment on clear days, especially by the intermediate leaf layers (Fig. 4). No difference in light interception between the diffuse and direct light treatments was observed on cloudy days (data not shown). Leaves at intermediate leaf layers on the main stem as well as young leaves on the secondary branches had a higher rate of photosynthesis at normal light conditions (500 µmol $m^{-2}$ $s^{-1}$) in diffuse light (Fig. 5). Photosynthesis at light-saturating conditions (1250 µmol $m^{-2}$ $s^{-1}$) was higher under direct light and in all leaf layers. Upper and middle leaves also contained more chlorophyll when grown under diffuse light, whereas lower leaves showed lower SPAD values (Table 2**Error! Reference source not found.**).

It can be concluded that more light is absorbed by the middle leaf layers and photosynthesis is increased, thus the assimilation rate was higher due to diffuse light. The crop temperature probably influenced this process as well, as it was much higher under direct than under diffuse light conditions. According to theory, the physiologically older leaves deeper in the crop receive less light, have less RuBisCo and are photosynthetically less active. RuBisCo was found to be slightly higher in diffuse light and decreased in lower layers of the crop (Table 3**Error! Reference source not found.**). This may be due to a better light absorption in the middle of the crop so that RuBisCo is still able to actively contribute to the photosynthesis process without being broken down and reallocated to younger parts of the crop receiving more light.

The proportion harvested cucumbers in relation to plant biomass increased from June onwards due to diffuse light. Cucumber production in kilo's increased by 4.3% and the number of cucumbers increased by 7.8% (data not shown). The fruits were somewhat smaller on average. However, the light transmission in the diffuse light treatment was ca. 4% lower than under clear covering. Given the same light transmission, the difference between treatments would have been even greater. With 4% more light, the estimated difference in production would have been 7.8% in kilo's and 11% in number of fruits. This increase in production might have been actually realized if suppliers had been able to produce greenhouse roof material without the loss of light transmission in the process. The quality of fruits was judged on a regular basis and was slightly lower in the diffuse light treatment. However, this did not influence the longevity of the fruits after harvest.

Similar positive effects of diffuse light have also been shown with pot plants. The growth rate of all pot plants was increased. After six weeks chrysanthemum showed a higher plant height, more branches, more leaves, a higher leaf area, a higher leaf and stem dry weight, a higher relative growth rate (RGR) and more flowers. Comparable results were observed for the other three species of pot plants after six weeks (data not shown). Similar to the photosynthesis in cucumber, that of the four pot plant species was higher under diffuse light than under the clear covering (Fig. 6). Crop experiments with pot plants were conducted in autumn to analyze the effect diffuse covering materials in different seasons. The positive effects of diffuse light were clearly visible until the beginning of November (week 45). After that the light loss of the covering used in the experiments, about 4%, overruled the positive effects of diffuse light. Since the experiment with chrysanthemum was finished by then, no negative effects were observed (Table 4**Error! Reference source not found.**). The experiment with *Ficus*, however, continued until the beginning of December (week 49). From **Error! Reference source not found.** it can be clearly seen that the growth rate decreased in December as a result of lower light levels in the diffuse treatment.

## CONCLUSIONS

In conclusion, diffuse light has a positive influence on the production of cucumbers, especially during the summer. This positive effect can be explained by a change in light penetration into the crop and by an increased photosynthesis capacity, so that a crop like cucumber can utilize diffuse light better than direct light. In addition, diffuse roof material results a lower crop temperature, especially higher in the crop which likely leads to a more optimal conditions for photosynthesis.

In our opinion, a diffuse roof material for greenhouses with a minimal loss of light should be further developed. This means that materials should be used with minimal 50% haze, a light transmission of at least 90% (perpendicular) and 82% (hemispherical). A lower light transmission will result in a loss of production, especially in the winter when light is the limiting factor. Diffuse light in the crop is actually less important in the winter because most of the natural light is already diffuse due to the predominantly cloudy weather. The advantage of diffuse light can be realized in late spring, summer and early autumn when natural light has a more direct character, and when too much (direct) light in undesirable for many crops. In an earlier study, Hemming et al. (2005) examined the economic prospects of diffuse roof material and concluded that at a 5% production increase is possible and a diffuse roof material can be profitable. Diffuse covering materials have potential advantages for other crops as well, i.e. sweet pepper, as well as for cut flowers like rose.

## ACKNOWLEDGEMENTS

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## Literature Cited

DeLucia, E.H., Nelson, K., Vogelmann, T.C. and Smith, W.K. 1996. Contribution of intercellular reflectance to photosynthesis in shade leaves. Plan, Cell and Environment 19: 159-170.

Farquhar, G.D. and Roderick, M.L. 2003. Pinatubo, diffuse light and the carbon cycle. Science 299: 1997-1998.

Goudriaan, J. 1988. The bare bones of leaf-angle distribution in radiation models for canopy photosynthesis and energy exchange. Agric. and Forest Meteo. 43: 155-169.

Gu, L., Baldocchi, D.D., Wofsy, S.C., Munger, J.W., Michalsky, J.J., Urbanski, S.P. and Boden, T.A. 2003. Response of a Deciduous Forest to the Mount Pinatubo Eruption: Enhanced Photosythesis. Science 299: 2035-2038.

Hemming, S., Dueck, T., Marissen, N., Jongschaap, R., Kempkes, F. and van de Braak, N. 2005. Diffuus licht – Het effect van lichtverstrooiende kasdekmaterialen op kasklimaat, lichtdoordringing en gewasgroei. Wageningen UR report 557.

Hemming, S., van der Braak, N., Dueck, T., Elings, A. and Marissen, N. 2005. Filtering natural light by the greenhouse covering – More production and better plant quality by diffuse light? Acta Hort. 711: 105-110.

Hovi, T., Nakkila, J. and Tahvonen, R. 2004. Interlighting improves production of year-round cucumber. Scientia Horticulturae 102 (3): 283-294.

Lakso, A.N. and Musselman, R.C. 1976. Effects of Cloudiness on Interior Diffuse Light in Apple Trees. J. Amer. Soc. Hort. Sci. 101 (6): 642-644.
Marcelis, L.F.M., van den Boogaard, H.A.G.M and Meinen, E. 2000. Control of crop growth and nutrient supply by the combined use of crop models and plant sensors. In: Proc. Int. Conf. Modelling and Control in Agriculture, Horticulture and Post-Harvested Processing. IFAC, p.351-356.
Sheehy, J.E. and Chapas, L.C. 1976. The Measurement and Distribution of Irradiance in Clear and Overcast Conditions in Four Temperature Forage Grass Canopies. J. Appl. Ecol. 13(3): 831-840.
Vogelmann, T.C., Bornman, J.F. and Yates, D.J. 1996. Physiologia Plantarum 98, 43-56.

## Tables

Table 1. Greenhouse climate during the cucumber experiments using a diffuse and a clear covering material in 2006.

| | | | Clear | Diffuse | Average North/South |
|---|---|---|---|---|---|
| Day | Air temperature [$^oC$] | North | 23.8 | 23.9 | 23.8 |
| | | South | 24.1 | 24.1 | 24.1 |
| | Average Clear/Diffuse | | 24.0 | 24.0 | |
| | Relative humidity [%] | North | 68.9 | 69.7 | 69.3 |
| | | South | 75.3 | 76.6 | 76.0 |
| | Average Clear/Diffuse | | 72.1 | 73.2 | |
| | $CO_2$-concentration [ppm] | North | 430.1 | 414.0 | 422.1 |
| | | South | 418.4 | 436.4 | 427.4 |
| | Average Clear/Diffuse | | 424.2 | 425.2 | |
| | Opening ventilation [%] | North | 93.3 | 94.2 | 93.8 |
| | | South | 99.6 | 101.1 | 100.4 |
| | Average Clear/Diffuse | | 96.5 | 97.6 | |

Table 2. Average SPAD-values (=f([chlorophyl] $m^{-2}$)) of four different leaf layers of cucumber, divided in stem and side branches, between 9th of May and 11th of July 2006. grown under a diffuse and clear covering.

| | | Stem | | Side branches | |
|---|---|---|---|---|---|
| Leaf layer | Crop height | Clear | Diffuse | Clear | Diffuse |
| 4 | 150-200 cm | 45,1 | 48,4 | 53,5 | 53,2 |
| 3 | 100-150 cm | 40,0 | 42,6 | 44,1 | 43,5 |
| 2 | 50-100 cm | 37,6 | 34,6 | - | - |
| 1 | 0-50 cm | 32,6 | 29,6 | - | - |

Table 3. RuBisCo content (mg $g^{-1}$ fresh weight) ± standard deviation in four different leaf layers of cucumber at the 9th of May and 16th of June 2006, grown under a diffuse and clear covering.

| | RuBisCo content [mg $g^{-1}$ fresh weight] 9th of May | | | | RuBisCo content [mg $g^{-1}$ fresh weight] 16th of June | | | |
|---|---|---|---|---|---|---|---|---|
| | Clear | | Diffuse | | Clear | | Diffuse | |
| Leaf layer | Side branch | Stem | Side branch | Stem | Side branch | Stem | Side branch | Stem |
| 4 | - | 3,1±2,3 | - | 3,9±2,2 | 4,0±2,1 | 5,4±3,1 | 5,9±1,9 | 5,2±3,2 |
| 3 | - | 1,3±1,1 | - | 1,7±1,6 | 7,5±3,4 | 0,9±0,2 | 6,5±2,2 | 1,6±1,7 |
| 2 | - | 0,9±0,8 | - | 1,2±0,8 | - | - | - | - |
| 1 | - | 0,6±0,4 | - | 0,8±0,6 | - | - | - | - |

Table 4. Plant growth parameters of chrysanthemum grown under a diffuse or clear covering. Significances are shown with * at α=0.05, n=10, ns=not significant, - parameter not measured.

| | Week 41 | | | Week 45 | | |
|---|---|---|---|---|---|---|
| | Clear | Diffuse | | Clear | Diffuse | |
| Plant height [cm] | 32.15 | 34.75 | * | 43.20 | 44.45 | * |
| Number of branches [-] | 4.50 | 5.50 | * | 4.90 | 4.85 | ns |
| Number leaves [-] | 71.0 | 93.2 | * | 78.2 | 88.7 | * |
| Leaf area [$cm^2$] | 900 | 1148 | * | 1175 | 1347 | * |
| Leaf dry weight [g] | 1.96 | 2.42 | * | 2.53 | 2.93 | * |
| Stem dry weight [g] | 1.39 | 1.78 | * | 4.31 | 5.00 | * |
| SLA [$m^2$ $g^{-1}$] | - | - | - | 0.047 | 0.046 | ns |
| RGR [average g $g^{-1}$ $wk^{-1}$] | 0.56 | 0.70 | | 0.94 | 1.06 | |
| Number flowers [-] | - | - | - | 27.4 | 30.7 | * |
| Flower dry weight [g] | - | - | - | 2.56 | 2.65 | ns |

Table 5. Plant growth parameters of *Ficus* grown under a diffuse or clear covering. Significances are shown with * at α=0.05 and ** at α=0.10, n=10, ns=not significant, - parameter not measured.

| | Week 41 | | | Week 49 | | |
|---|---|---|---|---|---|---|
| | Clear | Diffuse | | Clear | Diffuse | |
| Plant height [cm] | 39.2 | 41.1 | * | 64.1 | 63.0 | ns |
| Number of branches [-] | 9.25 | 9.95 | ** | 12.8 | 13.0 | ns |
| Number leaves [-] | 31.5 | 34.0 | ns | 68.8 | 65.2 | ns |
| Leaf area [$cm^2$] | 496 | 532 | ** | 1340 | 1247 | ** |
| Leaf dry weight [g] | 2.02 | 2.11 | ns | 5.66 | 5.06 | * |
| Stem dry weight [g] | 0.93 | 0.92 | ns | 3.38 | 3.21 | ns |
| RGR [average g $g^{-1}$ $wk^{-1}$] | 0.49 | 0.51 | | 0.65 | 0.59 | * |
| SLA [$m^2$ $g^{-1}$] | - | - | - | 0.024 | 0.025 | ns |

## Figures

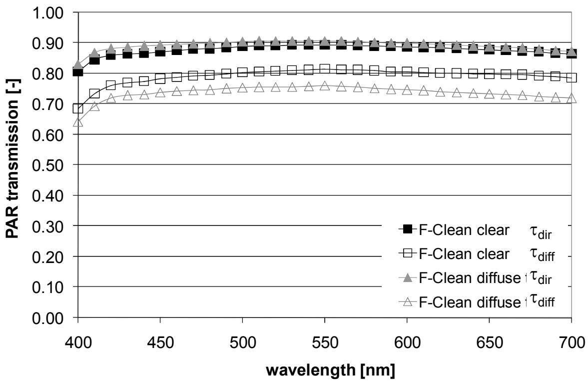


Fig. 1. Optical properties of a diffuse (F-Clean diffuse on glass) and a clear (F-Clean on glass) covering material used in experimental greenhouses.

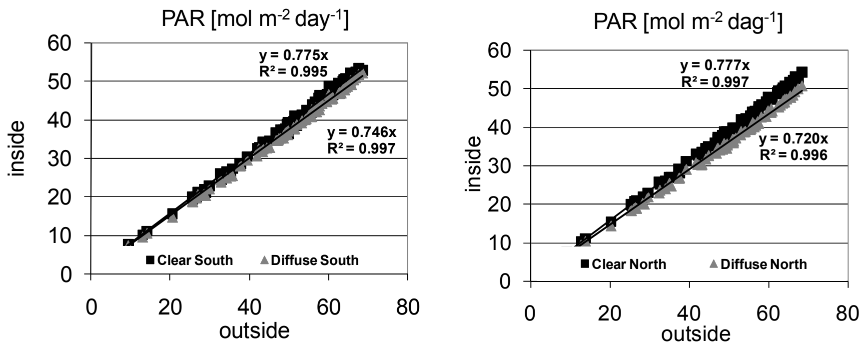


Fig. 2. PAR measurements inside and outside the greenhouse in experimental greenhouses covered with a diffuse and a clear covering.

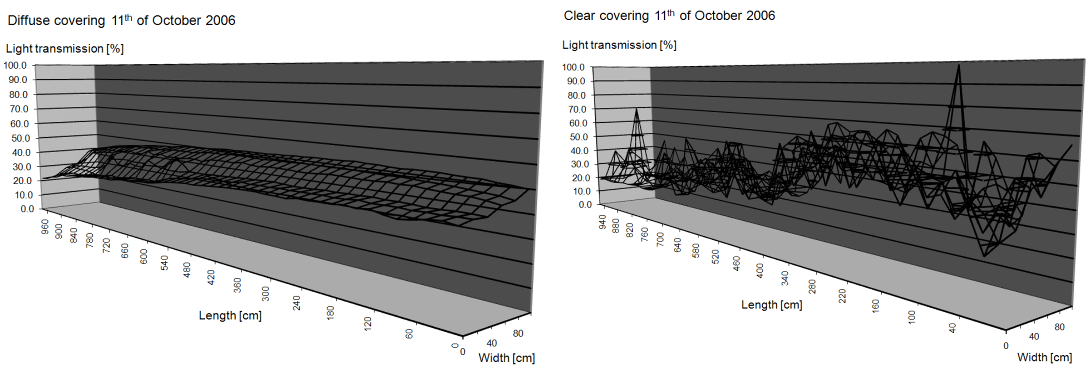


Fig. 3. Horizontal light distribution in greenhouses covered with a diffuse and a clear covering material on a clear day.

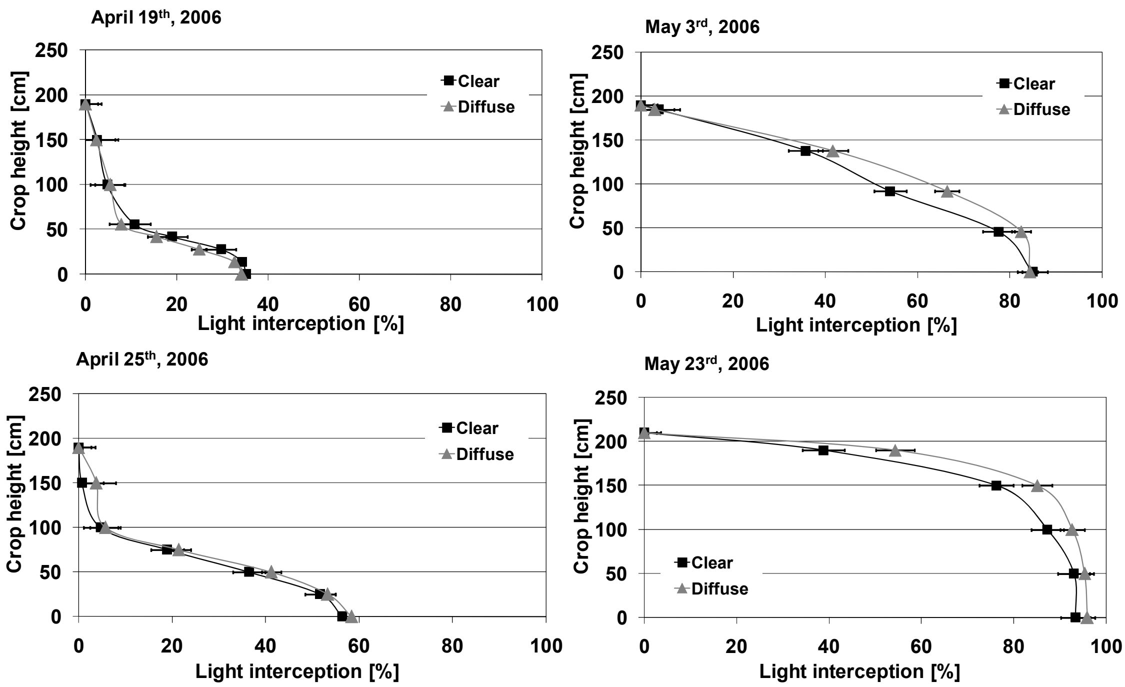


Fig. 4. Vertical light distribution and light interception of a cucumber crop on four different dates grown under a diffuse and a clear covering on four clear days.

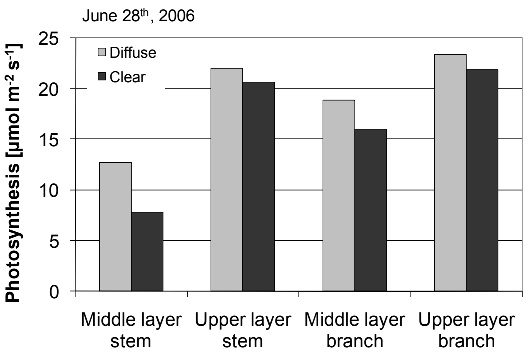


Fig. 5. Photosynthesis in two leaf layers of a cucumber crop on June, 28th, grown under a diffuse and a clear covering

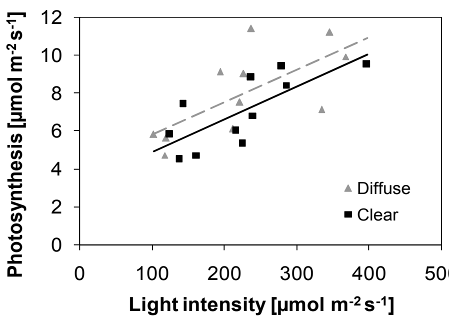


Fig. 6. Actual photosynthesis in four different pot plant crops grown under a diffuse and a clear covering.