Protective rain shields alter leaf microclimate and photosynthesis in organic apple production

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Abstract

Plastic rain shields reduce the leaf and fruit wetness and protect apple trees against major leaf diseases and hail damage. Shielding the trees may reduce incoming radiation, especially in the ultraviolet (UV) region of the light spectrum, and affect the microclimate and photosynthesis. In July of 2014 and June of 2015, we measured the leaf microclimate and photosynthetic performance using chlorophyll fluorescence and gas exchange in the apple cultivar 'Santana' grown in three treatments. In one treatment the trees were exposed to natural light and sprayed (control), and in two treatments the trees were unsprayed and shielded with a plastic film not permeable to UV-light (UV-) or a plastic film permeable to UV-light (UV+). The light transmittance was reduced in the shielded treatments, protecting the leaves from high solar irradiance during noon on sunny days, and avoiding afternoon depression of photosynthesis. Due to this, the leaf photosynthetic rates were often higher in the protected trees in comparison to the control trees at similar high light intensities, whereas there were no differences between treatments on cloudy days. The effect of the UV+ film on photosynthesis did not differ from the UV- film, except there was a tendency for higher values accompanied with increased light transmittance of the UV+ film. We conclude that a microclimate with more diffused light maintained the photosynthetic yield, despite a lower light level under the rain shields.

Keywords: light, stomatal conductance, chlorophyll fluorescence, covering material, UV

INTRODUCTION

Finding sustainable alternatives to pesticides in organic apple production is of large interest to growers in order to limit the extensive use of sulfur and potassium bicarbonate to control major diseases including apple scab (*Venturia inaequalis*) and storage rot. One such alternative is a plastic rain shield, which reduces leaf wetness and thereby reduces fungal growth and diseases. Rain shields have been shown to reduce rots at harvest in sweet cherry production (Børve and Stensvand, 2003), and apple scab and storage rots in organic apples (Bertelsen and Lindhard Petersen, 2014). However, using rain shields to protect fruit trees from diseases may affect the leaf microclimate and photosynthetic yield due to reductions in light intensity in relation to the specific plastic film chosen. On the other hand, a plastic film with a high diffusive transmittance increases the amount of diffused light underneath the rain shield. Diffused light penetrates deeper into a canopy than direct light (Lakso and Musselman, 1976; Urban et al., 2012) and increases photosynthesis in the middle layer of the canopy and crop yield (Farquhar and Roderick, 2003; Hemming et al., 2008). Furthermore, shadows in diffused light from upper and neighbouring leaves are less and the rain shields may reduce incidents of direct high light on the upper leaves during bright sunny days. On the other hand, most plastic films are non-UV penetrable and therefore the environment is limited in the ultraviolet region of the light spectrum. This may have a negative effect on fruit colour and content of secondary compounds (Bastías and Corelli-Grappadelli, 2012), and may also alter leaf gas-exchange due to spectral effects on stomatal regulation (Nogués et al., 1999).

The aim of the present study was to compare two types of plastic rain shields with or

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without UV-penetration on the efficiency of photosystem II, CO_2 assimilation, evapotranspiration and stomatal conductance in organic field-grown apple trees.

MATERIALS AND METHODS

The study was conducted in the experimental orchard of Aarhus University located in Aarslev, Denmark. The rain shields were added to an existing experiment planted in the spring of 2009, where organic spraying strategies were tested on different apple cultivars. The rain shields were constructed in the spring of 2014 in a row of 'Santana' (*Malus* × *domestica* Borkh.) on M9 rootstock planted at 1.0×3.3 m in a north-south orientation. The row consisted of 117 trees that were divided into three blocks of 39 trees. Within each block a rain shield was constructed spanning nine trees. The shields were made of three parallel steel pipes spanning the length of the shield. For every 2 m the three steel pipes were attached to 4"×4" wooden poles by means of 1" steel rafters in a 30° angle and stabilized by 3/4" flat diagonal steel pipes. From the ground to the ridge the construction was 2.8 m and the shield spanned a width of 1.9 m and a length of 10 m. Half of the shield in the longitudinal direction was covered with a non-UV penetrable Lumiterm polyethylene plastic film (UV-) and the other half with a Lumisol UV-B permeable film that allowed 70% UV-B penetration (UV+) (Folitec GmbH, Westerburg, Germany). Both plastic films had similar weight, a transparency of 88-90% and a light diffusive transmittance of 30%. The two types of films were taped together in the middle using greenhouse tape, and attached to the outer square steel pipes of the shield construction and held in place by a batten strip. The light transmittance was tested using a spectrophotometer (Jaz-ULM, Ocean Optics, Ostfildern, Germany) and the results are shown in Figure 1. Three experimental trees were assigned for each UV treatment while trees at the outer end of the shield and the middle tree were regarded as guard trees. The shield was installed in March 2014 before bud break and remained in place for the entire two seasons. All trees under the shields remained untreated with pesticides during the 2014 and 2015 seasons. The control treatment consisted of 3×3 trees that were sprayed with sulphur and/or potassium bicarbonate when scab infections were forecasted by the RIMpro scab warning program (Trapmann and Veens, 2015). For each block an untreated control treatment was present, but severe scab infections made it unsuitable for photosynthesis measurements.

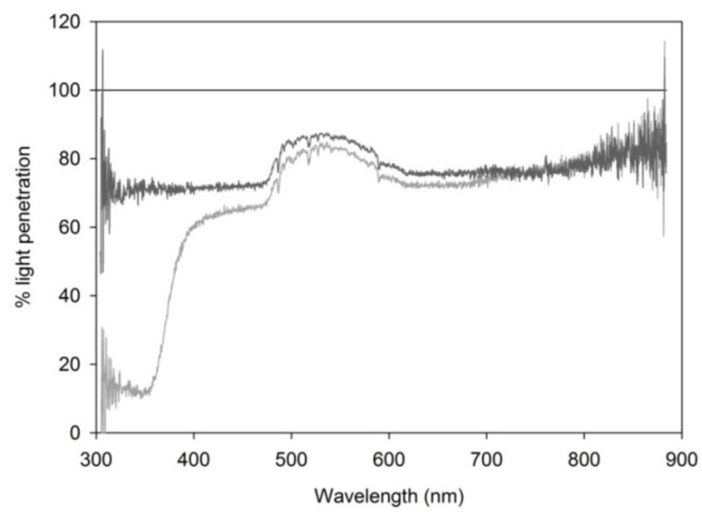

Figure 1. The spectral distribution of % transmitted light through two types of rain shields. A UV penetrable film (dark grey) and non-UV penetrable film (light grey). In the figure the light intensity values at the different wavelengths measured under a clear sky was set to 100%.

The climate was monitored in the top canopy just below the rain shield and at similar height in the control plots using an Imethos climate station (Fruitweb GmbH, Jork, Germany). The parameters of light intensity, air temperature, relative humidity, dew point, wind speed, wind direction, leaf wetness and precipitation were recorded and logged every hour. The day length at midsummer (June 24) is 17 h and 20 min with sunrise at 04.38 h and sunset at 21.58 h.

Chlorophyll fluorescence

Chlorophyll fluorescence was measured continuously with a PAM flourometer (MONI-PAM, Walz, Effeltrich, Germany). The chlorophyll fluorescence measuring system consisted of six emitter-detector units (MONI-heads), each representing independent fluorometers connected using RS-486 serial data communication and a central interface box to the monitoring PAM fluorometer. Three MONI-heads were placed in the top of the canopy, directly underneath the sky/rain shield avoiding shadows from neighbouring leaves, and the three additional MONI-heads were placed in the lower canopy on the east side of the trees allowing shadows from neighbouring leaves/trees and the construction. Leaves of vegetative shoots at similar age were secured in the MONI-head leaf clips, and measurements of maximum photochemical efficiency of PSII during the dark period; $F_v/F_m = (F_m\text{-}F_0)/F_m$, Quantum yield of PSII (Φ_{PSII}); $F'_q/F'_m = (F'_m\text{-}F')/F'_m$ and the relative electron transport rate (ETR) during the light period (Maxwell and Johnson, 2000) were recorded continuously every 30 min. The intensity of the light saturating pulse was 1800 µmol photons m^{-2} s^{-1} and the duration of the pulse was 0.8 s. The photosynthetic active irradiation in the range of 400-700 nm (PAR, µmol m^{-2} s^{-1}) was measured using the integrated quantum sensor. In 2014, measurements were carried out from July 15 to 25. In 2015, measurements were carried out from June 11 to 21. Every day at 8:00 h a new part of the leaf or a new leaf was secured in a MONI-head for measurements.

Gas exchange measurements

CO_2 assimilation rate (P_N), stomatal conductance (g_s) and vapour pressure deficit (VPD) were measured throughout the day on intact shoots in their natural orientation on the east side of the trees using three identical gas exchange systems (CIRAS-2, PP-systems, Hitchin, United Kingdom). In 2014, measurements were carried out on the upper leaves in the canopy with no shading from other leaves during the July 15-17 period. In 2015, measurements were carried out on the upper leaves during the June 11-30 period. The gas-exchange systems were placed on a fixed platform next to the canopy and the cuvette was attached using tape to one of the wooden columns before clamping the cuvette onto a leaf. The measurements started at 8:00 h in the morning. The gas-exchange parameters were recorded every 5 min until 21:00 h in the evening. The set points followed the natural light intensity, CO_2 and temperature conditions during the day, and the humidity was set to 60 to 100%, to keep VPD close to 1 kPA. Batteries were charged continuously and replaced every third hour to avoid loss of data. Every day the three gas-exchange systems were randomized among the treatments. The continuous measurements of P_N were plotted in relation to PAR to illustrate the direct light response of the plants. The relationship was fitted to a non-rectangular hyperbola (Ögren, 1993) using a user-defined curvefit function in Sigmaplot 11.0 (Systat software, Inc. SigmaPlot for Windows).

RESULTS

Climate conditions

In July 2014, the average temperature was relatively high, the days were predominantly sunny with few clouds and almost no precipitation. This resulted in no differences in air temperature and RH in the top of the canopy just below the sky/rain shield, though there was a tendency for slightly higher temperatures and lower RH under the rain shields compared to the control treatment (Table 1, Figure 2). In June 2015, it was rainy, windy with variable cloud cover and low temperatures. There were no differences in air temperatures and RH, but a tendency for slightly higher temperatures and lower RH similar to 2014. The rain shields decreased the total radiation and the measured intensity of the PAR passing through the film and reaching the leaves in the upper canopy of the apple trees was 20-40% depending on whether it was a sunny or cloudy day (Table 2). The two types of plastic film did not alter the percentage distribution of the different wavelengths in the light spectrum of the solar irradiance in the visible range of 400-700 nm, but the UV- film reduced the intensity of the UV light (300-400 nm) with 75% whereas the UV+ film only reduced the intensity of the UV light with 30% (Figure 1).

Table 1. Average values of environmental parameters from July of 2014 and June of 2015. Measurements were recorded every hour and averaged for each day (n=30/31 days ± SE). PAR values not measured in 2014.

Year month	Treatment	Air temp. (°C)	Air humidity (%RH)	Total precipitation (mm)	Wind speed (mm s^{-1})	PAR (µmol m^{-2} s^{-1})
2014	Control	20.0±0.4	72±1.5	0.125	0.8±0.1	
July	UV+ UV-	20.3±0.4	71±1.5	(one day)	0.08±0.02	
2015	Control	13.5±0.4	78±1.3	69.2	1.1±0.1	422±26
June	UV+ UV-	13.6±0.4	77±1.3	(14 days)	0.3±0.1	310±19 321±20

Table 2. Photosynthetic active radiation (PAR, µmol m^{-2} s^{-1}) for three sunny and three cloudy days in the unshielded control and underneath two types of plastic rain shields (n=3 days ± SE).

Treatment	Cloudy day (µmol m^{-2} s^{-1})	Cloudy day (%)	Sunny day (µmol m^{-2} s^{-1})	Sunny day (%)
Control	136±10	100	460±8	100
UV+	108±6	79	311±4	68
UV-	93±6	68	275±7	60

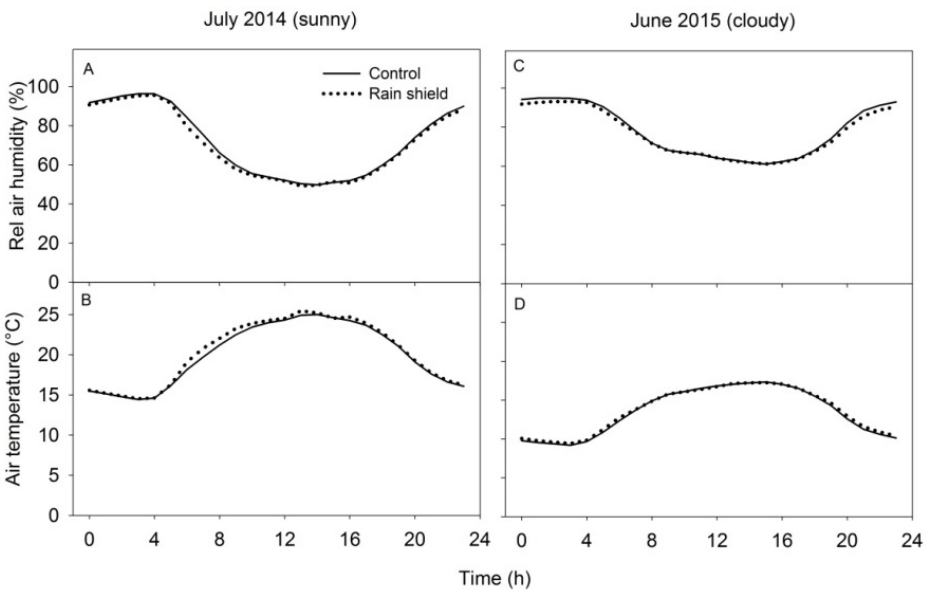

Figure 2. Hourly average values of the relative air humidity (%RH) and air temperature (T_{leaf},°C) in the shielded and unshielded treatments (control).

Photosynthesis and stomatal conductance

In July 2014, light response curves generated from three sunny days showed that leaves in the top of the canopy had higher P_N values when covered with either type of plastic compared to leaves in control treatments (data not shown). P_N values were higher under both low and high PAR below the UV+ film compared to the UV- film. Under high PAR, the UV+ film P_N values were mainly higher than those in control treatments. The differences in P_N among treatments during the three sunny days in July 2014 were highly dependent on the climatic conditions of the individual day of measurement and the positioning of the measured leaves. The lower P_N values in the control treatment were aligned with slightly lower g_s values, but on average only small differences were seen for values of c_i, leaf temperature (T_{leaf}) and VPD (Table 3). In 2015, similar light response curves could be generated for the three days with variable cloud cover (data not shown). On average, no differences were recorded for P_N, but the g_s values were highly reduced in the control treatment with corresponding effects on T_{leaf}, C_i, evapotranspiration and VPD (Table 3).

Table 3. Photosynthetic parameters measured during three days in July of 2014 and three days in June of 2015 on the upper leaves in an apple canopy (*n*=3±SE).

Year month	Treatment	P_N (µmol m^{-2} s^{-1})	g_s (mmol m^{-2} s^{-1})	T_{leaf} (°C)	C_i (µl L^{-1})	E (mmol m^{-2} s^{-1})	VPD (kPa)
2014	Control	8.0±1.3	161±33	25±1	267±6	2.4±0.4	1.6±0.3
July	UV+	10.1±0.4	193±26	25±1	251±7	2.6±0.1	1.6±0.3
	UV-	9.4±0.3	255±13	26±1	261±1	3.4±0.1	1.7±0.2
2015	Control	4.7±1.7	71±37	25±3	237±16	1.4±0.4	2.2±0.5
June	UV+	5.7±3.2	268±96	21±2	320±11	1.8±0.6	0.9±0.1
	UV-	4.8±3.0	216±82	20±1	300±24	2.0±0.2	1.1±0.2

Chlorophyll fluorescence

Hourly average values of PAR, Φ_{PSII} and relative electron transport rate (ETR) were calculated for the ten days of July 2014 and June 2015. The resulting curves are shown in Figures 3 and 4. During the ten days from July 15 to 25, 2014, the highest PAR reaching the upper leaves was just before noon (11:00 h). The PAR reaching the shielded leaves below both types of plastic was lower (Figure 3A). Deeper in the canopy, the patterns were different showing a tendency for higher PAR values in the morning under plastic, whereas the differences were smaller among treatments just before noon and in the afternoon (Figure 3D).

Solar irradiance resulted in higher ETR before noon, but lower values of both Φ_{PSII} and ETR in the afternoon for directly exposed leaves in comparison to leaves shielded with plastic (Figure 4B, C). A similar pattern was recorded for Φ_{PSII} lower in the canopy (Figure 3E), but ETR was not affected (Figure 3F). In contrast, lower PAR in the morning reduced the ETR compared to the shielded treatments.

During the ten days in June 2015, the PAR values were continuously higher during the morning and afternoon for the unshielded leaves in both the upper and lower canopies compared to shielded leaves under the plastic. At noon however, the difference was smaller or not present (Figure 4A, D). The lower light intensity at noon was related to the variable cloud cover of the period, but may also have been caused by windy conditions hampering the positioning of the monitoring heads. The quantum yield of PSII (Φ_{PSII}) showed a diurnal variation and a reduction in all treatments corresponding to the higher light intensities immediately before noon (Figure 4B, E), but with different degree of response in relation to light intensity. This was in contrast to the ETR values, which were closer related to the light intensity in the three treatments. The ETR was consistently higher for directly exposed leaves compared to shielded leaves (Figure 4C, F).

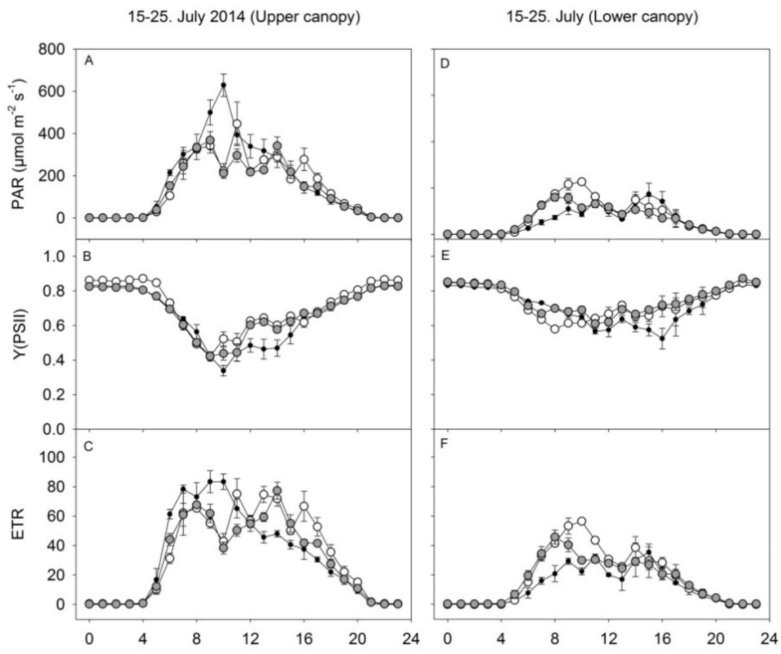

Figure 3. PAR, yield of PSII (ϕPSII), and electron transport rate (ETR) of apple leaves positioned in the upper and lower canopy of unshielded trees (black) and trees shielded with UV penetrable film (grey) and non-UV penetrable film (white), (*n*=15±SE).

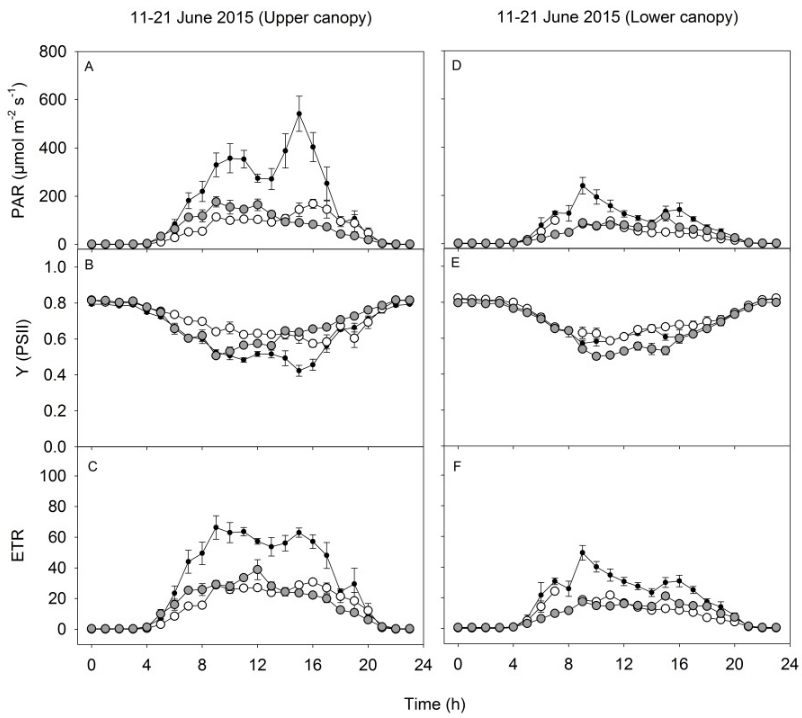

Figure 4. PAR, yield of PSII (ϕPSII), and electron transport rate (ETR) of apple leaves positioned in the upper and lower canopy of unshielded trees (black) and trees shielded with UV penetrable film (grey) and non-UV penetrable film (white), (*n*=15±SE).

DISCUSSION

The rain shields are designed to reduce the wetness of the leaves, and a major portion of the leaves in the canopy are exposed to direct sunlight, as well as transmitted light through the rain shields in the morning and in the afternoon due to changing sun angles; at noon when the sun is in zenith, most light passes through the rain shield. Our measurements were done in the east and top canopies during midsummer. The light intensity increased steeply in the morning from 04:00 h to 09:00 h and decreased more slowly in the afternoon. The values were higher at noon in the top canopy of unshielded trees compared to shielded trees during the sunny period in 2014. However, for the shielded trees there was a tendency for higher values of PAR in lower canopy during sunny mornings, suggesting that a higher percentage of the solar radiation penetrates deeper into the canopy than in the unshielded trees which are more affected by shadows (Hemming et al., 2008). This tendency was not seen during the cloudy period in 2015 where a larger percentage of the solar radiation was diffuse and therefore did not produce shadows and theoretically had similar ability to penetrate the canopy in both treatments. The lower PAR measured in the lower part of the canopy in the shielded treatment may therefore solely be related to the lower transmittance of the rain shield. Similar results are not easy to find in the literature as the light conditions under partly shielded canopies are not easily measured. However, it is well-known that radiation decreases under various types of shielding materials (Jifon and Syvertsen, 2003; Smit et al., 2008; Tanny, 2013).

Despite large effects on the light environment, wind speed and leaf wetness, the rain shields did not impose effects on the average air humidity or air temperature. However when the data were calculated on an hourly basis small microclimate differences became visible, showing a tendency for lower air humidity values and higher air temperature, especially during night and in the morning in the control compared to the shielded treatments. In general, shading from the rain shields was expected to reduce air temperature due to reductions in radiation compared to control treatments. Additional factors such as reductions in wind speed, air exchange, evapotranspiration because of lower radiant energy, and reduced leaf wetness may affect air temperatures inside or outside agricultural shields (Tanny, 2013). Our results correspond with earlier studies showing higher air temperatures and lower air humidity underneath various types of shelters (Tanny et al., 2009).

The lower CO_2 assimilation in unshielded control leaves at high irradiances on warm sunny days in 2014 implied an afternoon depression of photosynthesis that was not observed in leaves shielded by the rain shields. However, the lower CO_2 assimilation was only partly accompanied with lower stomatal conductance. The higher C_i values showed that reductions in CO_2 assimilation were not directly related to stomatal closure. This corresponds with other studies on afternoon depression (Jifon and Syvertsen, 2003; Huang et al., 2006). Instead the decrease in quantum yield of PSII and ETR during the afternoon in unshielded trees in 2014, clearly demonstrated that afternoon depression of photosynthesis occurred, because the light absorbed by the plants exceeded the photo-utilization capacity of the chloroplasts, as a protective mechanisms of PSII (Logan et al., 2007). The results on CO_2 assimilation from 2015 also show a promising effect of rain shields in respect to carbon gain and final yield during cloudy days. The electron transport rate and ϕPSII showed that the efficiency of the photosynthetic apparatus was lower in shielded leaves during cloudy days simply because of reduced light transmission through the plastic rain shields. However, the CO_2 assimilation did not decrease but was similar during the three measured days. Instead a decreased stomatal conductance in the unshielded leaves may have caused stomatal limitations of photosynthesis. C_i and evapotranspiration also decreased, while leaf temperature increased in unshielded leaves. It could be regarded that differences in leaf wetness and air exchange affects stomatal responsiveness, but these parameters were largely the same under sunny and cloudy conditions (results not shown). Leaves exposed directly to the sun may not be fully adapted to high light in June, and therefore more prone to closed stomata. The stomatal conductance could also have been affected by the sprays of sulphur and/or potassium bicarbonate in the unshielded control, as shown earlier by McAfee and Rom (2003), or simply due to differences in source-sink relationships as related to light intensity and discussed by Li et al. (2005).

The UV+ film had a small positive effect on CO_2 assimilation compared to the UV- film during both years. The positive effect corresponded with a higher transmission of light in the PAR region of the light spectrum, suggesting that final yield was not affected by properties of the films to transmit radiation in the UV-region of the spectrum.

In summary, the rain shields protected the field-grown apple trees from afternoon depression of photosynthesis in the upper leaves of the canopy on warm sunny days. The high diffusivity of the plastic films increased light penetration into the canopy. The decreased leaf wetness, light intensity, wind speed and absence of spraying possibly maintained a higher stomatal conductance in the protected apple trees during more cloudy periods for positive effects on leaf water balance and CO_2 assimilation.

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