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Original Research Paper

Total and diffuse light distribution within the canopy of an apple orchard as affected by reflective ground covers

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Abstract: In recent years, anti-hail nets have been increasingly used to protect apple orchards. As they reduce the light intensity at canopy level, reflective ground covers are frequently placed on the soil surface before fruit harvest with the main aim to enhance color development in bicolored apples. It is not clear however, to which extent the light penetration inside the whole canopy is affected by the reflective ground covers. We performed a study in an intensively cultivated apple district of South Tyrol (northern Italy), with and without reflective ground covers. We measured light intensity at different heights from the ground and different distances from the tree trunk, using two instruments: an 80-cm long ceptometer and a point-like sensor capable of measuring the diffuse radiation component in addition to the total visible light. We found that the reflective ground cover significantly increased the quantity of diffuse light reflected from the orchard floor. The largest effect was recorded at 1 m height from the ground, but it was still significant at 2.5 m height. The influence of the reflective ground cover was particularly remarkable when sun and tree lines were aligned. The increase of total PAR inside the canopy due to the reflective material was however relatively small, suggesting a moderate effect on tree photosynthesis and therefore on apple yields.

Keywords: Apple orchard, light environment, photosynthesis, reflective films.

1. Introduction

Like for many other important crops, light is a primary resource for apple production, directly affecting leaf photosynthesis and the fruit quality parameters such as the fruit skin color. It is also a fundamental condition during plant development, influencing for instance the formation of flower buds (Corelli Grappadelli, 2003). In orchards, the amount of light that reaches the leaves within the canopy is determined by the growers' decisions when they set tree row orientation, tree height and shape, obtained by pruning. In the recent years, the increase in the frequency of the hailstorms has boosted the installation of anti-hail nets in apple orchards, structures that have the potential to modify the light quality and quantity in the orchard. The light reduction varies to different extents depending on the nets color and characteristics (Mupambi et al., 2018). Therefore, it may be required to overcome these

effects by enhancing the light reflection using reflective materials placed on the ground. Reflective films aim to improve fruit skin coloration before harvest, but potentially lead to significant changes in environmental light and therefore in photosynthesis and fruit yield (Schmidt et al., 2014; Thalheimer and Paoli, 2001).

As described by Corelli Grappadelli (2003), the photosynthetic response of an apple leaf to light follows the well-known pattern of non-rectangular hyperbola. At low light intensities, the net photosynthesis increases almost linearly, it reaches the compensation point where photosynthesis compensates respiration rate, then at higher light intensity, being the apple a C3 plant, the competitive process of photorespiration starts. At even higher light intensity values, the leaf becomes Rubisco-limited and photochemical damages can occur. It follows that an apple grower should seek intermediate values of photosynthetically active radiation (PAR) inside the canopy and minimize the presence of shaded leaves.

The solar disk has a mean angular diameter of 0.533° and the part of solar rays that does not change its direction when crossing the atmosphere and reach the Earth surface, represent the direct radiation (Smith et al., 1989). A portion of solar rays, however, interacts with clouds and/or the sky molecules and particles and the fraction that is not absorbed is either transmitted or reflected, causing the diffuse light component. Diffuse light, being scattered, comes from all directions and, for this reason, it may better penetrate inside the tree canopies and promote the photosynthetic activities of a higher fraction of tree leaves (Anderson, 1964; Gu et al., 2002). Other physical elements in the orchard like the nets or the ground cover material may affect the direct/diffuse light ratio. Sun-exposed leaves, i.e. those situated in the external part of the crown, mostly receive direct light. Instead, inner leaves mostly receive diffuse light or direct light for short period of time, termed sunflecks (Li and Yang, 2015).

The manipulation of the light environment in orchard greatly affects (Corelli Grappadelli et al., 2017) plant photosynthesis. If protective hail nets reduce light intensity and protect trees from excess radiation, the ground cover reflective films, with albedo values higher than the grasses present in the alleys, can increase the light availability for the trees and therefore enhance the use efficiency of the light penetrating under the nets. Furthermore, in several production areas apple growers use reflective strips with different degree of roughness (Meinhold et al., 2010) to trigger the biosynthesis of red pigments in fruit skin (Layne et al., 2002).

Against this background, using an apple orchard where protective (anti-hail) nets were present, we addressed the question whether the use of a ground cover reflective material modifies the original distribution of direct and diffuse light within the canopy. Furthermore, the light response curve of sun and shade adapted leaves was characterized to evaluate the possible beneficial influence of reflective material on leaf net photosynthesis in apple trees.

2. Materials and methods

2.1. Site description

The experiment was carried out in an apple orchard located in the municipality of Auer/Ora, South Tyrol, Italy (46.344449 N 11.27875 E, 222 m a.s.l.). The apple trees of the cv. Nicoter grafted on M9 rootstock were planted in 2007 with a density of 4167 trees/ha (3 m between the rows and 0.8 m between trees within the rows). The cv. Nicoter is a hybrid between Braeburn and Gala, whose premium apples are sold under the brand Kanzi©. The tree rows were oriented along 20° - 200° N direction. Anti-hail protective black nets (CMG, Schio, Italy) of 3.2×2.1 mm mesh size were installed at a height of 4.5 m from the ground during the whole experimental period. The nets were almost horizontal, with a slight downhill slope toward the center of the alleys where their height was approximately 4 m. Trees, trained as slender spindle, were around 3.2 m tall and the average maximum leaf area index (LAI max), measured by defoliating three randomly chosen trees in September 2019, was 2.52 m^2

m^{-2}. The average crown width, assessed at the end of 2019 season was 70 cm, 56 cm and 42 cm at 1 m, 2 m and 2.5 m height, respectively. Average fruit yield was 65 t/ha in 2018 and 80 t/ha in 2019. Fruit harvest started on 24 September 2018 and 25 September 2019.

Two weeks before the beginning of fruit harvest (on 11 September 2018 and 12 September 2019) 2.6 m wide white reflective plastic fabric strips (model Agritela Lux, Arrigoni SpA, Uggiate Trevano, Italy) were placed on the soil surface in the alleys all along the tree rows.

2.2. Light measurements

The measurements of light intensity were taken on two sunny days in summer: 12 September 2018 and 16 September 2019. On each date, measurements were taken before and after the removal of the reflective strip. The measurement period was selected in reason of the presence of the reflective strips used to give coloration to fruit.

In 2018, measurements of PAR intensity were taken with a ceptometer (Accupar Linear PAR, Decagon Devices, Pullman, WA, USA), which consists of 80 sensors spaced 1 cm away from each other and placed along a portable horizontal bar. The instrument provides the average photosynthetically active radiation (PAR) measured by all the sensors in micromoles of photons per square meter per second (μmol m^{-2} s^{-1}). We considered the light distribution along two of the three main directions in which the tree canopies are organized, the vertical distribution and the horizontal distribution along the rows, while we neglected the variability perpendicular to the rows.

Five representative trees were randomly selected and for each of them the downward and the upward reflected PAR measurement were taken at three different heights from the ground (1 m, 2 m, and 2.5 m) following Jarvis's indications about canopy sampling representativeness (Rayment et al., 2002). Measurements were first taken in the presence of the reflective ground cover and then after its removal. The ceptometer was placed perpendicular to the row, crossing the crown with the same number of the sensors at the two sides of the row. At each height, measurements were taken at 0.1 m and 0.3 m distance from the trunk, moving the ceptometer in the direction of the neighboring tree. The incoming PAR at ground level under nets in an area that was not affected by the trees canopy and outside the nets has been quantified before starting the measurements inside the canopies. Measurements started at 10:15 and ended at 11:45 (UTM+1).

In 2019, total and diffuse light measurements were performed with an adapted BF5 radiometer (Delta-T Devices, Cambridge, UK). The BF5 is composed by several photodiodes, partly screened by a black mask, inserted in a glass hemispherical dome. The combination of mask and diodes allows the instrument to have always a photodiode in the light and one in the shade, allowing the estimate of the total (direct + diffuse) PAR and its diffuse component alone. We adapted the instrument to the direct use in the field, adding a 1.2 m boom to bear the dome and to avoid the shading of the sensors by the operator. Additionally, we placed two multimeters to read the output voltage of the total and diffuse light components. The measurements were taken at six locations within the apple crown, at 1 m, 2 m, and 2.5 m above the ground, and at 0.3 m and 0.1 m distance from the trunk for each height, always at the center of the tree line. In each measurement point, we took the values of total and diffuse radiation, both upward and in downward direction, for a total of 24 measurement values for each tree. Five tree replicates at approximately 6 m distance between each other were used.

On 16 September 2019, we took measurements in three sampling sessions starting at 9:10, 10:45 and 13:00 (UTM+1). Each repetition lasted about 90 minutes, approximately 45 min with the presence of white strips and 45 minutes with the reflective strips wrapped up, therefore minimizing their reflectivity. In addition, to assess the effect of the nets on downward radiation, at the end of each measurement session we measured the radiation

outside the protective nets and below the nets in the middle of the alley at about 1 m height. Both the ceptometer and the BF5 sensor provide a measurement of the PAR, but while the former integrates the values measured along an 80 cm line, the latter provides a punctual data in a given point of the canopy.

To calculate the frequency distribution of the PAR in the different canopy positions and different times in the day, we divided the PAR range into 100 µmol m^{-2} s^{-1} bins and we computed the number of occurrences in the bins. Then, to evaluate the presence of a condition of bimodality (presence of sun and shade leaves, or a more homogeneous distribution of PAR), we applied the procedure described by De Michele and Accatino (2014). According to that method, we evaluated the level of bimodality as $\beta = |\mu - \mu M|$, where μ is the mean of the distribution and μM is $\mu M = \frac{\sum_{i=1}^{L} m_i x_i}{\sum_{i=1}^{L} m_i}$, where x_i is the center of i^{th} bin, m_i the absolute frequency of the i^{th} bin, m is the mean of the distribution and µM is the mean of the more frequent dynamic. Following this computational procedure, β=0.1 is the threshold discriminating unimodal (β<0.1) and bimodal (β>0.1) conditions.

2.3. Photosynthesis measurements

The light response curve was measured on 20 August 2019 on 9 years-old apple trees of the cv. Gala on M9 located in an orchard at close distance from the experimental orchard described above. Trees were around 4 m tall, they were spaced 3.2 m between the rows and 0.8 m along the row and trained as slender spindle. Sun adapted and shade adapted leaves were selected in the outer (sunny leaves) or inner parts (shaded leaves) of the crown based on their morphology (sunny leaves are thicker and smaller, while shaded leaves are thinner and bigger; Taiz and Zieger, 2002). Four representative trees have been chosen and the light response curve of net photosynthetic rate (Pn) was measured on four leaf replicates in each category with a portable ADC-Pro (ADC BioScientific Ltd., Hoddesdon, UK). Increasing PAR intensity values were imposed using the artificial light source of the instrument at 91, 183, 275, 367, 459, 643, 827, 1011, 1195 and 1379 µmol m^{-2} s^{-1}, for a total of 80 measurement points. Measurements were carried out in ambient CO_2 molar density conditions (400-420 µmol mol^{-1}).

Light response curves of each leaf category were interpolated by using a non-rectangular hyperbola equation (Ruimy et al., 1995):

$$Pn = -(a \cdot PAR \cdot b) / (a \cdot PAR + b) + c \qquad \text{(eq. 1)}$$

where the equation parameter *a* approximates the quantum yield of assimilation, *b* the maximal photosynthetic capacity, and *c* the dark respiration. Measured data were interpolated separately for sun-adapted and shade-adapted leaves.

2.4. Statistical analysis

PAR data were analyzed by analysis of variance (ANOVA) for randomized block design to assess the effects of the reflective materials, the tree height and the distance from the trunk. The level of significance of the statistical difference between the presence and the absence of the reflective ground cover on PAR measurements has been calculated for each height by one way ANOVA and reported in the figures. All analyses and graphs were implemented with the statistical software R.

3. Results

3.1. Protective nets effect.

Although the experiment was not conceived to assess the effect of protective nets on penetrating light, we performed anyway punctual measurements to assess it. Protective nets showed variable influence on light transmission according to the measurement time. As expected, since the nets were almost horizontal, the amount of light penetrating below the nets was highest at noon (86%), and lowest during the morning (from 72 to 75%). Instead, and contrary to our expectations, the presence of the nets did not increase significantly the fraction of diffuse to total light (Table 1).

Table 1. PAR intensity measured above and below the anti-hail nets at three times of the day. Values of total light measured by the ceptometer on 12 September 2018, values of diffuse and total incident light measured by the BF5 on 16 September 2019.

Time (UTM+1)	Total PAR 12 Sep. 2018 (by ceptometer)		Total PAR 16 Sep 2019 (by BF5)		Diffuse PAR 16 Sep 2019 (by BF5)	
	above nets	below nets	above nets	below nets	above nets	below nets
9:10	-	-	896	666	181	150
10:15	1170*	877				
10:45	1574**	1173	1414	1020	236	160
13:00	-	-	1340	1150	215	209

* and ** PAR just before taking measurements with reflective ground cover or without it, respectively.

3.2. Vertical and horizontal distribution of light in presence and absence of reflective materials

Ceptometer measurements performed in 2018 are displayed in Figures 1 and 2. Downward PAR slightly increased from 1 to 2 m tree height (Figure 1a), while similar values were found at 0.1 and 0.3 m from the trunk (Figure 1b). As expected, the incoming PAR was unaffected by the presence of the reflective ground cover.

The upward PAR is shown in Figure 2, where data are reported both as absolute values (2a) and as percentage of the downward radiation (2b). Compared to the grassed alleys, the presence of reflective ground cover significantly increased the upward PAR regardless the height, although the highest effect was recorded in the bottom part of the canopy (Figure 2). Differences between the presence and the absence of the reflective ground cover was even larger when data are presented as fraction of incoming PAR (Figure 2 b).

Point-like measurements performed with the BF5 sensor in 2019 (Figure 3) showed a higher variability in incident total PAR distribution along the vertical axis than along the row (horizontal).

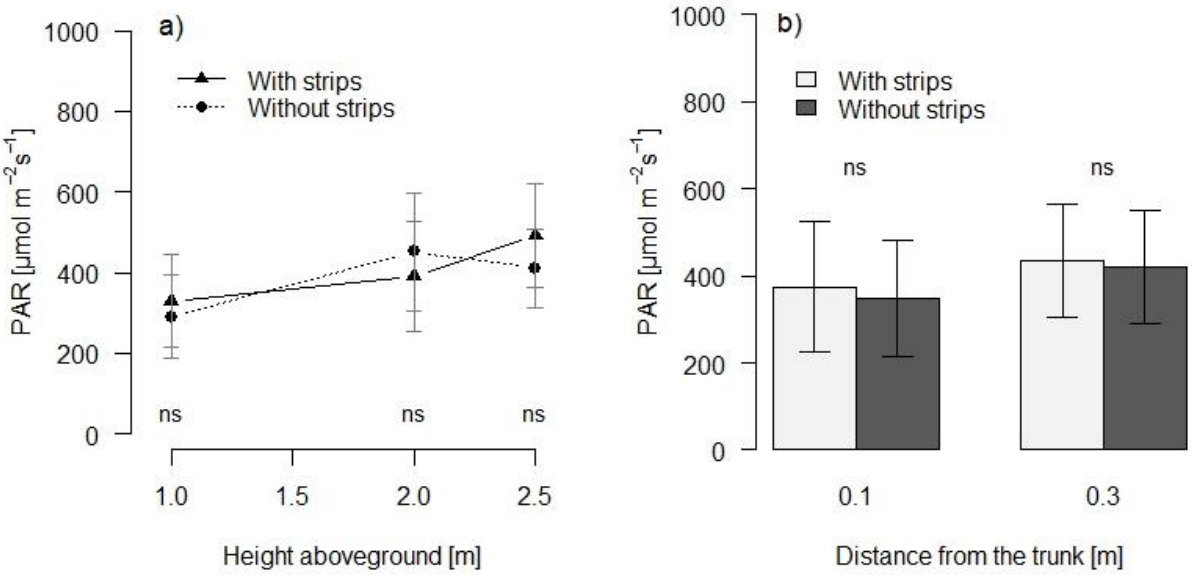

Figure 1. Total downward PAR distribution in the vertical **(a)** and horizontal **(b)** directions within the canopy, measured by the ceptometer on 12 September 2018 in the presence (with strips) and in the absence (without strips) of the reflective ground cover. Bars represent one standard deviation of the mean. ns = not significant difference (P>0.05) between with strips and without strips.

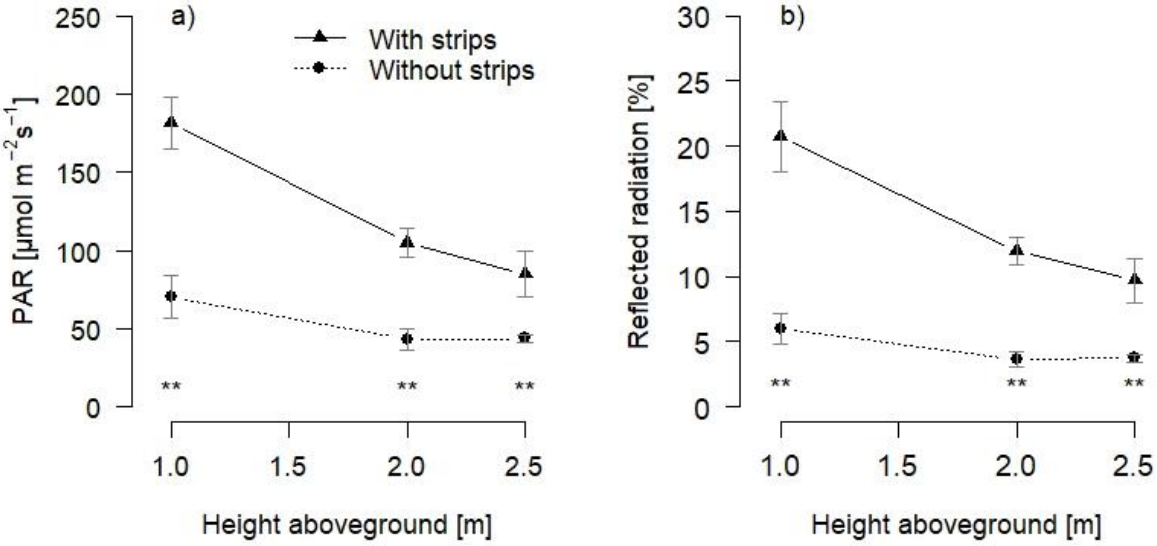

Figure 2. Upward PAR measured by the ceptometer inside the apple tree canopy as affected by the presence of reflective ground cover ('with strips') or by the grass ('without strips') in the alleys. The PAR data were reported as **(a)** original data or **(b)** as percentage of the downward radiation measured under the nets at the beginning of the measurements session (Table 1). Each point represents the average of the two distances from the trunk taken on 12 September 2018 between 10:15 and 11:45 (UTM +1). Bars represent one standard deviation of the mean. ** = significant difference between with strips and without strips at P<0.01.

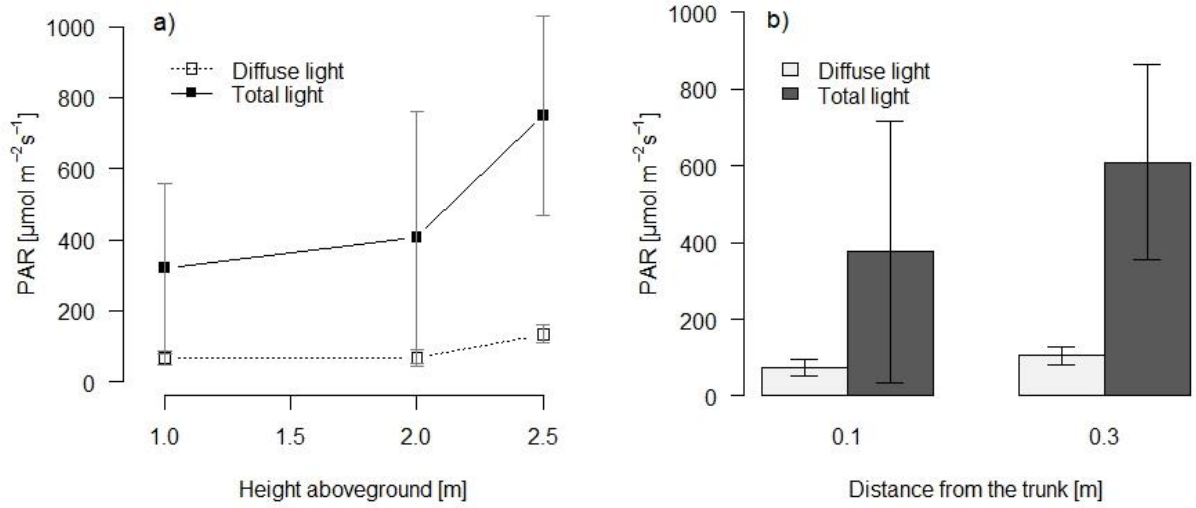

Figure 3. Vertical **(a)** and horizontal **(b)** distribution of diffuse and total downward PAR, measured on 16 September 2019 in the presence and in the absence of the strips, with a BF5 radiometer. Bars represent one standard deviation of the mean.

Diffuse PAR component varied inside the canopy less than total PAR, suggesting its better penetration inside the tree crown (Figure 3). The upward PAR component was clearly enhanced when the reflective strips were used; the effect was higher particularly at 1 and 2 m height above the ground (Figure 4). The PAR intensity around noon at 2 m height was on average 63.3 µmol quanta m^{-2} s^{-1} without reflective strips and 152.6 µmol quanta m^{-2} s^{-1} with reflective strips, while the effect of the reflective strip in comparison to the grassed alleys was rather low in the first two measurement periods (at 9:10 and at 10:45) (Figure 4, bottom). Differently from the downward PAR (Figure 3), the upward PAR was mainly made up by diffuse light (Figure 4).

As influenced by solar radiation intensity, nets, canopy interception, solar zenithal and azimuthal angles, and by the interaction with the reflective strips, downward and upward radiation showed a marked variability during the measurements.

It is noticeable the marked reduction in total (downward+upward) PAR intensity in the lower parts of the crown as observed at noon (Figure 5), when the tree row is parallel to the solar azimuthal angle. In this condition of self-shading by the tree crowns, the solar radiation in the lowest canopy levels was very low when reflective strips were not used. The presence of the reflective strips significantly increased the diffuse light reaching the canopy ($p<0.0001$) but did not significantly affect ($p=0.1103$) the total radiation. It should be considered that the downward PAR was the main component of the total PAR reaching the leaves.

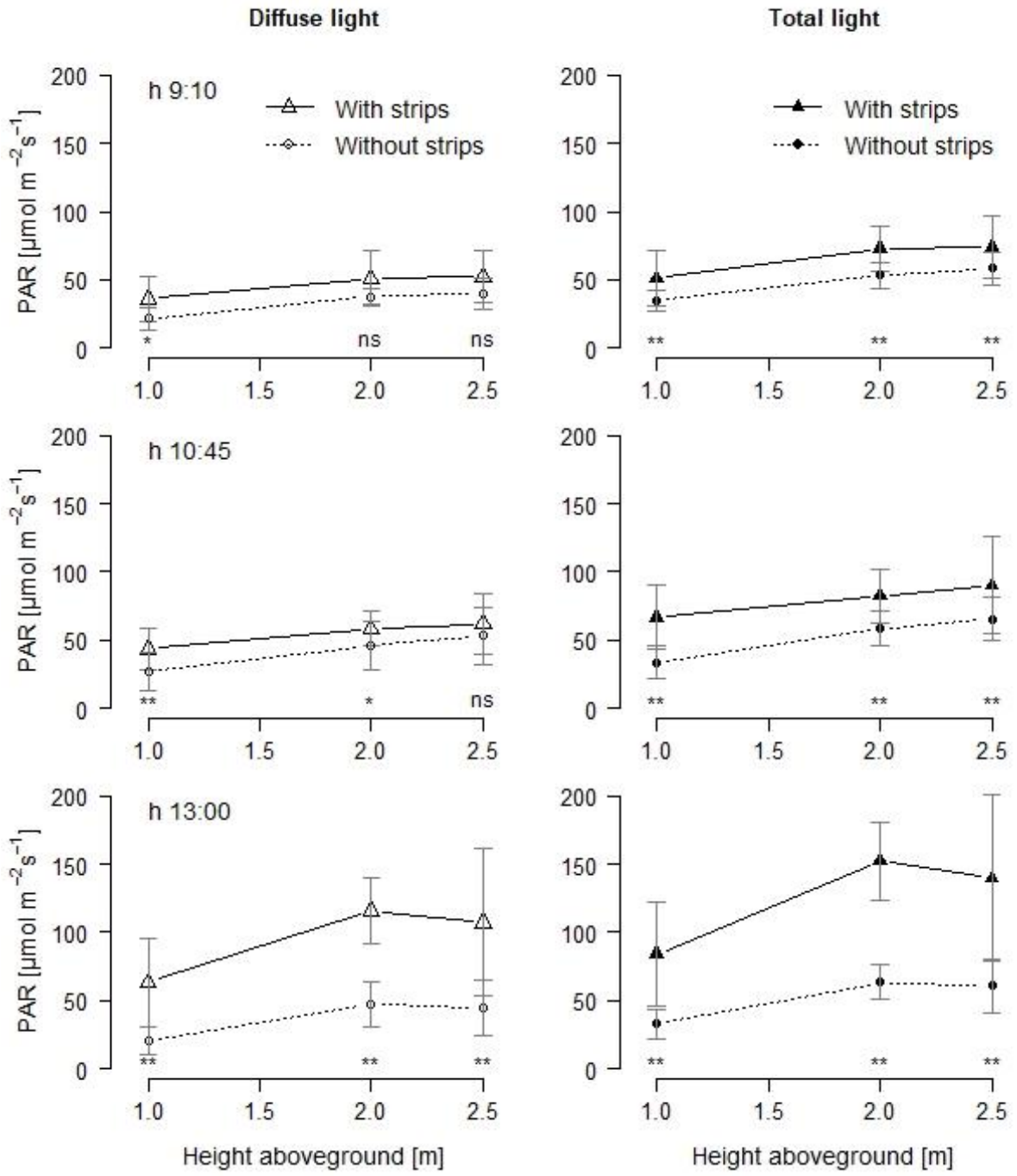

Figure 4. Upward diffuse (left) and total (right) PAR within the canopy at 9:10 am (top), 10:45 am (middle), and at 13:00 (bottom) on 16 September 2019. Bars represent one standard deviation of the mean. *, ** = significant difference between with strips and without strips at P<0.05 and 0.01, respectively. ns = not significant difference (P>0.05) between with strips and without strips.

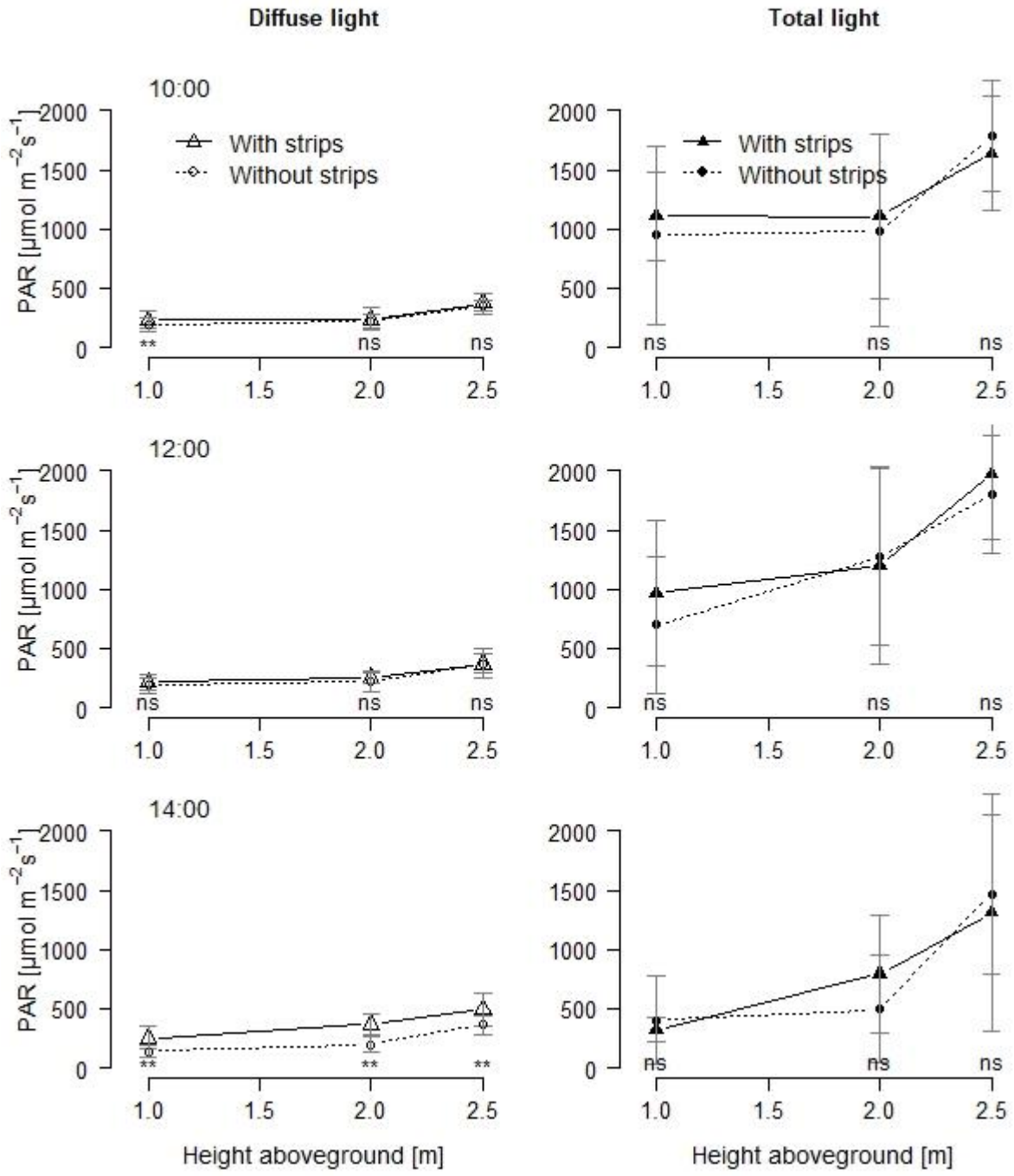

Figure 5. Total PAR (downward + upward) reported as diffuse and total light components at the three measuring times (9:00-10:00; 11.00-12:00; 13:00-14:00) in the presence (with strips= and absence (without strips) of the reflective ground cover on 16 September 2019. Diffuse light on the left; total light on the right. Bars represent one standard deviation of the mean. ** = significant difference between with strips and without strips at 0.01. ns = not significant difference (P>0.05) between with strips and without strips.

3.3. Frequency distribution of light intensities in absence and presence of reflective materials

PAR distribution within tree canopies when reflective strips were not present was always markedly bimodal (Figure 6 and Table 2). The level of bimodality decreased along the day from 9:10 to 13:00 regardless the presence of the reflective strips. At 13:00, the β value in the presence of the reflective ground cover was below the bimodality threshold. Most of the PAR intensities were generally below the threshold of 200 µmol m^{-2} s^{-1} (44% of measured occurrences) and 33% of the values recorded above >900 µmol m^{-2} s^{-1}. Only 23% of the values occurred between these values (200-900 µmol m^{-2} s^{-1}). Leaves located in the inner parts of the canopy represent a large portion of leaves and are predominantly in the shade. This feature is particularly evident when the sun was aligned along the tree row (60% of the leaves were in the shade, < 200 µmol m^{-2} s^{-1}). The presence of reflective strips improved the homogeneity of the light distribution within the canopy and the percentage of light conditions with intermediate PAR intensities (Figure 6).

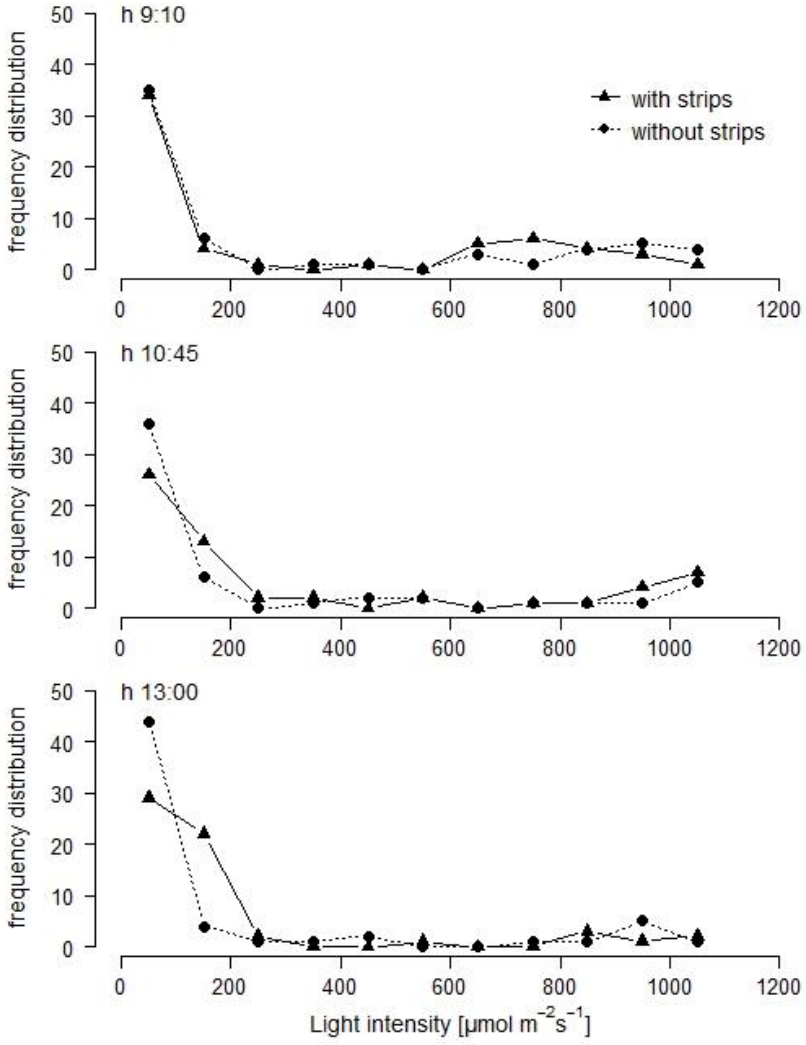

Figure 6. Average frequency distribution of total PAR (downward + upward) binned at 100 µmol m^{-2} s^{-1} light intensity with and without reflective materials at different times measured at (a) 9:10, (b) 10:45 and (c) 13:00 on 16 September 2019.

Table 2. Significance of the bimodal distribution of the PAR data measured on 16 September 2019. Following this computational procedure, β = 0.1 is the threshold discriminating unimodal (β <0.1) and bimodal (β >0.1) conditions.

Treatment	β value		
	Time of the day		
	9:10	10:45	13:00
With strips	0.229	0.202	0.087
Without strips	0.226	0.155	0.121

3.4. Light response curves of sun-adapted and shade-adapted leaves

In order to understand the photosynthetic response of the apple trees to the variable light conditions, we studied the light response curves of both light-adapted and shade adapted leaves (Figure 7 and Table 3). In particular, light adapted leaves reached a higher maximal photosynthetic rate (20.86 µmol CO_2 m^{-2} s^{-1}, Table 3) than shade adapted leaves (15.51 µmol CO_2 m^{-2} s^{-1}).

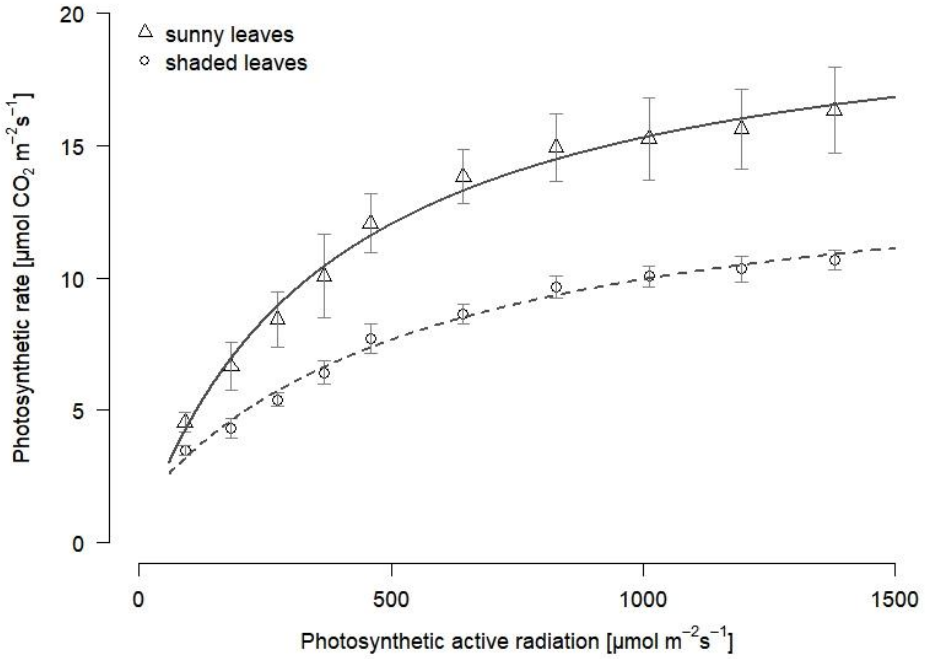

Figure 7. Photosynthetic light response curves. Triangles (continuous line): measured (modeled) Net photosynthesis (Pn) of sun-adapted leaves. Circles (dotted line): measured (modeled) Pn of shade-adapted leaves. Bars represent one standard deviation of the mean.

Table 3. Regression parameters for the photosynthetic response to light of sun and shade-adapted leaves.

Parameter	Coefficient	s.e.	p-value
Sun adapted leaves			
a	-0.055	0.013	0.003
b	-20.857	0.787	<0.001
c	0.173	1.110	0.881
Shade adapted leaves			
a	-0.024	0.005	0.002
b	-13.507	0.642	<0.001
c	1.298	0.566	0.055

4. Discussion

4.1. PAR distribution in the apple canopy

Downward PAR measured inside the canopies at different heights in two measurement days provided comparable absolute values in spite of the fact that different instruments were employed (Figures 1 and 3), although values were slightly higher in 2019. We speculate that two factors might contribute to explain this result. Firstly, the downward radiation at 10:45 was higher in 2019 than in 2018 (Table 1); secondly, the values obtained with the ceptometer are the average of PAR along a 80 cm long a line centered in the tree row and therefore includes light intensity values of both sides of the tree, including the side that is shaded during the morning.

The measurement technique applied in 2018 and in 2019 were different. The ceptometer deployed in 2018 provides an average PAR value that is representative of a transect within the canopy, providing information on the PAR reaching on average the leaves located on that transect. Point-like sensors (used in 2019) are more representative of the light reaching a leaf (even though their size is much smaller than leaf blade area). Being the light response curve non-linear (Figure 8), for the correct assessment of the amount of light received by the leaf and to model photosynthesis, it is necessary to measure the light intensity within a space of size similar to that occupied by the tree crown and not in a wider transect as in the case of the ceptometer.

Our measurements are not representative of the entire leaf population, but they provide a picture for the six measurements points inside the canopy. The description of the light intensities obtained with this technique highlights the presence of a bimodal distribution of light intensity and this suggests that part of the crown is under shade conditions, with light intensities lower than 200 µmol quanta m^{-2} s^{-1}, and a second, smaller, maximum of light intensity frequency around 1000 µmol quanta m^{-2} s^{-1}, representing around 90% of leaf light saturation. Reflective strips were able to alleviate this bimodality (i.e., the light was more evenly distributed in the canopy) only at noon, when the sun had the highest zenithal angle and the tree lines were aligned with sun direction, and the reflective strips were fully illuminated.

If the radiation intensities were at an intermediate level with respect to these two intensities, the photosynthesis would be higher, as indicated by the light response curve. In addition, it is noteworthy to mention that our results are representative of the period when reflective ground covers are laid to favour fruit color development, while in full summer, with a higher solar angle, the results could be different.

The use of shading nets and of reflective materials allows to decrease light excess and increase the diffuse light component, thus the potentially harvested light might be higher.

Meinhold et al. (2010 and 2011) have studied under laboratory and field conditions over a range of angles of reflectance the reflective properties of some reflective materials. Using a material with similar characteristics to that employed in this study, Meinhold et al. (2011) measured 42 to 60% PAR reflection at 1 m above ground in the middle of the alleyways under black anti-hail net on sunny days.

4.2. Vertical and lateral distribution of total and diffuse light in the tree canopy

One of the main goals of training and pruning fruit trees is to provide adequate radiation to all the parts of the canopy (Corelli Grappadelli, 2003). Ideally, light distribution inside the canopy should be homogeneous. Our data, however, have shown a high vertical variability in light intensity, with a considerable portion of the leaves in the lowest parts of the canopy standing predominantly in the shade. It should also be considered that the trees used in this experiment had a relatively low LAI and such effect would presumably enhance with denser apple tree canopies.

We observed an average 61% decrease in total downward PAR moving from 3 m to 1 m, and a modest horizontal variability, with a decrease of 19% moving from 0.3 m to 0.1 m distance from the trunk. The diffuse radiation component showed a smaller decrease (54%) along the same height gradient, and an 11% reduction moving from 0.3 m to 0.1 m distance from the trunk, confirming the higher capacity of diffuse radiation of entering the canopy. The exponential vertical decrease in the direct light from the top to the bottom of the canopy has been described before by Beer-Lambert-Buoguer law (Chandrasekhar, 1950; Monsi and Saeki, 2005). Their light extinction coefficient can be used to quantify the vertical light distribution within the canopy, while the diffuse light shows lower extinction coefficient than direct light as reported by Urban et al. (2012) and Li et al. (2014).

Previous studies also reported that the horizontal light distribution within the canopy is more homogeneous in case of the diffuse light (Acock et al., 1970; Li et al., 2014). The upward light was clearly enhanced when the reflective ground cover was used, and its effects were measured even at 2.5 m height. This can be explained by the reflection of the downward light by the canopy leafage. Zanotelli et al. (2019) found an albedo of 0.16 in a nearby, although older, apple orchard. This means that a fraction of around 16% of the downward light is redirected upward. This has to be summed to the PAR redirected upward from the ground (point measurements at midday indicated an albedo of 0.55 above the reflective strips and 0.10 above the soil).

We must recall that all the measurements were taken below the nets that reduced the downward light, but had little influence on the directionality of the light itself, with a negligible impact on diffuse light component. The amount of light transmitted through the nets was in the lowest part of range of what previously observed for a set of different shading nets, with some experimental types of nets, like the Zebra-nets, allowing a higher transmission (Protze et al., 2012).

4.3. Percentage of shaded and sunlit leaves within the canopy

In natural vegetation, leaves are traditionally categorized into sun and shade leaves (Corelli Grappadelli, 2003; Gu et al., 2002). This definition found a remarkable confirmation from our study on apple leaves. In fact, solar radiation measurements showed the existence of a bimodal distribution of light in most conditions. Depending in particular on solar azimuthal angle, and on tree row orientation, a considerable part of the canopy is in conditions of substantial shade. This amount of shaded leaves increases when the tree lines are aligned with the sun azimuth. In our experiment, rows had a North-South orientation and the maximum amount of self-shading took place at noon. In addition, the most efficient condition to use the reflective strips was observed during the same sun-tree line alignment,

when the strips are not shaded by the plants and receive direct light. Under such conditions, they reflect a considerable amount of diffuse light especially to the lowest part of the canopy.

4.4. Light response curve of sun and shade adapted leaves

The analysis of photosynthetic response of the apple leaves to light confirmed the typical C3 type behavior of apple plants to light (Blanke and Lenz, 1989). In both sun- and shade-adapted leaves, the response to light was almost linear at low light intensity. Then, with increasing light availability the light use efficiency decreases. At even higher light intensities, the increments in photosynthesis are progressively lower, but a full saturation was not observed. Ninety percent of the photosynthesis observed at 1500 µmol quanta m^{-2} s^{-1} was observed at 964 µmol quanta m^{-2} s^{-1} for sun-adapted and 1022 µmol quanta m^{-2} s^{-1} for shade adapted leaves, respectively. In case of high radiation load, sunburns and photochemical damages frequently occur (Asada, 1999; Niyogi, 1999; Kasahara et al., 2002). To prevent these damages, nets reducing the maximal amount of downward radiation can represent a suitable solution. In addition, it is worth noting that having intermediate light intensities values, instead of a combination of sun and shade conditions, would be favorable for plant photosynthesis, but the use of opaque nets and strips with a modest reflection capacity gives a contribution in the improvement of light conditions below the limits of significance.

4.5. Considerations on the sustainability of use of reflective strips

The use of a reflective ground cover, that reflects both PAR and UV light, was reported to stimulate anthocyanin biosynthesis in apple fruit skin (Andris et al., 1998; Layne at el., 2002) and to enhance the skin coloration of fruits located in the lowest part of the crown. Extensive studies on the use of reflective ground covers in the USA have concluded that these materials can significantly enhance not only fruit color, but also fruit yields (Schmidt et al., 2016). These studies did not ascertain, however, if the combined use of the nets and reflective strips can also favorably influence canopy photosynthesis and hence the quantity of the production. More comprehensive studies on these aspects have to be undertaken, with different combination of nets and strips tested in a perspective of economic (Meinhold et al., 2011) and environmental sustainability. These studies should also analyze the possible release of microplastics in the soil.

5. Conclusions

In our experimental conditions, the light distribution in the canopy was bimodal in most conditions, with a variable fraction of shaded leaves in the canopy, as a function of height above the ground, sun elevation and azimuth. The presence of a white reflective ground cover caused a slight improvement of the homogeneity of light distribution within the canopy, with a reduced bimodality in the light distribution at noon. We observed a significant increase in upward PAR coming from the reflective ground cover (mainly diffuse light) to max values of approx. +100 µmol quanta m^{-2} s^{-1}, in the lower part of the canopy (Figures 2 and 4). As most PAR derives from directly downward radiation, the reflective strips presumably enhanced only slightly photosynthesis in the internal parts of the canopy. In spite of the extensive research carried out on light relations in orchard, there is probably still space for research aimed at improving the light distribution inside the canopy, by taking advantage of an enhancement of the diffuse light intensity.

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