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Sun Protection for Fruit: Dynamic Agrivoltaics Reduces Apple Temperature and Sunburn Damage

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Abstract. Heatwaves are a risk to fruit tree yield and production. In this study, a dynamic agrivoltaic system was tested as a solution to protect trees from high temperatures by shading the fruits when irradiance and air temperature peak at their maximum values. The study was completed in an apple dynamic agrivoltaic system in France in 2022 and 2023. The agrivoltaic system was compared to a control without solar panels. The study was initiated in 2022 with measurements of microclimate (incident solar radiation and air temperature) and sunburn damage. In 2023, these measures were complemented with detailed measurements of fruit surface temperature and fruit growth. In 2023, fruit surface temperature was continuously measured for two control and two agrivoltaic trees using type T thermocouples (12 apples per treatment). Fruit diameter of 18 tagged fruit per treatment was monitored weekly. Air temperature at the agrivoltaic trees was lower compared to control trees due to a reduction of 50% in daily incident radiation. Sunburn damage was reduced for agrivoltaic apples in 2022 (control 13% *vs.* agrivoltaics 2%). In 2023, although there were low sunburn values for both the control and agrivoltaic apples, it was found that agrivoltaic apples were cooler than control apples. The maximal fruit surface temperature reduction during the study was 3.3 °C. Fruit diameter was the same across treatments. Dynamic agrivoltaic systems can be used to reduce apple fruit surface temperature and minimize the risk of sunburn when trees are shaded during periods of high irradiance and temperature.

Keywords: Climate Change, Fruit Damage, Fruit Protection, Heatwave, Malus Domestica, Shading Crops

1. Introduction

Apple sunburn is a physiological disorder caused by excessive solar radiation and high fruit surface temperatures [1]. Symptoms on apple fruit can range from white patches to dark brown burned spots depending on cultivar and environmental conditions. Sunburn can severely decrease fruit market value and reduce grower income [1]. A survey in WA state (USA) indicated that 98% of apple fruit growers declared being interested in protecting their orchards from sunburn [2]. Deploying nets in the last period of fruit growth (near to harvest time) has been proposed as a solution to protect apples from sunburn. Results show that sunburns were reduced because the shade of the nets reduced apple temperature [3]. The mean daily maximum fruit surface temperatures for trees that were netted were 2.5 °C cooler than those from trees without netting and the trees without netting had more than double the amount of fruit classified with severe sunburn damage [3].

Since panels in dynamic agrivoltaic systems can be steered to shade crops at the necessary periods, it would be logical to think that shading apple trees before harvest may also prove an effective technique to protect apples from sunburn. Although a previous three-year apple quality study (2019-2021) in a ‘Golden Delicious’ dynamic agrivoltaic system indicated that shading reduce air temperatures at tree canopy by 2°C [4], no information was reported for evaluation of sunburn damage and fruit surface temperature. The objective of this study was to start quantifying sunburn damage and fruit temperature of control and dynamic agrivoltaic apples in the ‘Golden Delicious’ dynamic agrivoltaic system.

2. Material and Methods

2.1 Experimental orchard

The experiment was carried out in an apple orchard (*Malus x domestica* Borkh.) located in the experimental station of La Pugère (Mallemort, France: 43.74°N; 5.125°E). The trees were planted in 2010. The ‘Golden Delicious’ variety was grafted on ’Pajam® 2 Cepiland’. Trees were trained to a centrifugal training system. The orchard had a north-south orientation (16° east), and it was composed of nine rows, two of which were considered border trees. Each row had a total of 60 trees. The distance between trees was 1.25 m within rows and the inter-row distance was 4 m.

In 2019, a dynamic agrivoltaic system was constructed above the orchard with 735 m^2 for the dynamic agrivoltaic area while preserving 1482 m^2 for the control [4]. The system consists of photovoltaic solar panels (PW2450F, Photowatt, France) positioned at 5.4 m height, above the trees. The solar panels can rotate +/- 90° from east to west using a one axis-tracker positioned on a south-north axis, allowing for complete shading of the trees or total exposure to sunlight depending on the requirements of the crop and environmental conditions. The solar panel width over the apple row was 1.7 m, covering 42.5% of the row surface when placed in a horizontal position. Both control and agrivoltaic trees were below an anti-hail net that reduced light by 10% (Figure 1). Previous reports demonstrated that apple trees could tolerate high levels of shading in the last period of fruit growth [5]. To test the capacity of protection from high solar radiation and temperature, agrivoltaic trees were shaded before harvest in 2022 and 2023. The agrivoltaic system was compared to the control without solar panels.

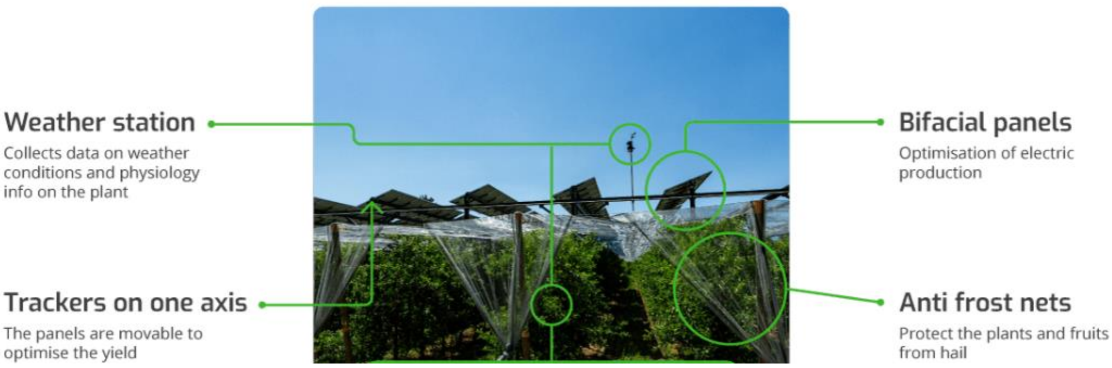

Figure 1. *General view of the agrivoltaic system with the main components: Solar panels mounted on a single axis tracker, anti-hail nets and weather station above the solar panels.*

2.2 Measurements

In 2022 and 2023, sensors to continuously determine the global solar radiation (pyranometer, SP110, Campbell Scientific, USA), air temperature and air humidity (thermo-hygrometer, CS215, Campbell Scientific, USA) and wind speed (anemometer 05103, Campbell Scientific, USA) were connected to a weather station (CR1000, Campbell Scientific, USA) outside the orchard. The weather station communicated automatically with the trackers of the agrivoltaic system and was used to determine the shading strategies. To determine microclimate at the tree canopy, the same variables were collected continuously with two additional weather stations (Wireless Vantage Pro2 Weather Station, Davis instruments, USA) installed in each treatment (below the nets for the control trees and below the nets and solar panels for the agrivoltaic area). The microclimate stations were installed in the central part of each treatment area and were tested for their accuracy before the installation by placing them in the same location for several days.

In 2023, the surface temperature of 12 fruits for each treatment was continuously measured using type T thermocouples (RS Pro type T, RS components, U.K) during the hottest months of the year. Two consecutive trees for the control and agrivoltaic treatment were selected in the central row of the orchard for the thermocouple installation (row number 4). For each tree, three thermocouples were pushed gently into the fruit as close as possible to the fruit surface in the east side of the canopy and another three in the west side of the canopy at different heights (low, medium, and high) (Figure 2). Since sunburns were evaluated on the whole harvest, fruits were chosen to be representative of most of the fruits that would be harvested later, therefore avoiding fruits in the most outer and most inner part of the canopy (Figure 2). The fruits were chosen between 90 and 190 centimetres high and within 100 centimetres close to the trunk in both east and west directions for each treatment (Figure 2).

Fruit growth was quantified in 2023 by monitoring weekly the diameter of 18 tagged fruits per treatment. These fruits were sampled in nine different trees located in row number 4 for the control and row number 3 for the agrivoltaic treatment.

Fruit sunburns were quantified at harvest time in 2022 and 2023. All fruits for ten experimental trees for each treatment were separated in two categories using a grading machine: marketable fruit and discarded fruit from the market. Then, the percentage of discarded fruits due to sunburn was quantified.

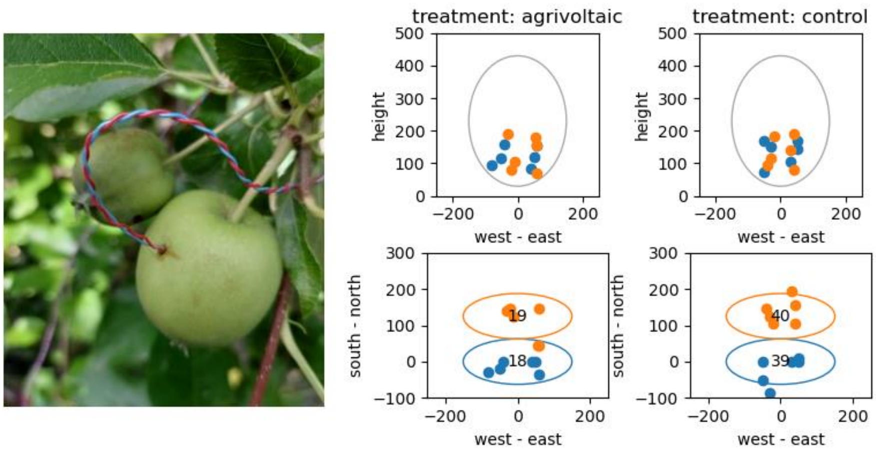

Figure 2. *Details of height and distance (in centimeters) from the trunk from south-north and west-east for 12 thermocouples for two consecutive trees for each treatment. Each tree for a given treatment is highlighted with a different color and annotated with their position within the row. The canopy is represented by an ellipse. Thermocouples were pushed gently into the fruit as close as possible to the surface as shown in the picture.*

3. Results and discussion

3.1 Weather conditions

In both 2022 and 2023, in the dynamic agrivoltaic system, shading was applied when incoming solar radiation and temperatures peak at their maximum values measured using the weather station located outside the orchard (Figure 3). Data collected from this weather station indicated that 2022 and 2023 were different in terms of maximum air temperatures (t_air max daily in Figure 3c) during the shading period. The first half of the period was hotter in 2022, and the second half was hotter in 2023 (Figure 3c, d). The daily irradiance remained similar on average between years (Figure 3a, b).

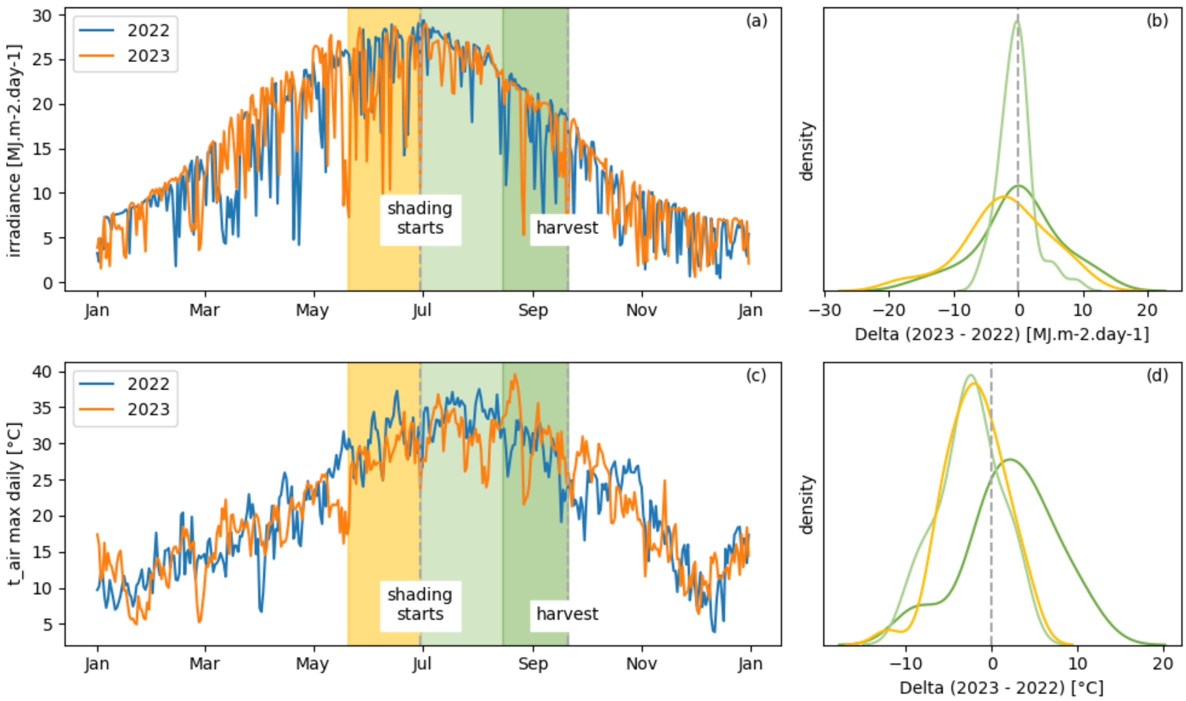

Figure 3. *Seasonal patterns of daily irradiance (a) and maximum daily air temperature (t_air max daily, c) collected from the weather station located outside the orchard in 2022 and 2023; and density plots with the difference between 2023 and 2022 (Delta) in irradiance (b) and t_air max daily (d) before and after the shading period (yellow period just before shading, light green just after shading, and dark green last shading period before harvest).*

3.2 Tree microclimate

There was a slight reduction of about 10% in daily incident light (DLI) due to the agrivoltaic structure before shading the trees with the solar panels (Figure 4a, b). The reduction in daily incident light was increased up to almost 50% after shading the trees (Figure 4a, b). Air temperature for agrivoltaic trees was lower than for the control trees due to the reduction in DLI while it remained similar before shading (Figure 4c, d). The microclimate modifications induced by shading are consistent with a previous study of three years (2019-2021) in the same orchard [4]. Similar results have been observed in a dynamic agrivoltaic system in grapevine [6]: during heatwaves, air temperature of vines under panels was lower than for control vines. Now, it is therefore well documented that agrivoltaic systems alter how heat is absorbed, stored, and released [7], affecting the microclimate surrounding the crops, indicating the potential of agrivoltaic system to maintain crops under less stressful conditions.

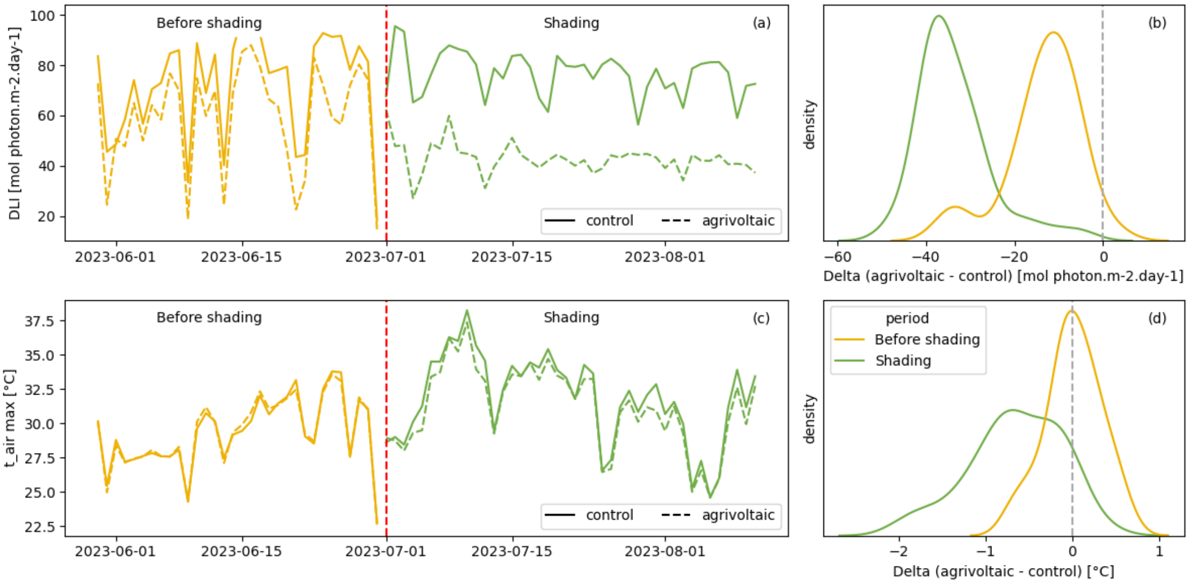

Figure 4. *Seasonal patterns of daily incident light (DLI, a) and maximum daily air temperature (t_air max, c) in the control and agrivoltaic treatments in 2023 before and after shading the trees using microclimate stations; and density plots with the difference between treatments (Delta) in DLI (b) and t_air_max (d) before and after the shading period.*

3.3 Fruit surface temperature

Due to the changes in the microclimate of the trees, agrivoltaic apples were cooler than control apples when they were monitored in 2023 (Figure 5a). The difference in temperature between agrivoltaic and control apples (see Delta t in Figure 5a) increased during the shading period, indicating a direct capacity of dynamic agrivoltaic systems to reduce fruit temperature when trees are shaded. The mean reduction of maximal daily temperature was about 2.1 °C (see Delta t in Figure 5a) with a maximal reduction of 3.3 °C during the study. In a recent study, the mean daily maximum fruit surface temperature for trees that were netted was 2.5 °C cooler than without netting [3]. This indicates that the protective capacity offered by shading nets can be extrapolated to agrivoltaic systems.

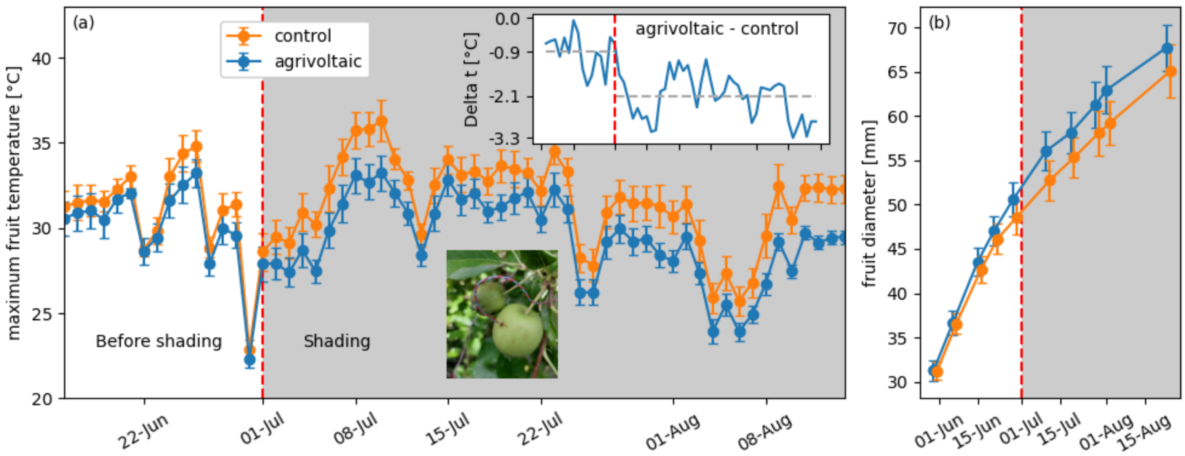

Figure 5. *Seasonal patterns of maximum fruit surface temperature (a) and fruit diameter (b) for agrivoltaic and control apples in 2023. Values are means with confidence interval at 90%. Fruit temperature, N=12. Fruit diameter, N=18. 'Delta t' indicates the difference in maximum fruit surface temperature between agrivoltaic and control apples. The vertical red line marks the date when trees were shaded.*

3.4 Sunburn damage

Fruit discards due to several disorders were higher in the control area than in the agrivoltaic area in both experimental years (Table 1). In 2022, sunburn damage was high for control trees (13%) and was reduced for agrivoltaic apples down to values of 2% (Table 1). In 2023, sunburn damage was low for the control treatment (1%) and the agrivoltaic treatment (0%) (Table 1). As previously reported in multiple studies, it could be difficult to establish a direct link between the environmental conditions of the year (Figure 3) and sunburn damage in apple (Table 1). Other factors such as fruit adaptation to a gradual increase in temperature, the time of exposure of fruits to solar radiation and the water status of the trees may be also important factors explaining differences between years [8]. Other indirect factors such as relative humidity, air movement and various cultural practices may also affect the incidence and severity of sunburn [8]. There are still many inconsistencies in correlating ambient air temperatures and fruit surface temperatures to sunburn values [3]. The year-to-year differences of fruit surface temperature and sunburn damage levels reported in previous studies indicates that the physiological responses of apple fruits to heat need to be more closely studied [3]. We expect that further monitoring in the coming years will provide a better understanding of sunburn responses in agrivoltaic systems. Research should not end with visual observations of sunburn at harvest. While the response to solar stress begins in the orchard, it continues during the cold chain being the principal source of annual apple crop loss reaching approximately 10-25 % in many of the highest production regions worldwide [9]. Future studies of sunburn protection with agrivoltaics should also incorporate sequential changes during cold air storage in response to sun exposure.

Table 1. *Fruit discards due to several disorders and sunburn in 2022 and 2023. Each value is obtained using all the fruit harvested for ten trees in each treatment.*

Variable	**2022**		**2023**	
	control	agrivoltaic	control	agrivoltaic
Fruit discards due to several disorders (%)	30%	21%	39%	20%
Fruit discards due to sunburn (%)	13%	2%	1%	0%

3.5 Fruit growth

The microclimate of the trees may have had consequences on fruit growth. Any technique to protect fruit from high temperatures should also maintain fruit growth to avoid negative impacts on yield and therefore growers' incomes. In 2023, fruit diameter was not reduced by shading the trees before harvest (Figure 5b). The maintenance of fruit growth under shading conditions has been previously reported in a prior three-year study in the same orchard [10] and in other studies in apples that applied severe shading using nets [5].

4. Conclusions

This study evaluated the capacity of dynamic agrivoltaic systems to protect crops from high radiation and temperature. It complements previous studies on the capacity of protection of dynamic agrivoltaic systems from climate change including frost and drought protection in the orchard [11, 12]. To protect from solar stress, the photovoltaic panels of the dynamic agrivoltaic system were positioned to shade the trees when incoming solar radiation and temperature peak their maximum values in 2022 and 2023. When the study was initiated in 2022, 13% of control apples had sunburn damage while only 2% of agrivoltaic apples suffered from sunburn. These first results indicated that agrivoltaics can be used to reduce the risk of sunburn when shading is applied during the hottest months of the year. In 2023, when the study was complemented with fruit surface temperature measurements, it was found that agrivoltaic apples were cooler than control apples. The maximal reduction during the study was 3.3 °C. In 2023, although the sunburn damage was lower than in 2022 (1% for the control and 0% for the agrivoltaic apples), the study indicates that shading apples during high radiation and temperature periods is an efficient technique to reduce the temperature of apples. Besides this capacity of fruit protection, fruit growth was not impacted by shading the trees. These results may inform fruit growers and encourage them to implement dynamic agrivoltaics in their orchards as an alternative to shading nets. We expect to collect similar data in the coming years to have a better understanding of apple sunburn responses in agrivoltaic systems.

Data availability statement

The data of this study is confidential.

Author contributions

GL, AP, VH, VL, and MB: Investigation. GL, VH, AP, JC, SP and PJ: Data curation, Writing – original draft. DF: Validation, Project administration.

Competing interests

The authors declare that they have no competing interests.

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