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Protecting Flowers of Fruit Trees From Frost With Dynamic Agrivoltaic Systems

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Abstract. Spring frost is a risk for fruit tree production. In this study, a dynamic agrivoltaic system (AV) was tested as a solution to protect trees from frosts. The study was done in a nectarine AV in France in 2022 and 2023. The AV plot was paired with an adjacent control plot without panels. Air temperature nearby the trees was measured continuously with thermo-hygrometers each year. In 2022 and 2023 frost sensors to mimic organ temperature were also used. In 2023, bud temperatures were continuously measured during bloom. Frosts during bloom were observed in 2022 and 2023 but only the 2022 frost was associated with flower damage. Solar panels were positioned in horizontal position during the nights with frost. Night air temperature nearby the AV trees was warmer in comparison with control trees (increases between 0.27 and 0.47 °C). An increase between 0.25-1.29 °C was also observed for frost sensors and between 1.61-1.69 °C for the flower buds. Phenology was similar between control and AV trees. In 2002, 35% of control flowers were injured during frost while less than 10% were injured in the AV. We conclude that agrivoltaics can be used to protect flowers from frost.

Keywords: Climate Change, Flower Damage, Frost Protection, Nectarine, Organ Temperature, Spring Frost

1. Introduction

Freezing temperatures during spring can damage the flowers on the tree and any potential fruit production from those flowers could be lost. Consequently, spring frost is a risk for fruit tree production in temperate regions [1]. Frost damage occurs when the ambient temperature drops below a stage-specific critical threshold, that can vary between -6 °C and -1 °C depending on the crop and phenological stage of flower buds' development [2]. Another important consideration is the type of frost. Frost can be classified as advective or radiative. Advection frost occurs when a large, cold, dry air mass moves into an area with strong winds. Radiation frosts, occurs when a local cold air mass settles in an area with little wind or clouds [2]. For advection frost, management systems provide little benefit. However, management practices can minimize frost damage for radiation frosts [2]. Several methods exist to protect fruit trees from spring frost including water spraying, heating devices, air ventilation, use of chemicals and anti-frost nets. AV is another solution. As reported for shading screens stretched horizontally above the ground [3], we hypothesised that solar panels positioned in a horizontal position during the night with radiation frosts may reduce the loss of long-wave radiation from the ground to the sky during the night and thus keep the temperature of the plants under the panels at a higher temperature than ambient. If so, AV may be effective in reducing the risk of frost damage. The objectives of this study were: 1) to determine if AV can increase the temperature nearby the tree and flower buds during radiation frosts, and 2) to determine if this increase in air temperature during frost is enough to reduce the damage to flowers of fruit trees. We expect that this study will be useful to illustrate one of the services that agrivoltaics can provide for the agricultural sector.

2. Material and Methods

2.1 Experimental orchards

The frost study was done in a nectarine AV site constructed by Sun'Agri in France [4]. The photovoltaic structure was constructed in 2022 in Étoile-sur-Rhône above a mature 'Kinolea' orchard. The orchard consisted in 1725 m^2 for the AV and 1500 m^2 for the control (Figure 1) [4]. To protect trees from radiation frost, solar panels were placed in horizontal position during the nights when temperatures were below 5 °C. The orchard was not complemented with any other frost protection system, except for the first night with frost in 2022, when anti-frost candles were additionally used. This technique was no longer used afterward due to its high cost.

Figure 1. View of the 'Kinolea' nectarine orchard during bloom. Contrary to the picture, panels were in horizontal position during the night with frosts.

2.2 Tree phenology

Because freezing resistance is dependent on tree phenology [2], flowering phenology was recorded for both control and AV trees by visual estimation according to the BBCH scales for nectarine [5]. A single value was recorded for each treatment (control and AV) considering all the trees of each treatment. For this study we present the dates of bloom.

2.3 Air and organ temperature

Air temperature nearby the trees was measured continuously (every 30 seconds) during the 2022 and 2023 season with two thermo-hygrometers placed inside radiation shields in the central row of trees for one control tree and two AV trees. The sensors were placed close to the canopy of trees at 1.80 m height (Aquafox, Agralis, France) (Figure 2A). Frost sensors designed to mimic organ temperature (Sf-110, Apogee Instruments, Inc., USA) were also installed for one control and AV trees in 2022 and 2023 (Figure 2B). Detailed measurements of flower bud's temperature were performed in 2023. Bud temperatures were continuously measured during bloom period for two control and AV trees using thermocouples (RS Pro type T, RS components, U.K) (Figure 2C). Three thermocouples were positioned in the east side and another three in the west side for each tree at three different heights (low, medium, and high). Therefore, a total of 24 buds were monitored. Each thermocouple was pushed gently into the flower bud during stage C as previously done by [6]. The thermocouples remained into the nectary ultrastructure as flowers developed until they dropped in stage G (petal fall). The coherence of thermocouples was tested in the laboratory just before the installation using as reference melting ice and boiling water in a container to allow temperature homogeneity. The test indicated that the maximum difference between sensors was around 0.4°C.

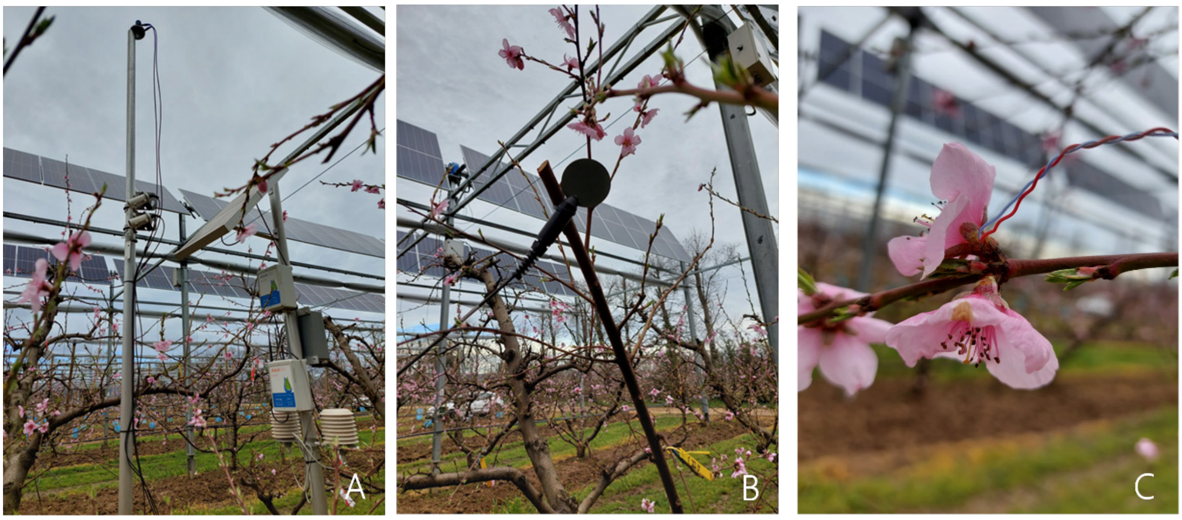

Figure 2. Different methods used to identify frost events in nectarine: thermo-hygrometers to measure air temperature nearby the trees (A), frost sensors to mimic organ temperature (B), and thermocouples inside flower buds (C).

2.4 Flower injury

A protocol to determine the percentage of frozen flowers was elaborated in case a frost occurred. All the flowers for 16 shoots for control and 32 shoots for the AV would be destructively sampled after a frost. All the flowers would be sampled at a height between 1.50 and 1.90 m. Flower damage evaluation was only necessary in 2022.

3. Results and discussion

3.1 Dates of bloom and frost occurrence

Bloom in control trees started the 10th and 11th of March in 2022 and 2023, respectively. A delay of one day between treatments was observed in 2022 while the same date was observed in 2023. We can therefore consider that both AV and control trees were in a similar phenological stage during the frost periods and that there were no interactions between the damage of flowers and a potential delay of phenological stage during the frosts (Table 1). This is consistent with other studies were the flowering date hardly varied with shading [7, 8].

Table 1. Dates of bloom and frosts events for 'Kinolea' nectarine.

Year	Bloom date Control	Bloom date Agrivoltaics	Frost events
2022	March 10	March 11	March 6 to 9, March 23 to 24
2023	March 11	March 11	March 6 to 7, March 16

Several frosts events were observed (Table 1) but only the frosts between the 6th and 9th of March in 2022 caused damage in the flowers.

3.2 Air and organ temperature

Solar panels placed over crops alter how heat is absorbed, stored, and released [9], affecting night temperatures. In this study, air temperature at night nearby AV trees was higher than for control trees during the frosts in 2022 (Figure 3) and 2023 (Figure 4). On March 9, 2022, it was observed that the temperature of the air got up during the night due to anti-frosts candles while the natural pattern is a decrease until sun rise (Figure 3). The candles raised air temperature by 2 °C. The effect of AV on warming was estimated at 0.44 °C. The other days no anti-frosts candles were lit, and it was still observed that air temperatures around control trees were consistently lower throughout the night (Figure 3, 4). This is consistent with other AV studies in apple [10]. These results also agree with [9], where night temperature of crops increased by 3-4 °C in crops below solar panels. The differences of the absolute values between experiments can be explained by the different sensors used in each experiment, the environmental conditions during the frost, the shading system used and the specific characteristics of the field.

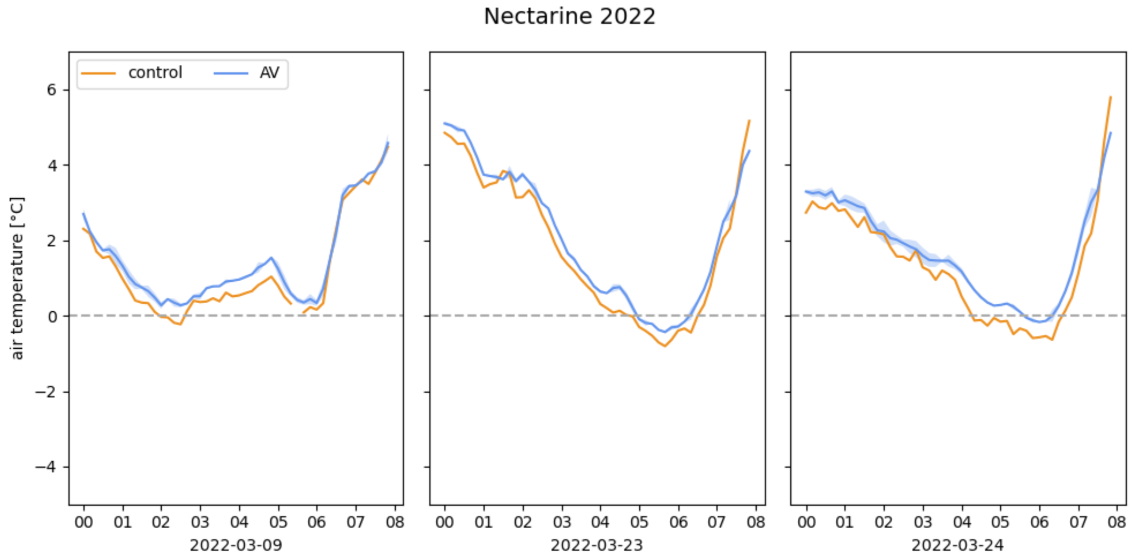

Figure 3. Air temperature at night nearby control and AV nectarines during the 2022 bloom period. Each curve is the mean value of two thermo-hygrometers for control and four thermo-hygrometers for AV trees. On March 9, anti-frost candles were used in the orchard explaining the increase in temperatures at the middle of the night (ca. 02:30).

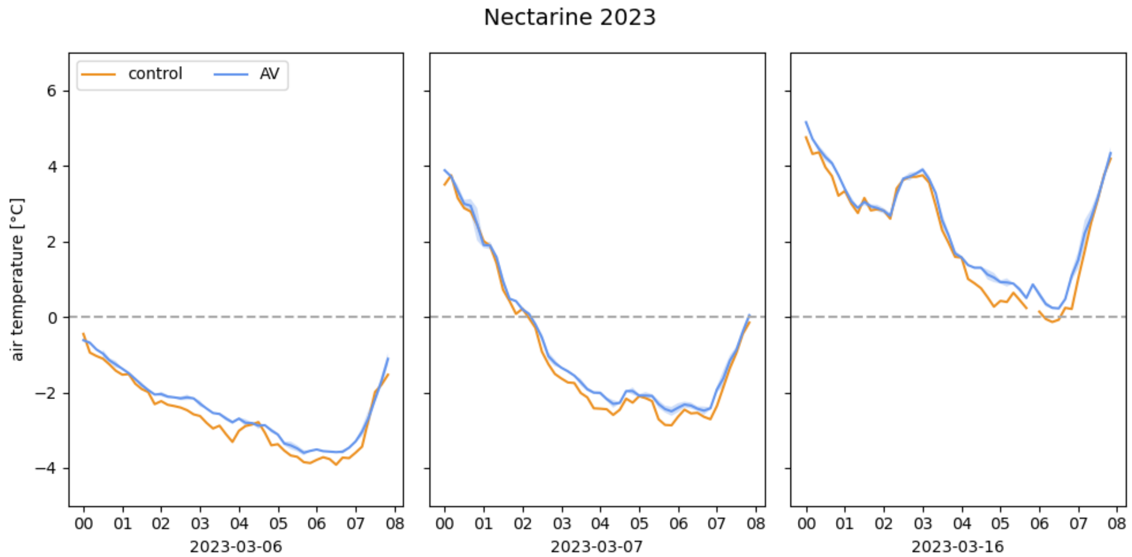

Figure 4. Air temperature at night nearby control and AV nectarines during the 2023 bloom period. Each curve is the mean value of two thermo-hygrometers for control and four thermo-hygrometers for AV trees.

Frost sensors provided a trend similar to air temperature, but the values were lower in comparison with air temperature (e.g., year 2023 in Figure 5). This agrees with studies that indicated that organ temperature drops at night to lower levels than air temperature [3]. The measurements of flower buds confirm the maintenance of higher temperatures during the night with frosts in AV (Figure 6) and the lower values than air temperature (Figure 6). The highest differences between control and AV were observed in the flower buds (Table 2). Deployment of protective devices in the case of frost could be more effective if they are triggered by organ temperature and not by air temperature [3].

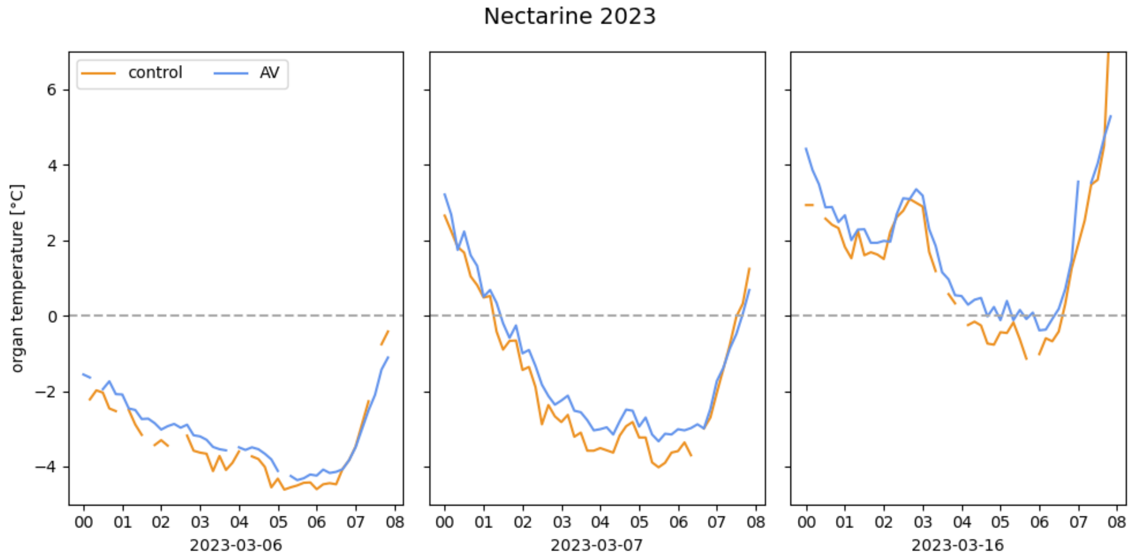

Figure 5. Estimation of organ air temperature using a frost sensor that mimic organ temperature nearby control and AV nectarine trees during the 2023 bloom period.

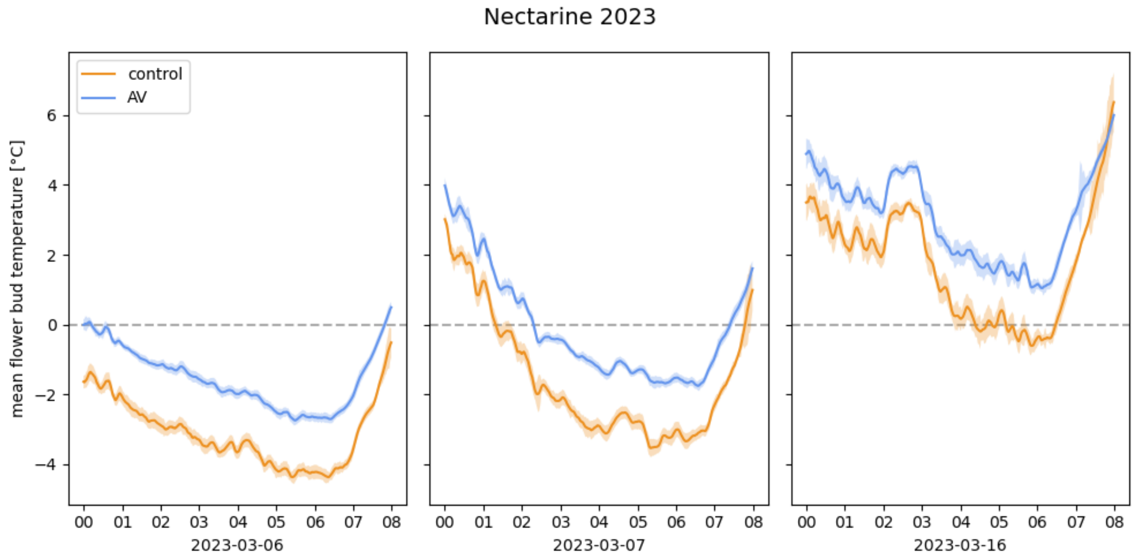

Figure 6. Hourly patterns of the temperature of nectarine flower buds throughout the bloom period of 2023 for control and AV trees. Each curve represented the mean value of 12 thermocouples. Standard deviation is represented as shaded bands around the mean values.

3.3 Flower injury

As well as for shading screens stretched horizontally above the ground [3], solar panels were found effective in reducing the risk of frost damage in a previous study in apple [7]. AV trees produced 20 t/ha and control trees 10 t/ha, whereas the expected yield was 40 t/ha [7]. In our study in nectarine, the percentage of frozen flowers after the first event of frost in 2022 was higher in control trees than AV trees (Figure 7). Despite the frost, crop loads for both control and AV trees were still too high for commercial purpose and fruit thinning was still required.

Table 2. Minimal temperature observed during three nights with frost in 2022 and 2023 with several methods (thermo-hygrometers to measure air temperature nearby the trees, frost sensors to mimic organ temperature, and thermocouples inside the flower buds) for control and AV in nectarine. n.a.: data not available.

	2022			2023		
Method	**Minimal Control**	**Minimal AV**	**Difference AV-Control**	**Minimal Control**	**Minimal AV**	**Difference AV-Control**
Day 1						
Thermo-hygro	-0.23	0.21	0.44	-3.91	-3.64	0.27
Frost sensor	-1.72	-0.43	1.29	-4.61	-4.36	0.25
Thermocouples	n.a.	n.a.	n.a.	-4.57	-2.78	1.67
Day 2						
Thermo-hygro	-0.81	-0.46	0.35	-2.87	-2.58	0.29
Frost sensor	-1.82	-1.17	0.65	-4.02	-3.33	0.69
Thermocouples	n.a.	n.a.	n.a.	-3.76	-1.86	1.90
Day 3						
Thermo-hygro	-0.64	-0.17	0.47	-0.13	0.21	0.34
Frost sensor	-1.39	-0.85	0.54	-1.14	-0.39	0.75
Thermocouples	n.a.	n.a.	n.a.	-0.72	0.89	1.61

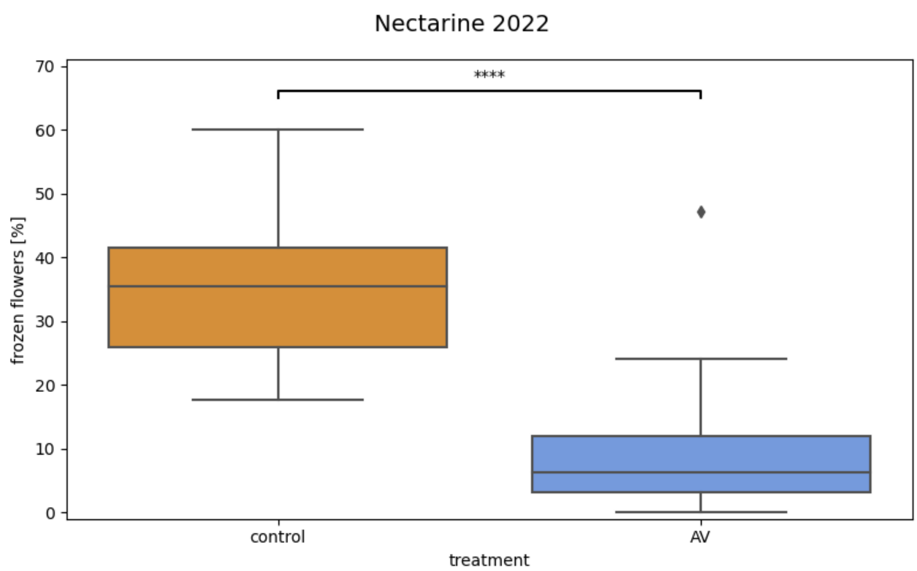

Figure 7. Percentage of flower injury after a frost event in nectarine for control and AV trees in 2022. Abbreviations from python scipy Kruskal test: ****: significant at p <0.0001.

4. Conclusions

Several frosts occurred during bloom in a nectarine orchard in 2022 and 2023. For the AV treatment, the solar panels covering the plot were steered in a horizontal position during the night with frosts. The AV maintained a higher air temperature at night nearby the trees than the control. This result was similarly observed for sensors that mimic organ temperature and organ temperature measured with thermocouples inside the flower buds. While floral phenology was similar between AV and control trees, less flower injuries were observed in AV following the frost event of 2022. The protection can be therefore linked to AV itself and not to a change in the phenology. While primarily developed to protect crops from the effects of heatwaves linked to climate change, AV can also be used to protect flowers from frost. According to climate projection models, despite global warming, frost events will persist until 2100 [11] so agrivoltaism can be a useful protective system. Also, because organ temperature was lower than air temperature and the highest differences between control and AV were observed for the temperature of flower buds, protective devices such as solar panels in the case of frost could be more effective if they are triggered by organ temperature and not by air temperature.

Data availability statement

The data of this study is confidential.

Author contributions

GL, VH, YM, and YE: Investigation. GL, 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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