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Effects of Dynamic Agrivoltaics on Containerized Raspberry Plants: Results of the First Season

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Abstract. Raspberries need to be protected from various stresses (radiative, thermal, hydric), and the Sun'Agri dynamic agrivoltaic system (DAV) could be a more sustainable solution than the plastic tunnels currently in use. Compagnie Nationale du Rhône (CNR) started a three-year experiment in 2023 to compare a dynamic agrivoltaic system (combined with insect proof nets) with a plastic tunnel serving as a control (CTL) in Dardilly (France) using 'Kwanza' raspberry containerized plants. The first year of experimentation revealed similar cumulative daily light integral between the two treatments over the growing season despite different patterns within the day. The protection from the DAV reduced mean air temperature by 1.8°C and increased mean relative humidity by 7.3% in comparison to the CTL. That improvement in the micro-environment was even more pronounced in the container substrate temperature. Daily maximum substrate temperatures were reduced by 5°C. The number of days reaching 35°C, that is considered deleterious for raspberries, was observed only four days in the DAV treatment versus 27 days in the CTL treatment. The less stressful micro-environment in the DAV was associated with water savings of 41%, increases in marketable yields and fruit weight of 32% and 39%, respectively. Satisfactory fruit quality was observed for both treatments. Two additional years of research will be performed to have a better understanding of raspberry performance cultivated in DAV.

Keywords: Shading, Berry, Micro-Environment, Yield, Quality, Water Saving

1. Introduction

Raspberries are very sensitive to thermal, radiative and water stresses. Their cultivation already necessitates a lot of care and is currently performed in tunnels to protect the crops from the elements [1]. Loss of yield has already been observed due to heat waves and their impact is expected to increase with climate change [2]. In this context, dynamic agrivoltaics has demonstrated its effectiveness to protect fruit trees [3]. However, the impact of this dynamic shading solution on raspberry yield and quality components needs to be assessed. With this in mind, Compagnie Nationale du Rhône (CNR) in France has undertaken an experiment "Les Parcelles du Futur" between 2023 and 2025 with the Horticultural High School of Dardilly and Sun'Agri to assess the impact of dynamic agrivoltaic (DAV) on several crops, including raspberry. The objectives of this experiment are to compare DAV and plastic tunnels in terms of micro-environment, irrigation water supply, yield, and fruit quality.

2. Material and Methods

2.1 Study site and experimental set-up

The research site is located in Dardilly, France (45°48'53"N 4°45'54"E). The dynamic agrivoltaic (DAV) system was established at the end of 2022 on an area of 783 m2 with dynamic panels mounted on 1-axis trackers. Each row of panels is spaced 4.5 m apart and located approximately 4.5 m above the ground. The DAV system consists of seven rows of trackers, each composed of bifacial monocrystalline photovoltaic panels (DM450M6-B72HSW, DMEGC Solar, China) oriented in the north-south direction for a total installed power of 150 kWp. The ground coverage ratio (GCR) of the DAV system is 46%. Trackers are electrically controlled and can be tilted by +/- 90° from east to west according to a steering policy based on sun position and plants' needs.

This study was carried out in 2023 on containerized raspberry plants (*Rubus idaeus* L. 'Kwanza'). 'Kwanza' is a late primocane long cane variety. The raspberry seedlings were planted in 10-L containers in a substrate (30% of blonde peat 10-25mm, 30% of blonde peat 0-20mm, 30% of wood fibers, and 10% of coarse perlite), with one cane per pot at the end of April. After a month in the greenhouse to ensure good root development of the young plants, the containers were installed early June in the two experimental treatments with a density of two containers per linear meter. Hydroponic-type mineral nutrition was used with the delivery of all fertilizing elements through drip irrigation. After analysing the water (pH = 7.7), the following inputs were added to reach a target pH of 5.8 during the vegetative phase: 140 $mg.L^{-1}$ of $N\text{-}NO_3^-$, 126 $mg.L^{-1}$ of $H_2PO_4^-$, 137 $mg.L^{-1}$ of K^+, 140 $mg.L^{-1}$ of Ca^{2+}, and 36 $mg.L^{-1}$ of Mg^{2+}. During the production phase, the following inputs were applied: 168 $mg.L^{-1}$ of $N\text{-}NO_3^-$, 116 $mg.L^{-1}$ of $H_2PO_4^-$, 235 $mg.L^{-1}$ of K^+, 120 $mg.L^{-1}$ of Ca^{2+}, and 36 $mg.L^{-1}$ of Mg^{2+}. Irrigation was based on tensiometric thresholds and differentiated between the two treatments.

The DAV treatment was characterized by 363 plants in eight rows. A typical anti-hail and insect-proof net with a shading rate of 25% was deployed in the DAV treatment on 2023-07-05 (*Figure 1, b*). The steering system of the solar panels allows switching to anti-tracking mode (panels parallel to the sun's rays) to minimize shading on the raspberry plants, or to solar tracking mode (panels perpendicular to the sun's rays) to maximize shading on the raspberry plants. Between planting (May) and flowering (August), the panels were in anti-tracking mode to ensure proper development of the vegetative part, with a switch to solar tracking if the temperature was too high. Between flowering and the end of harvesting (end of October), the panels remained in anti-tracking mode, switching to solar tracking if the temperature or radiation levels were too high to protect the fruits.

The control treatment (CTL) consisted of two plastic tunnels, to represent growers' current practices, covering an area of 200 m^2 with 135 containers in two rows (*Figure 1, a*). These tunnels, with a light transmission of 91% were whitened (ReduSol, ReduSystems, Netherlands) with a backpack sprayer and closed at the start of fruiting.

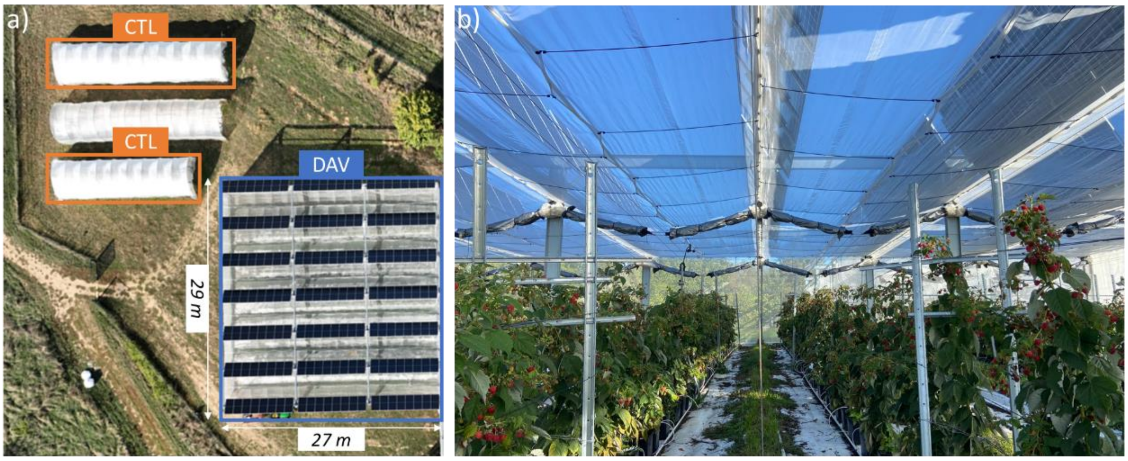

Figure 1. *a) Aerial photo of the experiment with the two treatments (control tunnel: CTL and dynamic agrivoltaics: DAV), b) Photo of raspberry plants under the DAV.*

2.2 Measurements

Weather data including air temperature, solar radiation, relative humidity, wind speed, and precipitation, were continuously collected using a weather station (6820OV, Davis Instruments, CA, USA) located close to the DAV and the tunnel to measure the outdoor climate and control the solar panels. The micro-environment underneath the CTL and the DAV was measured using a mast equipped with sensors, including an anemometer (6410, Davis Instruments, CA, USA), a thermo-hygrometer (6410, Davis Instruments, CA, USA), and a quantum sensor (SQ202XSS, Apogee instruments, UT, USA). Micro-environment variables were measured every five minutes. In addition, a temperature sensor (6477, Davis Instruments, CA, USA) and three tensiometers (Watermark 6440, Davis Instruments, CA, USA) were positioned in the substrate at a depth of 10 cm in both treatments to measure substrate temperature and substrate water tension in raspberry containers.

For quality and yield measurements, two replicates of 12 experimental plants were sampled in the CTL and three replicates in the DAV to represent the largest size and heterogeneity of this treatment. Harvesting was carried out and measured per plant every two or three days between September and the end of October, following the commercial criterion of easy detachment of the fruit from the receptacle [4]. At each harvest and for each replicate, unmarketable fruits (heterogeneity of colour, unhealthy or deformed fruit) were weighed and counted as well as marketable fruits. Quality parameters (fresh mass, sugar content, and pH) were measured on 30 mature fruits randomly selected per replicate on September 18 when the harvest was abundant. Each sampled raspberry was weighed. Individual fruits were blended to measure their sugar concentration (°Brix) with a refractometer (HI96800, Hanna Instruments, USA) and pH using a pH meter (HI9814, Hanna Instruments, USA).

3. Results and discussion

The cumulative daily light integral (DLI) for the 2023 growing season for DAV and CTL is illustrated in *Figure 2 (a)*. DAV and CTL had the same values of cumulative DLI until the change in steering policy (addition of a radiation threshold) from the start of fruiting in the DAV. This change in steering policy was implemented to protect raspberries from excessive radiation, to which they are highly sensitive [5], and resulted in greater shading than at the start of the season in the DAV treatment. Despite this greater shading in the DAV treatment in the second half of the season, cumulative DLI at the end of the season was very similar between the two treatments, with only 4% less under DAV. On a daily level, photosynthetically active radiation (PAR) is highly variable in the DAV treatment (*Figure 2 b*), with a succession of light and shade conditions, in contrast to the more stable PAR values in the CTL. This high variability had already been demonstrated for apple orchards using the same agrivoltaic technology, with daily shading ranging from 4% to 88% compared with a full-sun control [6].

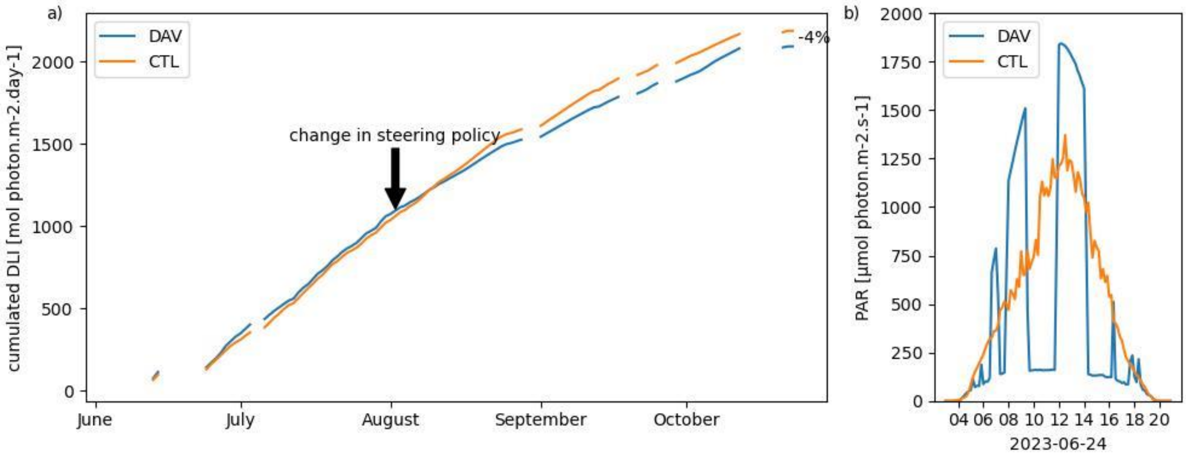

Figure 2. *a) Cumulative daily light integral (DLI) for the 2023 growing season and b) Daily photosynthetically active radiation (PAR) for a typical clear summer day (2023-06-24) for dynamic agrivoltaic (DAV) and control (CTL). The arrow indicates a change in the steering policy.*

The conditions produced by the DAV reduced air temperature by an average of 1.8°C and increased relative humidity by an average of 7.3% during the 2023 growing season (*Table 1*). The increase in shading in August following the change of steering policy (*Figure 2*) did not increase the differences observed in terms of air temperature and relative humidity between treatments. These results seem to indicate that differences in the micro-environment may be explained by the structure itself, with potentially better air circulation in the DAV treatment than in the plastic tunnel constituting the control.

Table 1. *Monthly average daily air temperature decrease [°C] and daily relative humidity increase [%] under dynamic agrivoltaic (DAV) compared with control.*

Month	Average daily air temperature decrease (t_DAV – t_CTL) [°C]	Average daily relative humidity increase (rh_DAV – rh_CTL) [%]
June	1.7	5.5
July	2.0	8.0
August	2.2	8.3
September	1.7	7.6
October	1.5	7.3

This more moderated micro-environment in the DAV treatment was even more pronounced for the substrate temperature measured in the containers (Figure 4), with maximum daily temperatures down by 5°C. Indeed, in the case of raspberry containerized plants, a current standard practice for growers, the temperature in the root zone is much more variable than in the open field, and highly dependent on the climate outside [7]. This reduction in substrate temperature in the DAV treatment helped to limit the number of days reaching 35°C, with only four days in the DAV treatment versus 27 days in the CTL treatment during the data collection period (Figure 4). Substrate temperatures above 35°C may cause a 75% reduction in root growth, while exposure to temperatures between 40 and 45°C kills root tips [8].

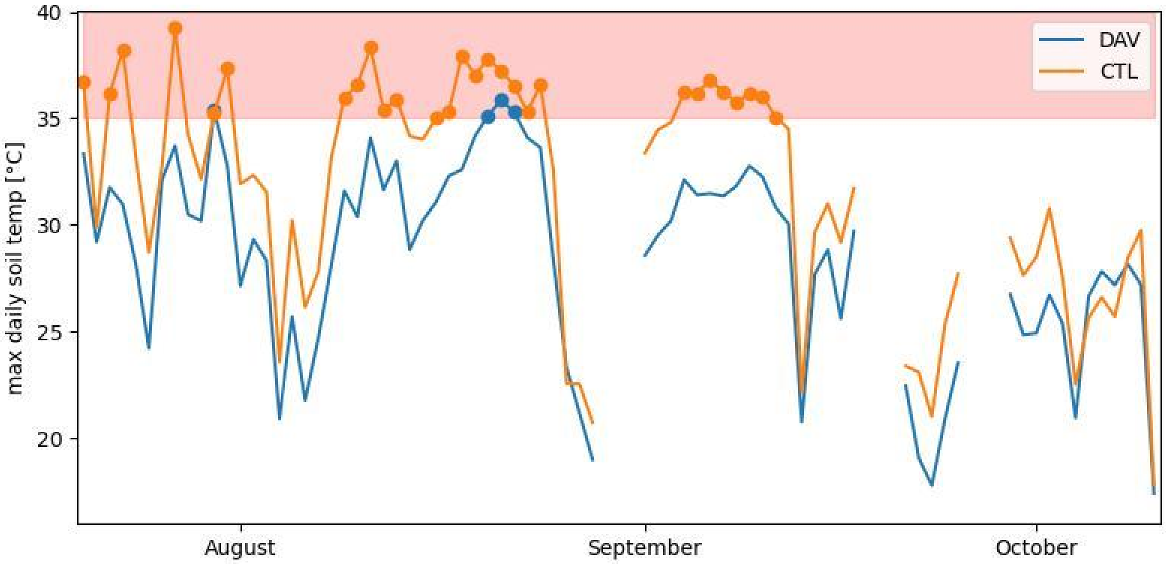

Figure 3. *Seasonal patterns of maximal daily substrate temperature [°C] for the 2023 growing season for dynamic agrivoltaic (DAV) and control (CTL). The red zone represents substrate temperature above 35°C. Each point represents a day with maximal daily substrate temperature above 35°C.*

This more moderated microclimate in the DAV treatment also resulted in a 41% reduction in irrigation requirement over the whole season compared with the CTL. Irrigation in each treatment was based on tensiometric data. A high substrate moisture content was maintained throughout the season for both treatments. In this study substrate moisture was similar between CTL and DAV with values considered optimal for raspberry production (tensiometer values never exceeded 50 kPa, see *Figure 4*).

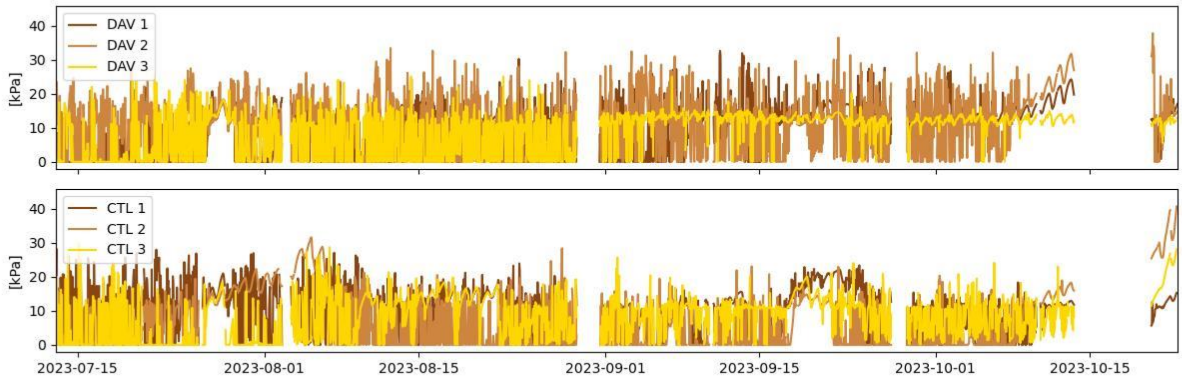

Figure 4. *Seasonal patterns of substrate water tension [kPa] for the 2023 growing season for dynamic agrivoltaics (DAV) and control (CTL) at 10-cm-depth for three sensors.*

High air and substrate temperatures can be detrimental to raspberry production including delayed time to ripening, decreased carbon assimilation, and reduced fruit quality and overall yield [9,10]. In terms of marketable yield, while similar at the start of the season, cumulative yield at the end of the season was 32% higher for the DAV treatment than for CTL, with an average production per plant of 860 g for the DAV treatment and 650 g for the CTL treatment (*Figure 5*). The possibility of installing an anti-hail and anti-insect net on the agrivoltaic structure is an additional innovation made possible by the agrivoltaic structure, restoring the protection provided by the tunnel in terms of hail and pests for the fruit production.

In our study, wide yield variability was observed for CTL, with one of the control replicates containing water-stressed plants after the end of September. Despite a good substrate water content, substrate water tension may have not been effective to reflect differences in water status between the plants. It is well known that substrate moisture did not always corresponds to plant water stress. Plant water stress often reflect weather conditions, and the level of stress can vary as the weather changes, even if substrate moisture is relatively stable [11]. Due to the more stressful micro-environment inside the tunnel with higher air temperature and lower relative humidity, it is likely that some raspberry plants of the control treatment had suffered from water stress. In further research, measurements of plant water potential may help to determine differences in water status between DAV and CTL plants. These water-stressed plants limited the number of fruits per plant on this CTL replicate, unlike the other CTL replicate which showed a similar number of fruits to the DAV treatment. Nevertheless, both CTL replicates had lower cumulative fruit mass per plant than the DAV replicates, indicating lower fruit fresh mass for CTL, as illustrated in *Figure 6 (a)* with increases of fruit weight of about 39% for DAV fruits.

In terms of quality, CTL and DAV fruits showed similar sugar concentration, with DAV fruits showing a slightly higher pH (*Figure 6*). Acidity in raspberries is negatively correlated with the amount of light received during fruit development [12]. The lower cumulative DLI during the September and October period for DAV compared to the control could have led to this slight increase in pH. This increase in acidity could have a positive impact on taste, since high sugars and high acids are required for good berry flavor [13]. Both treatments met the requirements for the fresh market. These results are more encouraging than the preliminary results on AV-grown raspberries by others [14]. They observed a yield reduction of between 20-32% while maintaining the taste quality in the agrivoltaic treatment compared to raspberries protected by plastic umbrellas.

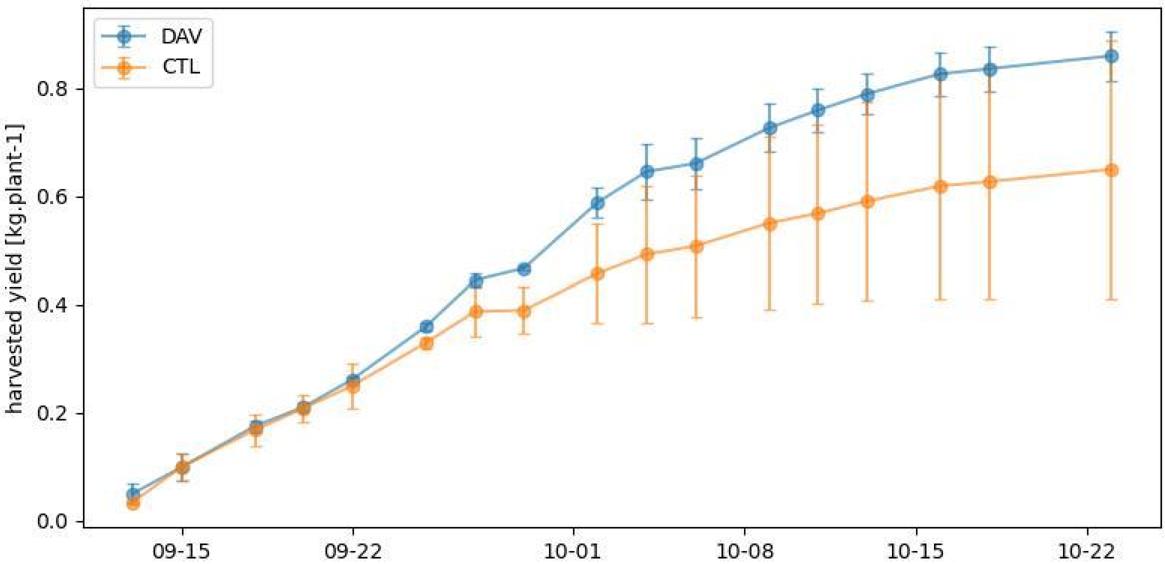

Figure 5. *Cumulated marketable harvested yield (mean ± confidence interval at 95%) [kg.plant^{-1}] for dynamic agrivoltaic (DAV, n=3 replicates of 12 plants) and control (CTL, n=2 replicates of 12 plants) in 2023.*

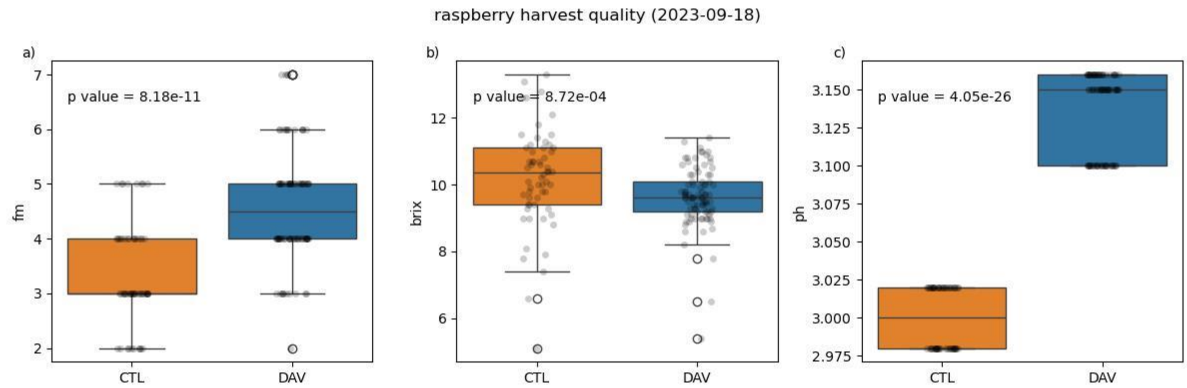

Figure 6. *Fruit a) fresh mass [g], b) refractometric index [Brix] and c) pH at harvest (2023-09-18) (n=30) for dynamic agrivoltaic (DAV) and control (CTL).*

4. Conclusion

This first experimental year provided relevant results to compare two production systems for containerized raspberry plants: the traditional whitened plastic tunnel compared to a dynamic agrivoltaic (DAV) system with nets. Both systems had similar cumulative daily light integral (DLI) at the end of the season, but a more moderated microclimate in the DAV system, with lower air temperatures, lower substrate temperatures, and higher air relative humidity. In addition to saving 41% on irrigation water in the DAV treatment compared with CTL, this microclimate induced less plant water stress, resulting in higher marketable yield with larger fruit and satisfactory fruit quality. Two more years of experimentation will enable us to confirm the interest in climatic protection of the Sun'Agri DAV for raspberry production, and to fine-tune the steering policy of the solar panels according to the crops' needs.

Data availability statement

The data that has been used is confidential.

Author contributions

KN, JN and PJ: Investigation. PJ, GL, JC: Formal analysis. BV: Software. PJ and CT: Writing – original draft. DF, CC and XB: Conceptualization, Supervision and Project administration.

Competing interests

The authors declare that they have no competing interests.

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