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Modelling Canopy Temperature of Crops With Heterogeneous Canopies Grown Under Solar Panels

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Abstract. With global warming and the increase of heatwaves frequencies, it has become urgent to protect crops. Agrivoltaic systems tackle this issue by shading plants with photovoltaic panels to lower the temperature of canopies. However, a permanent shading would lead to an important loss of carbon for plants. For this reason, dynamic agrivoltaic systems (AVD) emerged with panels which could be steered in real time according to the needs of plants. Shading at the right time is not that easy with the risk to either miss a hot event and cause serious and irreversible injuries to the plants or shade too often, and impact carbon production. In this paper we present first an experiment with measurements of leaf temperature at different positions of grapevine canopy for two summer days in 2020 and 2021. Then, the energy balance sub-model part of a crop model that simulate plant growth for fruit trees and vines grown in heterogeneous AVD environments is presented. Finally, after having evaluated the coherence of the model with experimental results, the relevance of a mechanistic model to steer solar panels and protect plants from heat is illustrated through several examples. The heterogeneity of temperature within the canopy observed in the field experiments related with different variables such as air and ground temperature, leaf orientation and self-shading was correctly reproduced by the model. This work indicated that canopy temperature could be more integrative than a unique threshold of air temperature to take decisions on panel orientation to protect plants from heat stress.

Keywords: Dynamic Agrivoltaic System, Crop Protection, PV Steering Policies

1. Introduction

One of the major agricultural issues associated with climate change is the increase in air temperature [1] and the associated reduction in some crop yields [2]. The increases in air temperature may alter plant functionality. Organ temperature is important for plants, and controls most of physiological processes such as phenology, carbon production, growth, and maturity. While optimal temperature for photosynthesis sits around 30°C [3], it has been demonstrated that temperatures above 35 °C have drastic effects on photosynthesis and ultimately yield at harvest. Higher temperatures may further cause serious and perhaps irreversible injury on grapevines' leaves [4].

It is urgent to adapt agriculture to climate change and find solutions to protect vulnerable plants from the expected increases in air temperature. As a corrective solution, shading crops with photovoltaic panels (PV) to form an agriphotovoltaic system has recently attracted a lot of interest. There has been an increased number of studies related with the development of such systems, including the development of new prototypes [5, 6], evaluation of the potential adoption [7] and the responses of crops to the shade [8, 9, 10, 11]. However, no studies focused on the effect of PV shading on detailed responses of organ temperature and whether PV panels are efficient systems to maintain plants in optimal temperature conditions. With this problem in mind, dynamic agrivoltaic systems (AVD) where panels can rotate with angles +/- 90° throughout the day have been proposed [10, 11]. They operate in several modes: i) tracking, panels are perpendicular to sun rays and protect crops from climatic stress or ii) antitracking, panels are parallel to sun rays and let all the light available through, fulfilling the physiological needs of crops, iii) fix position, especially useful during night and rain.

AVD can relief heat stress by shading the plants when air temperature is above a given threshold as a first approach [12]. However, predictions of heat stress based on air temperature are not always accurate because there are several physiological (e.g., transpiration) and environmental factors (e.g., light intensity, wind) that affect the temperature of organs [13]. To estimate organ temperatures and take local shading into account, mechanistic models based on energy balance are an option [13]. In this paper we present the energy balance part of a full crop model that simulate plant growth for fruit trees and vines grown in heterogeneous AVD environments. This study includes a description of the energy balance, and measurements of leaf temperature at different positions of grapevine canopies to evaluate the coherence of the model. Some examples will be presented to show the added value of the mechanistic model to steer solar panels and protect crops from heat stress.

2. Materials and methods

2.1 A crop model as Decision Support System to steer solar panels

A mechanistic model of soil-plant-atmosphere has been developed. The model connects a balance of energy, a carbon budget and a balance of water interacting with each other and providing three crop status indicators: the range of temperatures in the canopy, the amount of carbohydrates produced through photosynthesis, and the predawn water potential, respectively. Using specific thresholds that vary throughout the season for each indicator, it is possible to take decisions on solar panel orientation to maintain an optimal performance of the crop. Detail of the whole model and its usage have been presented in a former agrivoltaics conference [14].

In this study, we focus on the canopy temperature indicator that is directly related with heat stress. Other physiological processes, like carbon assimilation and water transpiration, while also being modelled will not be described here. The range of temperatures in the canopy is calculated on an hourly basis because thermal stress can cause symptoms in plants in the short term [4]. We used an energy balance between net incoming radiation (Rn), sensible heat loss (H), and latent heat loss (λE) [15] (figure 1). Our model has the specificity, first, to consider the heterogeneity of light above the crop spatially and temporally and second, to deal with non-homogeneous canopies. For crops planted in rows, leaf angles are not distributed uniformly inside the whole canopy. Therefore, the canopy is subdivided in zones where leaves have the same orientation and a similar distance to the ground on average. Each sub-canopy is then partitioned into leaves that are directly lit by the sun and leaves that are in the shade of panels or other leaves (same plant or neighbors). Following the course of the sun and the change in panel orientation throughout the day, some leaves move from one cohort to the other and therefore they are exposed to a given Rn, altering the energy balance of that part of the canopy as well as its functionality (leaf conductance and photosynthesis). A simple ray-tracing algorithm is used to estimate which part of the canopy is visible from which zone of the sky. No delays for the transition from shade to light and vice versa have been introduced in the model since our measurements have shown that temperature change in response to light is fast compared to the model time step.

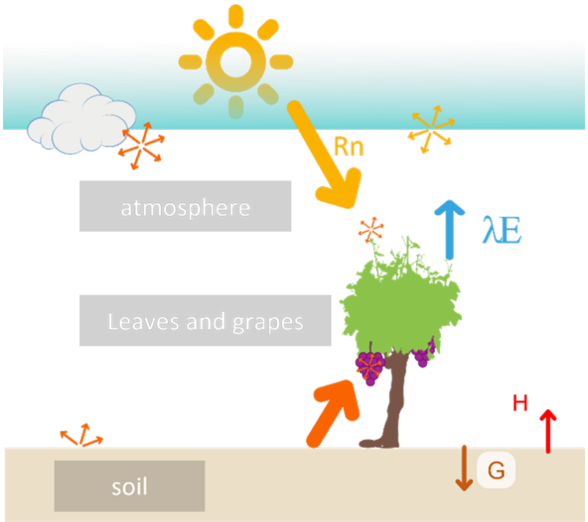

Figure 1. Schematic representation of the energy balance included in mechanistic model of soil-plant-atmosphere developed to pilot solar panels orientation.

2.2 Experimentations to evaluate the crop model

To evaluate the model, measurements of leaf temperature were performed in mature grapevines grown in an AVD system (Piolenc AVD experimental field, France) in 2020 and 2021 using a portable infrared thermometer on the 29th of July in both years. We selected that period of the year and sampling method to capture a high variability of air temperatures (ca. between 25 and 36 °C). 40 vines (half under PV and half outside as control) were monitored four times during the day in 2020 and nine times in 2021. Measurements were done in the east and west side of the canopy and at three different heights. For each vine, side, and height, a measurement of leaf temperature was recorded (six measurements per each vine and hour). Air temperature and incoming solar radiation were also recorded during the experiment.

3. Results

3.1 Heterogeneous leaf temperatures

Leaf temperature measurement over the course of a day indicated that, even without PV panels shading the plant, there is great variability in leaf temperature within the canopy of a single plant, mainly between leaves exposed to direct light and leaves in the shade. Leaves exposed to the sun showed higher values than air temperature in the first and last hours of the day (figure 2). Leaf temperature was therefore not simply coordinated with air temperature. Leaves exposed to the sun exhibited up to 7.5 °C above air temperature mainly due to radiation energy converted to heat. Leaves in the shade experienced more constant values over the day than leaves exposed to the sun. Their values were close to air temperature or some-what below. There seems to be a soil effect in 2020 (not observed in 2021). The leaves near the ground stayed cooler than the leaves at the top of the canopy in the morning. This pattern changed in the afternoon, with the upper leaves being cooler than the leaves closer to the ground in the evening (figure 2), potentially reflecting really high temperatures measured at that time on the dry ground.

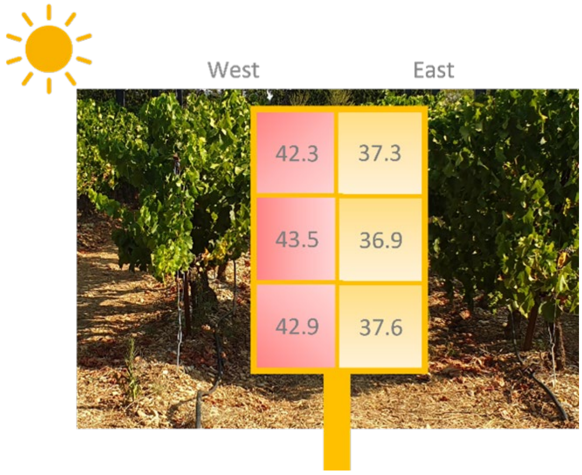

Figure 2. Distribution of mean leaf temperature at 18p.m (local time) for control grapevines according to the orientation and height of leaves in summer 2021. Air temperature was 36.0°C.

3.2 Simulation of distribution of leaf temperatures

Figure 3 below shows the results of a simulation for the same vineyard in the conditions where measurements were performed. The model indicates that although the overall trend of the average canopy temperature follows air temperature, there is a significant spatial heterogeneity inside the canopy due to changes of incoming radiation and leaf physiology. The role of actors such as the ground and leaves inducing self-shading in canopy temperature is correctly simulated.

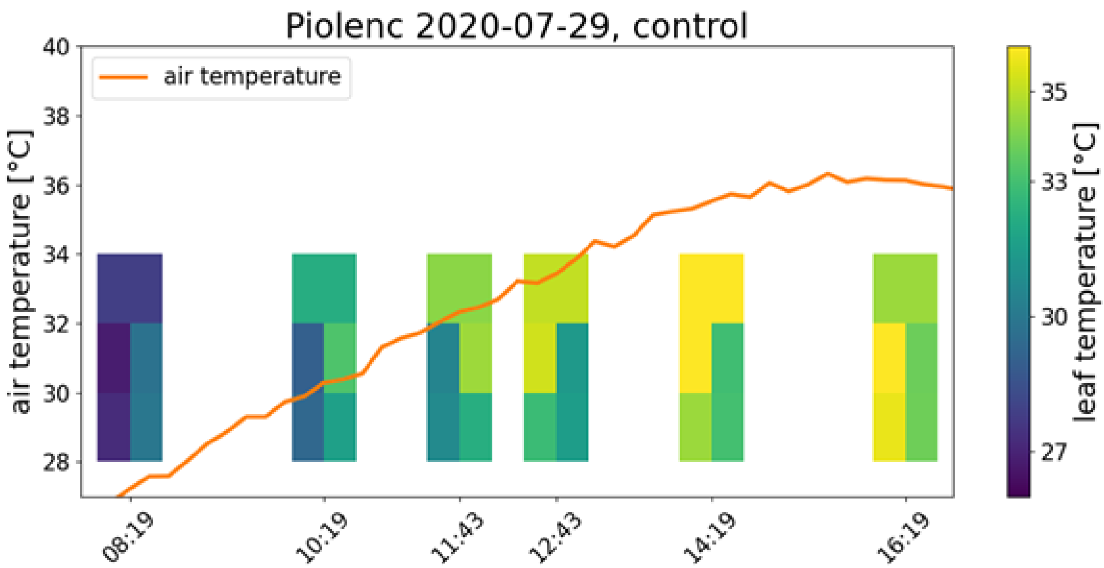

Figure 3. Simulation of leaf temperature throughout a summer day of 2020 in the South of France in the AVD experimental station of Piolenc for control grapevines. At each given solar time, canopies are subdivided in blocks which correspond to a portion of the canopy as measured in fig2.

3.3 Effect of panel steering policy on leaf temperature

The model was used to simulate the dynamic of leaf temperature for two different steering policies: the first steering policy forces PV in tracking to shade the plant once air temperature reaches a fixed threshold (fig4a and fig4b). This threshold varies with different species and time of the year depending on grower policy. The one used in our simulation is for illustration purpose only. The second policy directly uses simulated leaf temperature as an indicator (fig4c and fig4d). The figure 4 below displays a comparison of both policies for two hot days of summer 2019. On fig4a, with an air temperature threshold of 36 °C, the policy stays antitracking allowing the plant to fully use solar radiation for photosynthesis. However, that day, the interaction between air temperature, radiation, wind speed and soil temperature are such that leaf temperatures can reach above 39 °C and the plant will suffer heat damage. Lowering the air temperature threshold can prevent this situation to arise and ensure that the canopy is protected. However, as shown on the second day of simulation, fig4b the 2019-08-08, with an air temperature threshold of 35 °C, this time, the steering policy turns to tracking to protect the plant of potential heat damage. Simulations of leaf temperature, however, show that in the actual conditions, leaf temperature will not wander into the damaging zone (fig4d). Therefore, by forcing the policy in tracking, some radiations have been lost for photosynthesis and the carbon budget of the plant has been decreased with potential impacts on yield at harvest. In both cases, using the actual leaf temperature instead of a proxy (i.e., air temperature) will have permitted to optimize photosynthesis without risking overheating of the plant (fig4c and fig4d).

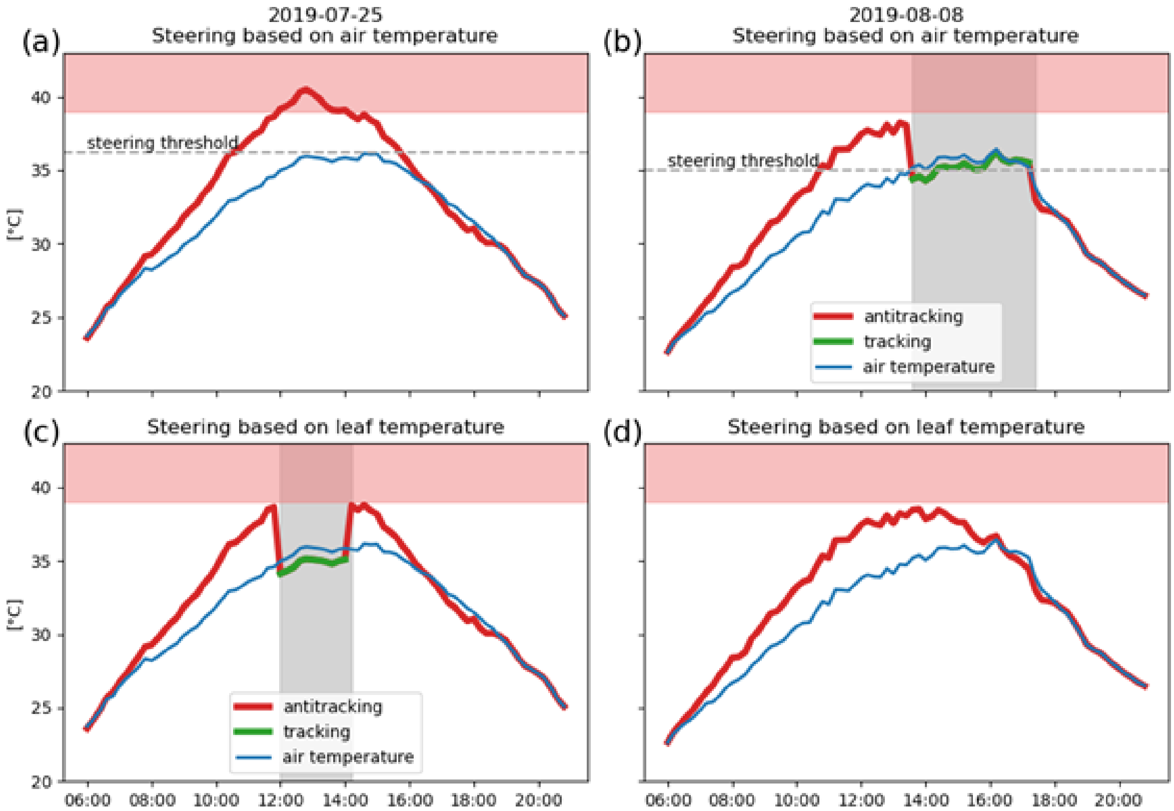

Figure 4. Simulation of the effect of two steering policies on the maximal temperature of the canopy. Grey zones correspond to times when panels are in tracking. The red zone corresponds to temperatures potentially permanently damaging the photosynthesis apparatus.

As explained above, for any steering policy aiming at protecting the plant from heat waves, there is two possible errors. The first one consists of keeping the panels in antitracking and not shade the plant when leaf temperatures reach above 39°C potentially incurring severe damage to the canopy. This situation is characterized by a probability of missing hot events defined as the ratio of time spend antitracking while leaves are in the damaging zone divided by the whole duration of time spend by leaves in the damaging zone without panels over the entire season. The second one measures the duration of useless tracking. It is de-fined as the ratio of time spend tracking while leaves would stay below the damaging zone even in full sun divided by the total amount of time spend tracking during the season. The figure 5 below shows the respective evolution of these two errors, for the year 2019 in Piolenc, for a panel steering policy based on air temperature. For low thresholds (i.e., air temperature < 30 °C), the probability of missing hot events is null, but the frequency of useless tracking is 100 %. When the threshold increases, the frequency of useless tracking drops to zero but the probability of missing hot events and killing the plant raises all the way up to 100% when the threshold is higher than 40 °C. Simulations show that both these probabilities are modified by the water status of the plant, preventing to find a single optimum. Once again, using a steering policy based on leaf temperature instead of air temperature ensures that both probabilities of error are zero.

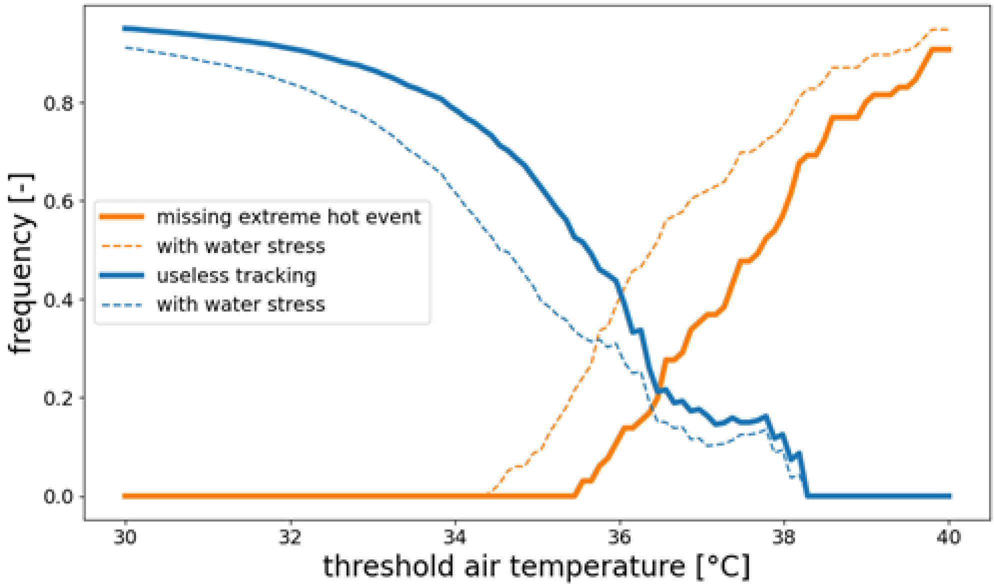

Figure 5. Evolution of PV steering errors for increasing threshold of air temperature used by the steering policy to decide when to perform tracking vs. antitracking. See text for definition of both errors. Simulations have been performed on grapevines using data from year 2019 in AVD station of Piolenc. Solid lines correspond to well-watered plants while dotted lines correspond to grapevine simulated with water stress.

4. Discussion

Avoiding heat stress and heat damage on canopies is a complex task because temperatures vary both spatially between leaves of the canopy and temporally throughout the day and the season depending on weather conditions, plant water status and grower practices [16, 17]. In this paper we have shown, both empirically and using an energy balance model, that shading a plant using PV panels is an effective way to lower the temperature of its canopy. However, reducing the amount of radiation reaching a plant also reduces photosynthesis and therefore its carbon acquisition. Therefore, finding the right period to shade the plant is a complex task with the risk to either miss a hot event and kill the canopy or shade too often, too strongly and affect photosynthesis and carbon gain by the plant [18].

Since continuously measuring the temperature of each individual leaf in the field is not feasible, AVD systems have relied on air temperature as a proxy to inform their steering policy. Using air temperature suffers from biases. As demonstrated, there is no unique threshold that will protect the plants in all cases while not also restraining its carbon balance. Our model reproduces the observed variability. Using only available entries readily measured in AVD systems, it simulates the temperature range of a canopy both in plain field and AVD systems. This information can be passed to the grower to be used in conjunction with his risk aversion to decide of the best steering policy.

Our energy balance model also considers the water status of the plant. Therefore, panel steering can be adjusted to irrigation practices and vice versa. Moreover, since our energy balance model also includes other actors like the soil, other steering strategies can be also implemented to shade the soil and control the temperature of the lower part of the canopy where fruits are attached. The exact effect of soil temperature and evaporation on canopy temperature will, however, require more studies than presented in this paper. All these considerations make steering panels another practice, alongside training systems and pruning [19, 20], in the arsenal of growers to ensure quality harvests.

5. Conclusion

Dynamic agrivoltaic systems are an innovative solution to protect plants from climate change and help the energetic transition. It is expected that the adoption of this new AVD technology in commercial farms will increase. Then, the management of the shading level throughout the season in the farms will become a new horticultural practice. This could be an extremely difficult task for growers due to the multiple interacting factors that shading causes in all the physiological and agronomical responses of the crops. Mechanistic models may be useful to help growers take sound decisions because they integrate multiple interacting factors. In this study we illustrated how a model of canopy temperature could be more integrative than a unique threshold of air temperature to take decisions on panel orientation to protect plants from heat stress. Moreover, the proposed model provides other indicators to steer panels including the water status of the crop and carbon production that are difficult to measure in the field. In its current state, the model is currently used on experimental AVD setups for testing purposes. More efforts are still required to make the model more robust before trusting it with steering PV panels in commercial settings. The model is also used to run virtual simulations and evaluate different steering policies not implemented in the field without the necessity of constructing expensive experimental sites and the need to wait several years for the experimental results.

Data availability statement

Research data are not shared.

Underlying and related material

Not available.

Author contributions

Conceptualization, J.C, G.L, S.P., D.F.; Data curation, J.C, G.L, S.P., D.F.; Formal Analysis, J.C, G.L, S.P., D.F.; Investigation, J.C, G.L, S.P., D.F.; Methodology, J.C, G.L, S.P., D.F.; Project administration, D.F.; Software, J.C, G.L, S.P., D.F.; Supervision, D.F.; Validation, J.C, G.L, S.P., D.F.; Visualization, J.C, G.L, S.P., D.F.; Writing – original draft, J.C, G.L, S.P.; Writing – review & editing, J.C, G.L, S.P., D.F.

Competing interests

The authors declare that they have no competing interests.

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