Development of a Decision Support System to Evaluate Crop Performance under Dynamic Solar Panels

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Abstract. Achieving optimal yield and quality at harvest depends on the grower's ability to avoid abiotic stresses (water, light, and temperature). This task has usually been satisfied through the implementation of adequate horticultural practices. In the context of clean energy transition and global climate change, growers nowadays have the possibility to grow their crops under solar panels, which modify the micro-environment of the crops. Being able to anticipate the behavior of plants under these new micro-environmental conditions would help growers adapt their horticultural practices. For electricity producers, in the context of dynamic agrivoltaic systems, anticipating the crop status is useful to choose a solar panels steering policy that maximizes electricity production while ensuring favorable environmental conditions for the crop to grow. To help electricity producers and growers estimate a crop status under panels, we developed a decision support system (DSS) called crop_sim. As of now, it can be used to monitor two types of perennial crops: grapevines and apple trees. crop_sim produces three indicators of the crop status: predawn water potential, canopy temperature and carbon production. Besides providing information on the crop status, the DSS incorporates an expert system which indicates the best time and the amount of irrigation to maintain a desired water status under the new micro-environmental conditions.

This paper first focuses on the description of crop_sim and the usefulness of the three indicators. Then, a case study is presented. Our results show that, in a mature vineyard, with a typical panel steering policy conservative on crop yield, growers could save 13% of water compared to an open-field reference.

Experimental data pertaining to apple trees, grapevines, tomatoes, and maize are being collected. They will be used to adapt the model to tomato and maize, evaluate it and make it robust enough to bring to market. Further improvements of the crop_sim model may be required to finely reproduce observations in the field. A full validation of the model is expected when all data from the experiments will be available. The DSS will evolve depending on the requirements of the agrivoltaics community and may incorporate additional plant indicators and new expert system rules.

INTRODUCTION

Agrophotovoltaics (APV) is an innovative agricultural system that creates two main benefits: i) production of energy and ii) reduction of environmental stresses to crops in a context of global warming [1]. Indeed, APV systems could reduce air temperature above the crops during the day by about 1.5°C and increase air moisture in comparison with open-field cultivated crops [2, 3]. However, the new environmental conditions induced by APV systems are not always beneficial to crops. In particular, the amount of incoming photosynthetically active radiation (PAR) is significantly lower in fixed APV systems than in traditional open-field cultivated crops [3]. The R&D project "Sun'Agri3" has been proposed to study dynamic agrivoltaic systems with rotating solar panels as a way to mitigate this problem. Indeed, reduction in the amount of energy may limit the capacity of crops to assimilate carbon through the process of photosynthesis and allocate carbohydrates to the organs to achieve optimal yield and quality. Therefore, the installation of APV systems implies a trade-off between electricity production and crop production [4].

Solar electricity producers have developed algorithms to maximize energy production and simulate the abiotic environment below the panel [1]. Less attention has been devoted to estimate the crop performance under panels. Being able to monitor and anticipate crop performance under panels would help take decisions regarding solar panels orientation that optimize the production of energy while preserving crop yield and quality.

The assessment of a crop status under panels could be done with several approaches: field measurements (hand made, using sensors that monitor in real time or using remote sensing), and crop models. The main limitation of field measurements is that they can only provide real time information and they can not be used to predict the future behavior of the plant. This limits the capacity of growers and electricity producers to anticipate the behavior of plants under different panels orientation policies. Taking advantage of increasing accuracy in weather forecast, crop models however can overcome that limitation. Multiple crop models have been developed by the scientific community to account for the complex interactions between the soil, plant, and atmosphere [5]. These models can be translated into decision support system (DSS) to facilitate the operation of solar panels providers and provide useful recommendations to growers.

Another advantage of using a DSS is that it can inform growers on the necessary adaptations of their horticultural techniques to the new environment generated by the panels. For example, since irrigation requirements are substantially reduced under panels [2, 3], irrigation recommendations under open-field conditions are no longer valid under panels. A DSS can inform growers about multiple aspects of irrigation scheduling like the dates of irrigation events and the associated amounts of water that are adequate to maintain a desired plant water status. Moreover, considering that weather forecasting is widely available in the agricultural domain, a DSS has the potential to provide real-time, weekly, and even whole-season predictions of the performance of their crop under a given APV panel steering policy.

We developed an agronomic model-based DSS (crop_sim) to assist energy providers to perform the optimal solar panels management and assist growers in their horticultural practices. In this article, we:

- describe the main components of the crop_sim model and how the soil-plant-atmosphere under panels is simulated to calculate relevant plant indicators to take decisions (predawn water potential, canopy temperature and carbon production).
- illustrate how crop_sim can assist growers to adapt their irrigation practices with a case study of a mature vineyard cultivated both under open-field conditions and APV systems.

DEFINITION OF USEFUL AGRONOMIC INDICATORS

The first step to implement our DSS was to identify useful agronomic indicators associated with crop development under panels. The goal of a grower is to ensure optimal crop yield and quality. However, it is difficult to predict these two variables from the beginning of the season because they depend on all future abiotic stresses that will occur until harvest. Therefore, the reliability of yield and quality estimates may not be high enough during the season to help take relevant decisions. Thus, we chose to use well recognized plant-based indicators that can be used to ensure that plants have a correct behavior throughout the season. If the plant-based indicators have a good performance all throughout the season, it is expected that the grower will optimize crop yield and quality in the end. From all the existing plant-based indicators documented in the scientific literature [3, 6], three of them were selected as outputs of the crop_sim model (Table I): i) the predawn water potential, ii) the canopy temperature, and iii) the amount of carbohydrates produced through photosynthesis. The three indicators aim to capture the three main characteristics of a crop status that are expected to be influenced by APV systems [3].

Under solar panels, the predawn water potential (expressed as units of -MPa) can increase (less water stress) in comparison with open-field conditions because of the reduced atmospheric demand for water, that is associated with a reduction in the amount of water evaporating from the soil and transpired from the crop canopies. An optimal trajectory of predawn water potential to reach a given production objective can be defined (e.g., for grapevine [7]). Thus, the predawn water potential indicates whether a crop is within the desired water status boundaries. If the values of predawn water potential are lower than what is expected in order to maintain the desired water status (more water stress), the grower can add supplemental irrigation or close the solar panels to reduce the evapotranspiration of the plant. If the values are less negative (less water stress), the grower can reduce the irrigation or open the panel to increase the crop evapotranspiration.

With APV, the canopy temperature is expected to be lower under solar panels because the amount of energy that reaches the leaves is diminished. Optimal values of canopy temperature have been also determined for several physiological processes for each crop during the growing season. Values of canopy temperature above the optimal values can impair leaf photosynthesis, cause canopy defoliation or fruit sunburn. Values of temperature lower than the optimal can also impair leaf photosynthetic activity or delay fruit development and growth. The canopy temperature indicator is useful to determine if the crop is within its optimal range of temperature, given its phenological stage.

The amount of carbon assimilated through photosynthesis can also differ between crops grown under solar panels and crop grown in open-field conditions. The consequences are difficult to predict because carbon production is affected by the interaction of water, light, and heat stresses. All of these factors are influenced by the solar panels. The carbon production is then an integrative indicator of all the abiotic stresses that a plant may suffer. The resulting carbon production under a given APV policy must be enough to satisfy the demand for organ growth. Otherwise the plant may reduce its yield due to an inhibition of fruits (less fruit number per plant) or a reduction in the growth of the remaining fruits. In perennial crops, the carbon production must be high enough to guarantee that, before the end of the growing season, the plant can refill the carbohydrate pool stored in woody parts. In absence of such refill, the long-term sustainability of the plant may be compromised. Most crops depend on their reserves at bud-break for leaf development and fruit set.

As detailed in Table I, each indicator can be used to anticipate and prevent specific types of risks.

TABLE I. Selected plant-based indicators

Indicator	Usefulness	Time step
Predawn water potential	Identification of an optimal management zone to avoid under and over irrigation	Daily
Canopy temperature	Identification of heat stresses that can induce plant defoliation and fruit sunburn	Hourly
Carbon production	Identification of risks to have a negative balance between the carbon assimilated through photosynthesis and the demand for carbohydrates. This could lead to the inhibition of fruits growth and the depletion of storage at the end of the season	Hourly

DESCRIPTION OF THE DECISION SUPPORT SYSTEM

To estimate the three indicators described in Table I, crop_sim relies on a mechanistic model that simulates the soil, the plant, the atmosphere and the interactions between them.

In crop_sim, the soil is characterized by the volume explored by the roots and by its texture. Both are used to estimate the soil capacity to store the water available for plant growth. The soil in crop_sim is represented as multiple layers to capture the heterogeneity in soil texture or root density throughout the soil profile.

In crop_sim, the crop is represented by an average plant subdivided into whole-organ compartments: leaf, fruit, structure and storage. Individual organs (e.g. each leaf in the canopy) are not differentiated. At each time step, the canopy compartment is subdivided between the leaf area directly exposed to sun light and the leaf area that receive only diffuse light from the atmosphere. Carbon assimilated by the leaf compartment is then allocated to each compartments according to their needs for maintenance and growth.

To perform a simulation, the model requires as inputs basic informations from the crop system (e.g., crop species, variety, soil texture, row orientation, plant density, and estimated root depth), the geolocation (latitude and longitude), the weather (global radiation, precipitation, air temperature, wind speed) and microenvironmental conditions under the solar panel calculated by a 3D simulator [1]. Additional inputs as agricultural practices performed by the growers may be added (e.g., date and amount of irrigation applied). If no information is available about the real irrigation events, an expert system takes over and maintains the crop in a specified water status. The model has initially been developed for grapevines and apple trees, but will be extended to other perennial crops such as cherry and kiwifruit and horticultural crops such as tomato. crop_sim combines two temporal time scales: 1) a one hour time step which captures the consequences of changing micro-environmental conditions under multiple APV policies in real time throughout the day, and 2) a daily time step to accumulate changes at the scale of the growing season and help decide on the overall panel steering strategy to maintain yield and harvest quality.

The crop and environmental inputs are fed to three sub-models (water balance, energy balance, and carbon budget) specifically designed to capture the effect of solar panels on crops. Each sub-model is composed of several formalisms well recognized from the scientific literature.

- Water balance: this sub-model balances the amount of water reaching the crop through rain and irrigation with water leaving the system either through the ground (runoff and drainage) or through the atmosphere with the process of evapotranspiration. As a result, the model estimates the amount of water in the soil and the predawn water potential (leaf water potential measured just before dawn). The predawn water potential is a good indicator of the water status of the plant and optimal predawn water potential thresholds have been already determined to achieve production objectives [8].

- Energy balance: this sub-model uses canopy temperature as the free variable to balance the amount of radiation intercepted by the crop, the amount of heat stored in the ground or radiated back to the atmosphere and the latent energy lost by the plant through transpiration [9]. The latest component, latent energy lost through evapotranspiration, depends on the actual water status of the plant and connect this computation to the water balance sub-model.

- Carbon budget: this sub-model simulates the carbon assimilation through the process of photosynthesis and allocates the carbohydrates to the different compartments for organs growth and maintenance respiration. Photosynthetic light response curves, specific to each species, are used to estimate instantaneous photosynthesis at leaf scale. This photosynthesis is then scaled-up at the whole plant level using the subdivision of the canopy between leaves receiving direct sun light and leaves receiving only the diffuse part of atmospheric radiations. Because photosynthesis depends on water and temperature, information from the water and energy balance sub-models are also required to estimate photosynthesis [10]. Photosynthesis is only one of the sources of non-structural carbohydrates in the plant. Storage can also release carbohydrates and increase the pool of labile carbohydrates. In the model, storage is defined as a standalone component with its own demand. Its maximum size is constrained to a fraction of the structural compartment size. At each time step, the pool of carbohydrates is first allocated to the maintenance respiration of organs (function of their dimension and temperature). The remaining labile carbohydrates still available are then used to support organ growth. All the organs types are considered as sinks (demand for carbohydrates) and therefore compete to accumulate carbohydrates. The demand of each organ is dependent on its size and relative growth rate [10].

All together, these three sub-models interact to simulate the internal state of the crop-system throughout time. This internal state is then summarized by the three indicators described in Table I. The simulated internal state of the crop is also used in combination with state of the art agronomic rules to derive recommendations adapted to a specific solar panel steering policy.

EXAMPLES OF SIMULATIONS FOR IRRIGATION

Water status of plants reflects their overall behavior. A bad water status impacts the metabolism of plants which leads to crop damage and to a decrease of yield and fruit quality. For that reason, many studies have been conducted to determine the water requirements of plants, including grapevines, under different agroclimatic situations [7]. With this knowledge and their own experience, winegrowers manage the irrigation according to their terroir, the varieties, and their production target. Some institutes, such as IFV (Institut Français de la Vigne et du Vin) in France, also give recommendations to optimize irrigation. However, these recommendations pertain to crops cultivated in open-field conditions. In this section, we illustrate with an example how crop_sim can help growers adapt their irrigation schedule under panels.

Case Study: Irrigation of Classical Vineyard

For a mature vineyard of variety Merlot, located in a dry Mediterranean climate in a silt loam soil of 80 cm of depth, grapevines need 245 mm of water well distributed in 8 events during the season (Figure 1). This ensures an optimal irrigation reflected by a recommended predawn water potential ranging between -0.20 and -0.40 MPa [7].

Transition to Agrivoltaism

Agrivoltaics systems are fairly recent. Most current knowledge comes from shading nets and fixed solar panels. They are known to modify the micro-environment of plants and to decrease their water requirements [11]. Using dynamic solar panels however is a completely new way to perceive agrivoltaics systems. Therefore winegrowers cannot leverage their expertise, nor institute their recommendations, to decide when and how much to irrigate. The water status of the same vineyard as presented above (Figure 1) was simulated adding 50% shading around noon (between 11a.m. and 2 p.m.). Our DSS indicates that using, under panels, the same irrigation management as for the vines in open-field, leads to an over-irrigation. This over-irrigation is reflected on Figure 2 by a less negative predawn water potential, the simulated trajectory outreaches the comfort zone. This results in a waste of water for the winegrowers and has a negative impact on the crop with a higher risk of illness and an excess of vegetative growth to the detriment of fruit quality.

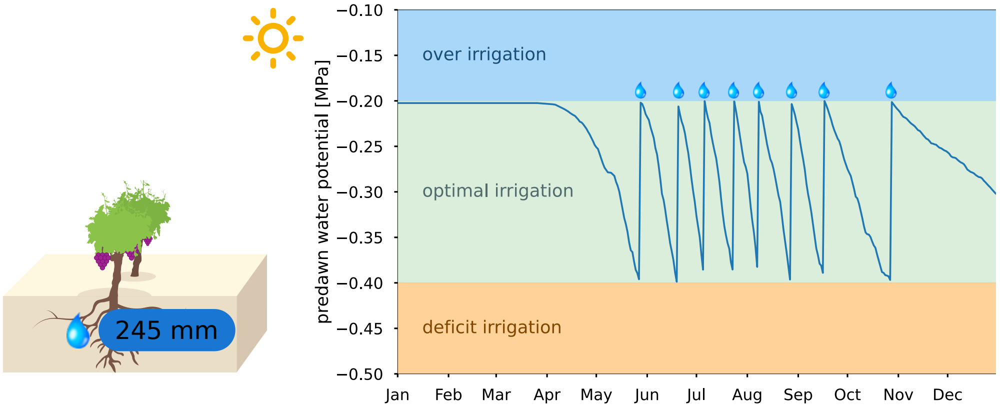

FIGURE 1. Predawn water potential (in MPa) simulated by our DSS throughout the season (a drop represents an irrigation event performed by the grower) for a vineyard without solar panel and with usual irrigation applied by winegrowers.

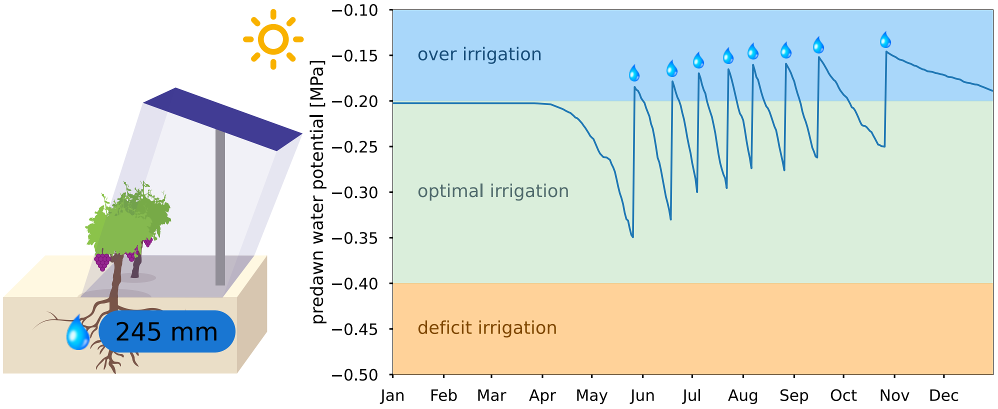

FIGURE 2. Predawn water potential (in MPa) simulated by our DSS throughout the season (a drop represents an irrigation event) for a vineyard shaded by 50% around noon and with the same irrigation usually applied by winegrowers in fields without solar panels (i.e. like figure 1).

Usefulness of a DSS Adapted to Agrivoltaism

To deal with this new situation, winegrowers could perform field measurements. A measure of leaf water potential at predawn using a pressure bomb provides an indication of plant water status that can be used to manage irrigation. However, this method is time and money consuming. Also, solar panel steering policy can change during the season and would require continuous measurements throughout the season. Our DSS allows to simulate predawn water potential to avoid field measurements. It is particularly adapted to agrivoltaics systems because it considers microclimate under panels. Moreover, it includes an expert system for irrigation helping winegrowers manage their irrigation. For the same vineyard presented before and 50% of shading around noon, our DSS advises only 214mm of water split into 7 irrigation events (Figure 3).

The DSS recommendation results in 13% of water saved and prevents over or under irrigation. Moreover, according to the DSS, the kind of management of solar panels considered (with 50% of shading around noon which corresponds to roughly 23% less radiation reaching the crop over the season) does not have any negative impact on the carbon production of the vineyard (results not shown).

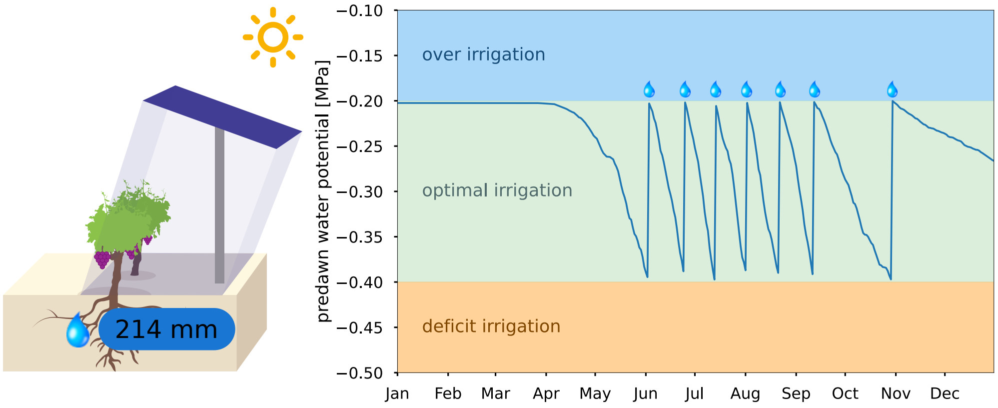

FIGURE 3. Predawn water potential (in MPa) throughout the season (a drop represents an irrigation event) for a vineyard covered by dynamic solar panels that apply 50% shading around noon. The applied irrigation corresponds to the recommendation given by the expert system of our DSS.

CONCLUSION

We developed a first prototype of a DSS (crop_sim) to determine crop status under panels. crop_sim will be used to help electricity producers and growers to optimize energy production without impacting crop performance. The DSS estimates relevant plant-based indicators (predawn water potential, canopy temperature, and carbon production) for several crops grown under panels. The DSS integrates, during crop growth, the complex interactions between plants and their environment, including the feedback of panels orientation. This work is part of the R&D project "Sun'Agri3". As such, the three indicators of the DSS have been preliminary evaluated with available field measurements in four 3-years-experiments with different shading policies and multiple crops (apple, grape, tomato, and annual crops). The final evaluation of the three indicators for each crop will be performed towards the end of the project once enough experimental data have been collected. The current data have enabled to construct the crop_sim model but a detailed evaluation of the model is necessary to ensure that the DSS is robust enough to take the right decisions and release the DSS on the market.

Our DSS has also been designed to provide recommendation towards the best agricultural practices under dynamic solar panels. The current implementation uses an expert system for irrigation to determine the best time and amount of irrigation to apply. In a case study of a mature grapewine, we performed a simulation for a APV that reduced 50% of incoming light around noon in comparison with an open-field simulation. Under panels, the date of the first irrigation event was delayed, the number of irrigation events decreased and the overall amount of water was reduced (about 13% less in the APV). Without the DSS, growers may not be able to adapt their irrigation practices and may waste natural resources and generate undesired effects related to over irrigation (excessive canopy growth, low quality, and higher risk of illness in grapevine).

Once validated, the DSS will predict, using weather forecast information, the consequences on crops of different solar panels steering policies to help optimize the orientation of panels in real time. Simultaneously, the DSS will also be used to determine the cultural practices adapted to the optimal panel steering policy and facilitate the implementation of dynamic solar panels in agriculture.

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