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Water budget and crop modelling for agrivoltaic systems: Application to irrigated lettuces

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ABSTRACT

The installation of tilting-angle solar panels above agricultural plots provides renewable energy and means of action to dampen some of the effects and hazards of climate change. When the panels are properly operated, their drop shadow reduces water consumption by the plants, as a consequence of alternating shade and sun bands with a short-term impact on the stomatal conductance and a global decrease of gas exchanges. This urged the development of a new model for crop growth and water budget, adapted here from existing literature to handle such transient conditions, characterized by short-term (infra-day) fluctuations. The main difficulty was to combine short-term fluctuations in the climatic forcings (radiation interception and rain redistribution by the panels) and long-term agronomic evaluation, hence the coexistence of several calculation time steps in model structure. All field experiments were conducted on purpose in the agrivoltaic plot of Lavalette (Montpellier, France). Specific adaptations consisted in describing the stomatal behavior of the plants for fluctuating solar radiations and varied water status, aiming at improving both the piloting of the solar panels and water management, i.e. the choice of irrigation amounts. Model simulations have been able to reproduce the expected benefits from agrivoltaic installations, for example showing that it is possible to improve land use efficiency and water productivity at once, by reducing irrigation amounts by 20%, when tolerating a decrease of 10% in yield or, alternatively, a slight extension of the cropping cycle. Agrivoltaism appears a solution for the future when facing climate change and the food and energy challenges, typically in the rural areas and the developing countries and especially if the procedure presented here proves relevant for other crops and contexts.

1. Introduction

The massive use of fossil fuels forbids perpetuating energy production at the global level and contributes to the unequivocal climate change (IPCC, 2011, 2014;[1] IEA, 2015)[2]. Several scenarios of climate evolution explored by the IPCC (2013) show an increase of summer temperatures up to 4 or 5 °C combined with a decrease of 20% of rain amounts during spring and summer, in the Mediterranean regions, at the 2100 horizon. As already established by the FAO[3] (Turral et al., 2011), the alarming consequences on the agricultural world consist in an increase of (hard-to-meet) water demands by the plants, a decrease or a capping of crop yields and a decrease of water availability in regions where irrigation would be necessary or currently allows considerable benefits. Facing the energy and food challenges, agrivoltaism appears as an innovating concept around the world (Marrou, 2012; Harinarayana et al., 2014; Ravi et al., 2014). First outlined by Goetzberger and Zastrow (1982), this concept as defined by Dupraz et al. (2011) consists of the association, on a same land area, of agricultural and photovoltaic productions, by means of solar panels (PV) located high enough above the crop to allow agricultural machinery to pass.

Agrivoltaism (AV) therefore deals with "symbiotic" electric and agricultural productions. On the energetic front, AV may deliver a production of 150 Wc per square meter of PV (Sun’R, 2014, **pers.**

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[1] IPCC : Intergovernmental Panel on Climate Change.
[2] International Energy Agency.
[3] Food and Agriculture Organization.

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comm.). On the agronomic front, the experiments conducted by Marrou (2012) insisted on (i) the maintenance of crop yield for lettuces irrigated with drip irrigation, (ii) the increase of land use efficiency (Land Equivalent Ratio, LER) and (iii) the absence of noticeable modifications of the reigning micro-meteorological conditions, to the exception of radiation. Water consumption by the crop was reduced by 20%–30%, under east-west PV rows responsible for strong radiative heterogeneities in the north-south direction, on the soil surface. The *modus operandi* has now changed and the most recent experiments (on the Lavalette station of IRSTEA,[4] Montpellier, France) involve tilting-angle PV able to revolve around their horizontal rotation axis, which finds itself in the north-south direction to reduce the unwanted spatial heterogeneities in radiation. The installation of such dynamic devices expectedly allows optimizing the shading conditions in function of soil water status, weather forecasts, plant needs and scheduled or possible irrigations. But still this achievement cannot be reached without the derivation of a new model that would predict the effect of the short-term fluctuations of climatic forcings (radiation interception and rain redistribution by the panels) on the long-term crop development and agronomic valuation. Moreover, such a model should probably be formulated in a simple enough way to fit within a meta-model or a multi-model global optimization procedure.

A first step in this direction was taken by Valle et al. (2017) who presented the AVstudio model that describes the dynamics of the spatial distribution of radiation transmitted to the crops together with a calculation of electricity production. From the morphologic adaptation of lettuces under fluctuating radiation conditions (number, thickness and surface of the leaves) the same authors also provided an overall evaluation of agrivoltaic systems in the form of promising values of the LER indicator. On the other side, Elamri et al. (2017) have tackled the impact of the tilting angle of the PV on rain redistribution on the soil surface in developing the AVrain model. This demonstrated the merits of a real-time piloting of the PV to reduce the spatial heterogeneities caused by rain interception by these PV. This paper therefore aims at complementing the cited developments to remedy the lack of a model that (i) evaluates the impact of rain redistribution on crop growth, yield and water consumption, (ii) evaluates water use and land use efficiencies, and (iii) allows optimizing the shading strategy from soil water status, climatic conditions, or other controls of interest to be identified later.

Moreover, there are clues that the advocated modelling framework should certainly include a description of stomatal conductance. To do so, this paper also takes advantage of the inaugural works by Marrou et al. (2013a) who noticed the influence of the drop shadow of the PV on the stomatal behavior of the crop but did not consider the link between water availability and photosynthesis (Pearcy et al., 1997; McAusland et al., 2016) or stomatal conductance (Jones, 1992; Martorell et al., 2015; Bota et al., 2016), the latter rather well documented in the literature (see the review of Damour et al., 2010). Numerous models indeed describe stomatal conductance (g_s) in function of soil water status (fraction of transpirable soil water) and environmental data (temperature, pressure vapor deficit) although acknowledging radiation as the key variable for an accurate prediction of g_s. However most models do not account for the short-term, high-frequency fluctuations in radiation (Vialet-Chabrand, 2013) inherent to agrivoltaic installations.

The aim of this paper is finally to model the water budget and crop growth of irrigated lettuces in agrivoltaic plots, for different strategies in piloting the tilting-angle PV. In addition, owing to the effect of a reduction of gaseous exchanges on both photosynthesis and water consumption by the plant, stomatal conductance is selected as the key variable to account for the succession of "sunny" and "shaded" conditions. In particular, emphasis is placed on the influence of the PV on the decrease of water consumption by the crop. This work is intended as a first step towards a multi-variable optimisation (piloting of the PV, irrigation scheduling) of agrivoltaic systems that starts with the derivation of the *ad hoc* (though intended generic enough) AVirrig water budget and crop growth model, adapted from Optirrig (Cheviron et al., 2016).

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2. Material and methods

2.1. The agrivoltaic installation of Lavalette

The agrivoltaic (AV) installation finds itself in the experimental platform of Lavalette (IRSTEA Montpellier, France : 43.6466 °N ; 3.8715 °E) and covers a total area of 1720 m^2 next to a control plot (CP) of 1120 m^2 located immediately south of the AV plot. There is no influence of the solar panels (PV) on the control plot, i.e., no drop shadow at any time of the day, whatever the season. The AV plot has 4 A V devices (Fig. 1), thus 4 shading methods in which the drop shadow corresponds to a decrease of the incoming solar radiation by 20%–50% in average (Table 1). The two fixed devices (*Half Density*: HD, and *Full Density*: FD) were built in 2010 and have been extensively described by Marrou (2012). They consist of 0.8 x 1.6 m PV aligned in rows of 22.4 m length, in the east-west direction (79 °N), held at 4 m above the ground. Each row is tilted southwards, with a fixed angle of 25° with respect to the horizontal. On the FD device, the distance between two rows is 1.6 m in the north-south direction, which was set to match the soil cover ratio (or shading rate) of traditional photovoltaic plants. On the HD device, only one row out of two remains and the distance between two rows is 3.2 m. Marrou (2012) suggested using tilting-angle PV with a coverage ratio equivalent to that of the HD fixed device to homogenize radiation maps, while the FD device was deemed too penalizing for crop growth either with fixed or tilting-angle PV.

Two new dynamic AV devices were installed in 2014, termed *Solar Tracking* (ST) and *Controlled Tracking* (CT) with the same shading rate as for the HD device, installed on each side of the preexisting devices. The PV are now 2 x 1 m, located 5 m above the ground, held by poles forming square arrays of 6.4 m side, allowing access for agricultural machinery. The length of a PV row is 19 m in the north-south direction (369 °N). The tilting angle of the panels may currently be varied between 50 °E and 50 °W operated by electrically controlled jacks. The ST and CT devices are independent and they receive specific setpoint values for their tilting angles in time.

The ST device was thought to maximize radiation interception (and the production of electricity) and thus the drop shadow on the soil surface by following the sun's course. This shading strategy reduces by 35% the transmitted radiation. This method of operation is termed "Tracking 1 axis". Quite differently, the CT device minimizes radiation interception before noon then shades the crops beneath the structure during the hot hours, between 9 and 14 h UTC. Later on in the afternoon, minimum radiation interception is sought again and the PV are operated to be as parallel to the sun rays as possible. This strategy allows homogenization of the transmitted radiation with a reduction of about 20%. Complementary indications may be found in Marrou et al. (2013b) and Valle et al. (2017) on the piloting of the PV and its effects on the microclimate, with a focus on the transmitted radiation and on the temperature.

2.2. Crop management and monitoring

The *Madelona* variety of romaine lettuce has been tested to evaluate the impact of varying shading conditions in AV installations. Lettuces have been chosen for their short cropping cycle (5–7 weeks) allowing two consecutive cycles, in spring and summer. The choice of the variety has been discussed with local gardeners, who advised *Madelona* for its tolerance to the Mediterranean climatic conditions and the morphology