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Agrivoltaic systems to optimise land use for electric energy production

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HIGHLIGHTS

- A simulation platform to simulate crops under agrivoltaic was developed.
- Shading under agrivoltaic improves soil water balance and increases water saving.
- Agrivoltaic conditions increased and stabilized yield of rainfed maize.
- Agrivoltaic doubled renewable energy land productivity.

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ABSTRACT

A system combining soil grown crops with photovoltaic panels (PV) installed several meters above the ground is referred to as agrivoltaic systems. In this work a patented agrivoltaic solar tracking system named Agrovoltaico®, was examined in combination with a maize crop in a simulation study. To this purpose a software platform was developed coupling a radiation and shading model to the generic crop growth simulator GECROS. The simulation was conducted using a 40-year climate dataset from a location in North Italy, rainfed maize and different Agrovoltaico configurations (that differ according to panel density and sun-tracking set up). Control simulations for an irrigated maize crop under full light were added to results.

Reduction of global radiation under the Agrovoltaico system was more affected by panel density (29.5% and 13.4% respectively for double density and single density), than by panel management (23.2% and 20.0% for sun-track and static panels, respectively).

Radiation reduction, under Agrovoltaico, affected mean soil temperature, evapotranspiration and soil water balance, on average providing more favorable conditions for plant growth than in full light. As a consequence, in rainfed conditions, average grain yield was higher and more stable under agrivoltaic than under full light. The advantage of growing maize in the shade of Agrovoltaico increased proportionally to drought stress, which indicates that agrivoltaic systems could increase crop resilience to climate change.

The benefit of producing renewable energy with Agrovoltaico was assessed using the Land Equivalent Ratio, comparing the electric energy produced by Agrovoltaico cultivated with biogas maize to that produced by a combination of conventional ground mounted PV systems and biogas maize in monoculture. Land Equivalent Ratio was always above 1, it increased with panel density and it was higher with sun tracking than with static panels. The best Agrivoltaico scenario produced twice as much energy, per unit area, as the combination of ground mounted PV systems and biogas maize in monoculture. For this Agrivoltaico can be considered a valuable system to produce renewable energy on farm without negatively affecting land productivity.

1. Introduction

Worldwide energy demand is expanding due to an increasing global population and energy use by industry. At the same time, the threat of global warming is reshaping strategies of energy production; the EU decreed that by 2020, 20% of the energy must come from renewable sources, (Renewable Energy Directive, 2009/28/EC), which should become at least 27% by 2030 (EC COM(2016) 767 final/2). Despite its intimate connection with sustainable development [1], renewable energy production is not immune to criticism, especially when it interferes with actual land use, as demonstrated by the fuel vs food debate [2].

Among renewable energies, solar photovoltaics (PV) is the fastest growing power generating technology [3]. A number of studies have addressed the potential impacts of PV plants, particularly in terms of

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the conflict that large scale PV plants can generate on agricultural land [4–7] while Calvert and Mabee [8] developed a methodology to compare the production potential and land-use efficiency of PV and bioenergy solutions. Although PV energy has a low land requirement compared to other renewable-energy options [9], its landscape integration should be designed to minimize adverse land use changes and favor community acceptance [10]. Combination of PV power production and agricultural activities has many potential declinations [11]. While integration of PV panels to agricultural infrastructures, to drying systems [12] or its use for waste water purification [13] and water pumping [14] proved to be technically feasible and provides multiple benefits [11], the use of agricultural land to install ground mounted PV has been constrained by governments and local authorities to avoid soil consumption, landscape impact, and competition with food production [15]. To date, PV systems designed to combine PV energy production with food crops in the same installation are mainly related to greenhouse applications, as an energy saving strategy [16] or to increase farmer's income [17]. Photovoltaic greenhouses are widespread in southern Europe, [18] and have seen a rapid expansion in China [19] thanks to incentive tariffs. In contrast, few PV systems have been designed to overcome the energy vs food competition by combining PV energy production with crops in open field conditions, a concept that was first proposed by Goetzberger and Zastrow [20]. An experimental system combining static PV panels installed 4 m above the ground, with soil grown crops under the panels (as described in [21;22]), was referred to as an *agrivoltaic system*. Such systems are based on the concept that a partial shading can be tolerated by crops and it might reduce water consumption by evapotranspiration during the summer and under drought conditions [23]. It has even been shown that a shade tolerant crop, such as lettuce, grown under PV panels adapts its morphology (e.g. producing wider leaves) without yield reduction, and that overall electricity coupled to lettuce production under agrivoltaic generated a 30% increase in economic value compared to conventional agriculture.

It was proposed that advantages of agrivoltaic systems might be related to their similarity to agroforestry systems [24]; the PV panels protect crops from excessive heat and provide soil temperature mitigation [25], which could imply that agrivoltaic systems are more resilient to climate change than monocultures [24]. Dinesh and Pearce [23] performed a modelling analysis in which lettuce cultivation under PV panels was also simulated in terms of crop yield and energy gain. They showed that the value of solar generated electricity coupled to shade tolerant crop production created an over 30% increase in economic value in farms deploying agrivoltaic systems.

In a recent paper, Majudmar and Pasqualetti [26] propose the implementation of agrivoltaic systems as a sustainable strategy in peri-urban areas to generate carbon-free electricity and preserve the agricultural land by providing urban growth boundaries and increasing land value and farmers' benefits. The successful implementation of agrivoltaic systems ultimately depends on farmers' acceptance, which is based on their perception of the benefits of agrivoltaic systems. Increased land value [23] and land productivity [21] are very convincing attributes of agrivoltaic systems and utility companies could further stimulate development of agrivoltaics with incentives for farmers [26]. An understanding that crop yield under agrivoltaics is not seriously affected (or in some cases remains equal or is increased) and/or water use efficiency can increase [23] would provide a further push towards the diffusion of agrivoltaic systems in open fields. The additional energy production would not radically transform farmers' businesses, but it would complement their income, increase self-consumption and ultimately reduce public spending on renewable energy [17].

Modelling analyses have shown that production in an agrivoltaic system can be optimized by modifying the architecture of the panels [23,27] and crop productivity can be stimulated by adjusting the tilting of the panel during the cropping cycle [27]. A step forward would therefore be to install PV panels that can move in order to either maximize energy production or food production, or to optimize both [27]. Early research on agrovoltaics was limited to case studies with fixed panels [22] and only one very recent research reports on mobile 1-axis PV system [27]. The system Agrovoltaico® (hereafter referred to as *Agrovoltaico*) was designed and built on a large scale to combine the cultivation of field crops, such as maize (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.), with the production of solar energy on the same land unit. The first two *Agrovoltaico* systems were installed in 2012 in Castelvetro Piacentino [28] and Monticelli d'Ongina [29] (Po valley, Northern Italy, N 45.09° E 10.00° and N 45.07° E 9.93°, respectively) covering an area of 7 ha and 20 ha, respectively.

Considering that radiation in agrivoltaic systems is reduced due to partial shading and many economically important field crops such as maize are considered not shade-tolerant, we developed a modeling platform that not only simulates maize production under a specific agrivoltaic system, but also optimizes crop yield and energy production by adjusting the agrivoltaic system configuration. The principal aims of this study were two-fold. The first was to simulate the production of maize cultivated under the partial shading of the *Agrovoltaico* system using a bespoke radiation model and the GECROS crop model [30]. The second was to compare both energy and crop production under different configurations of the *Agrovoltaico* system. In particular, four different configurations of the system were compared: static PV panels (F) versus sun tracking PV panels (ST), with each having two different PV panel densities (m^2 PV panel/m^2 ground).

In order to demonstrate the potential of our simulation platform to predict energy production and crop yield under different configurations, and to compare strategies for renewable energy production at farm level, the data produced in this study will be used to compare the global land productivity of *Agrovoltaico* systems to the more common options of either cultivating maize for biogas or producing electrical energy from ground mounted PV systems.

2. Materials and methods

2.1. The Agrovoltaico system

The *Agrovoltaico* system (Fig. 1) is a solar tracking system, built on suspended structures (stilts). On the stilts are mounted horizontal main axis, on which secondary axis holding the solar panels are hinged. The two axes can rotate as they are driven by electric motors interconnected through an innovative control system and wireless communication. Under *Agrovoltaico,* in contrast to traditional ground PV installations, agricultural practices can be performed with standard machinery. One relevant feature of *Agrivoltaico* is that panels are not evenly distributed on the soil surface, and this affects the shading patterns at soil level, with the creation of a band along the main axis of the panel arrays where shade is more intense and another band where the shade only occurs at certain periods during the day.

2.2. Software platform and data

To simulate the growth and production of crops cultivated under the shade of a *Agrovoltaico* system, a software platform was developed in Scilab [31] coupling a radiation and shading model to the generic crop growth simulator GECROS [30]. Scilab is a programming language associated with a rich collection of numerical algorithms covering many aspects of scientific computing problems. The platform is designed to maintain and handle large climatic dataset and different environmental situations using free software relational database (MySQL). The database includes soil information (Regional environmental services) and meteorological series provided by Meteorological Regional Services since 1990. Older meteorological series were reconstructed with the data obtained from the Joint Research Centre (Interpolated AGRI4CAST Meteorological, link; http://agri4cast.jrc.ec.europa.eu/DataPortal/Index.aspx).