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Enhancing Olive Production in Mediterranean Agrivoltaic Systems: A Microclimatic Analysis Using Computational Fluid Dynamics Modeling

Insights from the "Borgo Monteruga" project in Southern Italy

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Abstract. Agrivoltaic Systems (AVs), combining agriculture and solar power generation, represent a sustainable land use method. This research is conducted for the "Borgo Monteruga" agrivoltaic project, located in Southern Italy. The project is characterized by the inter-cropping of high-density olive groves, arranged in hedgerows between solar trackers, with fodder crops on either side or, alternatively, medicinal crops, depending on the soil quality. The park boasts a peak power capacity of 291.33 MWp, achieved through the installation of double-sided 600 W photovoltaic modules and a 50 MW storage system. The novelty of this project lies in the proactive assessment of microclimatic parameters to optimize the AVs layout, aiming to reduce shading on crops and enhance the efficiency of both agricultural and solar energy production. The photovoltaics modules in AVs significantly impacts the local microclimate, influencing aspects such as solar radiation, air and soil temperatures, wind speed, and groundwater retention. Understanding these microclimatic shifts is essential not only for the effective management of AVs and strategic crop selection but also for choosing optimal adaptive solutions to climate change. Additionally, this knowledge is key to establishing a tailored monitoring system with innovative and targeted strategies, ensuring the AVs resilience and productivity in the face of evolving environmental conditions. This study sets a new benchmark in AVs design and optimization by implementing advanced computational fluid dynamics (CFD) modeling for its microclimatic analysis, thereby contributing significantly to the field of sustainable agricultural practices.

Keywords: Planning & Design Agrivoltaic Systems, Environmental Modelling, Microclimate

Abbreviations: PV: photovoltaic; AV: agrivoltaic; AVs: agrivoltaic systems; CFD: computational fluid dynamics; i.r.: inter-row; Tair: air temperature; Tsoil: soil temperature

1. Introduction

1.1 Defining agrivoltaic systems: from agro-energy synergy to international regulatory criteria

Global food consumption has witnessed rapid growth, reaching a significant peak of 2.5 billion metric tons in 2021 [1]. This increase has led to a growing demand for agricultural land to meet food production needs. Simultaneously, the rise in global population has significantly increased energy consumption, and photovoltaic (PV) technology offers a beneficial response to this energy demand. But it also presents challenges related to the conflict with land-use for agriculture, thus necessitating a balance between food production and energy generation. In addition, climate change has imposed additional stresses on agriculture, such as altered precipitation patterns, increased frequency of extreme weather events, and shifting crop growing seasons. Summer stress, characterized by extreme heat and drought conditions, reduces crop yields and increases water demand.

In this context, agrivoltaic systems (AVs) emerge as a promising solution due to their dual-use capability, allowing for efficient food production and more energy generation. Studies have shown that shading from PV panels can reduce leaf photosynthesis and cause rapid stomatal closure, lowering leaf evapotranspiration, thereby enhancing water use efficiency. Moreover, PV panels help lower air temperatures beneath them, counteracting extreme heat, and balancing soil moisture levels, thus fostering an environment conducive to plant growth [2][3][4][5].

AVs can have varying impacts on agricultural production, with outcomes dependent largely on the crops grown. While the shading from PV panels and increased machinery and labor costs can reduce agricultural gross margins by about 74% for cereal and vegetable farms, there are also opportunities for synergies. For example, some crops, like strawberries, benefit from the shading and show increased yields [6].

Currently, definitions of AVs vary significantly based on regional specifics, reflecting the adaptation of standards to agricultural sectors and the priorities of each country. This has led to different qualification criteria for identifying AVs. For example, in 2021, Germany introduced the first European legislation on AVs with DIN SPEC 91434, distinguishing between elevated and inter-row systems and requiring that crop yields in these systems achieve at least 66% of standard yields. In that same year, France’s French Standardization Association (AFNOR) released its “Agrivoltaic Project Label: Standards for the Labeling of Class A Crop Projects,” stipulating that AV projects must achieve at least 80% of reference yields to qualify for "Class A" certification. In 2022, Italy followed with its “Guidelines for The Design, Construction and Operation of Agrovoltaic Plants,” mandating that agricultural activities must cover at least 70% of the total area of an AVs installation. Other nations are expected to introduce their own standards, creating further differences in international qualification criteria [7].

Beyond the various global criteria defining AVs, the primary focus should be on creating systems where agriculture and energy production enhance each other. This synergy is achieved through careful spatial and agricultural planning that aligns with local crop suitability and agricultural practices. Technological innovation and advanced predictive modeling systems, underpinned by rigorous scientific research, are imperative for the optimization of these integrated AVs.

1.2 The optimization parameters

The configurations of AVs vary in terms of project capacity, panel height, inter-row and inter-panel spacing, PV technology and racking system (Figure 1). Defining these parameters is essential to maximize both agricultural yields and energy generation, facilitating the selection of optimal crops for panel shading and establishing the most effective arrangement of photovoltaic panels to increase energy efficiency.

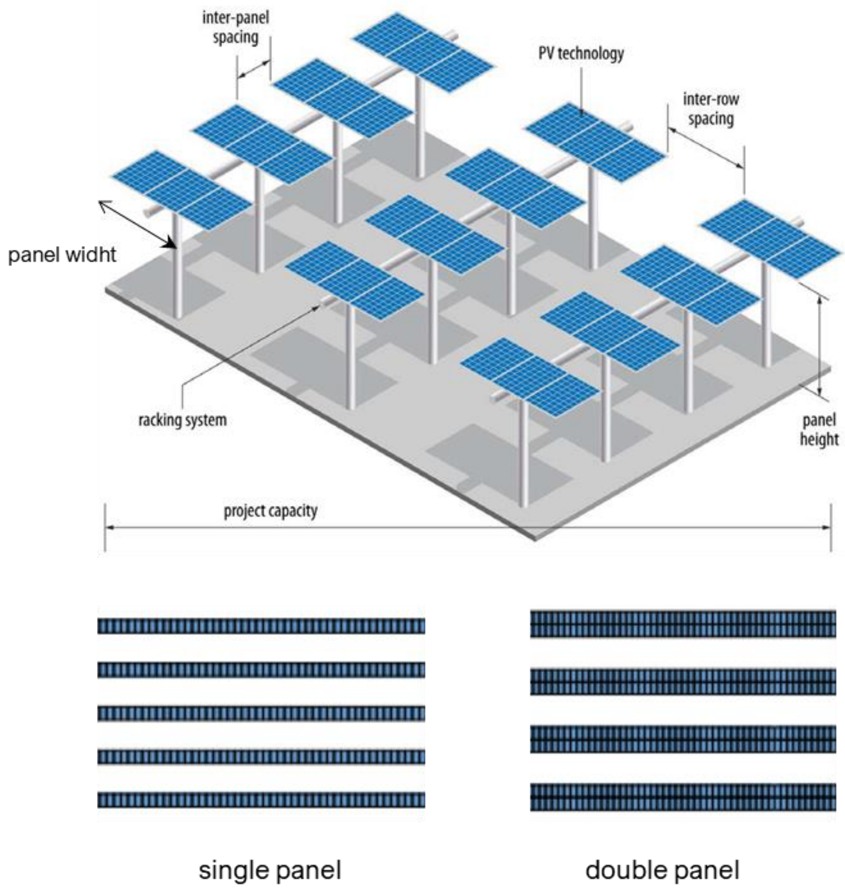


Figure 1. *Configuration and technology characteristics; modified from [7].*

Plant selection is also a critical factor for optimizing performance in AVs. Maximizing both crop production and power generation necessitates selecting plant genotypes with superior light use efficiency. A key factor in this selection process is the carbon assimilation pathway, which categorizes plants into C3, C4, and CAM subtypes [8]. C3 plants hold a distinct advantage in AVs due to their inherent shade tolerance. Unlike C4 and CAM plants that flourish in high-light environments, C3 species achieve peak photosynthetic rates at lower light intensities [9]. This characteristic allows C3 plants to maintain efficient photosynthesis even under the partial shading caused by PV panels.

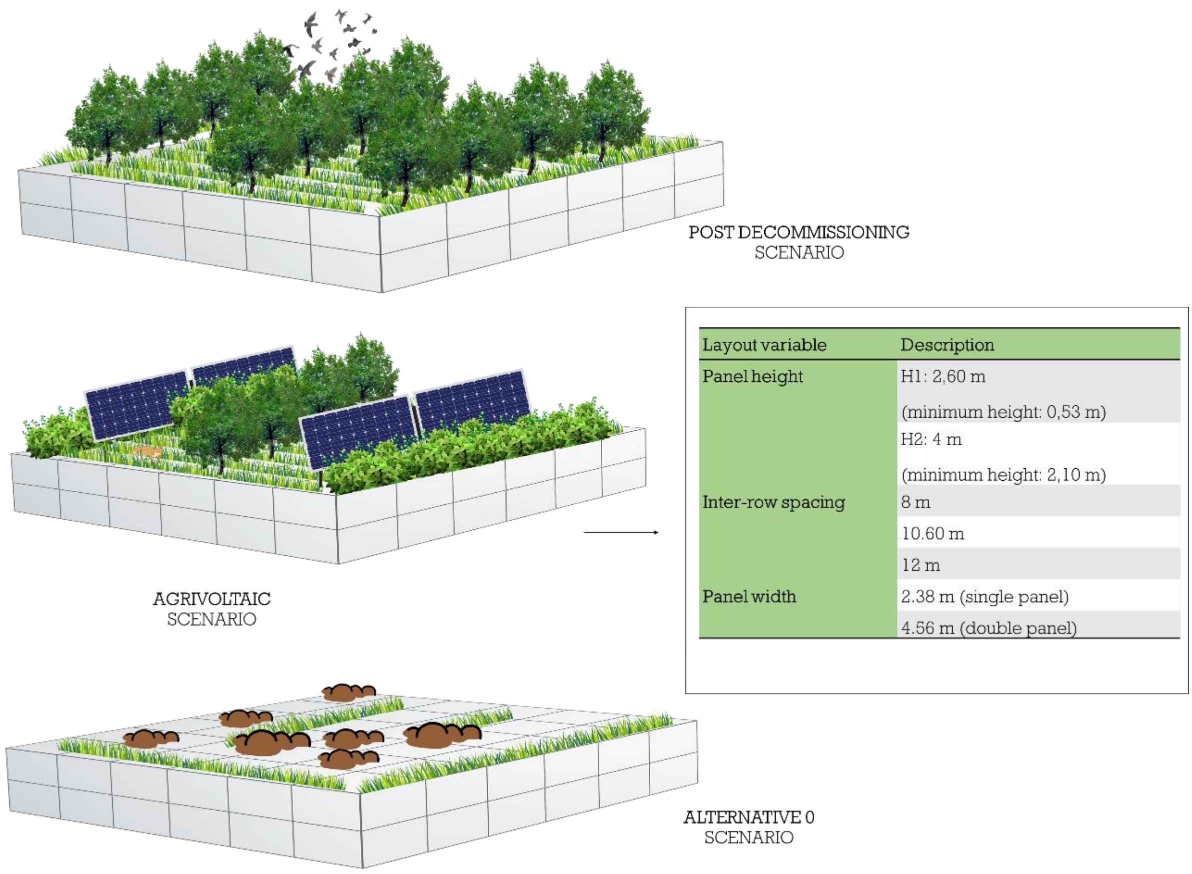
1.3 The “Borgo Monteruga” project: a microclimate-driven design approach for agrivoltaic system optimization

The Borgo Monteruga project will provide 291.33 MWp of peak power with double-sided 600 W modules and a 50 MW storage system. The project spans 420 hectares within a 588-hectare area. Central to the project is the cultivation of Xylella fastidiosa-resistant olive trees, intercropped with a diverse array of rotational fodder and medicinal plants, all designed for a high degree of mechanization [10]. The design of this project began with the selection of the optimal configuration for crop cultivation and energy production through rigorous numerical analysis and computational fluid dynamics (CFD) simulations. These analyses guided by environmental parameters, particularly microclimatic conditions, facilitated the determination of minimum panel heights and inter-row distances. This microclimate-driven approach ultimately created a synergistic environment in which renewable energy production and sustainable agriculture could thrive together.

2. Material and Methods

The study employs a dual-methodological approach:

- **Comprehensive mathematical simulation**: By applying mathematical methodologies from established research, the optimal height of olive hedges that avoids shading of solar trackers and the ideal inter-row spacing to maximize solar irradiance have been determined. More details of this methodology shall be elaborated in future publications.
- **Advanced microclimate modelling**: Numerical simulations were performed with ENVI-met [11], using mainly a 3D prognostic non-hydrostatic model for the simulation of surface-plant-air interactions, and additionally a one-dimensional atmospheric boundary layer model which extends from the ground surface up to 2500m. The 3D simulation area was 100m by 100m, with a grid resolution of 1m (x,y,z), except the lowest five cells which had a 0.4m resolution vertically. Five nesting grids were used to enhance accuracy and stability. The simulation, driven by hourly air temperature and relative humidity data from ERA5 for a typical summer day, analyzed fourteen AV configurations varying in panel height, inter-row spacing, and panel width (Figure 2). Additionally, an "Alternative 0" scenario, representing the current situation without the AVs and cultivation, and a "post-decommissioning" scenario were evaluated for environmental impact. The post-decommissioning scenario involves removing the installation and implementing environmental recovery actions, including planting new vegetation in the areas previously occupied by the panels. Several microclimatic variables, such as air and soil temperature, relative humidity, and ventilation, were also simulated.



Layout variable	Description
Panel height	H1: 2,60 m (minimum height: 0,53 m)
	H2: 4 m (minimum height: 2,10 m)
Inter-row spacing	8 m
	10.60 m
	12 m
Panel width	2.38 m (single panel)
	4.56 m (double panel)

Figure 2. *Simulated scenarios. For the AV scenario, several layout variables were considered (see the Table 1).*

The methodology and investigative process of the modeling study were scientifically validated through previous publications in international peer-reviewed scientific journals [12],[13].

3. Results

3.1 Air temperature (Tair)

Table 1 presents the average T_{air} values at 12 pm in various spatial contours of interest (under-panel and inter-row) for the different simulated scenarios.

Table 1*. Average T_{air} values in spatial contours at 12:00 pm*

		Area average	Under-panel		Inter-row	
			H1	**H2**	**H1**	**H2**
	Alternative 0	32.2 °C	-	-	-	-
DOUBLE PANEL	Agrivoltaic **i.r: 8m**	30.4 °C	30.25 °C	30.31 °C	30.52 °C	30.49 °C
	Agrivoltaic **i.r: 10.6m**	30.5 °C	30.25 °C	30.31 °C	30.84 °C	30.79 °C
	Agrivoltaic **i.r: 12m**	30.5 °C	30.25 °C	30.31 °C	30.87 °C	30.82 °C
SINGLE PANEL	Agrivoltaic **i.r: 8m**	30.8 °C	30.42 °C	30.49 °C	31.2 °C	30.9 °C
	Agrivoltaic **i.r: 10.6m**	30.9 °C	30.42 °C	30.49 °C	31.55 °C	31.15 °C
	Agrivoltaic **i.r: 12m**	30.9 °C	30.42 °C	30.49 °C	31.6 °C	31.42 °C
	Post decommissioning	29.3 °C	-	-	-	-

Tair reduction compared to “Alternative 0” scenario: In comparison to the “Alternative 0” scenario, there is a notable decrease in average temperature in the AV areas: a reduction of 1.8°C with double-panel configurations and 1.4°C with single-panel configurations. This indicates a significant positive impact on thermal moderation attributable to the installation of the panels, with double panels being more effective. In the post-decommissioning scenario, there is an additional temperature reduction of 2.9°C, due to environmental restoration activities, including the introduction of new vegetation and increased biodiversity compared to pre-existing conditions.

Comparison between single and double panels: For all simulated panel heights and inter-row distances, higher temperature of approximately 0.2°C is observed under the panels in the single-panel configuration. Additionally, for the single panel configuration, an increase of up to 0.7°C and 0.4°C is observed in the inter-row area, for lower panels (H1) and higher panels (H2), respectively.

Effect of inter-row panel distance: The trend remains consistent between single and double-panel configurations, with higher temperatures observed for single-panel setups. For the double-panel configuration:

Area under the panels: For same panel height, there is no significant change in temperature or shading intensity with varying inter-row spacing. However, for different inter-row spacing, a comparison across different panel heights indicates that lower panels exhibit lower temperatures of about 0.06 °C.

Inter-row area: in contrast to the observed trend under the panels, in this area lower panel heights lead to a temperature increase of approximately 0.30°C compared to higher panels.

This suggests that lower panels generate more intense and localized shading, resulting in more pronounced microclimatic differences between the area under the panel and the inter-row space. Additionally, increasing the inter-row spacing causes a temperature rise in these inter-row areas, indicating a reduction in shading effectiveness.

In summary, lower panel height promotes stronger microclimatic differentiation between the shaded area under the panels and the inter-row space. Conversely, raising panel height reduces direct shading intensity but expands its coverage, resulting in a more uniform thermal response across the inter-row area. Figure 2 presents spatial maps of Tair at 12:00 pm for the double-panel configuration, chosen due to its observed microclimatic discrepancies and higher energy production.

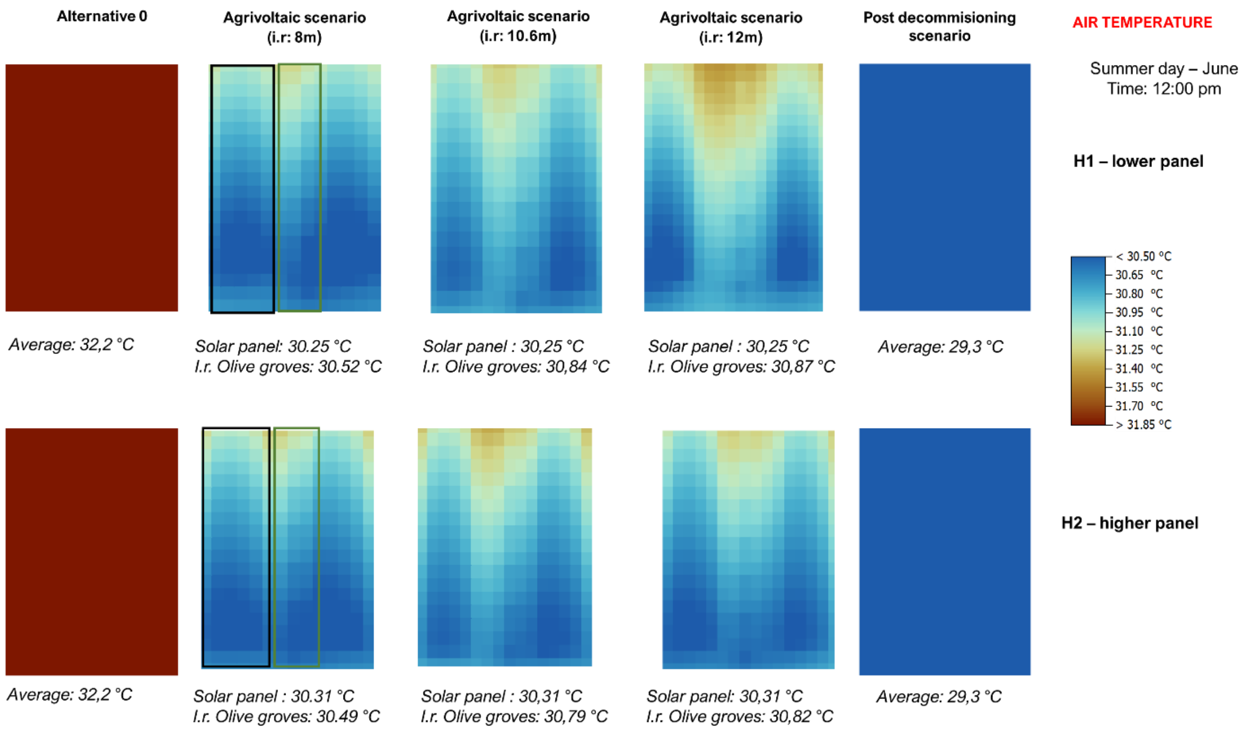


***Figure 3**. Spatial maps of T_{air} (°C) at 12:00 pm for the double-panel configuration. The averages under the panel (solar panel) and the averages in the inter-row area (i.r. olive groves) are indicated.*

3.2 Sun hours

The analysis of sun hours under various AV scenarios reveals the impact of solar panel configuration on sunlight exposure. Figure 4 presents spatial maps of sun hours at 12:00 pm in various spatial contours of interest (under-panel and inter-row) for the different simulated scenarios.

Under-panel sun hours: At height H1, an increase from 4.7 to 5 hours is noted as the inter-row distance increases. This suggests a reduction in shading intensity. At height H2, approximately 2 more hours of sunshine are observed, aligning with the variations in Tair and confirming lower shading intensity at higher panel heights.

Inter-row sun hours: At height H1, sun hours progressively increase from 7.9 to 9.3 hours with an increase in the inter-row distance. In contrast, at height H2, sun hours are consistently lower, ranging from 7.5 to 8 hours, indicating lower sun exposure in the inter-row areas compared to H1. This trend aligns with the Tair observations, suggesting more uniformly distributed shading conditions at the higher panel setting.

Although olive trees, being classified as C3 plants (discussed in subsection 1.2), have shade tolerance and can adapt to reduced light under photovoltaic (PV) modules, increased sunlight exposure has the potential to enhance growth conditions, leading to improved fruit yield and size [14],[15].

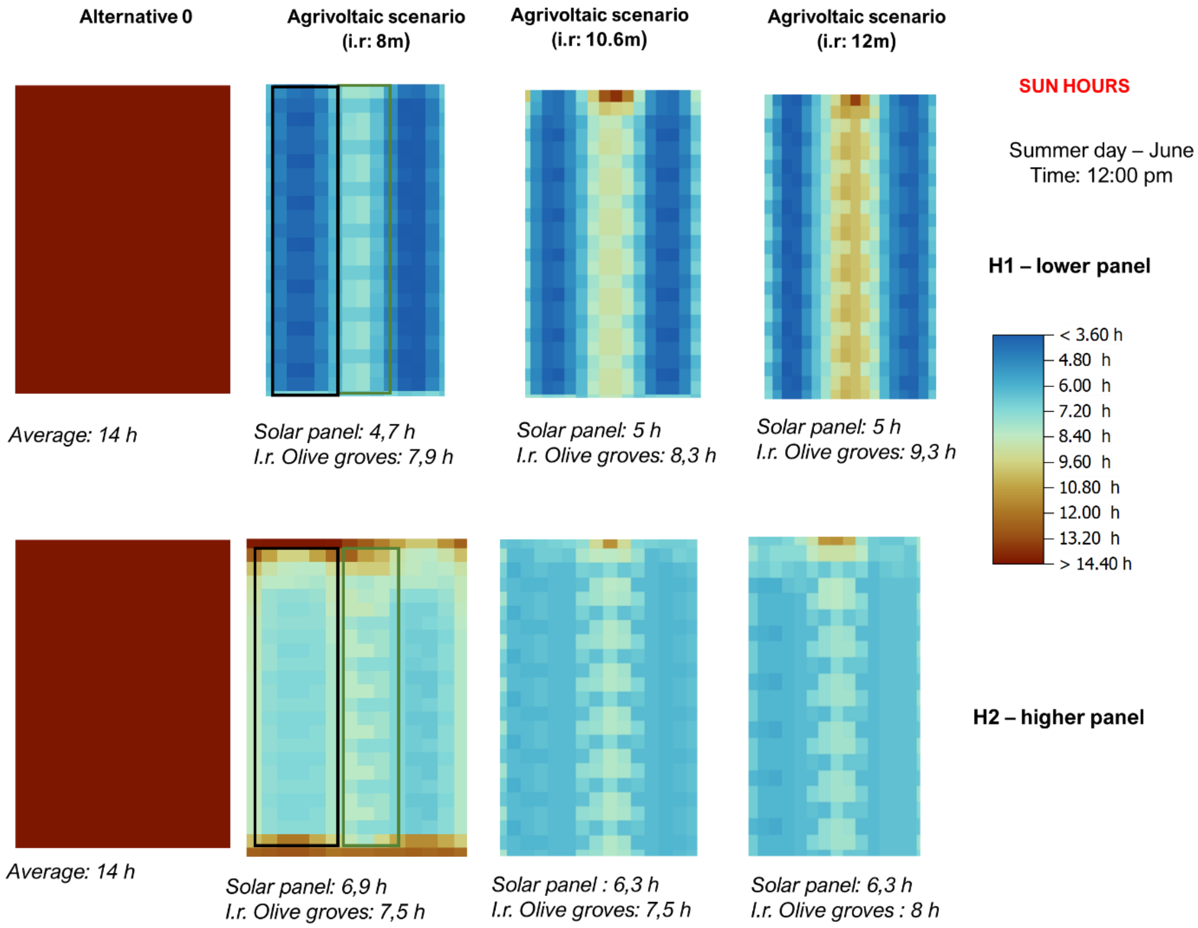


***Figure 4**. Spatial maps of sun hours (h) at 12:00 pm for the double-panel configuration. The averages under the panel (solar panel) and the averages in the inter-row area (i.r. olive groves) are indicated.*

3.3 Soil temperature (Tsoil)

The analysis of T_{soil} differences between AV scenarios and Alternative 0 reveals a crucial impact of panel shading on soil temperature. Figure 5 presents spatial maps of T_{soil} at 12:00 pm in various spatial contours of interest (under-panel and inter-row) for the different simulated scenarios.

Under-panel area: Tsoil differences indicate a marked reduction in temperature under panels compared to Alternative 0, with a decrease ranging from 13°C (H2) to 15°C (H1). This demonstrates that direct solar panel shading produces a substantial cooling effect in these areas, rendering microclimatic conditions significantly cooler than the unshaded external environment. Lower panel heights result in a greater reduction in soil temperature, with a decrease of more than 2°C compared to H2. Additionally, Tsoil is slightly lower when the panels are positioned closer with an inter-row spacing of 8m.

Inter-row area: the temperature reduction ranges from 9°C (H2) to 6.7°C (H1) compared to Alternative 0. These differences still indicate the effect of indirect shading and solar light reflection caused by the presence of panels. Increasing panel spacing (from 8m to 12m) and panel height leads to a slight decrease in the soil cooling effect in inter-row areas, consistent with observations from sun hours and air temperature analysis. A maximum difference of 1.2°C is observed in the 12m inter-row spacing scenario when comparing H1 and H2.

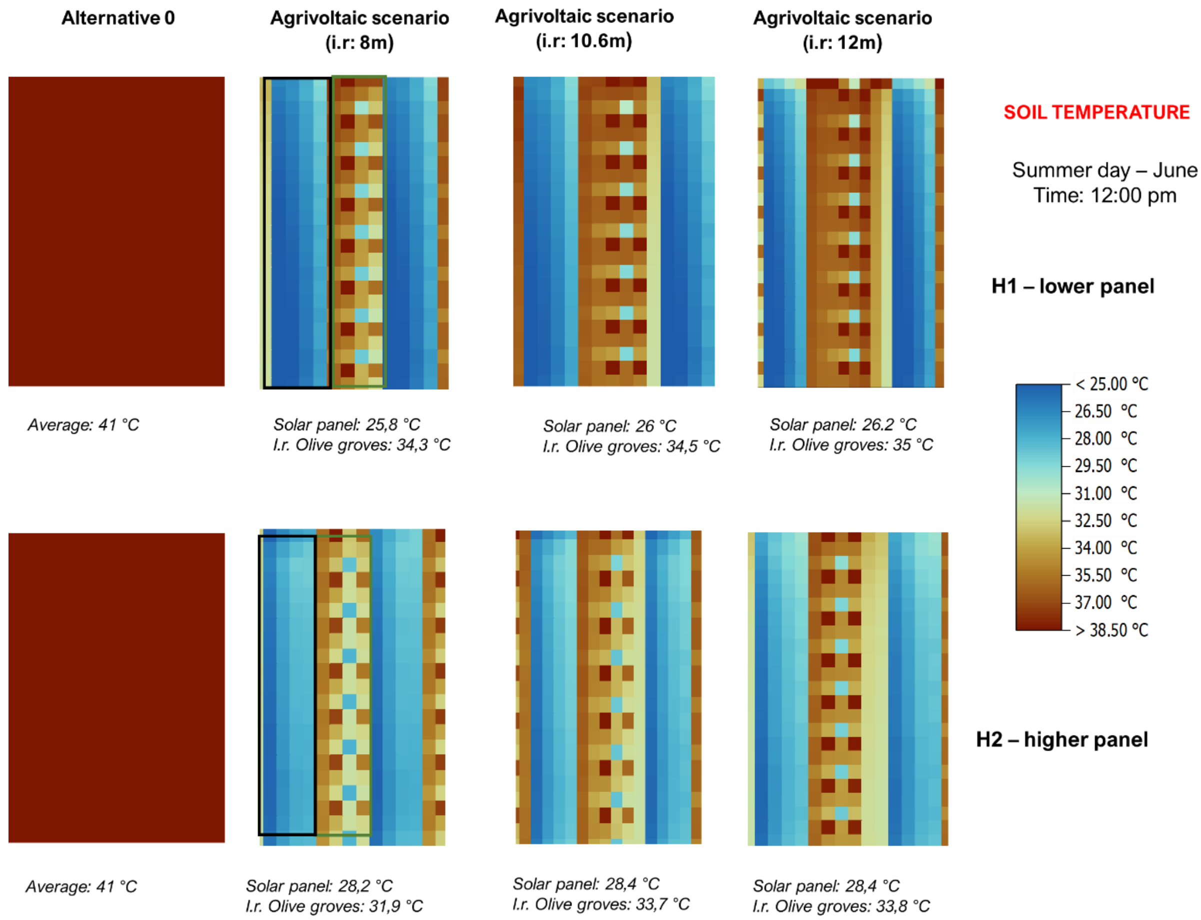


***Figure 5**. Spatial maps of T_{soil} (°C) at 12:00 pm for the double-panel configuration. The averages under the panel (solar panel) and the averages in the inter-row area (i.r. olive groves) are indicated.*

4. Conclusion

The study favored the 12m spacing and a panel height of 2.6m configuration for its benefits in maximizing sunlight exposure and facilitating agricultural operations.

Lower panel heights reduce shading intensity in the inter-row area and create distinct microclimatic conditions between the areas directly under the panels and the inter-row spaces. This differentiation enables more efficient utilization of solar radiation and humidity variations, optimizing growth and productivity. In the inter-row areas, increased exposure to direct sunlight, facilitated by a 12m inter-row spacing, enhances photosynthesis and plant development. Concurrently, moderate shading under the panels maintains cooler and more moist soil conditions, reducing water stress and promoting efficient water use.

This configuration effectively balances the requirements of crop cultivation with energy production, maximizing land use efficiency and supporting sustainable AVs development.

Data availability statement

Data sharing is not applicable to this article.

Author contributions

Author Contributions: Conceptualization, E.G. and M.M..; methodology, E.G.; formal analysis, E.G.; investigation, E.G., L.P., M.I. and M.G.; writing—original draft preparation E.G.; writing—review and editing E.G. and M.M.; funding acquisition, A.T.; investigation and resources, L.B., B.M., C.P., and C.T.; supervision and validation E.G., A.T.; All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare that they have no competing interests.

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