

Article

Effects of Agrivoltaic Cover on Soil Water Dynamics in a Wheat Crop: A Preliminary Case-Study Assessment Based on Field Measurements and Numerical Modelling

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Abstract

Agrivoltaic (AV) systems represent a promising strategy for integrating renewable energy production and agricultural activity on the same land unit, while contributing to soil water conservation under increasingly frequent drought conditions. This preliminary, single-site case study investigates the effects of a horizontal biaxial tracking AV system on soil water dynamics in a durum wheat field in the Po Valley (Borgo Virgilio, Mantua, Italy) over a full monitoring period, covering the final crop growth stages and the post-harvest bare soil phase (May–December 2024). Monitoring of soil temperature, volumetric water content (VWC), and soil water potential (SWP) was conducted at four depths (15, 30, 45, and 60 cm) at one representative monitoring station per treatment, comparing soil under AV cover (AVC) and in unshaded conditions (UC), located 10 m apart. Paired VWC and SWP measurements were used to derive site-specific soil water characteristic curves (SWCCs) and to calibrate the agro-hydrological model CRITERIA-1D, which was used to estimate available water (AW) in the first 80 cm of depth for both treatments. Measured VWC values were higher in the AVC profile than in the UC profile at all monitored depths throughout the May–September period, with differences persisting, although at lower values through October–December. Estimated AW was consistently higher under AVC than in UC during both the dry and wet periods. Despite higher VWC, the AVC profile showed more negative average SWP values at all depths during summer. This pattern is consistent with the shape of the derived SWCCs and may point to differences in water-retaining capacity between the two profiles, possibly related to structural modifications induced by 13 years of AV system operation. These preliminary findings suggest that AV systems could potentially improve soil water availability in the root zone of rainfed cereal crops and propose the hypothesis that long-term AV cover may act as a driver of changes in soil hydraulic properties, with implications for the sustainability and climate resilience of dryland farming systems. However, given the design of this case study, with only one monitoring point per treatment, the observed differences reflect the specific monitored locations and cannot fully disentangle the AV treatment effect from pre-existing spatial heterogeneity in soil properties. The preliminary results obtained in this study should therefore not be generalised beyond the specific conditions of this case study, and the interpretations proposed here should be treated as unproven hypotheses rather than established conclusions. Further studies with spatial replication and multi-year monitoring are needed to confirm these patterns.



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1. Introduction

Energy and food systems are facing severe pressures on a global scale, driven by population growth, competition for land use and the accelerating pace of climate change. The increase in world population has led to growing food demand, triggering widespread conversion of natural habitats into agricultural land [1–3]. At the same time, the transition towards renewable energy sources has led to the conversion of agricultural land into photovoltaic installations, diverting land away from food production and thus intensifying competition for land use [4,5]. In this context, agrivoltaic (AV) systems have emerged as one of the most promising solutions for reducing land use competition, as they can integrate agricultural activity and photovoltaic energy production on the same land unit [6,7]. AV systems can be categorised into fixed-tilt systems, single-axis tracking systems and dual-axis tracking systems, which can be installed on elevated structures (stilt-mounted) to allow machinery to pass underneath them, or as space-optimised (low-profile ground mounts). Fixed-tilt elevated AV systems have the advantage of structural simplicity, but they generate static and permanent shading patterns that can lead to spatial heterogeneity in soil moisture and crop development. In contrast, dynamic tracking systems (single or biaxial) continuously adjust their orientation with varying degrees of freedom to maximise solar tracking and, consequently, solar energy absorption. Whilst primarily designed to increase energy absorption, tracking systems also have the secondary effect of evenly redistributing shading across the field throughout the day, which can mitigate the formation of microclimatic gradients and offer flexible canopy-shading management during critical crop phenological stages [8].

In the current global warming scenario, which has brought about reduced precipitation and rising temperatures in temperate regions, AV systems could represent an effective strategy for mitigating the effects of climate change on agriculture, due to their capacity to modify the water regime of the underlying soil. The partial shading provided by the photovoltaic panels reduces the solar radiation incident on the soil surface, thereby limiting direct evaporation and evapotranspirative demand [9–12]. A systematic review of 33 studies published between 2013 and 2023 found that AV systems improve water-use efficiency by 20–47%, lower soil temperatures by 1–4 °C, and enhance crop resilience under water-scarce conditions [13]. Field experiments across different climatic contexts and crop types confirmed that volumetric water content (VWC) remained consistently higher under photovoltaic panels than under unshaded conditions. Adeg et al. [14] reported an increase in soil moisture underneath AV panels in Oregon (USA), with water-use efficiency improvements up to 328% in a grazing pasture system. Barron-Gafford et al. [15] demonstrated that AV systems in a dryland environment in Tucson (USA) maintained higher soil moisture. In kiwifruit orchards in southwest China, Jiang et al. [16] documented reductions in evapotranspiration up to 30.6% under the highest shading levels. Elamri et al. [9] reported estimated actual evapotranspiration reductions of 19 to 26% in irrigated lettuce systems in southern France, with improvements in water-use efficiency. In a study on maize under fixed and dynamic AV systems, Ramos-Fuentes et al. [17] showed that shading significantly slowed soil drying rates, preserving soil moisture during critical phenological stages, with water savings of up to 47%. These documented benefits of soil water dynamics could be particularly relevant also in the context of rainfed cereal crops, such as durum wheat, which represent a strategic crop in the Mediterranean and European

subcontinental region. Being predominantly grown under rainfed conditions, durum wheat is vulnerable to water deficit during the grain-filling stages, which constitutes the main yield-limiting factor under stress conditions [18,19]. An example of this vulnerability could be observed in the Po Valley, one of the most productive agricultural regions in Europe (accounting for approximately 35% of Italian agricultural output), which is experiencing increasingly frequent drought events [20,21]. Between late 2021 and early 2023, northern Italy was hit by a severe drought. Winter and spring rainfall dropped by 40% and 50% respectively compared with historical baselines, with prolonged dry spells lasting up to 100 consecutive days. These extreme conditions led to a large-scale shortage of agricultural water, resulting in a reduction in regional winter cereal yields ranging from 15% to 30%, causing substantial economic impacts [22,23].

Despite the growing amount of evidence on the hydrological benefits of AV systems, some knowledge gaps persist. Published studies tend to focus on surface or near-surface soil moisture, while the vertical distribution of soil water dynamics throughout the root zone remains poorly characterised. However, this is of fundamental importance, as crop water uptake progressively shifts to deeper layers as the crop matures and the surface layers dry out due to atmospheric demand [24]. This underscores the need to characterise soil moisture beyond the near-surface layer. Most studies rely only on volumetric water content (VWC) as the primary indicator of soil water status, without simultaneously monitoring soil water potential (SWP), which governs the actual plant-available water through the relationship described by the soil water characteristic curve (SWCC) [25]. Finally, the possible long-term effects of AV cover on the hydraulic properties of soil, such as porosity and saturated hydraulic conductivity (k_{sat}), have only recently begun to attract the attention of the scientific community and remain largely uncharacterised [26]. Simultaneously monitoring VWC and SWP values along vertical profiles within the root zone could have practical implications for crop management. Indeed, real-time measurements of these values could enable farmers to identify the onset of crop water stress before visible symptoms or permanent wilting appear. In irrigated crops, this information could also help prevent both under-irrigation and over-irrigation.

The present study contributes to addressing these gaps through a combined experimental and numerical modelling approach. Field measurements of soil temperature, VWC, and SWP were collected at four depths (15, 30, 45, and 60 cm) over a full monitoring period, covering the final crop growth stages and the post-harvest bare soil phase (May–December 2024) at a horizontal biaxial tracking AV system in Borgo Virgilio (Mantua, Lombardy, Italy), situated in the Po Valley, cropped with durum wheat. Paired measurements of VWC and SWP under AVC and UC were used to carry out a preliminary assessment of the potential effect of AVC on the vertical profile of soil water dynamics throughout the root zone, to derive site-specific SWCCs for both treatments, and to calibrate the physically based agro-hydrological model CRITERIA-1D, assessing its performance against field observations collected at the same monitoring site [27,28]. The model, once calibrated, was then utilised to estimate seasonal soil water availability in the top 80 cm of the soil profile under both treatments. To the best of the authors' knowledge, the methodological approach of combining a physically based soil water balance model with simultaneous monitoring of VWC and SWP at multiple depths in an agrivoltaic system has received limited attention in the existing literature. In particular, the use of CRITERIA-1D to estimate available water (AW) as a depth-integrated quantity (expressed in mm) could provide an agronomically meaningful indicator of root-zone water storage. Because it is expressed in the same units as rainfall and evapotranspiration, this indicator might be more directly interpretable for decision-making than a set of point values of VWC or SWP. Furthermore, a physically based agro-hydrological model such as CRITERIA-1D could potentially be used to extend

the AW estimates to depth of agronomic interest where no sensor was installed or to assess the impact of future alternative climate or management scenarios on soil water conditions.

Although still at a preliminary stage, the findings of this study may offer some initial, context-specific insights that could be of interest for the ongoing discussion on the integration of AV systems into agricultural land management. Policymakers and industry stakeholders are paying increasing attention to the multifunctional role of AV systems. A better understanding of their potential hydrological implications could help inform future incentive schemes or siting guidelines, particularly in drought-prone regions such as the Po Valley. Similarly, if further research corroborates the trends observed here, this evidence could eventually contribute, alongside other studies, to technical standards or design recommendations aimed at optimising the agronomic performance of AV installations. However, given the exploratory nature of the present work and the limited spatial and temporal scope of the dataset, these considerations remain tentative. Validation through further multi-site, multi-year investigations would be needed before any practical or regulatory implications can be drawn.

Building on these premises, this study aims to provide a preliminary, exploratory contribution towards a better understanding of the vertical soil water dynamics within the root zone of durum wheat grown under an AV system, compared to an unshaded control. It was hypothesised that the partial shading provided by the photovoltaic panels might be associated with more favourable soil moisture conditions along the monitored soil profile, potentially resulting in greater plant-available water during the crop cycle. A further objective was to explore whether a physically based agro-hydrological model, once calibrated on the limited field dataset available, could offer a tentative, first approximation of seasonal water availability under the two treatments. Given the relatively short monitoring period and the number of simplifying assumptions required for model calibration, the results presented here should be interpreted as indicative rather than conclusive and are intended primarily to lay the groundwork for more robust, longer-term investigations.

2. Materials and Methods

2.1. Study Area and Site Description

The AV system was installed in Borgo Virgilio, Mantua, Lombardy (45°05'40" N, 10°47'30" E) in April 2011 (Figure 1).

Spanning 11.42 hectares, it has a capacity of 2150 kWp. A total of 768 solar trackers, comprising 7680 photovoltaic panels, were installed using a biaxial technology, which automatically adjusts the tilt of the panels based on the sun position to optimise energy capture (Poly 280 WP, Bisol Group d.o.o., Latkova, Prebold, Slovenia). The poles on which the panels are installed are 4.5 m high, the distance between rows is 12.5 m and the tilt angle of the panels is $\pm 50^\circ$ on the main axis and $\pm 40^\circ$ on the secondary axis (Figure 2).

The total area covered by the photovoltaic panels is 1.30 hectares; consequently, the ground cover ratio (GCR), defined as the ratio of the panel area to the land area used for the AS, is 14%. The monitoring period spanned from May to December 2024. Throughout this period, an on-site weather station (MeteoSense 4.0, Netsens s.r.l., Calenzano, Florence, Italy) recorded daily maximum and minimum air temperature and precipitation.



Figure 1. Location of the study site. (a) Regional location of the experimental site within the Po Valley, northern Italy ($45^{\circ}05'40''$ N, $10^{\circ}47'30''$ E). (b) Aerial view of the agrivoltaic (AV) system investigated in this study, showing the boundaries of the AV array (red outline) equipped with horizontal biaxial tracking panels (Ground Cover Ratio = 14%). Imagery source: Google Earth, acquired on 12 March 2024 [29].

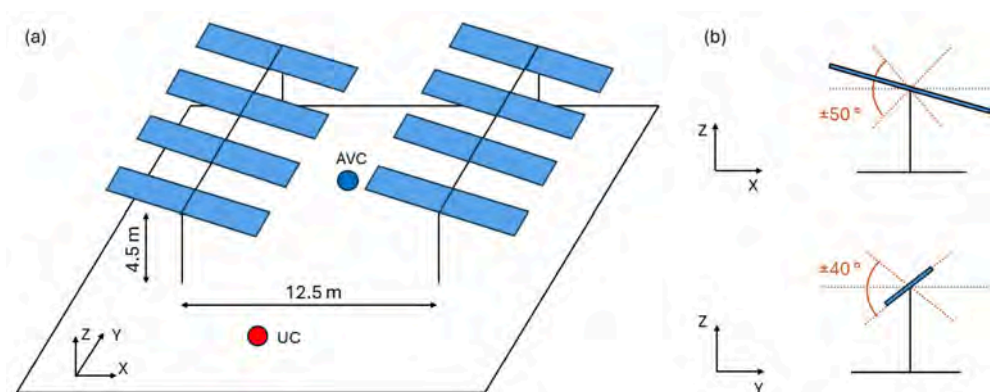


Figure 2. Schematic representation of the agrivoltaic (AV) system layout and tracker rotation axes. (a) Schematic view of the experimental site showing two rows of biaxial solar trackers, with pole height (4.5 m) and inter-row distance (12.5 m) indicated. The locations of the two monitoring stations are shown: AVC (blue dot), positioned beneath the AV panels, and UC (red dot), positioned in the unshaded control area. (b) Schematic representation of the biaxial tracking mechanism, showing panel rotation around the main axis (top; tilt range $\pm 50^{\circ}$) and the secondary axis (bottom; tilt range $\pm 40^{\circ}$), which allow continuous adjustment of panel orientation and tilt to track sun position throughout the day and across seasons.

2.2. Climatological Characterisation

The 1991–2020 climatological normals of rainfall, potential evapotranspiration, mean air temperature, and surface solar radiation for the study area in Borgo Virgilio were derived from ERA5-Land monthly averaged reanalysis data [30,31], at a spatial resolution of approximately 9 km ($0.1^{\circ} \times 0.1^{\circ}$). For the grid cell containing the study area, climatological normals of air temperature and solar radiation were computed as the 1991–2020 average of the ERA5-Land monthly mean values, whereas rainfall and potential evapotranspiration, being cumulative variables, were computed as the 1991–2020 average of the monthly cumulative totals.

Mean temperature and solar radiation (Figure 3) follow a seasonal pattern, peaking in June–July, reaching respectively 25 °C and 220 W/m², and reaching a minimum in December–January.

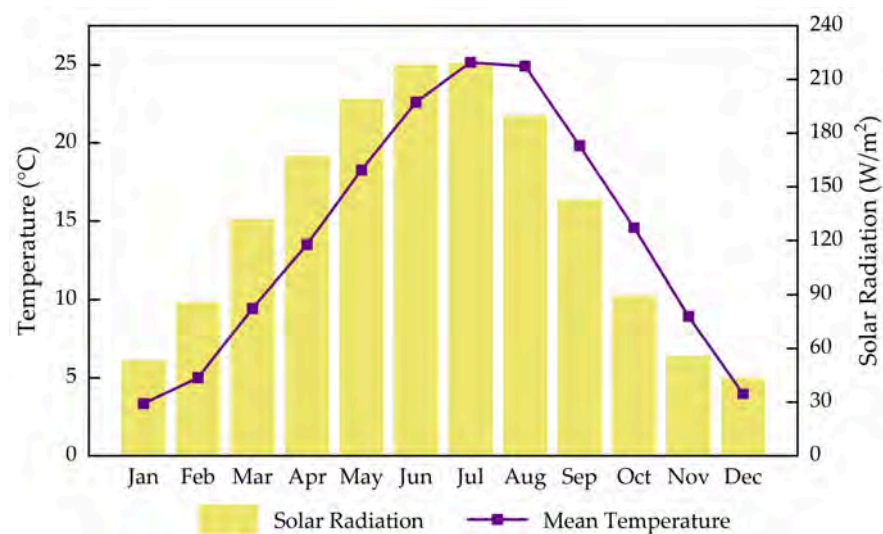


Figure 3. Monthly climatological normals (1991–2020) of surface solar radiation and mean air temperature for the grid cell containing the study area. Data were obtained from ERA5-Land monthly averaged reanalysis data [30,31]. Each monthly value represents the 30-year average (1991–2020) of the ERA5-Land monthly mean values.

This pattern is primarily driven by the seasonal cycle of solar declination, which at the latitude of the study area (45°05′40″ N) produces markedly longer days and higher solar elevation angles in the summer months, following the standard astronomical relationship proposed by Cooper [32].

Potential evapotranspiration tracks the radiative forcing, and highest values are reached in July (272 mm), about one month after the solar radiation maximum. Rainfall, in contrast, does not follow the same seasonal cycle: it shows a relative minimum in winter (January 50 mm and February 55 mm) and higher, more variable totals in spring and late summer (May and September exceeding 100 mm) (Figure 4).

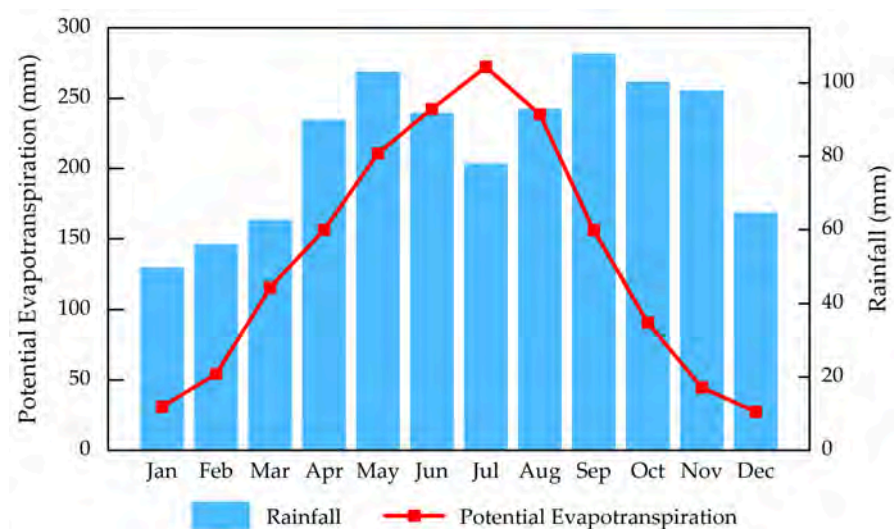


Figure 4. Monthly climatological normals (1991–2020) of total rainfall and potential evapotranspiration for the grid cell containing the study. Data were obtained from ERA5-Land monthly averaged reanalysis data [30,31]. Each monthly value represents the 30-year average (1991–2020) of the monthly cumulative totals.

This pattern reflects the dual origin of precipitation in the Po Valley: frontal and orographic systems associated with Atlantic disturbances dominate in the cold season, while convective rainfall, often short and intense, becomes increasingly important from late spring through summer, when surface heating destabilises the lower troposphere, occasionally leading to severe events such as hail and downbursts [33,34]. This convective component explains part of the interannual variability and short-term intensity of rainfall recorded during the experimental period. To contextualise the experimental period, the meteorological conditions recorded by the on-site weather station are detailed and compared against this 1991–2020 baseline in Section 3.1.

2.3. Experimental Design

Field measurements started on 23 May 2024 and were conducted along a row of durum wheat that was harvested on 7 July 2024. Data were collected at two measurement points: one between the rows of solar trackers (AVC), and one outside the AV system, in unshaded conditions (UC). To minimise the impact of uncontrolled factors such as soil type and characteristics, the distance between the two measurement points was kept to a minimum (10 m). The single monitoring location per treatment reflects the exploratory, preliminary nature of this study, intended as a first characterisation of soil water dynamics under AVC and UC conditions rather than a spatially replicated assessment, and to inform the design of future studies with more extensive monitoring (Figure 5).



Figure 5. (b) Detailed view of the monitoring study area (yellow outline) within the agrivoltaic (AV) array, showing the location of the AVC (blue marker) and UC (red marker) monitoring plots, where volumetric water content (VWC) and soil water potential (SWP) sensors were installed at 15, 30, 45, and 60 cm depth. (a) The inset shows the position of the study area (yellow marker) within the wider AV system boundaries (red outline), as shown in Figure 1b. Imagery source: Google Earth, acquired on 12 March 2024 [29].

Soil temperature and VWC were recorded daily, while SWP was measured at 15 min intervals. Data were collected at depths of 15, 30, 45, and 60 cm for both treatments.

2.4. Soil Temperature and Soil Volumetric Water Content Monitoring

Soil temperature and VWC were measured at both monitoring points using TerraSense (Netsens s.r.l., Calenzano, Florence, Italy) instruments. The sensors were installed at depths of 15, 30, 45, and 60 cm, by following the technique described in Bordoni et al. [35]. The sensors at the two monitoring points were connected to separate Netsens data loggers. Soil temperature and VWC were recorded daily from 23 May to 8 December 2024.

2.5. Soil Water Potential Monitoring

SWP was measured using TERSO 21 sensors (METER Group, Pullman, WA, USA), which were installed at the same depths as the Netsens sensors at both measurement sites. TERSO 21 sensors can measure SWP from near-saturated to dry conditions (from 0 to $-100,000$ kPa), operating based on the heat dissipation principle. They use the Flint et al. equation to convert the change in soil temperature, measured after a period of constant heating, into SWP [36]. The TERSO 21 sensors at the two measurement points were installed together with VWC sensors by following the same technique [35] and were connected to two separate ZL6 data loggers (METER Group, Pullman, WA, USA).

2.6. Modelling Approach

2.6.1. Model Description

CRITERIA-1D is a one-dimensional numerical model developed by the Hydro-Meteorological Service of the Emilia-Romagna Region (ARPAE-SIMC, Bologna, Italy) to simulate the main hydrological processes within the soil–plant–atmosphere system [37]. The model computes soil water balance by accounting for infiltration, plant water uptake, evaporation, and capillary rise, while coupling surface and subsurface water fluxes [38].

The main inputs for the model are daily air temperature and precipitation, soil physical and hydraulic properties, and crop parameters. The main outputs are daily values of VWC and SWP calculated at different depths, leaf area index (LAI), and available water (AW) in the first meter of soil depth. Rainfall infiltration is governed by surface conditions and hydraulic conductivity of the different soil layers. For each soil layer, the model considers key hydrological properties such as the VWC under saturated conditions (SAT), field capacity (FC), and permanent wilting point (WP). These values are derived from the Van Genuchten soil water characteristic curves (SWCCs):

$$\theta(h) = \theta_r + (\theta_s - \theta_r) \left(\frac{1}{[1 + (\alpha h)^n]^m} \right), \quad (1)$$

where $\theta(h)$ is the VWC at the water potential h , θ_s , and θ_r are the saturated and residual water contents, α is the coordinate of the inflexion point of the retention curve, m and n are dimensionless factors related to the pore-size distribution. SWCCs are obtained either by fitting paired VWC and SWP data or estimated by the model based on soil textural classes. The presence of vegetation is accounted for through conceptual models that modify the soil water balance by simulating water uptake and reduced evaporation due to canopy cover. Vegetation development is modelled based on cumulative growing degree days that, depending on the crop type, describe the trend of the Leaf Area Index (LAI) across the plant's different phenological stages up to harvest. Potential evapotranspiration is estimated using the Hargreaves–Samani equation [39]:

$$ET_0 = 0.0023 \frac{Rad_a}{2.456} \left(\frac{T_{max} + T_{min}}{2} + 17.78 \right) (T_{max} - T_{min})^{0.5}, \quad (2)$$

where R_a is the mean extraterrestrial radiation depending on site location geographical coordinates, altitude, and the day of the year [40], T_{max} is the maximum daily temperature, and T_{min} is the minimum daily temperature. ET_0 is then separated into maximum soil evaporation and maximum crop transpiration using a specific coefficient (k_c), which depends on the LAI value. The model only calculates actual transpiration for the rooted layers based on water availability and root density. More detailed information about CRITERIA-1D hydrology and vegetation modelling can be found in Bittelli et al. [37] and the manuals provided by Antolini et al. [40] and Tomei et al. [28].

2.6.2. Model Setup and Parameterisation

Table 1 shows the soil stratigraphy and the physical parameters of the corresponding horizons used to model the two treatments.

Table 1. Hypothesised soil stratigraphy and physical parameters of the different horizons.

Horizon	Upper Depth (cm)	Lower Depth (cm)	Sand (%)	Silt (%)	Clay (%)	O.M. (%)	B.D. (g/cm ³)
1	0	15	50	40	10	2	1.9
2	15	30	50	40	10	1	1.7
3	30	45	50	40	10	1	1.5
4	45	60	50	40	10	0.5	1.2
5	60	80	33	33	34	0.5	1.4

O.M.: Organic Matter; B.D.: Bulk Density.

Although the soil texture remained constant at depths ranging from 0 to 60 cm, as reported by previous studies at the Borgo Virgilio site [41], multiple horizons were identified to represent the soil's different hydraulic characteristics at the depths of interest. The soil in the study area is classified as Luvisol (WRB) according to the 1:250,000 soil map of Lombardy (ERSAF, Regional Agency for Agricultural and Forestry Services, Milan, Italy). Luvisols are characterised by an argic horizon in the subsoil, formed by pedogenetic clay illuviation [42]. This horizon typically has lower saturated hydraulic conductivity (k_{sat}) than the surface horizons and may restrict downward drainage at moderate depths [43,44]. To account for the possible presence of a less permeable horizon at a greater depth than those investigated, an additional horizon (horizon 5), 20 cm thick, was included at 60 cm depth during the modelling phase. This horizon was assigned to be a value of k_{sat} lower than the overlying layers, consistent with the hydraulic behaviour expected for an argic horizon.

In the absence of data, the percentages of coarse present in the various horizons were assumed to be zero. As for the bulk density (B.D.) and organic matter percentage (O.M.) values, those estimated by the model were adopted.

The Van Genuchten SWCC parameters were estimated by the model through a fitting procedure using paired VWC and SWP data measured during the July to September period. All paired observations were treated with equal weight during the fitting procedure, as the model does not allow the introduction of weighting factors during fitting procedure. The number of paired VWC–SWP observations used for fitting varied across treatments and depths (Table 2).

Only observations showing a monotonic decrease in VWC over time were retained to isolate the drying branch of the SWCCs. This was done because the model is incapable of simulating SWCC hysteresis and data for the wetting phase were limited compared to the drying phase. The period following wheat harvest was chosen for the fitting procedure because it was characterised by relatively stable conditions due to the absence of vegetation and significant rainfall events. Since these measurements were available at depths of 15, 30, 45, and 60 cm for both treatments, distinct SWCCs were obtained for each soil horizon. Field measurements did not include SWP values below -1500 kPa, as such conditions were

not observed in situ during the monitoring period. Consequently, no data points were available beyond this suction range to further constrain the dry end of the fitted curve. From the fitted SWCCs, VWC values corresponding to SAT, FC, and WP conditions were derived. The resulting Van Genuchten parameters and derived hydraulic properties for each horizon and treatment are reported in Section 3.4.1. In absence of saturated hydraulic conductivity data, the k_{sat} values used in the CRITERIA-1D simulations for each horizon were calibrated from the model's initial estimates.

Table 2. Number of paired VWC-SWP observations used for the fitting procedure of the SWCCs for every horizon and treatment.

Horizon	N. of Paired VWC-SWP Observations	
	UC	AVC
1	55	80
2	49	67
3	64	68
4	57	43

CRITERIA-1D was originally designed for agronomic applications; therefore, specific parameter sets are available for certain crop types. In the simulations conducted for the case studies, the “Rainfed Wheat” dataset was used to describe the LAI development of an unirrigated wheat crop. The maximum LAI value of $5 \text{ m}^2 \text{ m}^{-2}$ is reached in May, whereas the minimum value of 0 is reached at harvest, which was set on 7 July 2024 in the study case and remained equal to zero until next germination stage. Roots were assumed to start at a depth of 3 cm to simulate a root collar, and the maximum root depth was set at 0.8 m. The k_c coefficient was set at a 0.8 value.

Regarding the meteorological input data, daily precipitation and mean air temperature measured by the on-site MeteoSense sensor were considered for the period from 23 May 2024 till 8 December 2024. Since the model requires at least one year of simulation prior to the study period, the meteorological inputs from 1 January 2023 till 22 May 2024 were extrapolated from the Mantua Lunetta2 SMR weather station, located 7 km away from the study area. Regarding radiation data, no measured global or net radiation values were available for each treatment. The modelling phase therefore used potential radiation estimated by the model from the site's geographical coordinates, altitude, and day of year. As a result, the model does not explicitly account for the reduction in radiation under AVC compared to UC.

2.6.3. Model Calibration

Model calibration was conducted for both treatments by adjusting the k_{sat} coefficient for each soil horizon. Initial k_{sat} values were derived from pedological functions implemented in the model. The k_{sat} values were then iteratively adjusted to achieve the best balance between accuracy and consistency by comparing the simulated and field-measured values of VWC and SWP at different depths. It should be noted that, given the availability of field measurements from a single monitoring site and a single observation period, independent model validation against a separate dataset was not feasible. The performance metrics reported in Section 3.4.3. should therefore be interpreted as goodness-of-fit indicators on the calibration dataset, rather than as measures of predictive accuracy on independent data.

2.6.4. Soil Water Availability Estimation

Following calibration, the CRITERIA-1D model was used to estimate available water (AW) values in the top 80 cm of soil depth for both treatments, highlighting differences in water content in terms of absolute values and seasonal dynamics.

2.7. Overview of the Experimental Workflow

The methodological steps described in the previous subsections are summarised schematically in Figure 6, which illustrates the overall workflow of the study, from field data collection to the final estimation of available water in the first 80 cm of soil depth under the two treatments.

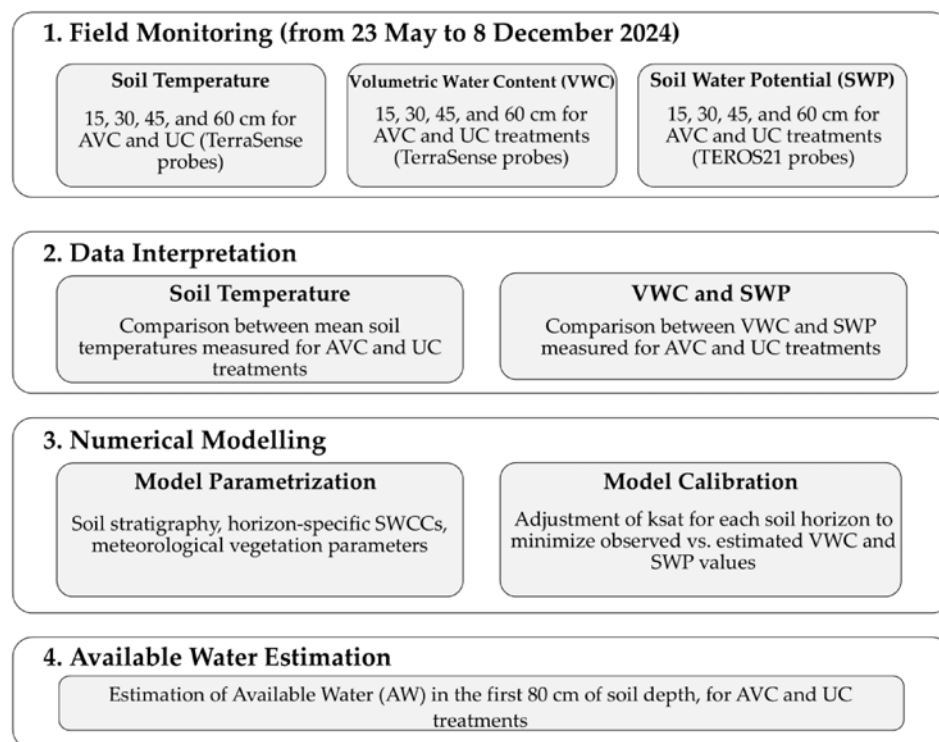


Figure 6. Schematic overview of the methodological workflow: (1) field monitoring of soil temperature, volumetric water content (VWC), and soil water potential (SWP) at four depths (15, 30, 45, and 60 cm) under agrivoltaic cover (AVC) and unshaded conditions (UC) from 23 May to 8 December 2024; (2) interpretation of the monitored data through comparison between the two treatments; (3) numerical modelling, including parametrisation of the agro-hydrological model CRITERIA-1D with site-specific soil, meteorological, and vegetation data, followed by calibration of the saturated hydraulic conductivity (k_{sat}) for each soil horizon; and (4) estimation of Available Water (AW) in the first 80 cm of soil depth for both treatments.

2.8. Statistical Analysis

2.8.1. Analysis of Measured Data

The mean values of VWC and SWP during the monitoring period were calculated at depths of 15, 30, 45, and 60 cm under both treatments. Prior to the analyses, normality of sample distributions was assessed using the Shapiro–Wilk test, which revealed non-normal distributions for all variables and depths ($p < 0.001$). The Wilcoxon signed-rank test was therefore applied to paired observations to assess the statistical significance of differences between treatments. Differences were considered statistically significant at $p < 0.001$. Statistical analyses were performed using Python (version 3.12) with the NumPy (version 2.4.4) and SciPy (version 1.17.1) libraries [45,46].

2.8.2. Model Performance Evaluation

The model's accuracy was evaluated using the statistical indicators coefficient of determination (R^2) and root mean square error (RMSE), calculated over the entire observation period with respect of the measured data. R^2 and RMSE values were computed using Microsoft Excel (Microsoft 365, Version 2603). Moreover, time series of measured VWC and SWP were plotted against values simulated by CRITERIA-1D to assess the model's ability to reproduce the temporal dynamics of those variables.

3. Results

3.1. Meteorological Conditions

During the monitoring period, weather conditions were characterised by high temperatures in the dry season and irregular precipitation distribution, resulting in alternating dry and wet periods (Figure 7).

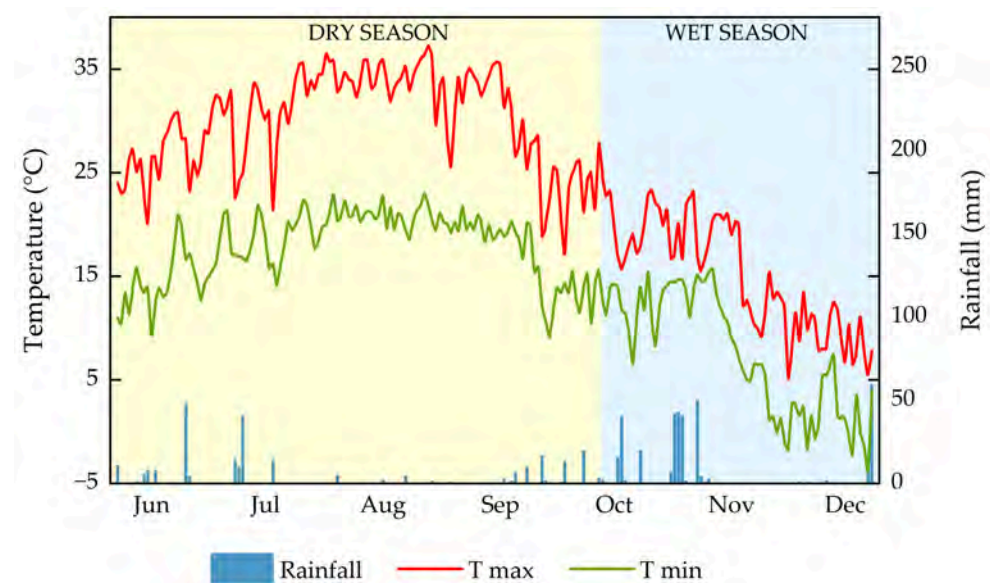


Figure 7. Meteorological daily measurements by the on-site MeteoSense 4.0 weather station over the monitoring period from 23 May to 8 December: minimum and maximum air temperature (T_{min} and T_{max}) and daily rainfall reported for the dry season (May till September 2024, yellow background), and the wet season (October till December 2024, blue background).

In summer (dry season), daily maximum temperatures frequently exceeded 30 °C after wheat harvest in early July, with peaks above 35 °C observed in August. From September onward, maximum temperatures progressively decreased. In the autumn period (wet season), an increase in rainfall events was observed, reaching a peak in October, when a cumulative rainfall of 178 mm was recorded over one week.

To quantify how the experimental period deviated from the local climate, the cumulative rainfall and mean monthly temperatures from the complete months of the monitoring period (June to November) were compared against the 1991–2020 climatological baseline described in Section 2.2 (Figures 8 and 9).

The comparison revealed a marked contrast between the core summer months and the autumn season. July and August exhibited thermal and water stress, with mean temperatures exceeding the historical average by 1.27 °C and 1.42 °C, respectively, and cumulative precipitations of 20.00 mm (an anomaly of −58 mm) in July and of just 9.40 mm (an anomaly of −83 mm) in August.

Conversely, the autumn period was defined by extreme hydrological fluctuations. October was characterised by extraordinary precipitation, recording a cumulative total of

272.30 mm, which represents an anomaly of +172 mm above the 30-year average. This trend is reflected in the sharp daily rainfall spikes shown in Figure 5. This wet phase was followed by a cold and dry November, which registered a negative thermal anomaly of $-1.97\text{ }^{\circ}\text{C}$ ($6.96\text{ }^{\circ}\text{C}$ vs. the historical $8.93\text{ }^{\circ}\text{C}$) and a lack of precipitation, totalling only 6.20 mm (an anomaly of -91.69 mm)

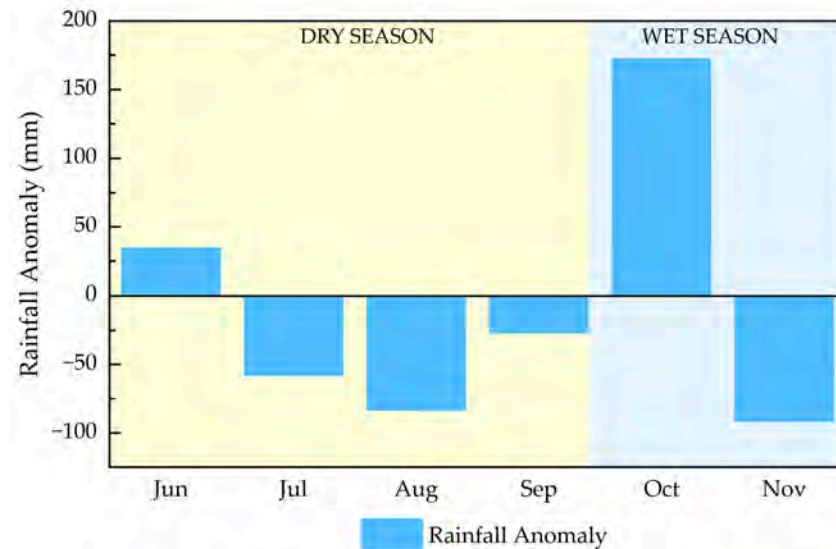


Figure 8. Monthly anomalies of cumulative rainfall for the monitoring period (June–November 2024), computed as $\Delta = \text{monthly cumulative rainfall value} - 1991\text{--}2020 \text{ climatological normal}$. Positive anomalies indicate a pluviometric surplus compared to the historical baseline; negative anomalies indicate a pluviometric deficit.

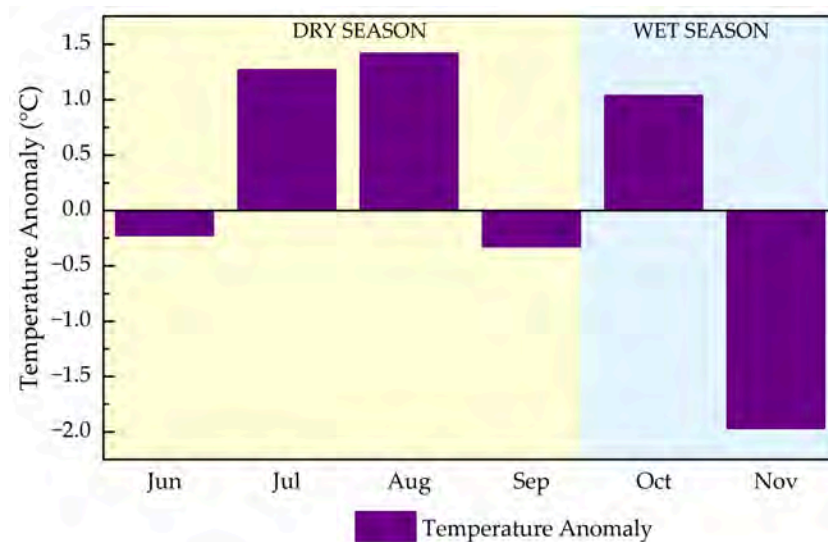


Figure 9. Monthly anomalies of mean air temperature for the monitoring period (June–November 2024), computed as $\Delta = \text{monthly average value} - 1991\text{--}2020 \text{ climatological normal}$. Positive anomalies indicate months warmer than the historical baseline; negative anomalies indicate months colder than the historical baseline.

3.2. Soil Temperature Dynamics

Daily mean soil temperatures showed a similar seasonal trend across all depths investigated for both treatments, characterised by a gradual increase during dry season, followed by a decline during wet season. The highest temperatures were observed at 15 cm depth, reaching approximately $30\text{ }^{\circ}\text{C}$ during dry season. In deeper soil layers,

temperatures progressively decreased, while thermal fluctuations became less pronounced with increasing depth [47]. During wet season, an opposite behaviour was observed compared to dry season, with higher temperatures recorded at 60 cm depth and lower temperatures in the shallower part of the soil. Soil temperatures under AVC treatment were lower than those recorded in the UC treatment at all monitored depths. During the May–September period, the cooling effect of the AVC was more evident at 15 cm depth, with a mean temperature decrease of 1.0 °C and a maximum daily difference of −4.7 °C recorded during August. The cooling effect decreased with depth, with mean temperature differences of −0.9 °C, observed at 30 and 45 cm, and −0.6 °C at 60 cm (Table 3).

Table 3. Mean soil temperature values (Mean T AVC and Mean T UC) and mean soil temperature differences (Mean T Diff.) calculated under AV cover (AVC) and unshaded conditions (UC) treatments at 15, 30, 45, and 60 cm of depth in the May–September monitoring period.

Depth (cm)	Mean T AVC (°C)	Mean T UC (°C)	Mean T Diff. (°C)
15	24.3	25.3	−1.0
30	23.3	24.2	−0.9
45	22.9	23.8	−0.9
60	22.1	22.7	−0.6

During the October–December period, mean temperature differences between treatments decreased substantially, not exceeding −0.1 °C at 15, 30, and 45 cm. In contrast, at 60 cm of depth, a mean temperature difference of −0.8 °C was maintained (Table 4).

Table 4. Mean soil temperature values (Mean T AVC and Mean T UC) and mean soil temperature differences (Mean T Diff.) calculated under AV cover (AVC) and unshaded conditions (UC) treatments at 15, 30, 45, and 60 cm of depth in the October–December monitoring period.

Depth (cm)	Mean T AVC (°C)	Mean T UC (°C)	Mean T Diff. (°C)
15	13.0	13.0	0.0
30	13.8	13.9	−0.1
45	14.6	14.7	−0.1
60	15.2	15.9	−0.8

3.3. Soil Water Dynamics

3.3.1. Volumetric Water Content

VWC showed a consistent increase with soil depth in both treatments throughout the monitoring period, with the highest values observed at 60 cm depth and the lowest at 15 cm (Figures 10 and 11).

At all depths, a progressive VWC decline was observed from early July, until minimum values were reached and remained relatively stable during August. This was followed by a recharge phase associated with precipitation events occurring from September onward, which clearly highlights the seasonal dynamics of VWC under both treatments.

During the May–September period, VWC under the AVC treatment was consistently higher than under UC. The largest differences in mean VWC were observed at 15 cm and 45 cm depth, reaching 0.07 m³ m^{−3} (+41% relative to UC) and 0.09 m³ m^{−3} (+26% relative to UC), respectively. At 30 cm and 60 cm depth, differences were more modest, with values of 0.04 m³ m^{−3} and 0.02 m³ m^{−3} respectively, representing a difference of +17% and +4% relative to UC treatment (Table 5).

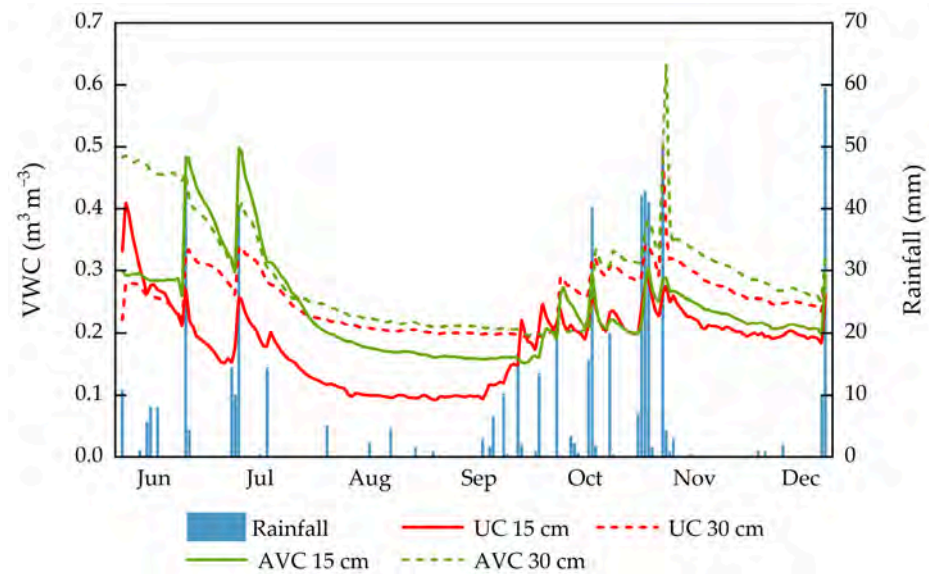


Figure 10. Daily mean volumetric water content (VWC) measured at 15 and 30 cm depth under AV cover (AVC) and unshaded conditions (UC) treatments, from 23 May to 8 December 2024, using TerraSense probes. Daily rainfall (mm) recorded over the same period by the on-site MeteoSense 4.0 weather station is shown for reference.

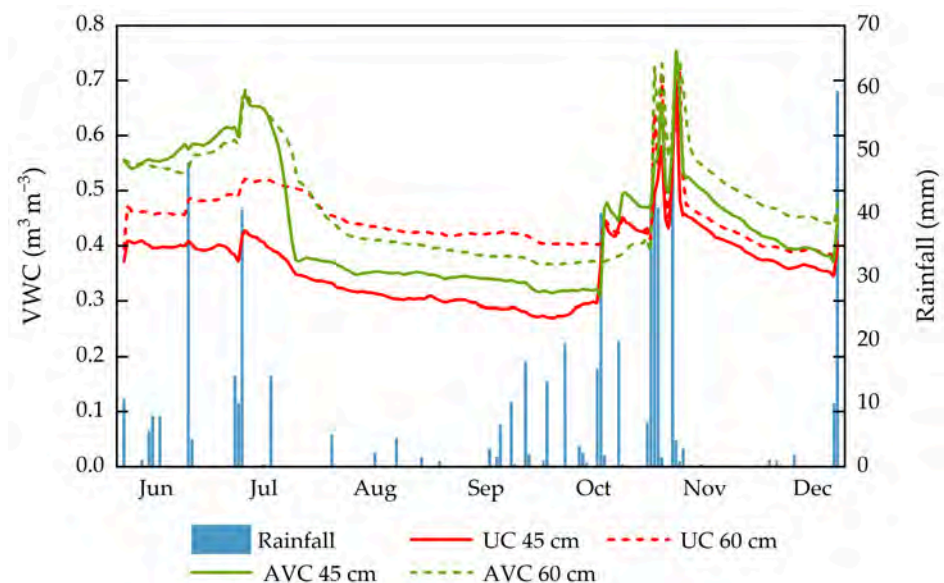


Figure 11. Daily mean volumetric water content (VWC) measured at 45 and 60 cm depth under AV cover (AVC) and unshaded conditions (UC) treatments, from 23 May to 8 December 2024, using TerraSense probes. Daily rainfall (mm) recorded over the same period by the on-site MeteoSense 4.0 weather station is shown for reference.

Table 5. Mean volumetric water content (VWC) values and mean volumetric water content differences (Mean VWC Diff.) calculated for AV cover (AVC) and unshaded conditions (UC) treatments at 15, 30, 45, and 60 cm depth for the May–September monitoring period.

Depth (cm)	Mean VWC AVC ($\text{m}^3 \text{m}^{-3}$)	Mean VWC UC ($\text{m}^3 \text{m}^{-3}$)	Mean VWC Diff. ($\text{m}^3 \text{m}^{-3}$)
15	0.24	0.17	0.07
30	0.28	0.24	0.04
45	0.43	0.34	0.09
60	0.47	0.45	0.02

During the October–December period, VWC remained higher under the AVC treatment across all depths; however, the magnitude of the differences was reduced compared to the summer period, with mean differences ranging from +5% at 15 cm to +12% at 45 cm (Table 6).

Table 6. Mean volumetric water content values (Mean VWC AVC and Mean VWC UC) and mean volumetric water content differences (Mean VWC Diff.) calculated for AV cover (AVC) and unshaded conditions (UC) treatments at 15, 30, 45, and 60 cm depth for the October–December monitoring period.

Depth (cm)	Mean VWC AVC ($\text{m}^3 \text{m}^{-3}$)	Mean VWC UC ($\text{m}^3 \text{m}^{-3}$)	Mean VWC Diff. ($\text{m}^3 \text{m}^{-3}$)
15	0.23	0.22	0.01
30	0.31	0.28	0.03
45	0.46	0.42	0.05
60	0.49	0.44	0.05

Differences in VWC between AVC and UC treatments, for both the monitoring periods, were statistically significant across all soil depths (Wilcoxon signed-rank test, $p < 0.001$).

3.3.2. Soil Water Potential

SWP showed a progressive decline from early July across all depths and treatments, with minimum values that were reached between late July and early August. Most extreme SWP values were recorded at 15 and 30 cm, while at 60 cm depth, under UC treatment, they remained comparatively stable throughout the dry period. Following precipitation events from September onward, a rapid recovery was observed across all depths for both treatments, with SWP values returning close to 0 kPa in early October (Figures 12 and 13).

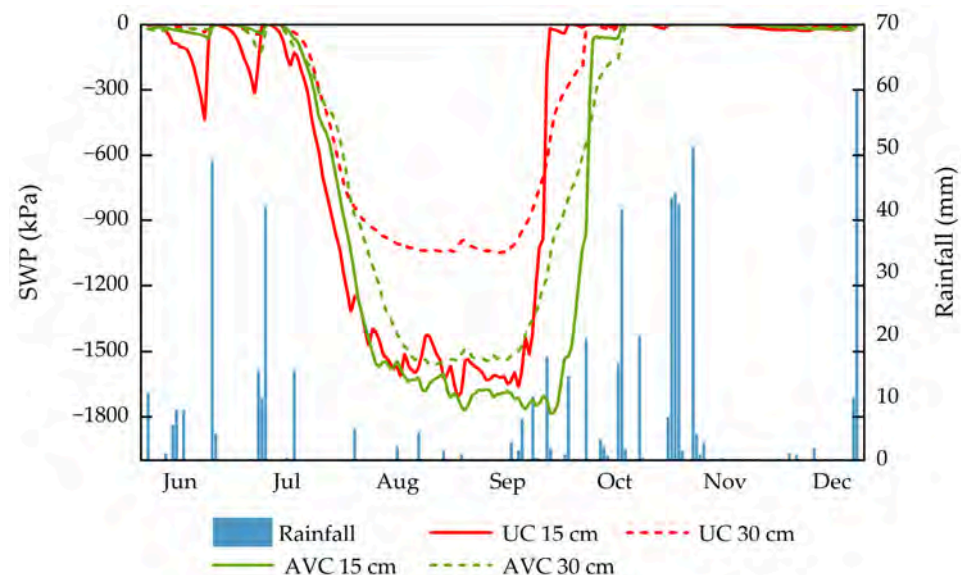


Figure 12. Daily mean soil water potential (SWP) measured at 15 and 30 cm depth under AV cover (AVC) and unshaded conditions (UC) treatments, from 23 May to 8 December 2024. SWP values represent daily averages of measurements recorded every 15 min by TEROs 21 probes. Daily rainfall (mm) recorded over the same period by the on-site MeteSense 4.0 weather station is shown for reference.

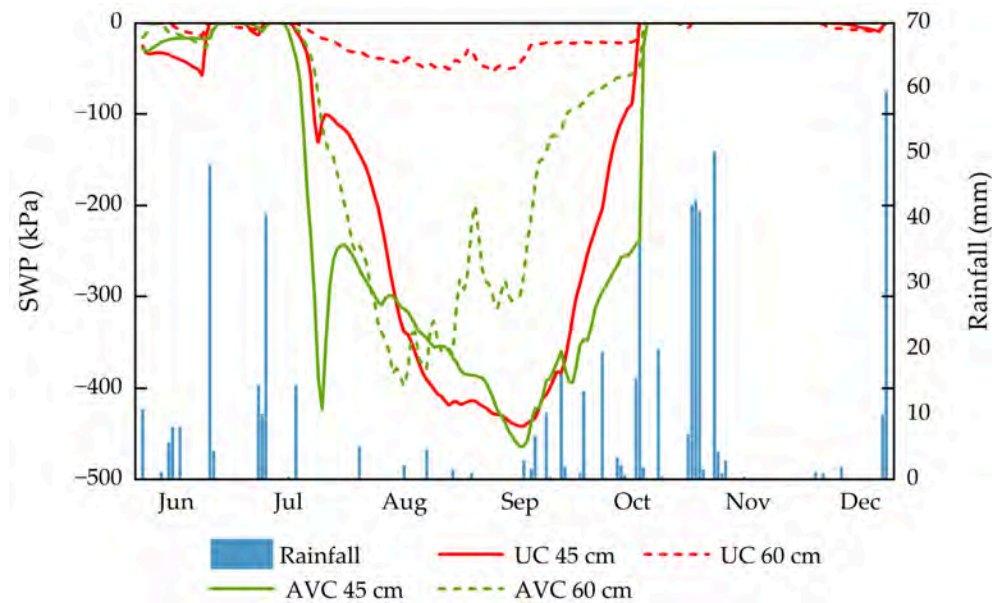


Figure 13. Daily mean soil water potential (SWP) measured at 45 and 60 cm depth under AV cover (AVC) and unshaded conditions (UC) treatments, from 23 May to 8 December 2024. SWP values represent daily averages of measurements recorded every 15 min by TEROS 21probes. Daily rainfall (mm) recorded over the same period by the on-site MeteoSense 4.0 weather station is shown for reference.

During the May–September period, the difference in mean SWP between AVC and UC treatments varied with soil depth (Table 7).

Table 7. Mean soil water potential values (Mean SWP AVC and Mean SWP UC) and mean soil water potential differences (Mean SWP Diff.) calculated under AV cover (AVC) and unshaded conditions (UC) at 15, 30, 45, and 60 cm depth for the May–September monitoring period.

Depth (cm)	Mean SWP AVC (kPa)	Mean SWP UC (kPa)	Mean SWP Diff. (kPa)
15	−862.9	−727.3	−135.6
30	−715.1	−476.0	−239.1
45	−233.5	−198.3	−35.2
60	−146.4	−22.6	−123.7

At 15 cm depth, mean SWP was more negative under the AVC treatment than under the UC, with values of −862.9 kPa and −727.3 kPa, respectively, corresponding to a +19% mean SWP variation. At 30 cm the AVC treatment showed a more negative mean SWP than the UC (−715.1 kPa vs. −476.0 kPa, +50%). At 45 and 60 cm depth, differences were more limited in absolute terms (−35.2 kPa and −123.7 kPa, respectively). During the October–December period, SWP values were close to 0 kPa for all investigated depths. At 15 cm, mean SWP was −11.7 kPa under UC treatment and −6.8 kPa under AVC. Progressively with depth, the SWP mean values became less negative until reaching −1.3 kPa at 45 cm and −0.2 kPa at 60 cm under AVC treatment (Table 8).

Differences in SWP between AVC and UC treatments, for the May–September monitoring period, were statistically significant across all soil depths (Wilcoxon signed-rank test, $p < 0.001$). For the October–December observation period, differences were statistically significant only at 15 cm, 30 cm, and 60 cm depths (Wilcoxon signed-rank test, $p < 0.001$), but not at 45 cm (Wilcoxon signed-rank test, $p = 0.317$). Nevertheless, although statistically significant during the October–December period, the differences at 15 cm, 30 cm, and 60 cm were zero on 60%, 82%, and 70% of days, respectively.

Table 8. Mean soil water potential values (Mean SWP AVC and Mean SWP UC) and mean soil water potential differences (Mean SWP Diff.) calculated under AV cover (AVC) and unshaded conditions (UC) at 15, 30, 45, and 60 cm depth for the October–December monitoring period.

Depth (cm)	Mean SWP AVC (kPa)	Mean SWP UC (kPa)	Mean SWP Diff. (kPa)
15	−6.8	−11.7	4.9
30	−1.9	−2.9	1.0
45	−1.3	−0.1	−1.2
60	−0.2	−2.0	1.8

3.4. Model Performance

3.4.1. Soil Water Characteristic Curves

Figures 14–17 present the Soil Water Characteristic Curves (SWCCs) for the soil horizons under UC and AVC treatments at 15, 30, 45, and 60 cm depths, respectively. The curves of the horizons 1–4 were fitted using the Van Genuchten model based on paired VWC and SWP measurements collected at depths of 15, 30, 45, and 60 cm during the soil drying phase following wheat harvest. The SWCC curve of the selected argic horizon (horizon 5), for which only the parameters are reported, was estimated by the model based on soil texture classes. The Van Genuchten parameters estimated for each horizon and treatment are reported in Tables 9 and 10.

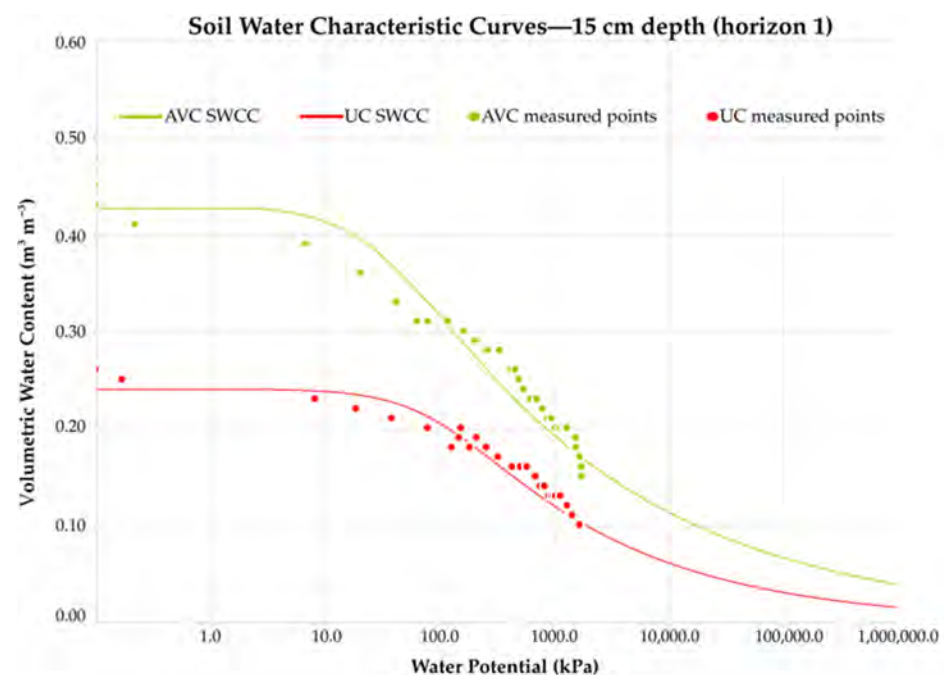


Figure 14. Soil Water Characteristic Curves (SWCCs) at 15 cm depth (horizon 1) for unshaded conditions (UC) and agrivoltaic cover (AVC) treatments: fitted Van Genuchten SWCCs and paired volumetric water content (VWC)–soil water potential (SWP) measurements recorded during soil drying phase (July–September 2024) using TerraSense and TEROS 21 probes ($n = 55$ paired measurements for UC and $n = 80$ for AVC). Van Genuchten parameters were estimated through inverse calibration within the CRITERIA-1D model.

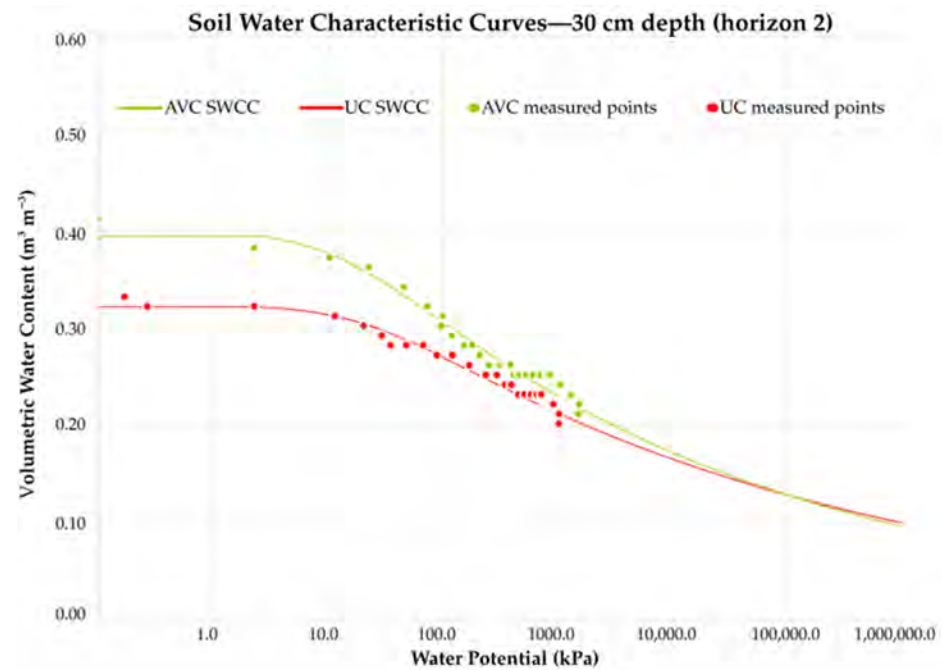


Figure 15. Soil Water Characteristic Curves (SWCCs) at 30 cm depth (horizon 2) for unshaded conditions (UC) and agrivoltaic cover (AVC) treatments: fitted Van Genuchten SWCCs and paired volumetric water content (VWC)–soil water potential (SWP) measurements recorded during soil drying phase (July–September 2024) using TerraSense and TEROS 21 probes ($n = 49$ paired measurements for UC and $n = 67$ for AVC). Van Genuchten parameters were estimated through inverse calibration within the CRITERIA-1D model.

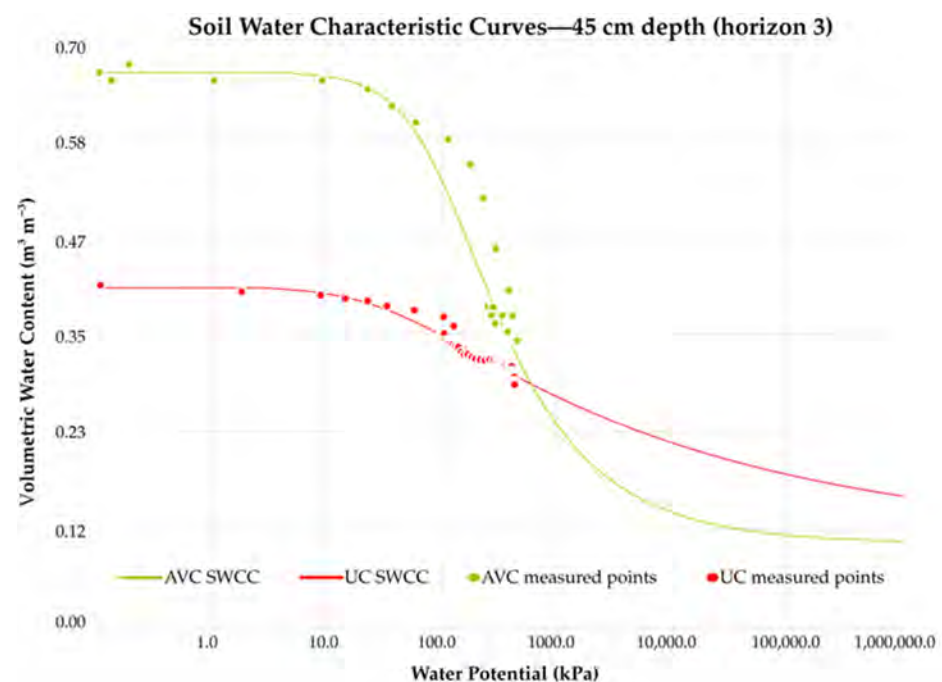


Figure 16. Soil Water Characteristic Curves (SWCCs) at 45 cm depth (horizon 3) for unshaded conditions (UC) and agrivoltaic cover (AVC) treatments: fitted Van Genuchten SWCCs and paired volumetric water content (VWC)–soil water potential (SWP) measurements recorded during soil drying phase (July–September 2024) using TerraSense and TEROS 21 probes ($n = 64$ paired measurements for UC and $n = 68$ for AVC). Van Genuchten parameters were estimated through inverse calibration within the CRITERIA-1D model.

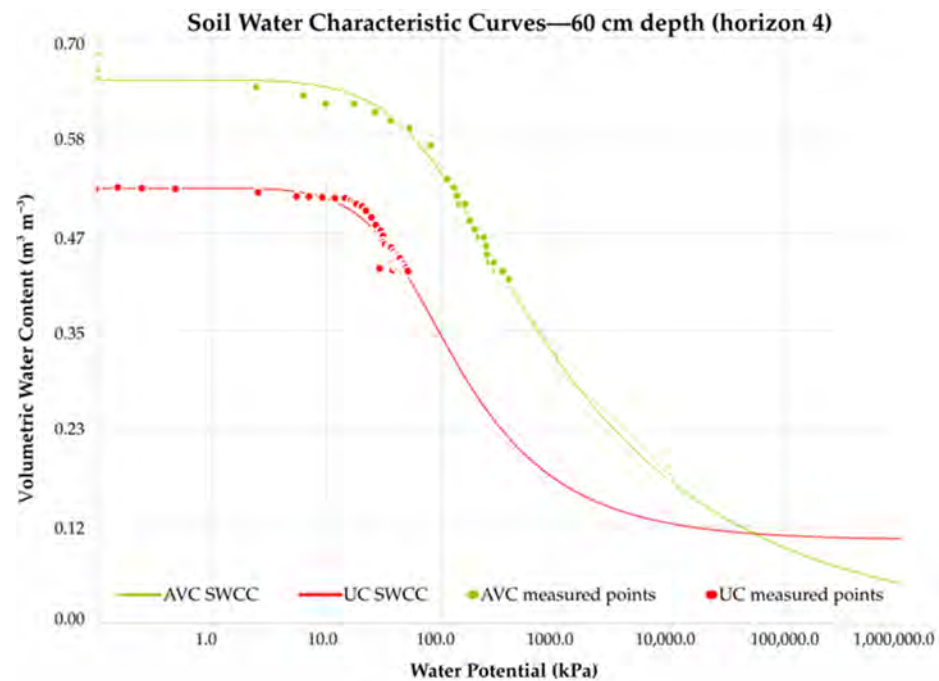


Figure 17. Soil Water Characteristic Curves (SWCCs) at 60 cm depth (horizon 4) for unshaded conditions (UC) and agrivoltaic cover (AVC) treatments: fitted Van Genuchten SWCCs and paired volumetric water content (VWC)–soil water potential (SWP) measurements recorded during soil drying phase (July–September 2024) using TerraSense and TEROS 21 probes ($n = 57$ paired measurements for UC and $n = 43$ for AVC). Van Genuchten parameters were estimated through inverse calibration within the CRITERIA-1D model.

Table 9. Parameters of the Soil Water Characteristic Curves (SWCCs) of the four horizons of the soil under unshaded conditions (UC).

Horizon	α (kPa ⁻¹)	n (-)	θ_s (m ³ m ⁻³)	θ_r (m ³ m ⁻³)
1	0.010	1.299	0.240	0.000
2	0.048	1.112	0.322	0.000
3	0.029	1.165	0.404	0.100
4	0.023	1.565	0.520	0.100
5	0.250	1.200	0.439	0.040

θ_s : saturated volumetric water content; θ_r : residual volumetric water content.

Table 10. Parameters of the Soil Water Characteristic Curves (SWCCs) of the four horizons of the soil under AV cover (AVC).

Horizon	α (kPa ⁻¹)	n (-)	θ_s (m ³ m ⁻³)	θ_r (m ³ m ⁻³)
1	0.032	1.230	0.427	0.000
2	0.078	1.128	0.393	0.000
3	0.010	1.593	0.661	0.100
4	0.013	1.275	0.650	0.000
5	0.250	1.200	0.439	0.040

θ_s : saturated volumetric water content; θ_r : residual volumetric water content.

At all depths estimated θ_s values were higher under AVC, with AVC SWCCs yielding higher VWC values than UC SWCCs at equivalent SWP, except at 45 cm depth where the AVC SWCC exceeded UC ones only up to approximately 1000 kPa. The most pronounced differences in θ_s emerged at 15, 45 and 60 cm depth (horizons 1, 3, and 4), while at 30 cm (horizon 2) the difference was smaller. In the UC treatment, estimated θ_s increased with depth, whereas under AVC the values of horizons 1 and 2 and of horizons 3 and

4 were pairwise similar. In both treatments, the fitted curves are well constrained in the low-to-intermediate SWP range, while values at SWP exceeding 1000–1500 kPa are subject to greater uncertainty. Tables 11 and 12 show the values of the hydrological constants estimated by CRITERIA-1D, based on the SWCCs, for horizons 1–4 under the two treatments.

Table 11. Hydrological constants estimated by CRITERIA-1D model for each horizon of the soil under unshaded conditions (UC).

Horizon	Saturation ($\text{m}^3 \text{ m}^{-3}$)	Field Capacity ($\text{m}^3 \text{ m}^{-3}$)	Wilting Point ($\text{m}^3 \text{ m}^{-3}$)	Available Water Capacity ($\text{m}^3 \text{ m}^{-3}$)
1	0.240	0.238	0.104	0.134
2	0.322	0.313	0.200	0.113
3	0.404	0.397	0.262	0.135
4	0.520	0.508	0.154	0.354

Table 12. Hydrological constants estimated by CRITERIA-1D model for each horizon of the soil under AV cover (AVC).

Horizon	Saturation ($\text{m}^3 \text{ m}^{-3}$)	Field Capacity ($\text{m}^3 \text{ m}^{-3}$)	Wilting Point ($\text{m}^3 \text{ m}^{-3}$)	Available Water Capacity ($\text{m}^3 \text{ m}^{-3}$)
1	0.427	0.413	0.174	0.239
2	0.393	0.375	0.216	0.159
3	0.661	0.656	0.208	0.448
4	0.650	0.641	0.280	0.361

In the UC treatment, estimated values of field capacity (FC) were close to the saturation (SAT) values across all horizons. The smallest difference between SAT and FC emerged in horizon 1. Wilting point (WP) values ranged from 0.104 to 0.262 $\text{m}^3 \text{ m}^{-3}$ with horizon 1 resulting in the lowest value between all horizons. Under AVC treatment, FC values were close to SAT, with differences not exceeding 0.01 $\text{m}^3 \text{ m}^{-3}$ in horizons 3 and 4. The estimated available water capacity (AWC), defined as the difference between FC and WP, was higher under AVC than under UC treatment at every depth.

3.4.2. Saturated Conductivity Calibration Results

Table 13 shows the k_{sat} values assigned to each horizon in the two treatments following calibration.

Table 13. Calibrated k_{sat} values for each horizon under unshaded conditions (UC) and AV cover (AVC).

Horizon	$k_{\text{sat}} (\text{m s}^{-1})$	
	Unshaded Control	AV Cover
1	4.63×10^{-8}	1.04×10^{-6}
2	2.31×10^{-7}	6.94×10^{-7}
3	8.10×10^{-7}	1.16×10^{-6}
4	1.16×10^{-8}	1.16×10^{-6}
5	1.16×10^{-7}	1.16×10^{-7}

Calibrated k_{sat} were higher for every horizon under the AVC treatment compared to the corresponding values for the UC. The most pronounced differences were observed in horizons 1 and 4, where the k_{sat} values calibrated under UC were two orders of magnitude lower than those estimated for the AVC treatment.

3.4.3. Simulated Soil Water Dynamics

The performance of CRITERIA-1D in simulating VWC dynamics for both treatments at various depths is shown in Figures 18–21. Tables 14 and 15 summarise the statistical indicators RMSE and R^2 calculated to evaluate the model performance under UC and AVC treatments.

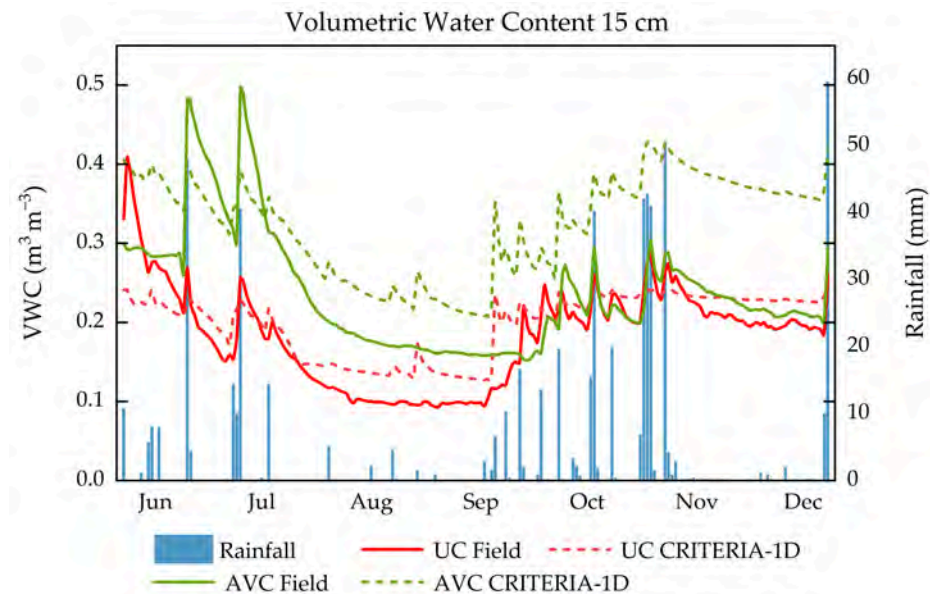


Figure 18. Daily volumetric water content (VWC) at 15 cm depth: comparison between values simulated by the CRITERIA-1D model and field measurements (TerraSense probes) for AVC and UC treatments, from 23 May to 8 December 2024. Daily rainfall (mm) recorded over the same period by the on-site MeteoSense 4.0 weather station is shown for reference.

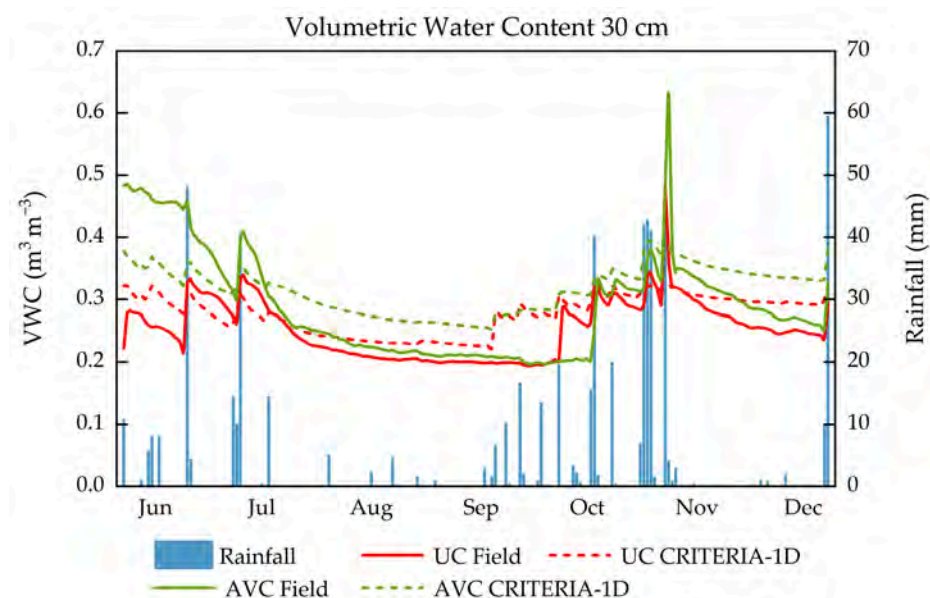


Figure 19. Daily volumetric water content (VWC) at 30 cm depth: comparison between values simulated by the CRITERIA-1D model and field measurements (TerraSense probes) for AVC and UC treatments, from 23 May to 8 December 2024. Daily rainfall (mm) recorded over the same period by the on-site MeteoSense 4.0 weather station is shown for reference.

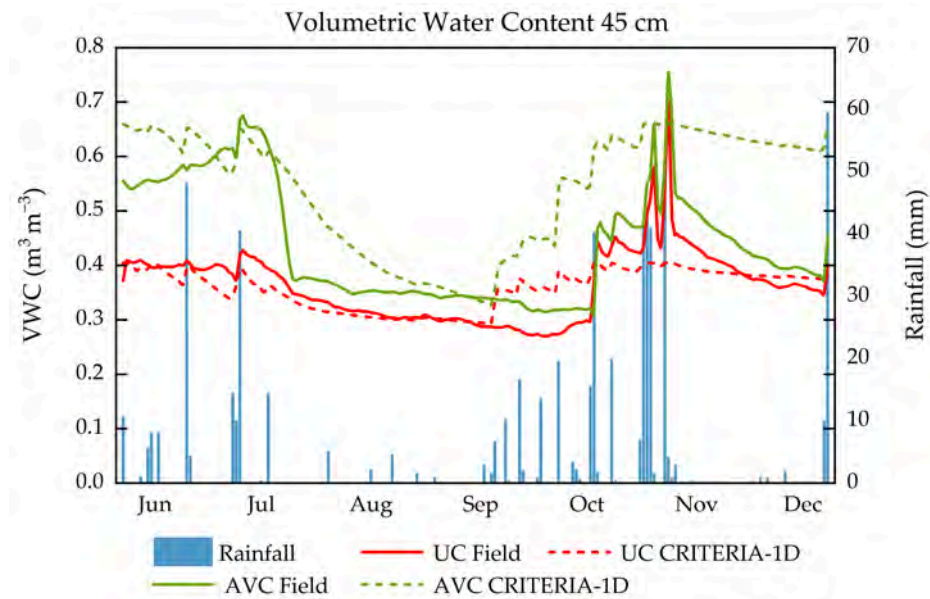


Figure 20. Daily volumetric water content (VWC) at 45 cm depth: comparison between values simulated by the CRITERIA-1D model and field measurements (TerraSense probes) for AVC and UC treatments, from 23 May to 8 December 2024. Daily rainfall (mm) recorded over the same period by the on-site MeteoSense 4.0 weather station is shown for reference.

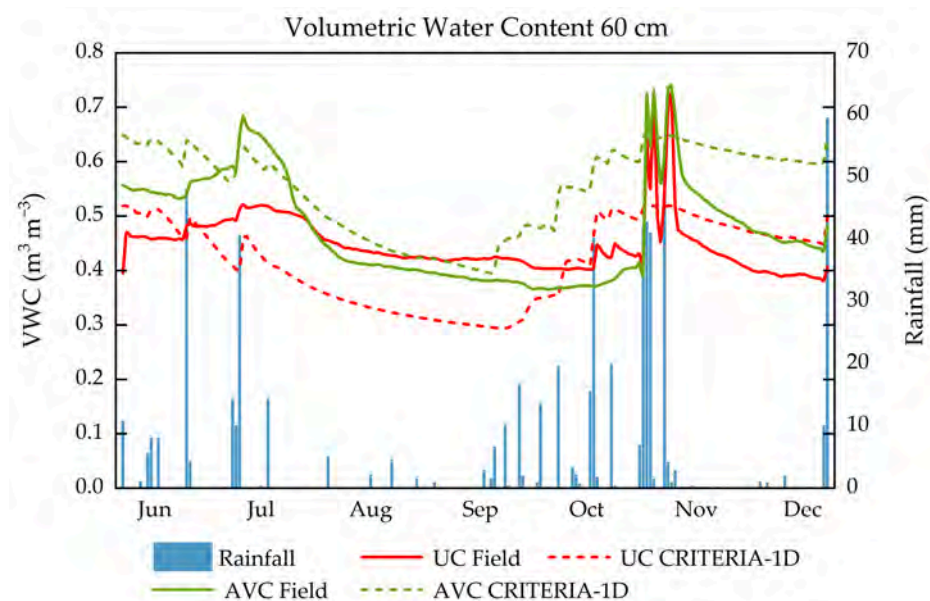


Figure 21. Daily volumetric water content (VWC) at 60 cm depth: comparison between values simulated by the CRITERIA-1D model and field measurements (TerraSense probes) for AVC and UC treatments, from 23 May to 8 December 2024. Daily rainfall (mm) recorded over the same period by the on-site MeteoSense 4.0 weather station is shown for reference.

Table 14. Statistical indicators Root Mean Square Error (RMSE) and R^2 calculated for volumetric water content (VWC) simulations under UC treatment at all depths.

Unshaded Conditions				
	VWC 15 cm	VWC 30 cm	VWC 45 cm	VWC 60 cm
RMSE ($\text{m}^3 \text{m}^{-3}$)	0.039	0.040	0.048	0.085
R^2	0.705	0.519	0.464	0.079

Table 15. Statistical indicators Root Mean Square Error (RMSE) and R^2 calculated for volumetric water content (VWC) simulations under AVC treatment at all depths.

Agrivoltaic Cover				
	VWC 15 cm	VWC 30 cm	VWC 45 cm	VWC 60 cm
RMSE ($\text{m}^3 \text{m}^{-3}$)	0.108	0.065	0.133	0.106
R^2	0.326	0.609	0.501	0.437

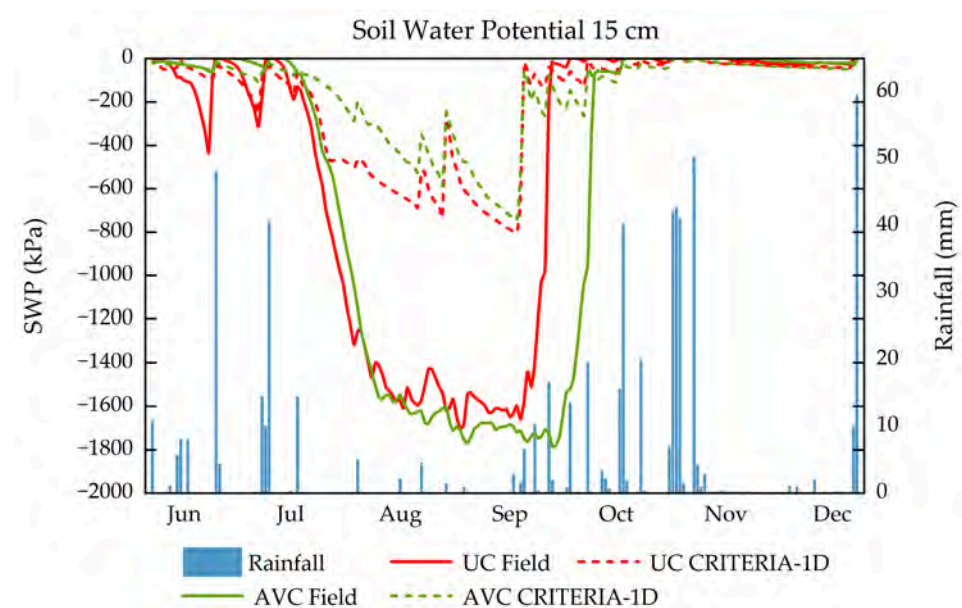
For both treatments, the model was able to reproduce the main seasonal trends, including the gradual soil drying in the beginning dry season, minimum VWC values in August, and the recharge following the first rainfall events in the wet season.

For the UC treatment, model performance was better in the upper soil layer (RMSE = $0.039 \text{ m}^3 \text{m}^{-3}$, $R^2 = 0.705$ at 15 cm), but deteriorated with depth, reaching values of RMSE = $0.085 \text{ m}^3 \text{m}^{-3}$ and $R^2 = 0.079$ at 60 cm, where the model underestimated VWC during the dry season. Under the AVC treatment, VWC was overestimated across all depths, especially during the dry period, with the greatest differences observed at depths of 15 cm (RMSE = $0.108 \text{ m}^3 \text{m}^{-3}$, $R^2 = 0.326$) and 45 cm (RMSE = $0.133 \text{ m}^3 \text{m}^{-3}$, $R^2 = 0.501$). For both treatments, simulated recharge after September precipitation occurred earlier and more abruptly than observed.

Figures 22–25 show the model performance in simulating SWP dynamics. The statistical indicators calculated for both treatments are summarised in Tables 16 and 17.

Table 16. Statistical indicators Root Mean Square Error (RMSE) and R^2 calculated for soil water potential (SWP) simulations under UC treatment at all depths.

Unshaded Control				
	SWP 15 cm	SWP 30 cm	SWP 45 cm	SWP 60 cm
RMSE (kPa)	522.642	331.310	95.174	57.586
R^2	0.843	0.852	0.693	0.774

**Figure 22.** Daily soil water potential (SWP) at 15 cm depth: comparison between values simulated by the CRITERIA-1D model and field measurements (TEROS 21 probes) for AVC and UC treatments, from 23 May to 8 December 2024. Daily rainfall (mm) recorded over the same period by the on-site MeteSense 4.0 weather station is shown for reference.

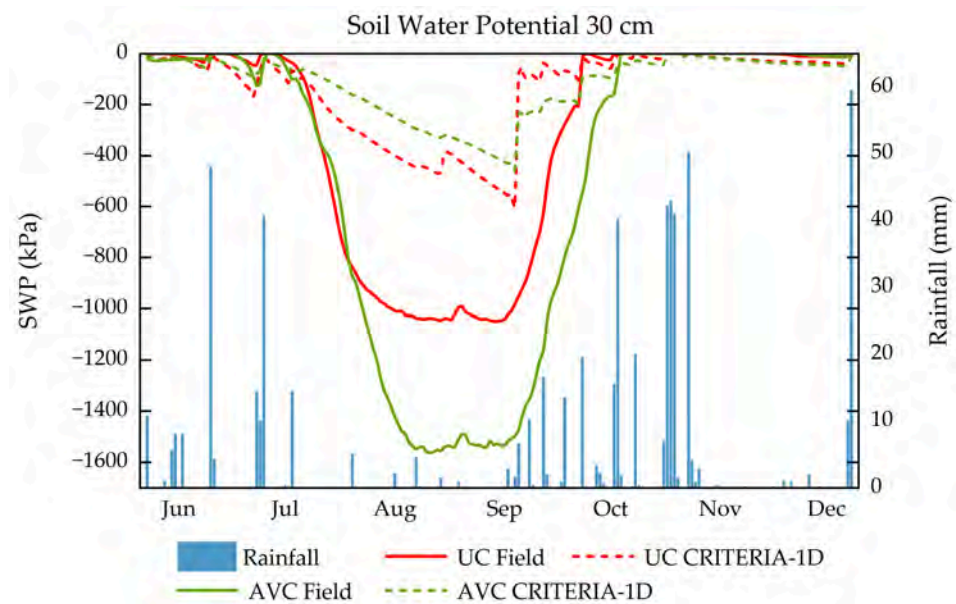


Figure 23. Daily soil water potential (SWP) at 30 cm depth: comparison between values simulated by the CRITERIA-1D model and field measurements (TEROS 21 probes) for AVC and UC treatments, from 23 May to 8 December 2024. Daily rainfall (mm) recorded over the same period by the on-site MeteoSense 4.0 weather station is shown for reference.

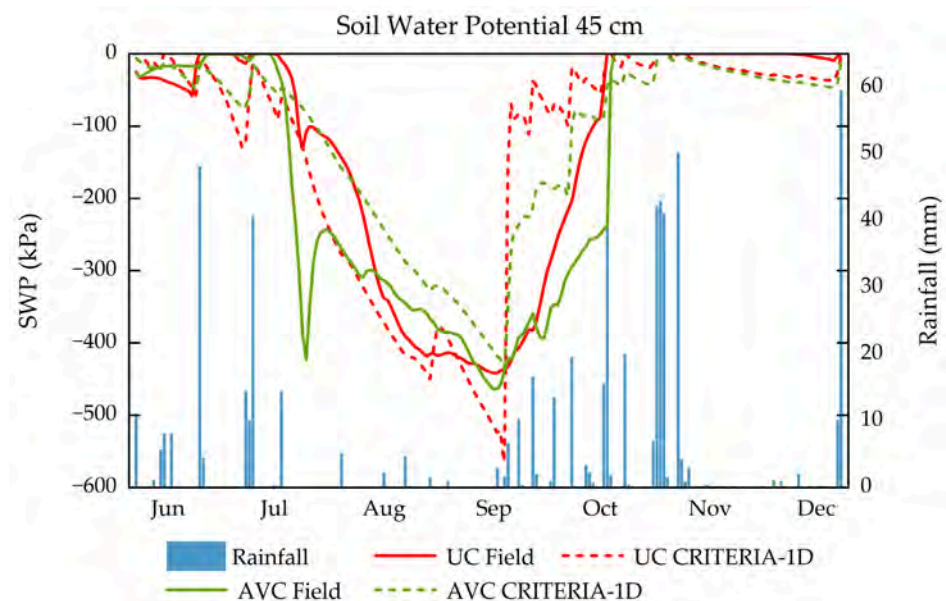


Figure 24. Daily soil water potential (SWP) at 45 cm depth: comparison between values simulated by the CRITERIA-1D model and field measurements (TEROS 21 probes) for AVC and UC treatments, from 23 May to 8 December 2024. Daily rainfall (mm) recorded over the same period by the on-site MeteoSense 4.0 weather station is shown for reference.

Table 17. Statistical indicators Root Mean Square Error (RMSE) and R^2 calculated for soil water potential (SWP) simulations under AVC treatment at all depths.

	AV Cover			
	SWP 15 cm	SWP 30 cm	SWP 45 cm	SWP 60 cm
RMSE (kPa)	717.340	615.630	91.055	67.320
R^2	0.721	0.928	0.767	0.757

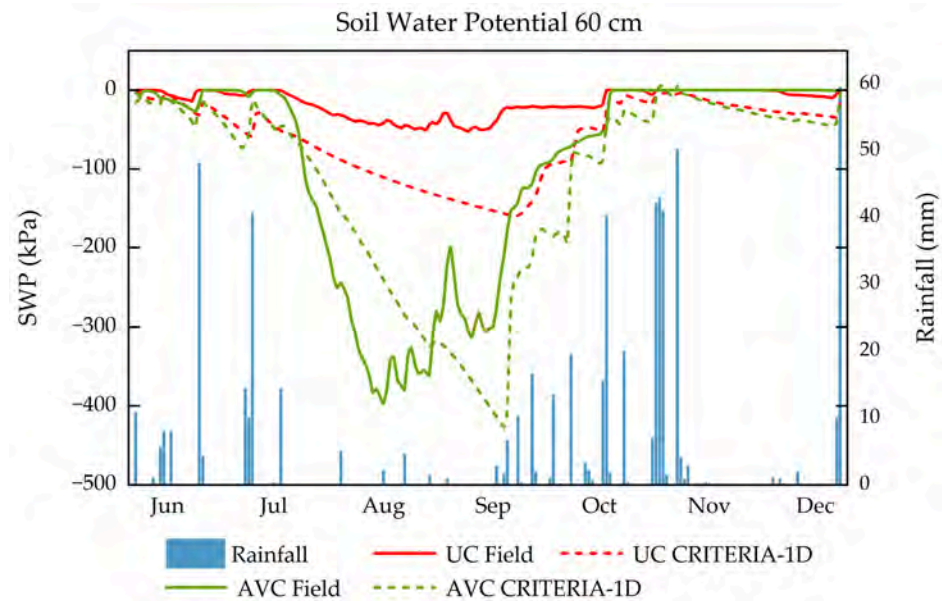


Figure 25. Daily soil water potential (SWP) at 60 cm depth: comparison between values simulated by the CRITERIA-1D model and field measurements (TEROS 21 probes) for AVC and UC treatments, from 23 May to 8 December 2024. Daily rainfall (mm) recorded over the same period by the on-site MeteoSense 4.0 weather station is shown for reference.

Regarding SWP, the R^2 values were higher compared to VWC in both case studies, although the RMSE values were high in the shallowest horizons due to the extreme SWP values recorded during the dry season. At 15 cm, the model underestimated the dry period minimum of the water potential for both treatments, with simulated SWP values reaching approximately -800 kPa compared to the -1800 and -1600 kPa recorded by the sensors for the AVC and UC treatments, respectively. At 30 cm, model performance improved for both the UC treatment (RMSE = 331.3 kPa, $R^2 = 0.852$) and AVC (RMSE = 615.6 kPa, $R^2 = 0.928$), showing an accurate reproduction of temporal dynamics, although still characterised by an underestimation of the minimum SWP values in the dry season. At depths of 45 and 60 cm, a decrease in RMSE was observed for both treatments, with satisfactory R^2 values. At 60 cm, the model overestimated the negative SWP peak under UC, whereas observed values recorded throughout the dry season were closer to 0 kPa. Overall, the model was able to reproduce both the drying phase and the SWP recovery following the wet season rainfalls.

3.5. Soil Water Availability Dynamics

Estimated available water (AW) dynamics in the 0–80 cm soil layer for both treatments are shown in Figure 26.

AW was higher under AVC than under UC during all the monitoring periods. In the dry season, average AW values of 131 and 87 mm were estimated under AVC and UC respectively. In the wet season, average AW remained higher under AVC with values of 200 vs. 139 mm. During the dry period, a more rapid decrease in AW was observed under the AVC treatment, which reached a minimum of 56 mm (vs. 42 mm under UC). Following the first rainfall events in September, the estimated AW under AV cover increased more sharply, reaching a peak of 243 mm in October (vs. 163 mm under UC).

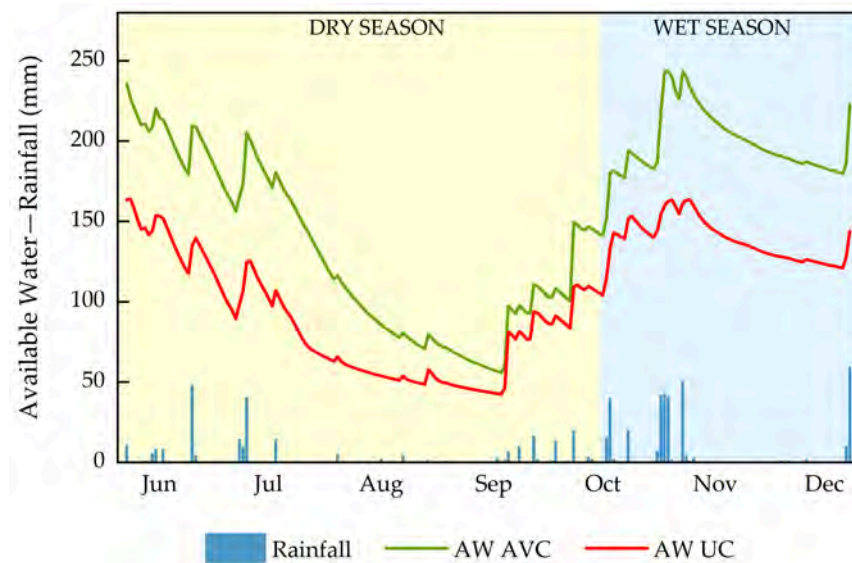


Figure 26. Daily available water (AW) dynamics in the first 80 cm of soil, simulated by the CRITERIA-1D model for both AVC and UC treatments, from 23 May to 8 December 2024. Data are reported separately for the dry season (May–September 2024, yellow background) and the wet season (October–December 2024, blue background), as defined in Section 3.

4. Discussion

4.1. Interpretation of the Results

Across the entire monitoring period, the AVC was associated with higher VWC values than those observed under UC, with the most pronounced differences occurring between the May–September period. The results were consistent with the available literature, which reports higher soil moisture conditions under photovoltaic panels compared to unshaded open-field conditions [9,14,16,17]. In most studies, this effect is attributed to the ability of the panels to reduce the solar radiation reaching the soil, which limits the energy available for evaporation and thus reduces cumulative water losses integrated over time [9–12]. The vertical distribution of the VWC differences observed in the Borgo Virgilio case study was characterised by higher values at 15 and 45 cm depths and lower values at 30 and 60 cm. This pattern suggests that soil moisture response to AVC may be modulated by the interaction of multiple concurrent factors, including surface evaporation, root water uptake during the wheat growing season, and the physical and hydraulic properties of the different soil horizons. The VWC values observed during the October–December period showed that the differences between AVC and UC, albeit smaller in magnitude, also persisted into the period following the growing season.

The ability of PV panels to reduce the amount of solar radiation reaching the surface limits the energy available to heat the soil surface [9–12]. During the May–September observation period, this mechanism is consistent with the lower soil temperatures observed at all depths under the AVC treatment compared to UC. Mean differences ranged from $-1.0\text{ }^{\circ}\text{C}$ at a depth of 15 cm to $-0.6\text{ }^{\circ}\text{C}$ at 60 cm, values that are in line with those reported in various studies [13,48,49]. The attenuation of the cooling effect with increasing depth is consistent with the progressive weakening of the surface thermal forcing as heat diffuses downward through the soil profile [50]. The reduction in soil temperatures is linked to the higher VWC values observed under AVC during the May–September period, as lower temperatures reduce both direct soil evaporation and crop transpiration. This is particularly evident at shallow depths, where direct soil evaporation is the primary driver of moisture loss during post-harvest phases when the soil surface is bare [51]. During the October–December period, the temperature difference between the two treatments

disappeared at depths of 15, 30, and 45 cm. This is consistent with the lower solar elevation angle in autumn and winter months, which reduces the effective shading provided by the panels and, consequently, diminishes the surface energy interception effect. At 60 cm depth, however, a persistent mean temperature difference of $-0.8\text{ }^{\circ}\text{C}$ between the two treatments was observed, which could be related to the greater thermal inertia of the deeper soil horizons, retaining the effects of summer cooling for a longer duration.

A relevant result emerging from this study is that, despite higher mean VWC values observed during the May–September period, the AVC treatment showed more negative average SWP values compared to the UC at all depths. One possible explanation to this apparently contradictory behaviour could be provided by the shape of the SWCCs derived for both treatments. Under AVC, fitted SWCCs showed higher saturated volumetric water content (θ_s) values across every horizon compared to UC treatment, suggesting that the soil could potentially retain greater volumes of water at a given SWP value. Consequently, during the drying process, the soil under AVC operates along a different portion of its SWCC, where the same VWC corresponds to a more negative SWP value compared to the soil under UC. Figure 27, which shows the fitted SWCCs for horizon 1 under AVC versus UC conditions, illustrates how two different SWCCs can yield distinct SWP values for the same VWC.

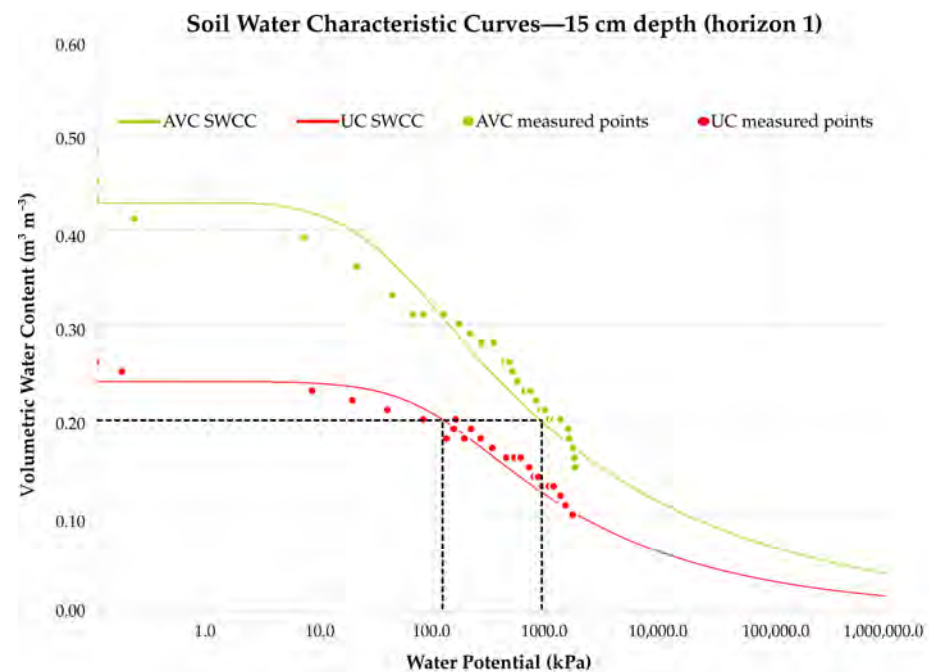


Figure 27. Example of Soil Water Characteristic Curves (SWCCs) for horizon 1 under AVC (green) and UC (red) treatments, illustrating how, at the same volumetric water content ($\text{VWC} = 0.2\text{ m}^3\text{ m}^{-3}$), the two curves correspond to different soil water potential (SWP) values, reflecting the potential different water retention behaviour of the soil under the two treatments. The dashed horizontal line indicates the selected VWC value ($0.2\text{ m}^3\text{ m}^{-3}$), while the dashed vertical lines show its corresponding SWP value for each treatment.

Due to its shape, it can be observed that for the SWCC of the soil under the AVC treatment, at a VWC value of $0.2\text{ m}^3\text{ m}^{-3}$, the corresponding SWP is 1000 kPa, whereas for the SWCC of the soil under UC, at the same VWC, a lower, in absolute terms, SWP value of 150 kPa is observed. This behaviour is consistent with the principle that soils with higher porosity and water-retaining capacity can maintain higher water content while exhibiting more negative SWP values than structurally denser soils [25,50]. Following this interpretation, the less negative SWP recorded under UC at all depths during the dry

season does not necessarily imply greater water availability in absolute terms. On the contrary, the Available Water Capacity (AWC), calculated as the difference between Field Capacity (FC) and Wilting Point (WP), estimated by CRITERIA-1D was consistently higher under AVC than UC at all depths. This could potentially mean that the soil under AVC can store and supply greater quantities of water to the crop root system before reaching the WP. The different SWCCs derived from coupled field measurements of VWC and SWP could lead to the hypothesis that the soil under AVC may have undergone modifications in its hydraulic properties compared to the UC.

Given that the AV system installed at the Borgo Virgilio site had been operational for 13 years prior to the monitoring period, a plausible but unproven hypothesis is that it induced a persistent microclimate modification that progressively altered the structure of the soil beneath the AVC. A possible explanation is that higher moisture conditions under AVC may have increased macro-invertebrates' activity [52], potentially leading to an increase in soil porosity [53,54]. The moderate microclimate may have also promoted a different root development under AVC treatment, creating a network of macropores [55,56] stabilised by the roots' exudates [57]. Alternatively, another hypothesis could be that the redistribution of precipitation by the panels may have created spatially heterogeneous wetting fronts, which modified the soil structure over time [58]. This latter mechanism could be particularly relevant for horizontal biaxial PV systems. By changing orientation throughout the day and seasons, these systems shift the position of the drip line, potentially redistributing the effect across broader areas than static PV systems. Recent review evidence supports the hypothesis that long-term PV or AV cover can induce measurable changes in soil physical and hydraulic properties [59,60], although the direction and magnitude of these changes appear to be highly site-specific. This interpretation, however, is subject to important limitations discussed in Section 4.2.

Calibrated k_{sat} values under AVC were higher than those under UC for all horizons. The most significant differences occurred in correspondence of horizons 1 and 4, where k_{sat} calibrated values under UC were two orders of magnitude lower than those under AVC treatment. For the soil texture class identified at the study site, which is a sandy loam (50% sand, 40% silt, 10% clay), pedotransfer functions typically estimate k_{sat} values ranging between 10^{-6} and 10^{-5} m s^{-1} [43,44]. While k_{sat} values calibrated for horizons 1 and 4 under UC fall significantly below this range, the calibrated AVC k_{sat} values are more consistent with the expected range for the described texture. One possible explanation of the higher calibrated k_{sat} values could be reconducted to a lesser soil compaction under AVC, at least in the shallower horizons, potentially due to lower mechanical traffic on that portion of the field. This interpretation, as discussed in Section 4.2, remains a hypothesis rather than a demonstrated result.

As it regards the modelling phase of the study, CRITERIA-1D successfully reproduced seasonal water dynamics for both treatments, capturing the drying phases, the minimum VWC values in August, and the recharge that occurred following wet season precipitation. The AW values estimated by the model in the 0–80 cm depth range appear broadly consistent with, and may be seen as extending, the general picture provided by field VWC measurements, tentatively suggesting higher water availability under AVC compared to UC throughout most of the observation period. In the May–September period, the average AW value under AVC treatment was on the order of 50% higher than that under UC. After wheat harvest (7 July 2024), the model estimated a faster rate of AW decline under AVC compared to UC. This behaviour is not in contradiction with the overall reduction in cumulative evaporative demand, but rather reflects a transitional mechanism observable at the beginning of the drying season, where a soil with higher initial water content and greater unsaturated hydraulic conductivity, as hypothesised in the case of

the soil under AVC compared to UC, facilitates upward capillary flux toward the surface, sustaining evaporative rates close to the atmospheric potential for a longer period [61] before hydraulic continuity is broken [62]. Once the soil surface dried sufficiently and both treatments entered the supply-limited evaporation stage, the rate of AW decline converged between treatments. This agrees with the theory of soil drying stages, according to which the evaporation rate remains close to potential as long as the soil surface is adequately supplied with water from below [63]. Despite this more rapid decline, the minimum AW values estimated for late August were similar for both treatments (56 mm vs. 42 mm), suggesting that, according to the model, the rate of water loss tended to converge once soil water content approached its lower limit. Following the first precipitation events in September, the AW recovery was faster and more pronounced under AVC, consistently with the hydraulic properties attributed to that soil, which can hypothetically store more water than the UC soil. The AW values estimated by the model were also higher under AVC during the wet season, suggesting that the effect of PV panel cover could help conserve soil water even after the cropping season, with potential benefits for subsequent crop cycles. From a crop management perspective, the higher AW estimated under AVC during the May–September period suggests that, under similar conditions, irrigation scheduling for rainfed or supplementally irrigated wheat beneath AV systems could allow longer intervals between water inputs before crops approach the wilting point. The persistence of higher VWC into the October–December period also suggests that AVC may extend soil water availability for subsequent crops in rotation, which could inform sowing-date or catch-crop decisions in AV fields. These implications, however, remain preliminary given the single-site design of this study and should be corroborated by field-scale management trials before being translated into operational recommendations. They should likewise be read considering the model limitations discussed in Section 4.2.

4.2. Limitations of the Study

Some important limitations must be acknowledged, as they constrain the strength of the inferences that can be drawn from the results presented above.

The main limitation of the study lies in the monitoring design. With only one vertical probe per treatment, located 10 metres apart, the dataset provides just two points of comparison, which are insufficient to robustly distinguish the effect of the AV cover from pre-existing soil heterogeneity. Although the distance between the two profiles was minimised, this does not exclude differences in the physical and hydraulic properties of the soil between the two locations, given how much these properties can vary even over short distances. With only one measurement point per treatment, it is impossible to determine whether such variability predates the AV system's installation, or to what extent it may have contributed to the differences observed. Consequently, the differences in VWC and soil temperature between AVC and UC cannot be unambiguously attributed to the shading effect of the AV structure, as they may equally reflect intrinsic variation in soil texture, structure, or hydraulic behaviour between the two sites. This same limitation also has implications for how the statistical results should be interpreted. The paired measurements gathered over time from the two profiles produced very low p -values ($p < 0.001$) when comparing treatments. However, these measurements were taken at the same two fixed locations rather than from multiple independent plots. The statistical strength of the result therefore mainly reflects how stable the difference was between these two specific points over time, rather than how representative it is of AVC and UC conditions more broadly. Therefore, the findings presented in this study should be understood as an initial, case-specific contribution to the understanding of how AV cover may influence soil moisture and temperature, rather than as definitive evidence applicable beyond the monitored site. A

further limitation relates to the duration of the monitoring campaign, which spanned only seven months. Extending future observations across multiple years and including several monitoring points or replicated plots for each treatment would help determine whether the patterns identified in this case study hold under varying weather conditions, allow the effect of the AV cover to be separated more reliably from site-specific soil variability, and clarify whether AV cover produces any lasting changes in soil hydraulic behaviour over longer periods.

The hypothesis discussed in Section 4.1, according to which 13 years of AVC induced a persistent microclimate modification altering soil structure, is subject to several limitations, and should therefore be regarded as one plausible scenario consistent with the available data rather than as a definitive characterisation of the hydraulic properties of the two treatments. No direct measurements of bulk density, porosity, soil structure, hydraulic conductivity, root density, or biological activity were carried out in this study, so the hypothesis of a structural change induced by 13 years of AVC remains speculative. This limitation is compounded by two aspects of how the SWCCs were obtained. First, they were fitted using pairs of VWC and SWP values measured under conditions ranging from wet to intermediate, while their behaviour in the dry range was modelled in the absence of measured data. The resulting uncertainty, particularly at SWP values beyond 1000–1500 kPa, implies that the pronounced difference in θ_s and AWC between AVC and UC, especially at greater depth, may partly reflect the limited density of observations in specific portions of the moisture range, together with simplifying assumptions inherent to the model (uniform texture within each horizon, no explicit representation of hysteresis, and a single wetting/drying path), rather than a genuine divergence in hydraulic behaviour. Second, the curves were derived from a single measurement point per treatment through an inverse estimation procedure; the resulting parameters are therefore plausible but cannot be considered sufficient to exhaustively describe the hydraulic properties of the soil under each treatment. Given the substantial spatial variability of hydraulic properties typically found in Po Plain soils, even within the same site, the differences observed between the two treatments' curve parameters could equally originate from pre-existing local heterogeneity rather than from any effect of AVC. Testing the AVC hypothesis robustly would therefore require spatially replicated field measurements of bulk density, porosity, soil structure, hydraulic conductivity, root density, and biological activity at multiple positions within and outside the AV array, which should be a priority for future research.

As noted in Section 4.1, the interpretation of higher calibrated k_{sat} values under AVC in terms of lesser soil compaction remains a hypothesis, since it rests solely on calibrated k_{sat} values rather than on direct structural measurements. Indeed, k_{sat} values were not measured directly but were obtained through an iterative process aimed at minimising the differences between simulated and observed VWC and SWP values; as such, they cannot be taken as independent evidence of physical differences between the two treatments. The inverse calibration is also subject to a degree of equifinality, whereby different combinations of k_{sat} and soil water characteristic curve (SWCCs) parameters can reproduce comparable VWC and SWP dynamics. The calibrated k_{sat} values may therefore partly compensate for uncertainties in other model inputs, such as soil texture or organic matter content, rather than uniquely reflecting the true hydraulic properties of each horizon.

Model performance was assessed on the same dataset used for calibration, as no independent validation dataset, either from a different period or a different location, was available. Therefore, the resulting agreement between simulated and observed values reflects the model's ability to reproduce the calibration dataset rather than an independently verified predictive capability, and the reported performance should be interpreted with this caveat in mind. Discrepancies were nonetheless observed between the values simulated by

the model and those recorded by the probes, particularly during the dry season, where at depths of 15 and 30 cm the model systematically overestimated VWC and underestimated SWP. The coefficient of determination (R^2) between simulated and observed VWC also varied across depths and treatments, with lower values found for UC at 60 cm and for AVC at 15 and 45 cm. This uneven performance across the profile suggests that the model's ability to reproduce the temporal dynamics of soil moisture is not uniform throughout the monitored depths, and that the deeper and more superficial horizons may be less reliably represented than the overall calibration performance would suggest. Several factors are likely to have contributed to this depth-dependent behaviour, including the assumption of uniform soil texture across horizons, the use of a single calibration point per treatment, and the uncertainty in the meteorological forcing used for the spin-up period, discussed below. Since these R^2 values reflect the model's capacity to capture VWC dynamics at the specific depths where sensors were installed, their heterogeneity should be considered when interpreting results derived from the full soil profile, such as the AW estimates discussed below.

During model configuration, a uniform soil texture was assumed across all horizons from 0 to 60 cm depth, consistent with data reported in previous studies conducted at the same site [41]; other parameters relevant to soil hydraulic behaviour, including bulk density, organic matter content, and an additional soil horizon introduced during model configuration, were assumed or estimated by the model rather than defined through direct field measurement, and the uncertainty associated with these assumptions should be regarded as an additional source of uncertainty in the simulated results, alongside that discussed above for k_{sat} . Direct measurements of these parameters would help constrain the calibration and reduce the reliance on assumed or calibrated values, thereby making the modelling results more reliable.

A further source of uncertainty concerns the meteorological forcing used to drive the model. Since CRITERIA-1D requires at least one year of simulation prior to the study period, data for the spin-up period (1 January 2023 to 22 May 2024) were sourced from a weather station 7 km from the study area rather than from the on-site MeteoSense sensor; differences between local and remote conditions during this period, particularly with respect to convective precipitation events, may have led to an inaccurate representation of the initial soil moisture state and contributed to the discrepancies observed between simulated and measured values in the first weeks of the study. More importantly, incident radiation was not differentiated between the two treatments during the simulation period either: potential radiation was estimated by CRITERIA-1D solely from the site's coordinates and the day of the year, identically for AVC and UC, in the absence of measured global and net radiation values specific to each treatment. This represents a significant simplification, since a substantial part of the interpretation of the results relies precisely on differences in the surface energy balance and evaporative demand induced by the panels. Field studies on similar elevated agrivoltaic structures report reductions in incident solar radiation beneath the panels typically in the order of 30%, with corresponding reductions in crop water use of a comparable magnitude [64,65]. However, the exact figure depends strongly on panel density, row spacing, and ground coverage ratio: some configurations maintain as little as 30–40%, others as much as 60–70%, of incident radiation at ground level [66]. Since CRITERIA-1D applies the same potential radiation to AVC and UC, this treatment-specific reduction in evaporative demand is not captured, meaning that any difference in simulated evapotranspiration between the two treatments currently derives entirely from the calibrated soil parameters and from the vegetation and soil evaporation routines, rather than from an explicit representation of the radiative shading effect. As a result, the model's ability to reproduce treatment-specific differences in evapotranspiration is likely underesti-

mated, particularly during periods of high solar elevation and clear-sky conditions, when the radiative effect of the panels is expected to be largest. The discrepancy between actual and estimated incident radiation under AVC therefore represents an additional, currently unquantified, source of error affecting the simulated water balance for that treatment. The incorporation of treatment-specific incident global and net radiation measurements would have allowed the differential radiation interception between AVC and UC to be accounted for explicitly. This would have enabled the application of alternative evapotranspiration estimation methods, such as the Penman-Monteith equation [67], with potential benefits for the accuracy of evapotranspiration estimates and the resulting water balance under each treatment.

Finally, given how the model's fit quality varies with depth and in particular the comparatively low R^2 values obtained for UC at 60 cm and for AVC at 15 and 45 cm, the AW differences reported in Section 4.1 should be interpreted with caution as the estimated VWC values contribute directly to the estimate obtained by integrating over the 0–80 cm profile, so their uncertainty propagates into it as well. The higher AW values estimated under AVC during May–September should, therefore, not be regarded as a robust quantification of the difference in water availability between treatments, but rather as an indicative signal, to be considered together with the uncertainties outlined above and possibly revisited once model performance across the full profile can be more thoroughly constrained. Likewise, the higher AW values estimated under AVC during the wet season should be taken as a tentative indication rather than a robust quantitative result. The suggestion that PV panel cover could help conserve soil water even after the cropping season, with potential benefits for subsequent crop cycles, would therefore need to be confirmed against independent field observations.

5. Conclusions

The present study investigated the effects of an AV system (Ground Cover Ratio of 14%) with horizontal biaxial tracking on soil water dynamics beneath it in a durum wheat field over a growing season in a humid subtropical climate. By combining field measurements with numerical modelling using the CRITERIA-1D model, this study provides preliminary evidence that AVC may improve soil water retention capacity, particularly during the May–September observation period. During this period, VWC values under AVC tended to be higher than those measured under UC at all depths, with the largest mean differences observed at 15 cm ($0.07 \text{ m}^3 \text{ m}^{-3}$, +41% compared to UC) and 45 cm ($0.09 \text{ m}^3 \text{ m}^{-3}$, +26% compared to UC). This tendency also appeared to persist during the October–December period, well after the wheat harvest in early July, suggesting that the shading effect of the AV system on soil moisture may extend beyond the cropping season, although confirmation over multiple years would be needed to establish this more robustly.

A further observation concerns SWP behaviour under the two treatments during the dry season. During this period, despite higher VWC values, the soil under AVC showed higher average SWP absolute values than those measured under UC, with the most pronounced differences at 15 and 30 cm (mean SWP values 19% and 50% higher than UC, respectively). A possible interpretation, based on the SWCCs derived for the different horizons of the two treatments, is that the soil under AVC could be characterised by greater water retention capacity at all investigated depths compared to the soil under UC. This pattern may hypothetically be linked to structural modifications induced by the thirteen-year presence of the AV system as discussed in Section 4.2.

The AW estimated by the CRITERIA-1D model in the first 80 cm of soil was higher under AVC than under UC in both periods considered, which is consistent with what could be inferred from the measured VWC data. CRITERIA-1D showed reasonable potential

in reproducing the main seasonal soil drying and recharge dynamics for both treatments, with satisfactory performance on the calibration dataset. However, model performance was more limited during the dry season, with SWP absolute values estimated at 15 and 30 cm generally lower than those measured in the field for both treatments, underscoring the need for caution in interpreting the simulated results.

Overall, the results of this study offer preliminary insights into the potential implications of AVC for the design and management of AV systems in humid subtropical environments. In a context such as the Po Valley, where future climate scenarios point to an increased frequency of drought [20,21], AVC could represent one possible strategy contributing to the conservation of subsurface water resources, potentially extending the period of water availability for plants in the root zone. This effect could be particularly relevant for rainfed farming systems, where adaptation options are constrained by the absence of supplemental irrigation. However, given the limitations of this study these findings should be regarded as indicative rather than conclusive. Future research should combine spatial replication with multi-year monitoring and laboratory characterisation of soil hydraulic properties, along the lines detailed in Section 4.2, to disentangle effects induced by the AVC from pre-existing spatial and inter-annual variability. Finally, comparative studies across AV systems with different configurations (GCR, crop type) and extended to additional sites and climatic contexts would help clarify the extent to which the mechanisms observed here can be generalised beyond the Po Valley.

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Conflicts of Interest: Author Giancarlo Ghidesi was employed by the company REM Tec S.r.l. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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