Impact of Various Agrivoltaic Systems on Different Apple and Plum Varieties

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1. Introduction and objectives

Agrivoltaic (AV) systems, which integrate solar energy production with agricultural practices, have shown variable impacts on fruit cultivation. Solar modules in AV systems may negatively impact both fruit yield and quality (see [1] for an overview of various fruit types). The mitigation of adverse effects associated with AV systems on fruit production remains a significant challenge that requires an adapted orientation of solar modules and suitable fruit varieties, as well as modified methods to determine optimal harvest dates. To address this, a comprehensive evaluation of the complex interactions between solar installations, horticultural crops, and site-specific conditions is imperative. Such an assessment is crucial for developing recommendations to optimize AV system performance in fruit cultivation contexts. This study contributes to the field by examining various fruit types and varieties, alongside different AV systems, across two distinct locations. This allows important conclusions to be drawn to fully unfold the potential of AV systems.

2. Methods

The experiments were conducted in 2024 at two distinct locations within the collaborative project "Modellregion Agri-Photovoltaik Baden-Württemberg". At the Vollmer fruit farm in Nußbach Oberkirch, Gemany, three apple cultivars (Bonita, Boskoop, and Topaz) and three plum cultivars (Franzi, Moni, and Toptaste) were cultivated under an agrivoltaic system with tracked solar modules. Three conditions were compared: an uncovered control, a full-sun tracking, and an agronomic tracking variant providing increased light availability to the crops. At the Landwirtschaftliches Technologiezentrum Augustenberg (Center for Agricultural Technology Augustenberg) (LTZ) in Karlsruhe, Germany, the apple cultivars Bonita, Natyra, Rubelit, and Topaz were grown under an uncovered control condition and beneath static solar modules. At the LTZ, fruit harvesting was performed at two distinct dates of the year. The first harvest date was determined by the optimal ripeness of the control group. The second harvest date, occurring approximately ten to fourteen days later, corresponded to the ideal harvesting time for the fixed solar module variant. At both sites, key parameters were measured to evaluate the effects of shading by solar modules on plant physiology. These included the length and number of annual shoots, flower formation and fruit set. Fruit quality parameters were evaluated as well to determine the effects of the agrivoltaic system on the final product. Fruit flesh firmness, a critical indicator of fruit ripeness and quality of apples, was measured using a penetrometer (ART-PE01). The sugar content of the plums and apples was assessed with a refractometer (KERN ORF 45BE). The Streif Index as outlined in [2], was used to determine fruit ripeness. Additionally, the fruit color was evaluated at the LTZ.

3. Results

At the Vollmer farm in Nußbach, formation of flower buds under AV modules was statistically significantly reduced (Games-Howell-test) for the apple cultivars Bonita ($p=0.002$ and $p=0.003$) and Topaz ($p<0.001$ and $p<0.001$) (see Fig. 1). Conversely, fruit load was higher (Games-Howell-test) under the solar modules compared to the control for the cultivars Boskoop ($p<0.001$ and $p<0.001$) and Topaz ($p<0.001$ and $p=0.001$). The sugar content of plums was slightly reduced under the solar modules. However, the sugar content (Brix value) and fruit weight (data not shown) between the control and the agronomic tracking for the cultivars Franzi ($p=1.000$) and Moni ($p=0.134$) was not statistically significant (Tukey-HSD-test). Kruskal-Wallis-tests confirmed the results of all parametric tests used. Shoots of apple trees showed adaption to shading under the AV modules regarding length and number (data not shown).

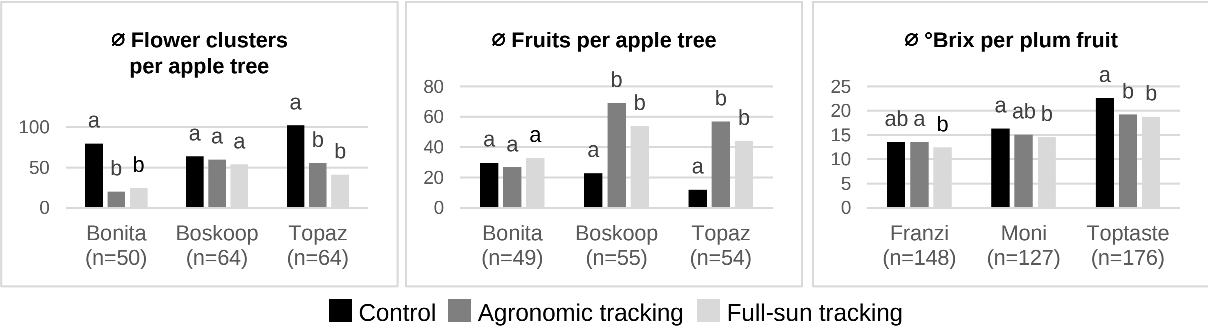

Figure 1. Results gathered at the Nußbach site. Within each cultivar, mean values with the same letter do not differ statistical significantly ($\alpha = 0.05$, Games-Howell-test, Tukey-test).

4. Discussion

The shading effect induced by the AV modules significantly impacted the physiology of the fruit trees during the experimental year, with negative influences on shoot elongation (data not shown) and flower bud formation. To mitigate adverse effects, future research could focus on optimizing orientation or the tracking algorithm of the solar panels to better account for phases critical for the physiological development of the fruit trees (e.g. during flower bud formation or morning hours (compare e.g. with [3])). Despite the diminished number of flower clusters, trees under the solar modules exhibited a higher fruit load. This outcome can be explained by frost that occurred during the observed growing season. The AV system has created a microclimate with higher night temperatures in winter, resulting in a protective effect against frost damage to the fruits. This buffering effect resulted in a higher survival rate of the fruits under the AV modules compared to the uncovered trees in the control variant. Our observations revealed a delayed ripening process for apples grown under the AV system. Notably, the starch content in these fruits often remained at levels not optimal for storage, and fruit coloring was reduced under the solar modules (data not shown). These findings suggests that the optimal harvest date of apples cultivated under AV conditions might differ from results of the Streif-index which is currently widely used in Germany, Switzerland and Austria to determine the optimal harvest time for apples. The impact of the AV system on the sugar content of plum cultivars Franzi and Moni did not show statistically significant difference under the agronomic tracking algorithm compared to the control variant. Subsequent experimental years will be crucial in evaluating whether Franzi and Moni plums indeed demonstrate high suitability for cultivation under solar modules and to further optimize tracking algorithms. The findings of our study suggest that integrating AV in fruit producing systems require optimized orientation of solar modules as well as an adapted determination of the optimal harvest date. The latter aspect, in particular, holds significant potential for fruit growers to operate AV systems economically.

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Evaluation of production costs and plant protection savings of conventional gala apple under agrivoltaics system in Kressbronn

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1. Introduction

Crop protection systems are becoming more and more required since high performance strains are more sensitive towards environmental impact and the inconsistent weather conditions due to climate change. By 2022 in Germany >22.000 ha were classified as protected cultivation. The development around the lake of constance, one of Germanys horticulture hotspots, is particularly imperessive, considering 0 ha under hail protection 2005 and almost a full coverage (>5.000 ha) by now. Agrivoltaic-Systems (AVS) have the potential to offer the crop protection and on top the generation of renewable energy. One pilot of the "Modelregion- Agrivoltaics BW" was established 2022. In 2023 and 2024 every application of water, funghizides and pesticides has been documented under AVS and on the reference. In addition the effort of individual working steps (e.g. net closing/opening, manual flower removal etc) has been documented and compared.

2. Content

A publication already exists that explores the extent to which economic synergies can reduce the costs of apple farming under agrivoltaics. While the economic analysis is broader and also includes investment costs, at the time of publication, no empirical data on operational costs of apple cultivation under agrivoltaics was available. The data used for the calculations was based on estimates derived from expert interviews. Although this was a reasonable approach at the time, it still left uncertainties regarding the system's economic performance. Since then, agrivoltaics pilot projects have advanced, collecting empirical data on apple farming under these systems. This paper contributes to the research on the economic performance of apple farming under agrivoltaics by utilizing this new data to evaluate the impact of agrivoltaics on operational costs in apple farming.

One point will be deeper discussed including non-economic perspectives as well, that is the possibility of reducing the amount of pesticides in apple farming when integrated in an agrivoltaic system. The german government aims on reducing the amount of pesticides used by half until 2030. (Quelle: Zukunftsprogramm Pflanzenschutz) Existing research states, that reducing the pesticide use in orchards in general as well as apple farming in particular can be quite challenging (Quelle: Simon 2011). With that being said, reducing pesticides is not only interesting from an economical point of view and will be analised as savings in money as well as savings in toxicity and environmental impacts of those.

In this approach a baseline scenario was set, that is based on the agrivoltaics facility and reference area in Kressbronn near lake constance. The are of the AVS is 0,4 ha. For a better analysis and transferability to farmers and other actors, all parameters have been normalized on 1 ha. Due to typically small farm sizes and labour intensive cultivation, no scale effects were included. The data is out of two input streams. The farmer that cultivates the pilot facility delivered data on the number of times each measure has been applied, the amount of irrigation water that was needed and the labour intensity of the measures. The second source is the "Maschinenring Verrechnungssätze". That is a list with estimated cost rates for machine use, plant protection and other material that is needed for cultivation, published by a regional agricultural institution. This combination of data improves the comparability and enables to include more data points from other farms. Due to specific conditions of owning/renting/sharing machinery, the results may differ from the actual costs for that farmer though.

The results of this study indicate, that agrivoltaics might have more potential in reducing the agricultural OPEX in apple farming than expected. While Trommsdorff et al estimated total savings of 8.2 %, the results of this study were 21.8% reduction in average. The main drivers of this cost reduction were significant savings in plant protection and some labour intensive tasks. It also appears, that weather conditions not only have a generally high impact on agricultural OPEX, but also on the potential of agrivoltaics to be more cost efficient considering the different weather in 2024 and 2023. 2024 beeing a very rain intense year particularly in spring, when fungus infections are most damaging the total harvest.

Enhancing Agrivoltaic Synergies Through Optimized Tracking Strategies

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1. Introduction and Methodology

Horizontal single-axis trackers (HSATs) are becoming increasingly significant in agrivoltaic applications due to their inherent flexibility, which allows for the effective balancing of light distribution between crops and solar panels during operation [1-6]. This adaptability is essential to tackle the dual challenges of food security and renewable energy production; however, it necessitates tailored tracking strategies.

This paper presents a methodology consisting of six key steps, as shown in *Figure 1*, to create a digital twin of an agrivoltaic system (see *Figure 4*) and dynamically optimize solar panel positioning to meet the varying light requirements of crops [7]. The analysis, focused on tree light availability, is performed using the custom-developed tool *ApyV.*

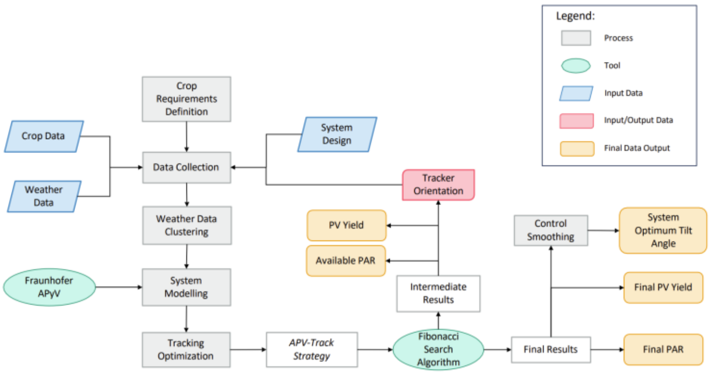


Figure 1. Flowchart of the simulation and tracking optimization methodology, with its six core steps, and the relevant inputs and outputs.

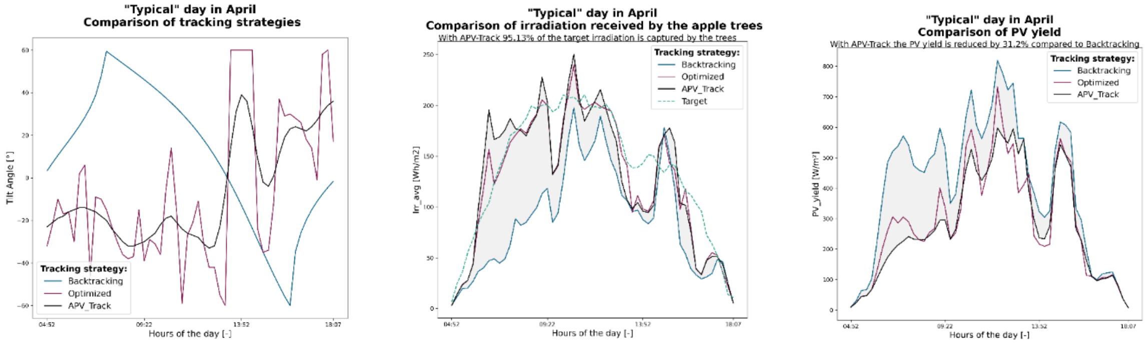
Moreover, conventional shading strategies for apple orchards, traditionally based on agronomic experience and hail nets, are challenged by proposing specific irradiance targets for regional apple varieties, expressed in W/m² or Wh/m²/day [8]. Unlike relative shading percentages, these absolute targets facilitate optimization and ensure consistent light availability, addressing issues related to weather variability.

Table 1. Absolute requirements expressed in terms of DLI for the different months of the cropping season. The results take into account the tolerated PAR percentage reduction.

Month	Daily received PAR [kWh/m²/day]
March	1.17
April	1.85
May	2.04
June	1.84
July	1.75
August	1.75
September	1.21

2. Results and Discussion

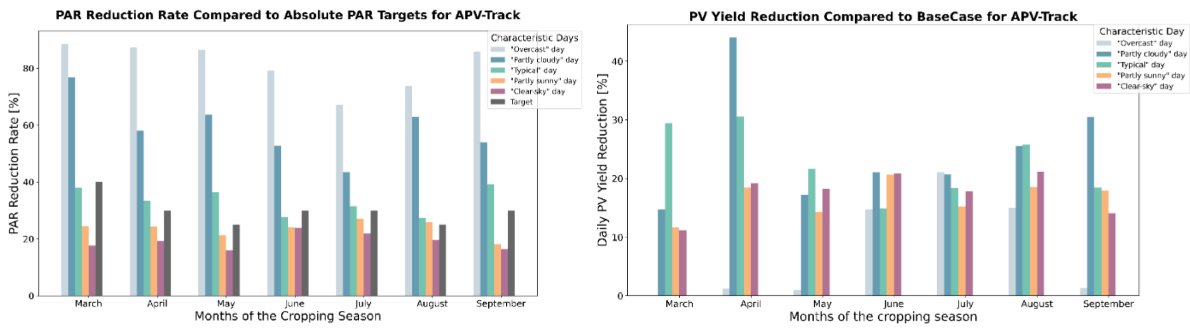
Results from a case study within the “Modellregion Baden-Württemberg” project, which incorporates solar panels into an apple orchard (see Figure 4), are presented. (see *Figure 4*). Relevant inputs are collected from the system, and simulations are performed for five days per month, clustered to represent weather trends. Key outputs for a representative day are presented in *Figure 2*.



(a) (b) (c)

Figure 2. Key results for the “typical” day of the month of April. Panel (a) reports a comparison of the tracking strategies, with the backtracking in blue, the optimized routine in red, and the final APV-Track in black. The corresponding average irradiation received by the apple trees is illustrated in panel (b) with the same color scheme and the addition of the targeted irradiation in green. Finally, panel (c) shows the comparison of the PV yield with the different control algorithms.

The effectiveness of the methodology and the tailored tracking algorithm is quantified by comparing the annual sums of the target daily light integral (DLI) with the actual values achieved. For the specific application, crop, and simulated year (2019), the targeted annual DLI is 351 kWh/m², whereas the achieved DLI is 319 kWh/m², indicating that 91% of the target irradiation is successfully achieved. In contrast, a backtracking strategy would provide only 67% of the required light to the trees. However, this strategy leads to a reduction of the PV yield by 20%. Breakdown of the monthly result is presented in *Figure 3.*



(a) (b)

Figure 3. Summary of the main results obtained with APV-Track. These graphs compare the performance of the algorithm over different weather conditions and thus characteristic days, for each month of the cropping season. Panel (a) shows the rates of reduction in photosynthetically active radiation (PAR) alongside the target values, whereas panel (b) illustrates the rates of reduction in photovoltaic yield.

The strength of the dynamic strategy lies in its ability to identify periods of low irradiation, during which APV-Track may not meet the target, as well as periods of high irradiation during which panel positioning can be maintained close to the electrical optimum. These findings underscore the limitations of crop-based optimization while offering valuable insights for future optimizations that better balance electrical yield with agronomic effectiveness. Field testing and validation of results are scheduled for the 2025 cropping season, beginning in March, with subsequent experimental insights to be reported.

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Appendix

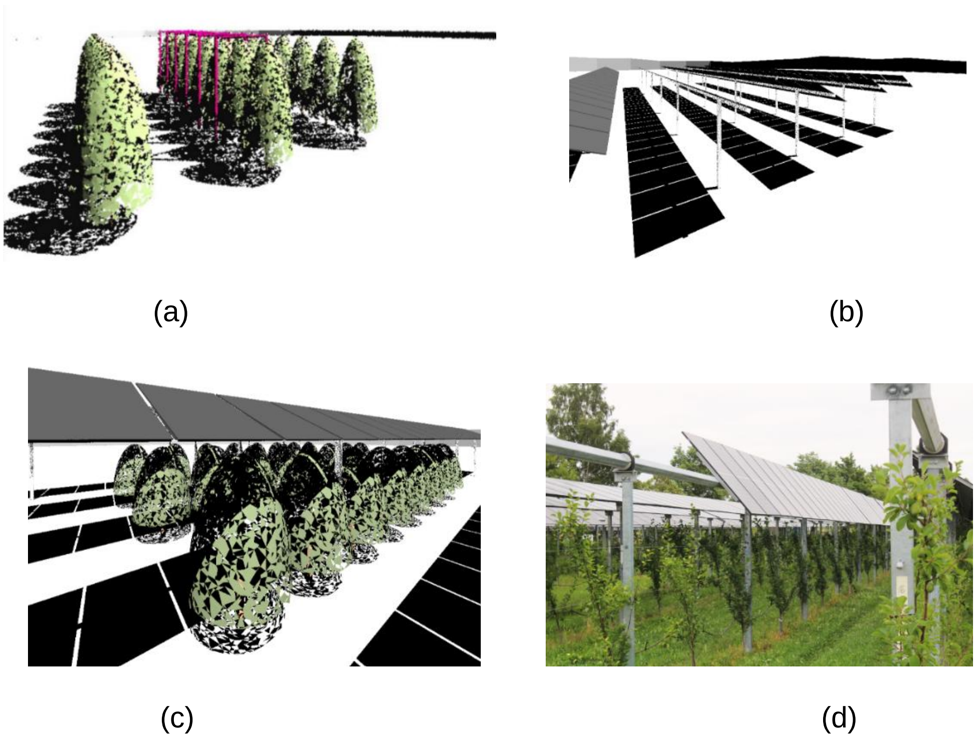

Figure 4. Renderings of the different radiance scenes created: (a) reference scenario with an apple orchard and light simulation sensors in violet, (b) PV system with torque tube and relevant substructure, and (c) BaseCase scenario: a combination of PV system and apple orchard. Last, a picture of the pilot project in Nussbach (d).

Field Study: Soil Microclimate in an Agrivoltaic Orchard

Assessment of Spatial Heterogeneity and Mitigation During Extreme Weather Conditions

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1. Introduction

Soil moisture and temperature are key parameters influencing plant growth and soil health, and their modification by agrivoltaic systems warrants investigation. While crop yields in these systems are well-studied, subsurface interactions, including seasonal and spatial variations in soil conditions, remain underexplored. This study presents field data comparing soil moisture and temperature in an operational agrivoltaic system and a reference field. Results reveal substantial seasonal differences between the systems and notable spatial heterogeneity within the agrivoltaic site, driven by panel placement.

2. Site Description and Monitoring Equipment

The study was conducted at an agrivoltaic installation in Kressbronn near Lake Constance, Germany (9.60425°E, 47.6017°N, WGS 84) at an elevation of 425 meters above sea level. The agrivoltaic system comprises two zones, differing in module transparency (40 and 51 percent). The system has an installed capacity of 242 kW_p at a clearance height of 3.5 meters. The local climate is classified as temperate oceanic, with average annual precipitation of ca. 1000 mm. The system covers an area of 0.4 hectares and is used for cultivating Gala apples. The reference field is located directly adjacent to the agrivoltaic system. Both areas are irrigated using drip hoses, which are suspended above the ground. The soil in the area is dominated by luvisols and gley soils, which are typical of alluvial and floodplain environments. These soils tend to exhibit good moisture retention capabilities and are often rich in nutrients, making them suitable for agricultural applications. Additionally, sandy and loamy textures contribute to effective drainage [1]. Monitoring equipment consists of dual-depth soil sensors (10 and 25 cm below surface; supplier: MMM tech support) positioned at three different locations within the agrivoltaic system: In the center of the interrow underneath the upper module edges (“interrow Λ”), in the center of the planting row beneath the PV modules (“crop row”), and underneath the gap between the lower module edges (“interrow V”). Two additional sensors were installed in the reference field, one in the interrow and one within the crop rows. Data recorded from May 11th, 2022, to August 11th, 2023, was used for preliminary analysis. To assess the system's ability to mitigate extreme weather conditions, the hottest and coldest weeks within this period (as identified by [2]) were selected for detailed analysis: July 18th–24th, 2022 and December 5th–11th, 2022.

3. Results and Discussion

Soil temperatures differ significantly between the agrivoltaic system and the reference field. In summer, soil temperatures in the agrivoltaic system are generally lower, with differences up to 5 °C beneath PV modules in the morning. Only the interrow temperatures in the system occasionally exceed those in the reference around sunset. The crop row shaded by both PV modules and canopy shows the lowest soil temperatures, especially at night, possibly due to localized radiative cooling. In winter, soil temperatures beneath PV modules in the agrivoltaic system are generally highest, comparable to the reference crop row. In the reference field, soil temperatures in the crop row are about 1.5 °C higher than between rows during wintertime. While PV modules moderate temperatures overall, nighttime temperatures in the crop row sometimes drop below the reference, possibly due to radiative cooling of the structure. Diurnal fluctuations are most pronounced in the reference interrows, but overall temperature patterns are consistent in both areas. Figure 1 presents soil moisture measurements (% volumetric water content) taken in the agrivoltaic system at two depths (T1: near-surface and T2: subsurface) for the three positions described above.

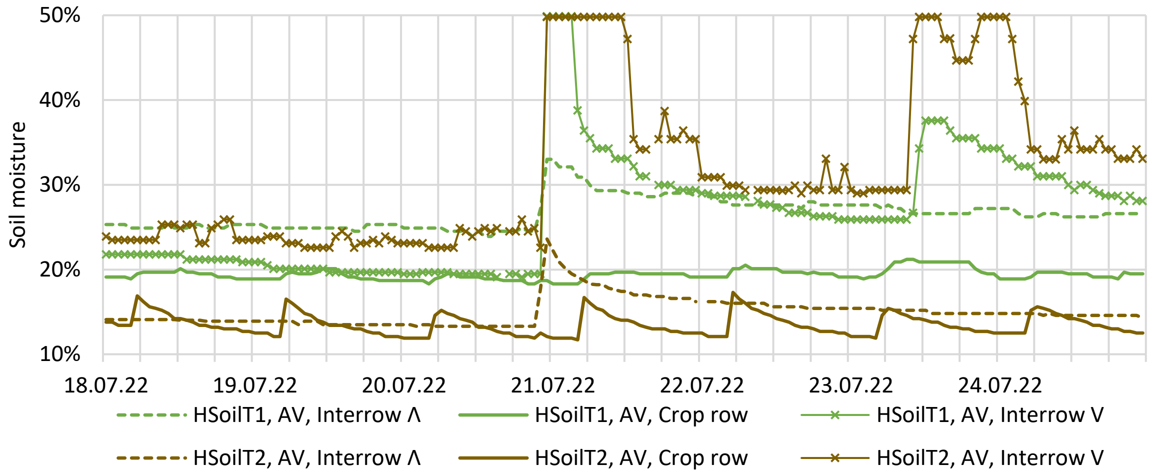

Figure 1: Soil moisture data from two depths in three positions inside the agrivoltaic system

The soil moisture in the interrow V position shows pronounced fluctuations at both depths. After a rainfall event on the night of 21st, moisture levels spike to their maximum, remaining elevated for several hours before declining. At T1, moisture decreases faster, reflecting surface evaporation and/or drainage, while T2 shows a slower decline, indicating water retention in the deeper soil layers. This suggests that water dripping from the module edges at this location creates transient but intense wetting of the soil, leading to substantial moisture variability within the planting area. The interrow Λ position demonstrates less pronounced fluctuations compared to interrow V, as it receives only direct precipitation without concentrated precipitation from the module edges. Overall, interrow Λ shows the most stable moisture conditions (likely due to receiving only a minimum of precipitation and the distance to the irrigation system). Yet, the biggest difference between T1 and T2 is also observed in this position. This could be evidence of a more homogenizing re-distribution of moisture at deeper soil levels. In the crop row, soil moisture patterns diverge from the other two locations. At T2, a sudden increase of approximately five percent occurs around 4-5 am each day. This can likely be attributed to irrigation rather than natural precipitation, as the crop row is directly shaded by the modules and would not typically receive rainfall. At T1, moisture levels are generally stable. A slight increase in response to the irrigation response can be observed, after which moisture level slightly declines, usually until the next irrigation event 24 hours later.

4. Limitations and Conclusion

Irrigation and precipitation data for the study site were unavailable during the observation period, constraining the interpretation of soil moisture dynamics. Additionally, the proximity of the irrigation system to the crop row sensor may have introduced localized anomalies in moisture readings. Nevertheless, the findings provide valuable insights into the complex interactions between photovoltaic installations and soil processes. Further analysis of these results, especially in the context of extreme weather conditions, is crucial for optimizing water management strategies and ensuring soil health and crop productivity in agrivoltaic orchard systems.

5. Acknowledgements and Author Contributions

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J.-V. Rößner: Conceptualization, Investigation, Formal analysis, Visualization, Writing – original draft

O. Hörnle: Conceptualization, Investigation, Funding acquisition, Supervision

A. Wilke: Writing – Review & Editing

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