ANALYSIS OF SOYBEAN BEHAVIOR WHEN INSERTED IN AN AGRIVOLTAIC SYSTEM

Bruno Jacomel Vieira[1], Alex R. A. Manito[1], Marcelo Pinho Almeida[1], Roberto Zilles[1] and Maurício Roberto Cherubin[2,3]

[1] University of São Paulo, Institute of Energy and Environment (IEE/USP), 1289 Prof. Luciano Gualberto Avenue, São Paulo, 05508-900, Brazil

[2] University of São Paulo, Luiz de Queiroz College of Agriculture (ESALQ/USP), Department of Soil Science, 11 Pádua Dias Avenue, Piracicaba, São Paulo, 13416-900, Brazil

[3] University of São Paulo, Center for Carbon Research in Tropical Agriculture (CCARBON), Piracicaba, São Paulo, Brazil

Abstract

The integration of food and energy production through agrivoltaic systems represents a promising strategy for enhancing land-use efficiency and promoting sustainable development. This study investigates soybean productivity within elevated and vertical agrivoltaic configurations in Piracicaba, Brazil, using simulations based on photosynthetically active radiation (PAR) and crop response curves derived from CO_2 assimilation under two hydric conditions: well-watered and drought-stressed. The analysis incorporated multiple structural layouts with variations in module height and row spacing to assess the influence of geometry on light distribution, energy generation, and crop yield. Results indicate that shading from the photovoltaic modules had minimal impact on soybean productivity during the growth season. Average agricultural productivity ranged from 62% to 84% of reference values, with losses primarily attributed to the terrain area covered by modules. Despite reduced photovoltaic generation, the combined system achieved Land Equivalent Ratios (LER) between 1.19 and 1.25 for both hydric conditions, demonstrating that the coexistence of soybean cultivation and solar generation enhances overall land-use efficiency by approximately 20% compared to conventional single-use systems. Vertical layouts exhibited particularly favorable results, maintaining over 82% crop productivity, suggesting that this configuration effectively balances shading and irradiance distribution. These findings reinforce the potential of agrivoltaic systems to synergize renewable energy generation with sustainable agricultural production in tropical regions.

Keywords: Soybean, photovoltaic solar energy, agrivoltaic, shading.

1. Introduction

By integrating photovoltaic technology with agricultural practices, Agri-PV enables the dual use of land, enhancing resource efficiency and promoting environmental sustainability. This synergy directly contributes to the advancement of several Sustainable Development Goals (SDGs), particularly those related to food security and clean energy. In Brazil, where soybean production represents one of the most important agricultural activities and the demand for renewable energy sources continues to grow, the adoption of agrivoltaic systems emerges as a viable strategy to mitigate land-use conflicts between agriculture and energy generation, aligning agricultural productivity with the broader objectives of sustainable energy transitions and climate resilience (Mehta and Zörner, 2025).

The variation in system geometry—particularly the row spacing—has a decisive influence on crop productivity and overall land-use efficiency. Wider spacings tend to enhance relative crop yield due to improved light penetration, whereas narrower configurations favor higher energy generation but intensify shading effects. These considerations emphasize the importance of precise PAR modeling and crop productivity assessment in Agri-PV design, as the optimization of structural parameters directly governs the balance between food and

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energy production efficiency (Berrian et al., 2025). In this context, the present study aims to contribute to a better understanding of the interaction between agricultural productivity and renewable energy generation by estimating the yield of soybean crops in the Agri-PV system, taking into account the shading effects caused by the photovoltaic modules. Furthermore, a comparative analysis was conducted to evaluate the variation in energy generation as a function of the Ground Coverage Ratio (GCR), considering different row spacings, heights, and module arrangements adapted to soybean cultivation. The remainder of the article presents the materials and methods, in section 2; the results and discussion, in section 3; and the final remarks, in section 4.

2. Materials and methods

The soybean crop productivity in an elevated agrivoltaic system was estimated based on the annual distribution of solar resources incident on the ground, converted to Photosynthetically Active Radiation (PAR), and associated with crop CO_2 assimilation curves. Accurate modeling of the Photosynthetically Active Radiation available to crops cultivated under agrivoltaic systems is fundamental for reliable yield estimation. In the literature, both finite View Factor and Ray Tracing approaches are commonly employed to simulate light distribution beneath photovoltaic modules, each offering different levels of computational complexity and spatial accuracy. In this paper, the ground between two consecutive PV rows is divided into ten portions, where the available solar resource and productivity are evaluated separately.

The adopted methodology is illustrated in Figure 1. Two crop conditions were considered—Well-Watered and Drought-Stressed—using the reference values provided by Zhang et al. (2011), as presented in Figure 2(a). Meteorological data for the year of 2023 were obtained from the National Solar Resource Database (NSRDB) for the city of Piracicaba, Brazil (22.72°S, 47.63°W).

The agrivoltaic configuration analyzed consists of 96 photovoltaic modules arranged in three rows. The module height and row spacing were selected to allow for intercropping with corn and to accommodate machinery passage, respectively. Based on common construction practices for photovoltaic plants, a Ground Coverage Ratio (GCR) of approximately 45% was adopted as the reference configuration, following Bolinger and Bolinger (2022). This standard configuration represents a conventional ground-mounted system, without elevation and without specific adaptation for agricultural integration, serving as a baseline for comparison.

To evaluate the influence of geometric parameters on the balance between energy generation and crop productivity, six distinct agrivoltaic configurations were simulated. These include systems with module heights of 2.5 m and 3.5 m, each evaluated at row spacings (pitch) of 9 m and 10 m, as well as two vertical systems with different pitches, presented in Figure 2(b). This discretization enables a detailed assessment of how height and spacing impact both solar irradiance distribution and soybean productivity in the inter-row area.

The main comparative metric among the systems is the estimated soybean production in the inter-row zones, where the interaction between light availability and shading from the photovoltaic modules plays a decisive role. Each geometric variable—height, spacing, and orientation—was selected to represent relevant structural scenarios in Agri-PV design, influencing factors such as photosynthetically active radiation (PAR) availability, machinery compatibility, and land-use efficiency.

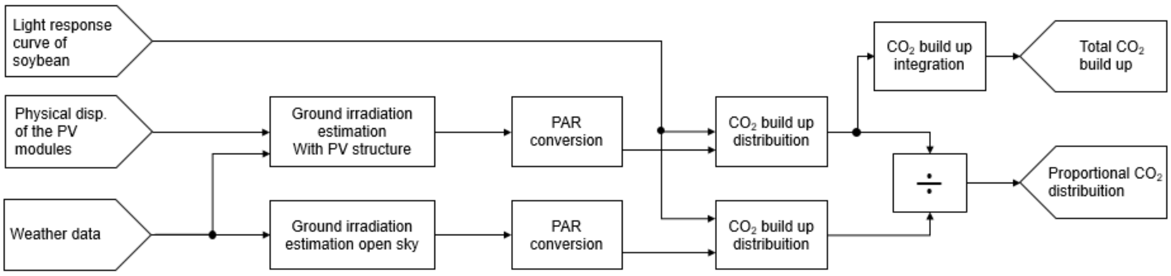
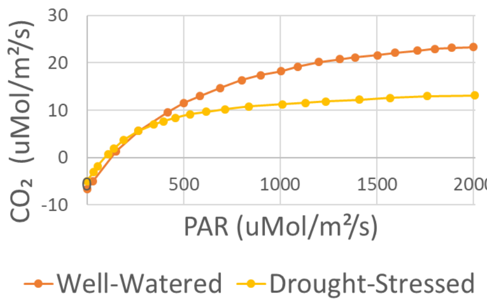


Figure 1: Overview of the methodology



(a)

System	Pitch (m)	Height (m)	Type
P9-H2.5	9	2.5	Fixed tilt
P9-H3.5	9	3.5	Fixed tilt
P10-H2.5	10	2.5	Fixed tilt
P10-H3.5	10	3.5	Fixed tilt
P9-V	9	X	Vertical
P10-V	10	X	Vertical

(b)

Figure 2: (a) Light response curve of the soybean (b) Layout variation of the simulated systems

3. Results

Figure 3 and Figure 4 show the total monthly irradiation for ten points (D) along the pitch, starting from the lower edge of the module, as well as the total irradiation for an unobstructed sky. All elevated systems showed similar ground PAR distribution. For instance, in Figure 3, corresponding to the P9-H2.5 system, it is observed that during the soybean cultivation months (from mid-September to January), the irradiation values along the row spacing are not significantly affected. This indicates that the elevated structure allows for a relatively uniform solar distribution on the ground during this period, maintaining satisfactory light availability for crop growth. During the winter months, however, there is a marked reduction in irradiation for points closer to the structure, mainly due to lower solar altitude and increased self-shading effects.

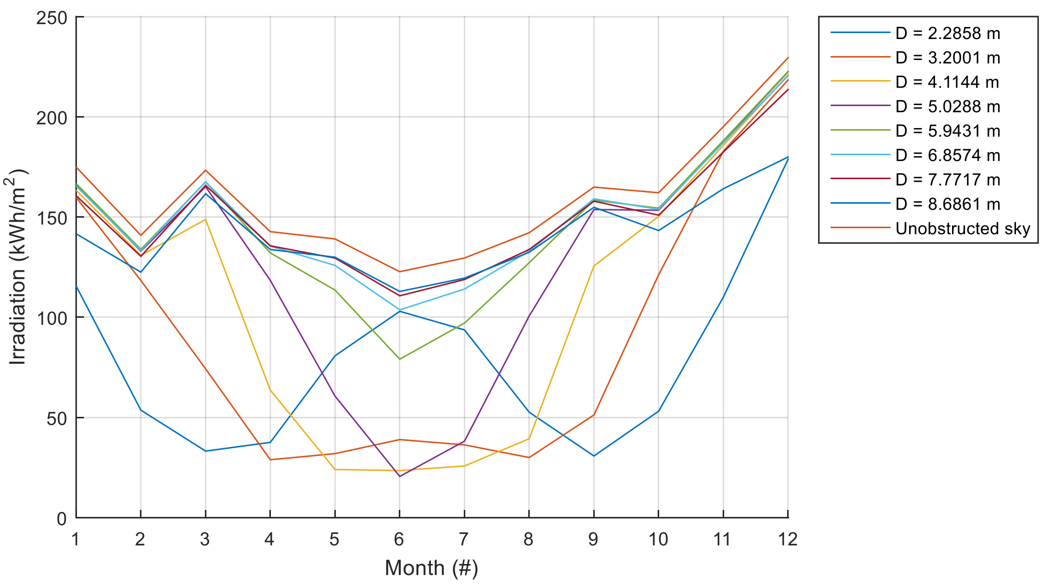


Figure 3: Irradiation distribution on the ground over the year for the system P9-H2.5

In contrast, vertical systems presented a smaller variation among the measured points throughout the year, indicating a more homogeneous distribution of light on the ground. For example, Figure 4 refers to the P9-V system, where it is noticeable that the evaluated points along the row spacing present great similarity with that of the unobstructed sky. These configurations tend to minimize seasonal fluctuations, which may impact crop productivity depending on the light requirements of the cultivated species.

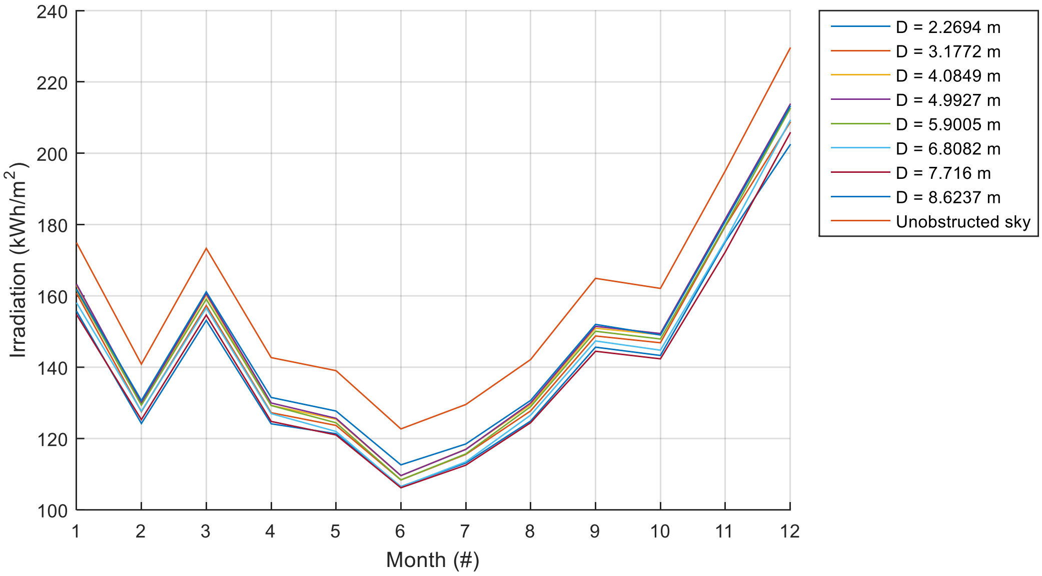


Figure 4: Irradiation distribution on the ground over the year for system P9-V

Figure 5 illustrates the relative productivity ratios based on CO_2 assimilation for drought-stressed and well-watered soybean crops across the different zones beneath each system configuration. It can be observed that, for the elevated systems (P9-H2.5, P9-H3.5, P10-H2.5, and P10-H3.5), productivity tends to be more variable along the row spacing, reflecting the heterogeneity of light distribution caused by the inclined module structure. The central regions, which receive more uniform and diffuse light, generally maintain higher yields, whereas the zones closer to the support structures exhibit slight reductions due to partial shading.

In contrast, the vertical systems (P9-V and P10-V) present a more homogeneous productivity pattern across the ground profile, consistent with the more uniform irradiation distribution observed in Figure 4. Although the central zones under inclined configurations reach the highest local productivity values, the overall production of the vertical systems surpasses that of the elevated systems, as the vertical arrangement provides a more balanced light environment throughout the crop area. This uniformity mitigates excessive shading and light saturation effects, leading to greater total yield when considering the entire cultivated surface. These findings highlight the significance of system geometry in balancing the trade-off between energy generation and agricultural productivity in agrivoltaic applications.

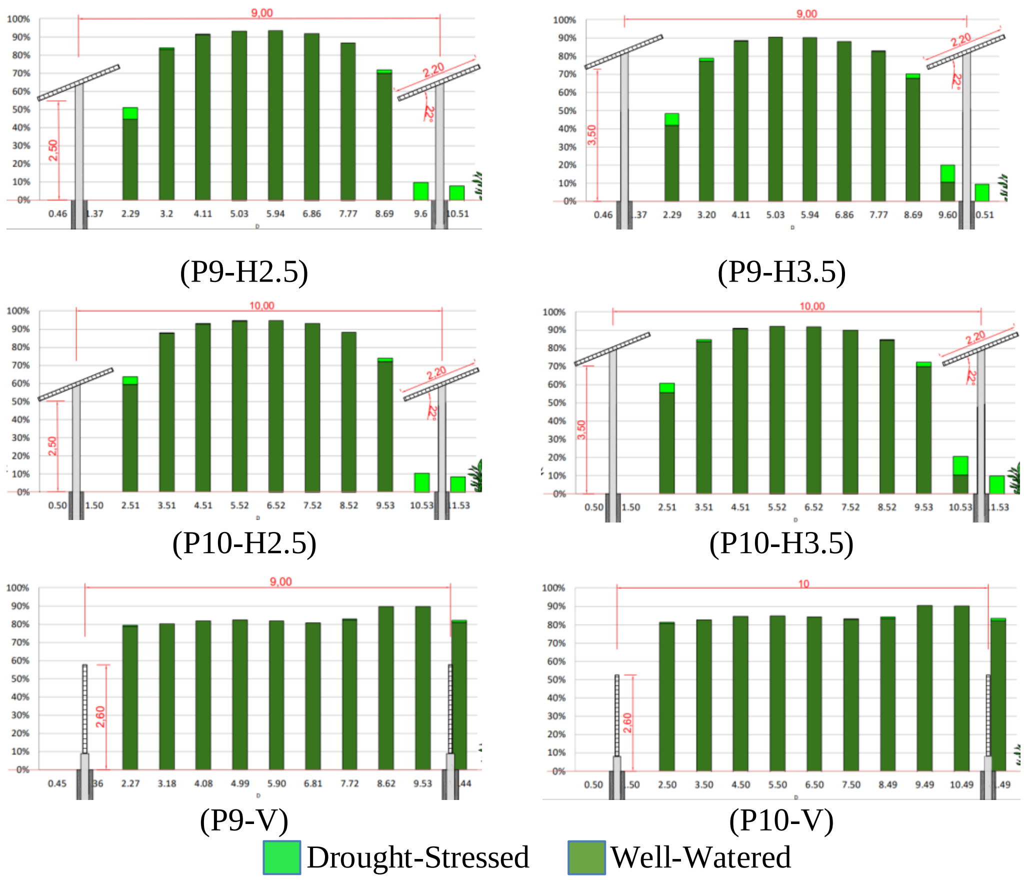


Figure 5: Relative productivity based on CO_2 assimilation over the soybean period for Well-Watered and Drought-Stressed cases along pitch distance in each system.

Figure 6 (a) and (b) show the results for the Well-Watered and Drought-Stressed scenarios in system P9-H2.5, respectively. As the methodology mentions, relative productivity is calculated considering a scenario without the photovoltaic system, using soybean grown in an open-field reference as the baseline. The figures indicate that during the soybean planting period, which lasts 120 days starting on day 274, the productivity in the row spacing does not appear to be significantly affected by the presence of the photovoltaic modules. This was expected due to the characteristics of the Sun-Earth movement at the mentioned latitude. It is noted that, during this period, the midday sun has an elevation close to 90°, which prevents the modules from casting significant shadows over the row spacing.

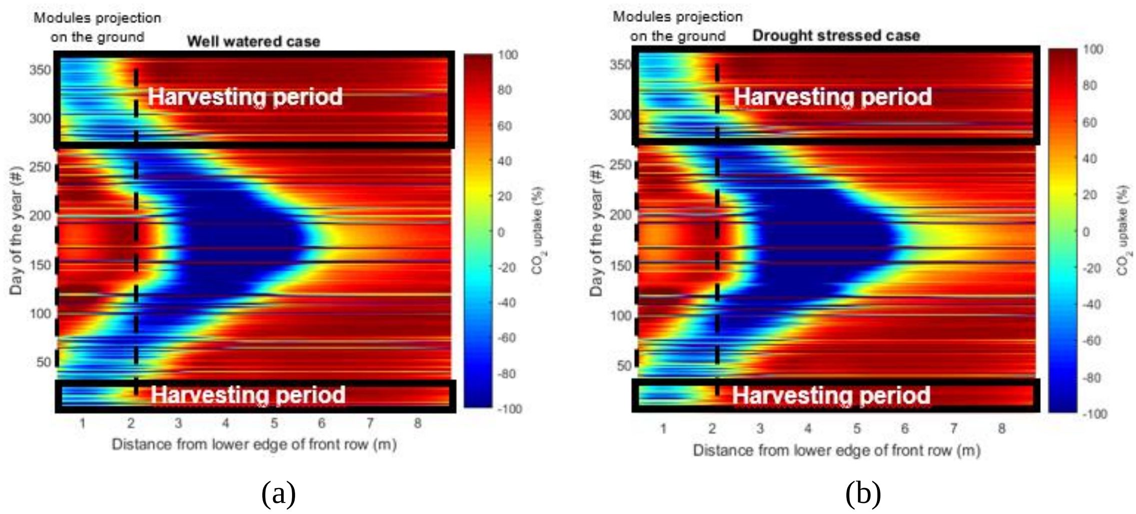


Figure 6: Relative CO_2 uptake over the year for (a) Well-Watered case and (b) Drought-Stressed case in P9-H2.5

Total soybean productivity over the 120 days was 62%-84% and 64%-84% of the reference productivity for the Well-Watered and Drought-Stressed cases, respectively, with most of the losses caused by the loss of useful terrain. The productivity of the photovoltaic system, relative to a conventional ground-mounted configuration, was evaluated across six layout variations, as illustrated in Table 1. The energy generation efficiency of the Agri-PV configurations, expressed as the generation fraction relative to the reference system, varies according to their structural design and shading conditions. Systems P9-H2.5 and P9-H3.5 achieve approximately 56–57% of the reference generation, systems P10-H2.5 and P10-H3.5 reach around 51%, while the vertically oriented systems produce about 38–42%. Based on these simulation results, the Land Equivalent Ratio (LER) was calculated, yielding values of 1.19 to 1.25 and 1.21 to 1.24 for the Well-Watered and Drought-Stressed scenarios, respectively, as shown in Figure 7. These findings indicate that, despite the reduction in photovoltaic yield, the combined land-use efficiency of the Agri-PV system surpasses that of conventional single-use systems, reinforcing its potential for sustainable energy–food integration.

Table 1: Summary of the results for the analyzed systems

				Drought-Stressed		Well-Watered	
System	GWh/ha	Generation Fraction	GCR	Prod.Agri.	LER	Prod.Agri.	LER
Standard	2.08	100%	0.45	0.00%	1.000	0.00%	1.000
P9-H2.5	1.18	56.85%	0.25	64.78%	1.216	62.16%	1.190
P9-H3.5	1.19	57.06%	0.25	65.24%	1.223	62.31%	1.194
P10-H2.5	1.07	51.23%	0.23	68.10%	1.193	65.61%	1.168
P10-H3.5	1.07	51.45%	0.23	68.82%	1.203	65.99%	1.174
P9-V	0.88	42.34%	0.12	82.29%	1.246	82.81%	1.252
P10-V	0.79	38.15%	0.11	84.11%	1.223	84.55%	1.227

The analysis reveals that system geometry has a strong influence on the modules shows that system geometry strongly influences light distribution and crop performance. Lower layouts exhibited reduced productivity under the central module zones due to increased shading, while greater heights and wider spacings promoted more homogeneous light penetration and improved yield uniformity. Among the elevated systems, the 3.5 m configurations demonstrated the best balance between shading and light diffusion. The vertical layouts, in turn, provided the highest and most uniform productivity across the terrain, as the absence of continuous shading allowed greater diffuse radiation to reach the crops.

The relationship between crop productivity and Ground Coverage Ratio (GCR) in agrivoltaic (Agri-PV) systems has been consistently demonstrated across multiple studies. Experiments involving soybean cultivation under Agri-PV conditions have reported GCR values ranging from 0.14 to 0.32. These findings align with the general trend described by Dupraz (2024), in which crop relative yields tend to decrease sharply as GCR increases, particularly beyond 25%. For soybeans, moderate GCR configurations (approximately 0.14–0.25) are typically associated with relative yields above 80%, indicating a balanced coexistence between energy generation and crop performance. Conversely, higher GCR values (>0.30) tend to impose excessive shading, leading to more pronounced reductions in photosynthetic activity and yield potential. This relationship highlights the importance of optimizing the structural design of Agri-PV systems, such as module height, tilt, and spacing, to maintain an adequate light distribution that preserves crop productivity while maximizing solar energy output. (Potenza et al, 2022), (Jo et al, 2022), (Kim et al, 2021), (Lee et al, 2022)

The results obtained in this study follow the same trend. Systems with lower GCR values, particularly the vertical configurations, achieved the highest agricultural productivity, exceeding 82% under both hydric conditions. The intermediate configurations—with GCR values between 0.23 and 0.25—showed moderate relative productivity (55–69%), indicating that increased row spacing effectively improves light distribution across the inter-row area. Differences between module heights (2.5 m and 3.5 m) were minor, suggesting that while elevation facilitates agricultural integration, the spacing and resulting GCR exert a stronger influence on crop yield. Overall, these findings reinforce that GCR remains a key design variable in Agri-PV systems, governing the trade-off between shading, light availability, and agricultural productivity.

4. Conclusion

The comparative analysis of the simulated configurations reveals a strong inverse relationship between the GCR and both the agricultural productivity and the overall land-use efficiency. As the GCR decreases, the shading on the crop canopy becomes less restrictive, resulting in higher agricultural yields and consequently higher LER values. This pattern was particularly evident in the vertical configurations, which, despite producing only around 40% of the reference energy generation, achieved the highest combined efficiencies, with LER values reaching 1.25 under Well-Watered conditions and 1.24 under Drought-Stressed conditions. These results indicate that reduced GCR configurations promote a better balance between agricultural and photovoltaic productivity, maximizing the total land-use efficiency.

A notable outcome is the high performance of vertical systems. Even with a significant reduction in annual energy generation (less than 0.9 GWh/ha), these layouts maintained agricultural productivity above 82%, resulting in LER values comparable to or superior to elevated configurations. This finding suggests that vertical Agri-PV systems can be particularly advantageous in scenarios where crop preservation, diffuse light distribution, and low structural shading are priorities. Conversely, conventional elevated systems demonstrated a clearer trade-off between power output and crop yield, showing that moderate spacings (9–10 m) and higher elevations (3.5 m) can still provide synergistic outcomes, with LER values ranging from 1.19 to 1.22.

A comparison between the two hydric conditions reveals an interesting shift in relative performance among the systems. Although the well-watered (WW) condition consistently resulted in higher absolute agricultural productivity, the drought-stressed (DS) condition exhibited a smaller reduction in productivity compared to open-sky conditions under moderate GCR configurations. This suggests that partial shading may have mitigated water stress, reducing the relative yield loss in DS systems. Conversely, in the vertical configurations, where crops received greater solar exposure, the WW condition outperformed DS by a larger margin, demonstrating that increased light availability enhances productivity when water is not a limiting factor. This behavior underscores the combined influence of shading intensity and hydric status on the overall balance between agricultural and photovoltaic performance.

Overall, the results confirm that adjusting height, spacing, and geometry is crucial for optimizing the coexistence between photovoltaic generation and agricultural productivity in agrivoltaic systems.

5. Acknowledgments

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