AgriVoltaics World Conference 2022
Agrivoltaic Systems
https://doi.org/10.52825/agripv.v1i.1036

Published: 06 Feb. 2024

A Case Study of Soybean (Glycine max L.) Under Agrivoltaic System and Modelling Simulation

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Abstract. Agrivoltaic systems (AVs) combine agricultural activities with the electricity production from photovoltaic (PV) panels constructed on the same area of land. Goetzberger and Zastrow[1] (1982) introduced the concept of AV but only more recently the increased environmental concerns and the economic and political frameworks have stimulated a growing interest in this technology. A critical issue, hampering the development of AVs, is the selection and cultivation of species adapted to the micrometeorological conditions generated by AV. This study reports on physiological, morphological and yield data of a soybean crop grown under AV. In addition, field data were compared with results from a simulation carried out with the modelling platform developed by Amaducci et al., 2018. Morphological and physiological and yield response of tomato and potato under Agrivoltaico® system parameters influenced by growth under AV were height, LAI and SLA, which were higher under AV than in normal "full light" (FL) conditions. Number of pods per plant decreased by 13% under AV compared to FL conditions while mean grain yield was reduced by 8%, only in one AV area was observed a slightly increase (+4.4%) in grain yield. The results on RMSE revealed that the model error was higher in two AV conditions compared to the other 3 treatments.

Keywords: Soybean, Agrivoltaic System, Modelling

1. Introduction

The main driver of the current interest in agrivoltaic systems (AV) is the development of sustainable renewable energies that have a low impact on soil consumption. The sustainable implementation of AV systems should therefore ensure that crop yield is not severely affected by shading. In fact, AV affects micro-meteorological conditions in particular reducing solar radiation. In general, information on industrial crops performance under AV system is scarce, and in particular no information is available on soybean (*Glycine max* L.). Soybean is an important source of food, protein, and oil, and it is a leguminous crop that has an important role in sustainable crop rotations. To evaluate how soybean responds to the cultivation under AV conditions is therefore relevant as this could be a sustainable option for AV crop rotations.

Objectives of this research were:

•To study the physiological and morphological response and yield potential of soybean cultivated under an Agrovoltaico® system;

•To validate the performance of a simulation platform developed for AV systems to predict the radiation environment and relative crop response.

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2. Data collection, experimental set-up and statistical analysis

The study was carried out in an AV plant (Remtec, Agrovoltaico®) in Monticelli d'Ongina (Italy, 45°04'10''N - 9°55'40''E) in which PV panels are stilt mounted on a bi-axial sun-tracking system. A soybean (*Glycine max* L.) crop, variety Namaste (Venturoli, maturity group 1/1+) was sown on 29th of April 2021. The experimental set-up included a "full light" area (FL, control, 180 m^2) located just outside the AV system and 8 experimental areas (Fig.1) characterized by 4 different shade depth (Formula 1) replicated 2 times: AV1=27%, AV2=16%, AV3=9% and AV4=18%. Each area included 4 soybean rows for a total of 16 rows and an area of 144 m^2 for single replicate. Soybean was fully subirrigated during the whole crop growth cycle.

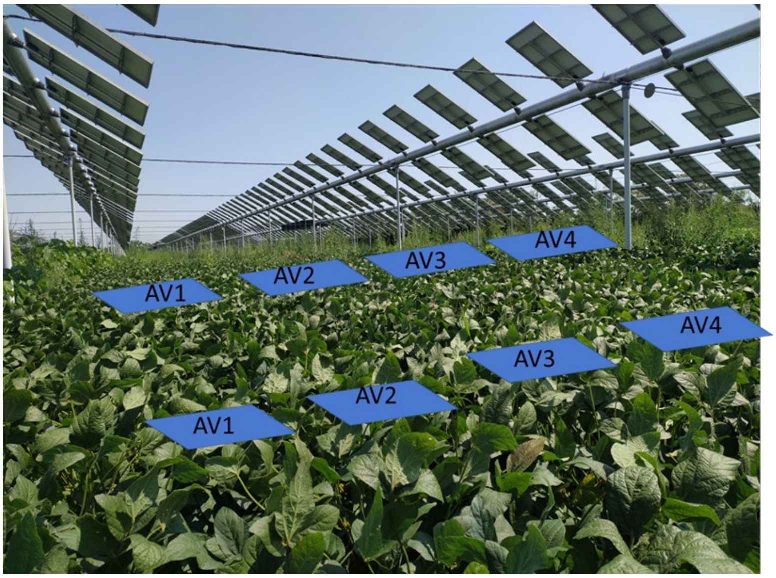

Figure 1 Experimental set-up of the soybean trial in Monticelli D'ongina

Data collected during the crop cycle was crop height, chlorophyll content expressed as SPAD, LAI (Leaf Area Index), SLA (Specific Leaf Area,cm^2 gr^{-1}), pods number, fresh and dry weight of the pods and grain yield.

3. Simulations

Simulations were performed with an updated version of the modelling platform described in Amaducci et al. (2018)[2]. The system couples a crop growth model (GECROS [3]) to a set of algorithms for the estimation and spatialization of shading, radiation, and crop related outputs. The crop model GECROS forecasts crop biomass and yield as affected by radiation vaport pressure, temperature and wind speed and available amount of nitrogen and soil water. Furthermore, GECROS includes the crop responses of physiological and morphological processes to environmental variables. Simulations were conducted on a 12m x 12m test area covering all shading conditions of the AV system used and the radiation mapping was calculated on cells with 30 min time step. Calculations were iterated in the test area on cells of size 0.5m x 0.5m allowing mapping of results. In this work we have examined the mapped values of the seasonal radiation reduction (Fig.2) and the grain yield compute as mean values of the pixel-plots (size 0.5m) contained in the experimental plots (1.5m x 1m).

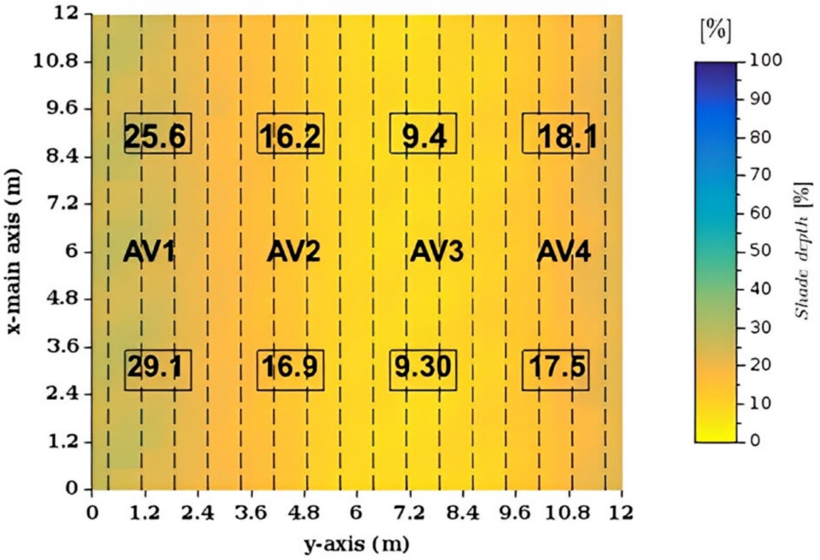

Figure 2 Radiation map: mapped values of radiation reduction "Shade Depth (%)". The vertical dotted lines represent crop rows and the boxes represent the plots positioning and size.

4. Shade depth

The Shade Depth (SD) indicates the percentage reduction of global radiation compared to full light calculated as:

$$SD\ (i,j) = 100^{*}\ [(I_{FL} - I(i,j)_{AV})\ ^{*}\ I_{FL-1}] \qquad (1.1)$$

Where IFL is the Cumulated radiation in full light:

$$I_{FL} = \int_{t_{start}}^{t_{end}} g_{FL}(t)dt \qquad (1.2)$$

and I(I, J) is the cumulated radiation in a portion I,j of the AV area:

$$I(i,j) = \int_{t_{start}}^{t_{end}} g(i,j)(t)dt \qquad (1.3)$$

5. Statistical analysis

Statistical analysis was performed using Rstudio, R version 4.2.1 (R Core Team, 2022). The statistical analysis of the physiological and morphological traits of the crop was carried out using two-way ANOVA to identify statistically significant differences among the experimental factors shading levels (FL, AV1, AV2, AV3, AV4) and time (dates) for the variables considered. One-way ANOVA was carried out for crop yield data. The ANOVA test was followed by the post hoc Tukey's Honestly Significant Difference test. Simulation data were analysed through Root Mean Square Errors (RMSE) and Normalised RMSE (nRMSE, %) to measure the differences between simulated and observed values of soybean grain yield.

6. Results

Grain yield and main crop parameters were significantly affected by shade depth (Figure 3, 4 and Table 1). In particular, average plant height (cm), measured during the whole growing cycle, of AV1 plants was significantly higher (p-value <0.05) than FL plants and all other AV treatments (Table 1), which indicated that only the most severe conditions of shade depth significantly affected stem elongation. Differences in chlorophyl content among treatments were very limited and apparently not directly related to shading depth (Table 1).

Table 1. Mean values of crop height and SPAD, and Tukey's HSD letters.

TRT	Shade depth % (SD)	Height (cm)		SPAD	
FL	0%	87.80	bc	43.58	a
AV1	27%	98.25	a	43.41	a
AV2	16%	86.95	bc	41.87	b
AV3	9%	85.04	c	42.87	ab
AV4	18%	90.81	b	42.33	ab

Mean LAI at FL (2.78) was significantly lower (p-value < 0.05, Figure 3A) than at AV1 (3.63). LAI of the other 3 shading levels were not different from that of FL, which indicates that also this important trait was only affected at the highest shading depth. This is also confirmed by SLA, which increased by 9% (213.3 cm^2 gr^{-1}) under AV1 compared to FL conditions (198 cm^2 gr^{-1}) m even though this difference, was not statistically significant (Figure 3B, p-value ≥ 0.05).

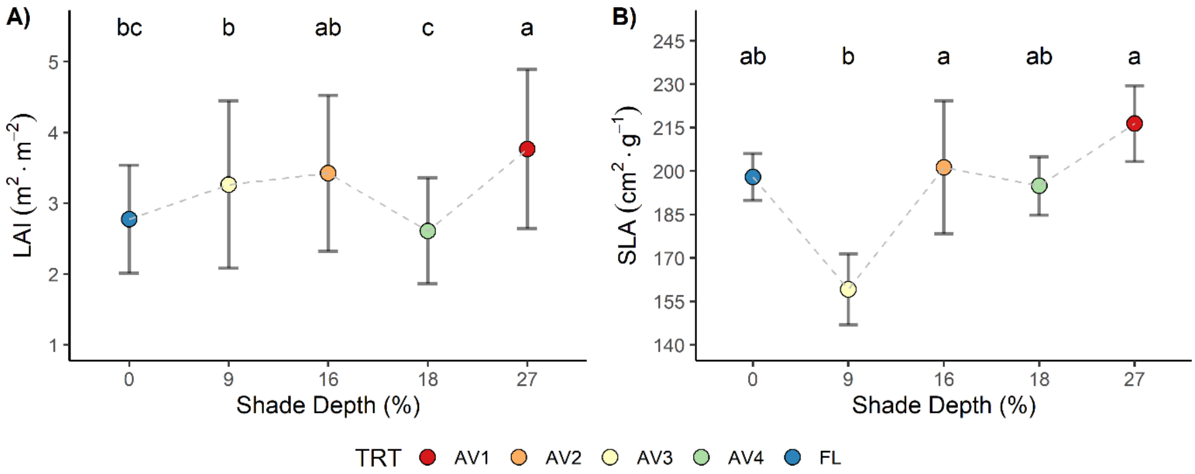

Figure 3 Mean value of LAI and SLA of soybean during the whole crop growth cycle and Tukey's HSD letters

Mean pods number per unit surface in FL was 2461 and it was reduced by 19.4% (1983), 3.3% (2379), 11.5% (2177) and 18.2% (2011), respectively under AV1, AV2, AV3 and AV4 (figure 4). The mean reduction was 13% for the whole total AV system. The grain yield reductions compared to FL were 8% (614.79 gr m^{-2}), 4.6% (636.80 gr m^{-2}), and 11.8% (588.81 gr m^{-2}) respectively for treatments AV1, AV3 and AV4, while for AV2, a slightly increase (+4.4%, 697.36 gr m^{-2}) was observed (Figure 4). Considering the bulk of AV treatments, the mean yield reductions compared to FL of pods fresh and dry weight, were respectively 5.9% and 6.6%.

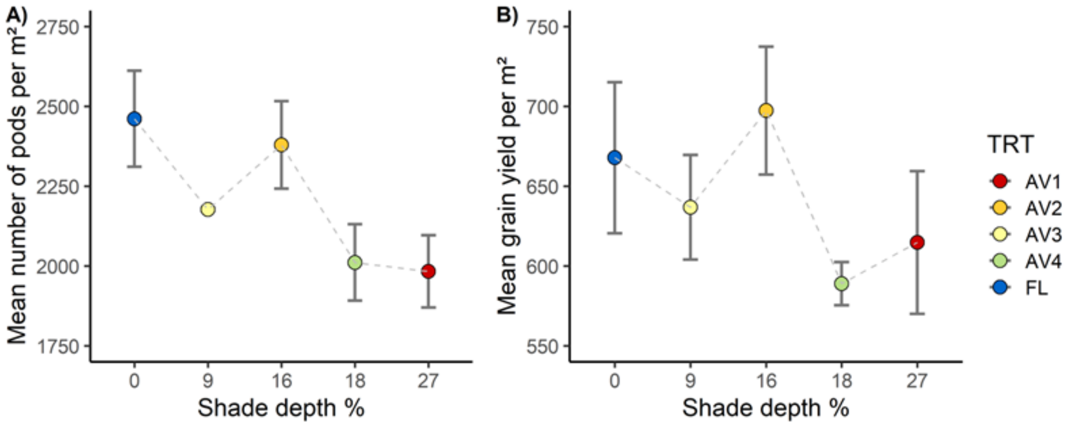

Figure 4 Observed mean number of pods per square meter and observed mean of grain yield (gr cm^{-2})

The normalized root means square error (NRMSE) value of predicted grain yield differs from the observed grain values of 12.9% for FL conditions, 15.7% in AV1, 16.5% in AV2, 6.71% in AV3, 2.82% in AV4. The results on RMSE revealed that the model error was higher in AV2 and AV1 condition (>15% NRMSE) compared to the other 3 treatments (Table 2).

Table 2. Root mean square error value (RMSE) and Normalized RMSE mean between simulated and observed grain yield (gr m^{-2}).

TRT	Shade depth % (SD)	RMSE	NRMSE mean
FL	0%	86.2	12.9%
AV1	27%	96.3	15.7%
AV2	16%	115.0	16.5%
AV3	9%	42.7	6.71%
AV4	18%	16.6	2.82%

The simulation system, despite being in a preliminary stage of calibration for soybeans, showed a good correspondence between observed and simulated values (Figure 5).

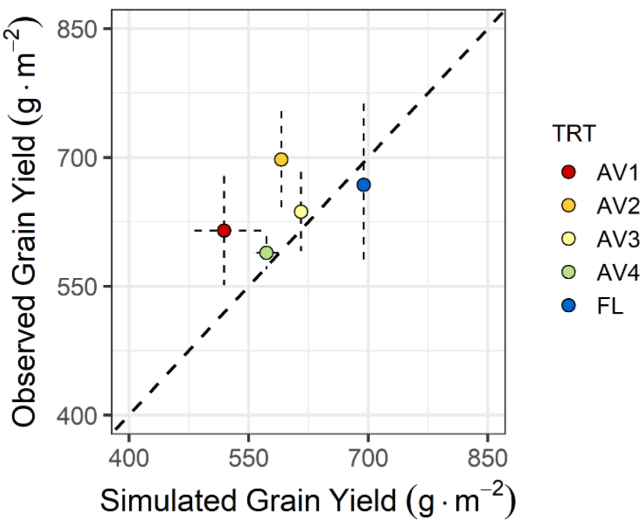

Figure 5 RMSE between observed and simulated grain yield (gr m^{-2}) per different Shade Depth treatments.

7. Conclusions

In this work yield responses, the physiological and morphological traits of soybean (*Glycine max* L.) growing under agrivoltaic system was investigated both by field data and model simulated results. The main morphological and physiological traits that increased significantly under the most shaded levels under AV system were plant height, leaf area index and specific leaf area. The soybean plasticity was confirmed by the observed results under AV system in fact, soybean tends to improve the capability to capture light by increasing leaf area (both for LAI and SLA) and by increasing stem elongation. Soybean showed a reduction in pod number as shade depth level increases under the AV system. The average yield reduction for the whole agrivoltaic system was 8% which suggests that soybean was able to have a satisfactory yield response under the AV system.

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

Author contributions

E.P.: conceptualisation, investigation, data curation, methodology, formal analysis, original draft preparation; M.C.: conceptualisation, software, review and editing; S.A.: conceptualization, review and editing. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare that they have no competing interests.

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