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Measurement of Light Interception by Crops under Solar Panels using PARbars

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Abstract. To analyse agrivoltaics systems and understand crop responses to shading, measurements of available light for the crop and light interception by the crop are important. Especially in row crops, there is a lot of variation in the amount of light at different heights, different positions relative to the row and over time. This spatial and temporal variation in light is difficult to capture with standard point measurement technology. Commercially available line quantum sensors are not long enough to cover the desired width within an agrivoltaics system and come at high cost. Therefore, custom made PARbars were used: bars of 1.5 m long having light sensors every 5 cm facing the sky and giving a total (line) irradiance value per time step. PARbars were installed above and below a raspberry crop row in both the agrivoltaics system and the control with a plastic foil cover, and a point sensor was installed in the open field. The difference between open field radiation and the top PARbar gives the light interception by the panel construction or the foil cover, the difference between the top and bottom PARbar gives the light interception by the crop. This information can be used in conjunction with destructive crop measurements to analyse impacts on leaf area and light interception, dry matter production and derived efficiency of photosynthesis. The crop in the current agrivoltaics system received half of the amount of light compared to the control system, but total biomass production was less reduced because of compensation by increasing specific leaf area and photosynthesis efficiency. Further analysis is needed to evaluate the agrivoltaics system and the impact of increasing shade on the crop, and to assess the trade-off between electricity production and crop production.

Keywords: Agrivoltaics, Raspberry, Photosynthesis

1. Introduction

In agrivoltaics systems, sunlight is used both by solar panels for electricity production and by crops for production of plant products. There can be synergy in the combination of crops with solar panels, e.g. when adverse conditions are relieved by the presence of the panels, but often there will be a trade-off between electricity yield and crop yield. To explore these synergies and trade-offs and to design best fitted agrivoltaics systems for specified conditions, two types of models can be combined that 1) describe radiation interception and electricity production by the solar panels and 2) describe crop production under the remaining light [1].

Crop growth and biomass production are determined by the amount of light that is intercepted by the canopy and used for photosynthesis. Light interception is therefore an important part of crop growth models [2]. Crops may adapt to shading by increasing stem elongation and leaf area and reducing leaf thickness in order to intercept a larger fraction of incoming radiation. Knowledge of these crop responses to shading is needed and can be gained by actual measurements on crops growing at different light levels. In addition to (non) destructive measurements such as stem length, specific leaf area (m^2/kg dry matter), total leaf area and biomass of various plant organs, light interception by the crop can be measured. Especially in row crops, there is a lot of variation in the amount of light at different heights, different positions relative to the row, and over time. With agrivoltaics, additional variation in light is introduced by the shade of the panels. In these situations, point measurements give an incomplete representation of light conditions for the crop and of light interception by the crop. Instead, line quantum sensors can be used that measure PAR integrated over their length. However, line sensors that are currently available on the market have a limited length and come at high cost. An alternative option is to use custom made line sensors (PARbars) for which detailed building instructions are available [3].The use of long PARbars and continuous logging can help in accurate measurement of the amount of light above and under a crop, and thus calculate the amount of light intercepted by the crop, at moderate costs.

The aim of this paper is to (a) describe the PARbar system that is applied in the Sunbiose project [www.sunbiose.nl] for continuous measurement of light interception by row crops under solar panels or under plastic foil, and (b) to illustrate the use of these light measurements in analysis of yield formation.

2. Materials and methods

2.1 Experiment description

Measurements were carried out at a commercial farm in Babberich (51°54’ N) that produces raspberries both in a conventional commercial production system under plastic rain cover and in an agrivoltaics system with solar panels as rain protection. The 3.2 ha agrivoltaics system was built in 2020 and has rows of 2 m wide panels above each plant row, alternately tilted to the east or west [4]. Plant row spacing is 2.6 m, and the gaps between the panel rows were closed with shading nets. The glass panels have solar cells at 60% of their surface and diffusive glass at the remaining 40%. The reference system has a plastic cover over the individual rows on a wooden support system, supplemented with shading nets above the grass alleyway in between the raspberry rows. The raspberry crop was planted March 2022 using cool stored 2 m-long canes cv. Lagorai (grown in a conventional system in the previous year), 2 plants per pot and 2 pots per running meter. Crops were irrigated and fertilized by drip irrigation. In both systems, rainwater drained into the alleyways.

2.2 Light measurements

Linear arrays of light sensors (PARbars) were built according to instructions by [3]. Light sensors measuring photosynthetically active radiation (PAR; 390-700 nm) were placed 5 cm apart in 1.5 m long aluminium bars. The sensors were connected in parallel to give one integrated signal per PARbar that was recorded by a data logger. For use in the raspberry crop, 20 cm of the PARbars was taped off to match with the row distance of 2.6 m. PARbars were calibrated against a Licor quantum sensor to translate the signal into a PAR value.

A carrying construction was designed to install the PARbars at two heights: 1) above the crop, below the solar panels, and 2) below the crop (Fig. 1). The construction consisted of two poles that slide into each other to adjust the height (Fig 2). A ball head allowed careful installation of the PARbar to place it horizontally in two directions, supported by two levels. The lower PARbar construction allowed for turning away the PARbar from the alley when machinery needed to pass (Fig. 3). Four PARbars covered the entire width of the system, starting and ending in the middle between two rows (Fig. 1). Incoming PAR radiation was measured with a sensor placed at 5 m height in the open field next to the agrivoltaics system.

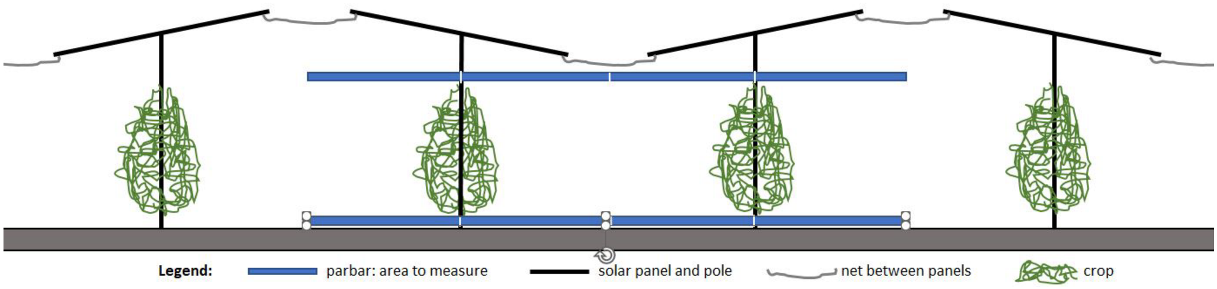

Figure 1. Schematic representation of PARbar locations in raspberry agrivoltaics. Rows are oriented north-south, so panels are facing east and west.

Figure 2. Details of the carrying construction of the PARbars.

2.3 Analysis of yield formation

Light interception by the panels or plastic cover was calculated as the difference between incoming light and the top PARbar. Light interception by the crop was calculated as the difference between the top PARbar and the bottom PARbar.

Crop measurements consisted of total biomass (g/m^2), leaf weight (g/m^2), leaf area (m^2/m^2) and cumulative fruit weight (g/m^2). Fruit weight was the sum of pickings between June 29 and July 20, 2022. Samples for assessment of total biomass and leaf area were taken on July 20. The specific leaf area (cm^2/g) was calculated from leaf weight and leaf area.

For the analysis of yield formation a simple equation was used that calculates biomass production based on light interception and light use efficiency (equation 1):

$$\text{Total biomass} = \text{intercepted radiation (PAR)} \times \text{light use efficiency} \quad (1)$$

Yield formation was analysed by comparing agrivoltaics with the reference under plastic for crop light availability, light interception by the crop, leaf weight, specific leaf area, total crop dry matter and light use efficiency as calculated with Eq. 1.

3. Results

3.1 Costs to build the PARbars

Costs to build the PARbars consisted of material costs and time. A total of 18 PARbars of 1.5 m length were made, together with a carrying construction for placement in the field. Total material costs per PARbar were about €200,- (Table 1). In addition, there were labour costs to design and build the system, and to calibrate the PARbars before use. The construction of the system is a single action, calibration needs to be carried out regularly. Commercially available point sensors in The Netherlands range in price between €500 to €1000, while a line sensor costs several thousand euros.

Table 1. Cost overview of building 18 PARbars.

Category	**Cost (ex VAT)**
Sensors (€1,- per sensor, 30 sensors/PARbar)	€ 540
Data loggers (2 channels/logger: 9 loggers	€ 1755
Other costs (aluminium u-tube, wire, resistor)	€ 360
PARbar holders	€ 1000
Total costs	€ 3655 (about 200 per PARbar)
Time for development and realization	~70 hours
Time for PARbar calibration incl. data analysis	~30 hours

3.2 Installation of the PARbars and light measurements

PARbars were installed in spring 2022 in the agrivoltaics system and in the control under plastic (Fig. 3). Results for a single fully sunny day are given in Fig. 4. The agrivoltaics system intercepted more light compared to the control under plastic, resulting in less light for the crop in the agrivoltaics system as measured with the top PARbar.

Figure 3. Left: PARbars above and below raspberry in agrivoltaics.
Right: raspberry control under plastic. The lower PARbar can be moved to a position parallel to the row for traffic to pass.

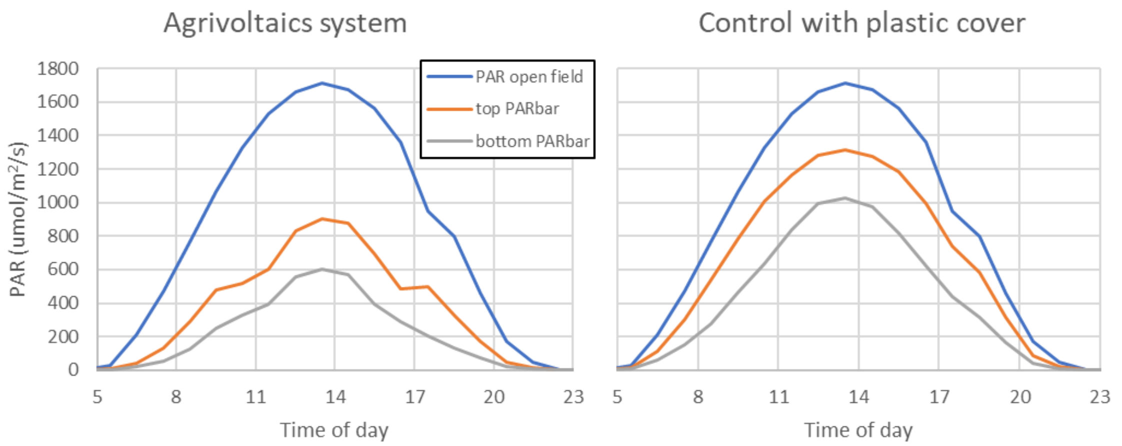

Figure 4. PAR measured on a fully sunny day (June 15) in the agrivoltaics system (left) and in the raspberry control under plastic (right).

3.3 Analysis of yield formation

The combination of light measurements with measurements on the crop can help to understand crop responses to differences in available light. Table 2 shows results for the agrivoltaics system relative to the reference under plastic foil. The transparency of the solar panels was lower than the plastic foil, and the amount of available light for the crop under the solar panels was half of that under the plastic foil. The reduction in light interception by the crop under the panels was relatively smaller, which could be explained by an increased leaf area under the panels. Leaf area increased because of an increased specific leaf area, as total leaf weight was smaller under the panels compared to the plastic. The reduction in total crop dry matter under the panels was again relatively smaller than the reduction in light interception, which can be explained by an increased light use efficiency under increasing shade [5]. Within the Sunbiose project, this analysis will be quantified and described in more detail in upcoming reports, also including financial aspects and the trade-off between electricity production and crop production.

Table 2. Comparison of the agrivoltaics system with the reference under plastic foil for a number of parameters of yield formation (relative differences).

	Reference	**Agrivoltaics**
Available light for the crop	1.00	0.50
Intercepted light by the crop	1.00	0.57
Leaf area	1.00	1.05
Leaf weight	1.00	0.85
Specific leaf area (area/weight)	1.00	1.23
Total crop dry matter	1.00	0.88
Calculated photosynthesis efficiency	1.00	1.55

Data availability statement

This paper describes the construction of PARbars and the methodology to use them. Data collected with this system are no part of this paper but will be part of future publications within the Sunbiose project.

Author contributions

FdR: Conceptualization, Methodology, Writing – original draft. BM: Conceptualization, Methodology, Writing – review & editing. EJJM: Investigation, MIH: Methodology, Writing – review & editing. HHMH: Methodology, Writing – review & editing.

Competing interests

The authors declare no competing interests.

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