AgriVoltaics World Conference 2023
System Accessment and Performance Indicator
https://doi.org/10.52825/agripv.v2i.1033

Effects of Agrivoltaics on the Microclimate in Horticulture

Enhancing Resilience of Agriculture in Semi-Arid Zones

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Abstract. Chilean agriculture must adapt to climate change as droughts are already affecting the country and water availability is expected to further decline. In this context, Agrivoltaics (AV) systems, that install photovoltaic (PV) panels over crops and thus provide shading and an altered microclimate could enhance the resilience of agriculture in semi-arid zones. We compare data measured under an AV system with a reference measurement to quantify the effects of AV on microclimate in horticulture in the Metropolitan Region of Santiago, Chile. Data on irradiation, air temperature, air humidity, and wind speed allow us to compute potential evapotranspiration (PET). We observe a reduction of Global Horizontal Irradiation (GHI) under the AV system of 42%. Mainly, as a result of the decreased GHI, we derive a diminution in PET of 31%, quantifying the potential to lower the water demand of crops and thus irrigation. Measured soil moisture is on average 29% higher under the AV system compared to the reference condition, hence validating PET computations. Also, we find a more moderate climate with slightly stabilized air temperature and lower soil temperatures. Our results give a glimpse of the effects of installing PV panels over horticulture crops concerning the challenges of Chilean agriculture. AV systems have the potential to increase water availability by lowering irrigation demand and protecting crops from the effects of extreme irradiation, such as sunburn and heat stress. Thus, AV could foster the transformation of agriculture towards sustainable production systems. The documented effects should be verified over longer periods with different crops to understand the impact of AV within seasonal and interannual climatical variation and the diversity of Chilean agriculture.

Keywords: Agrivoltaics Microclimate, Evapotranspiration, Climate Change Adaption

1. Introduction

Chile is the only South American country categorized with "high water stress" by the World Resource Institute [1]. Precipitation at the national level has decreased at a rate of 8% per decade over the last 41 years, with the period between 2010 and 2019 being classified as a mega-drought in the central zone of Chile with rainfall deficits of 30% [2]. Water scarcity is directly impacting agriculture, which accounts for 88% of the freshwater consumption in the country [3].

Apart from water shortages, agriculture has to deal with crop losses because of heat stress and sunburns, due to excessive solar irradiation, which can reach levels of 20% to 30% [4]. To cope with the increasing effects of climate change, farmers apply technology to maintain their productivity. Among the applied solutions, plastic covers and shading nets have been developed strongly in the last 10 years to create a beneficial microclimate for the crops and ensure a steady production flow [5].

In this context, Agrivoltaics (AV) represents an alternative to conventional shading and protection infrastructure, not only protecting crops from solar irradiation and heavy weather events but also increasing land-use efficiency. Various scholars investigate the micro climatical changes under AV quantifying its impact on plant growth and water use efficiency: Barron-Gafford et al. [6] investigate microclimatic changes under AV compared to reference data in the arid climate of the Arizona desert. The results indicate that AV creates a beneficial microclimate affecting crop growth positively. As stated in various publications, shading potentially decreases water evaporation from the soil and water loss through the transpiration of crops [7]. As a result, AV systems may improve water management efficiency in agriculture. Scientific evidence is provided in France where tracked PV panels above apple trees reduced irrigation water demand by between 6% - 31% depending on the season without negative effects on fruit growth [8]. Also in France, research indicates a decrease of 20 – 30% in the water consumption of lettuce in an AV system with fixed conventional PV modules [9].

In the present work, we present and interpret in-situ microclimate measurement data over a period of 81 days from November 2021 until January 2022 under an AV pilot in the Metropolitan Region of Santiago, Chile. Proceeding from these measurements, we derive the impact on potential evapotranspiration under the AV system in comparison to an open-field reference. Herewith, this work quantifies for the first time the alteration of the microclimatic changes under AV in a semi-arid context in Chile.

2. Methods and Data

2.1 Agrivoltaic Pilot in the Metropolitan Region of Santiago

Fraunhofer Chile has installed three AV pilot plants in the central zone of Chile in the Metropolitan Region of Santiago. The pilot plants were set up from 2016 to 2018 in the context of a project financed by the regional government with small to medium farmers as the beneficiaries [10]. This study was conducted at the AV pilot located in the commune of *Lampa* in the sector *Lo Vargas* at -33.274000, -70.860861. The local climate is characterized by average air temperatures between 9 °C during July and 21 °C during January while the average Global Horizontal Irradiance (GHI) is 5,65 kWh m^{-2} d^{-1} and annual average rainfall from 2010 - 2021 is documented with 153 mm y^{-1} [11], [12]. The pilot is installed on a field with a slight slope from north to south at elevations ranging from 488 m to 487 m above sea level. The land has the highest agricultural soil classification, which is characterized by good moisture retention and good natural fertility.

The AV system has a capacity of 12.48 kWp with PV panels installed at a fixed angle of 27° at a height of 3.9 m. A total of 6 rows with 8 PV panels each, spaced by a pitch distance of 5.33 m are orientated with an azimuth of 330° NW. The total area covered is 224 m^2.

2.2 Experimental sensor set-up and data analysis

The measurement period was in Chilean late spring and early summer, from 29-10-2021 until 17-01-2022: Basil was cultivated in the reference plot and under the AV pilot with the use of a drip irrigation system and plastic cover on the ground in order to obtain high irrigation efficiency.

Two identical measurement stations were installed, below the AV system and in reference conditions on the open field as illustrated in Figure 1. Microclimate data was collected by Campbell CR310 dataloggers, using a sampling rate of 1 minute. Apogee SP-110 silicon-cell pyranometers measure GHI [W m^{-2}] at a height of about 0,8 m, while DECAGON Device VP-4 sensors measure the air temperature [°C] and relative humidity [%]. Adafruit analog anemometers register wind speed [m s^{-1}] while three DECAGON 5TM sensors measure soil moisture as volumetric water content [% VWC] and soil temperature [°C] at each measurement station. The soil sensors are positioned within a perimeter of 2 m to the measuring station at a depth of 0.3 m as illustrated in Figure 1. The soil sensors for the AV and reference conditions are placed in the same line of drip irrigation.

Data is cleaned and handled with python library pandas and results are plotted with python library matplotlib [13], [14].

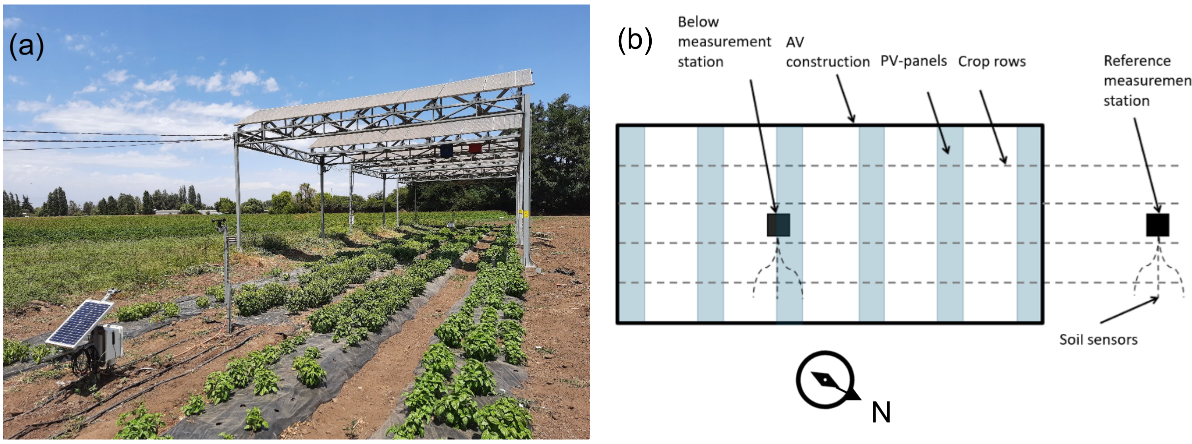

Figure 1. (a) Fraunhofer Chile Agrivoltaic pilot in the Metropolitan Region of Santiago with microclimate measurement stations (b) Scheme of the installed experimental sensor set-up

2.3 Evapotranspiration

We calculate potential evapotranspiration PET_{PM_FAO56} [mm d^{-1}] as described by Penman-Monteith [15], [16] and Allen et al. [17] and as implemented in python library *pyet* as the FAO-56 function [18]:

$$PET_{PM\_FAO56} = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_a + 273} u_2(e_a^* - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (1)$$

with Δ as the slope of saturation vapor pressure curve [kPa $°C^{-1}$], R_n is daily net radiation at the crop level [MJ m^{-2} d^{-1}], γ is the psychrometric constant [kPa $°C^{-1}$], T_a is air temperature [°C], u_2 is wind speed [m s^{-1}], and finally $(e_s - e_a)$ is the vapor pressure deficit [kPa] with e_a^* as the saturation vapor pressure [kPa] and e_a as the actual vapor pressure [kPa]. The soil heat flux G [MJ m^{-2} d^{-1}] is assumed to be 0.

All variables are calculated based on the methods described by Allen et al. [17] with the measured data for incoming solar radiation R_s [W m^{-2}], air temperature T_a [°C], relative air humidity RH_a [%] and wind speed u_2 [m s^{-1}].

Net radiation R_n [MJ m^{-2} d^{-1}] is being calculated based on net incoming solar short-wave radiation R_{ns} and net outgoing thermal long-wave radiation R_{nl}

$$R_n = R_{ns} - R_{nl} = (1 - \alpha) * R_s - R_{nl} \qquad (2)$$

where net short-wave radiation R_{ns} [MJ m^{-2} d^{-1}] is the difference in measured and integrated GHI [W m^{-2}] and calculated reflected outgoing solar irradiation under consideration of the albedo factor α for a vegetated surface of 23% [17].

3. Results and Discussion

Figure 2 displays measured Global Horizontal Irradiation (GHI) [W m^{-2}] in reference conditions and below the AV pilot in 15-minute timesteps as scattered and mean values. Comparing the two measurements we find a significant deviation of GHI under the AV pilot between about 12:00 and 16:00 hrs. In the morning and evening hours, measured values for solar irradiation are similar. The total measured irradiation underneath the AV pilot equals 58.26% of the irradiation in the reference condition, resulting in a shading rate of 41.74% with daily values fluctuating between 34.8% and 53.4%. The decrease in solar irradiation could potentially positively affect horticultural crops which are suffering from sunburns and heat stress in summer months.

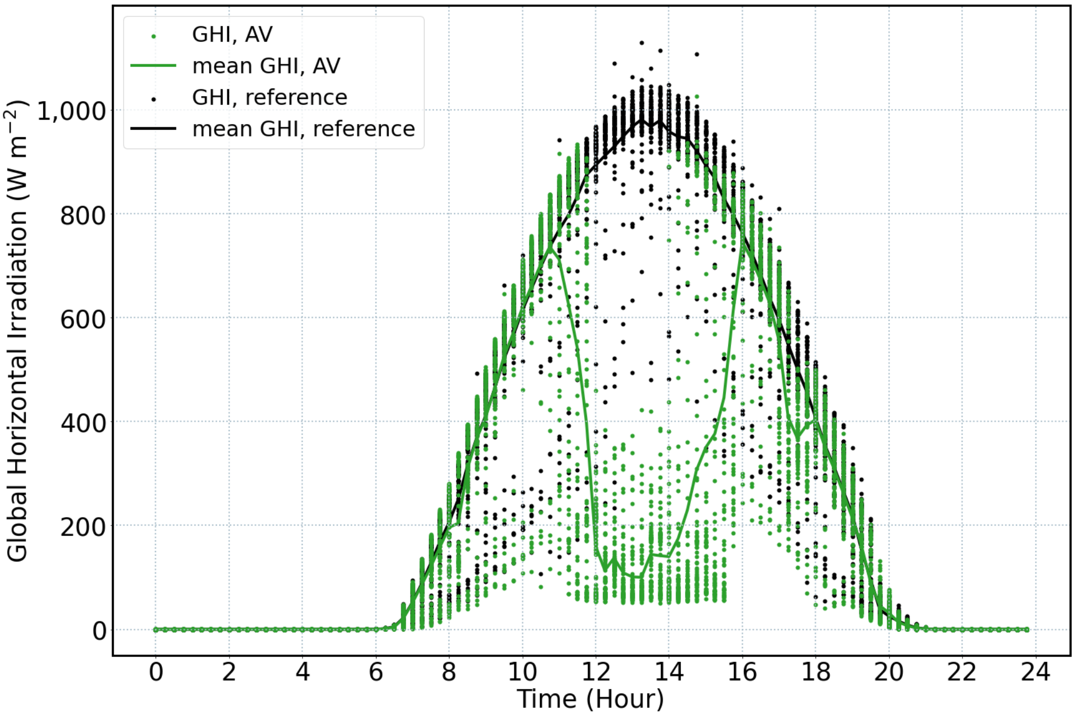

Figure 2. Global Horizontal Irradiation with and without influence of AV system, plotted in 15 min intervals for whole measurement period, with average values in W m^{-2}

Figure 3 shows the computation of the daily Potential Evapotranspiration (PET) [mm d^{-1}] based on measured parameters in the reference conditions and under the AV pilot. The daily average PET in reference conditions is 5.5 mm d^{-1} whereas this value decreases by 31.2% to 3.7 mm d^{-1} under the AV pilot. Of the four parameters used in PET calculation, GHI has the strongest impact as the sole change in GHI as measured in AV conditions leads to a decrease in PET of 29.8% compared to a decrease of 0.2% due to changes in air temperature and a decrease of 1.1% due to wind speed. Differences in relative air humidity between AV and reference conditions do not affect PET computation.

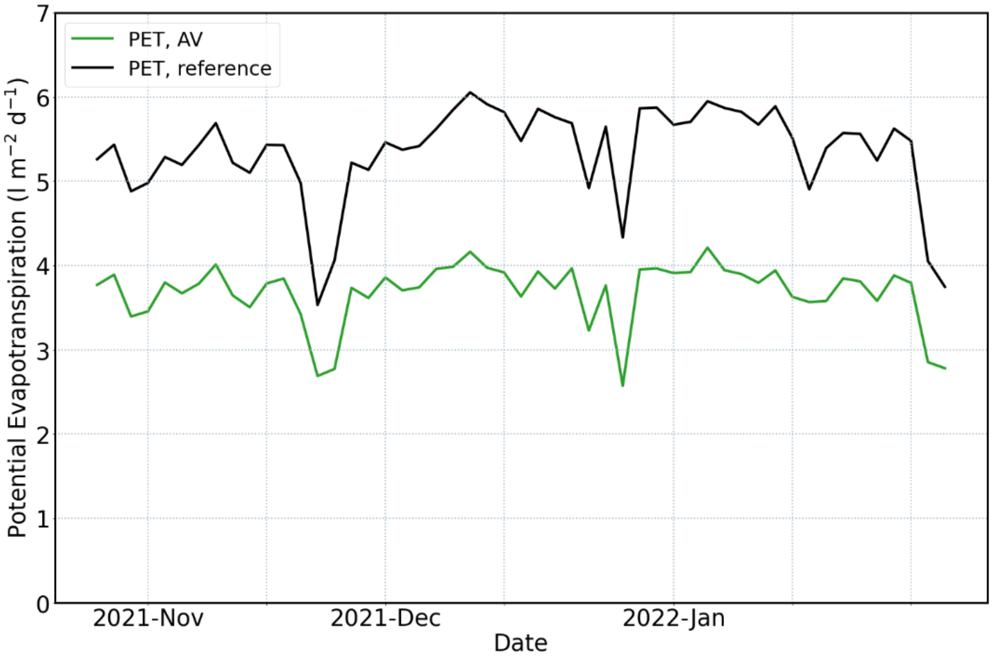

Figure 3. Computed daily Potential Evapotranspiration rates in AV and reference conditions in mm d^{-1}

The measured soil moisture at equal irrigation quantities was on average 29% higher under the AV system compared to the reference measurement as shown in Figure 4. The field was already irrigated before the observed period, resulting in an antecedent difference between conditions at the beginning of observation. Further, soil moisture under AV and in reference show similar peaks when irrigated and daily fluctuation as well as a general decreasing tendency over the measured period. Obtained patterns for soil moisture are similar to results from Barron-Gafford et al. [6] who also find that soil moisture remains constantly greater under AV than in a reference condition. Finally, differences in soil moisture present a comparable magnitude to the difference in PET between AV and reference which fosters the obtained results.

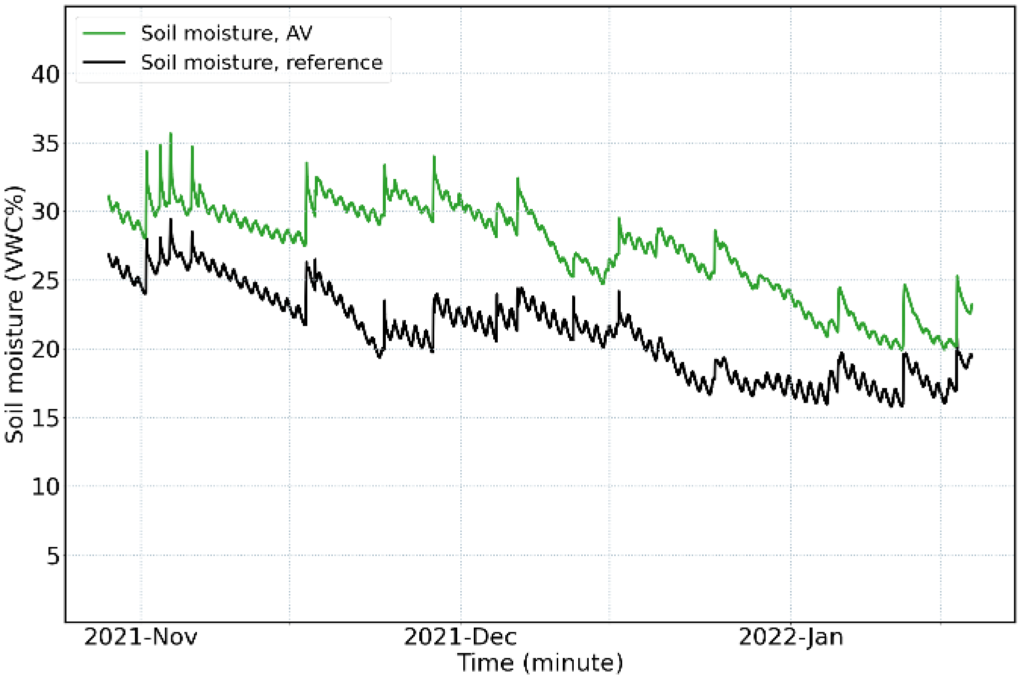

Figure 4: Soil moisture measured in VWC% over the complete observation period, displayed in an hourly resolution

Soil temperature was on average 2.83 °C lower under the AV system than in reference conditions as shown in Figure 5 (a), while both measurement stations show a similar increasing pattern and fluctuation. The difference in soil temperature can potentially be attributed to reduced GHI. Further, measurements show that during the night, the minimum daily air temperature under the AV system was on average 0.19 °C higher. In contrast, the maximum daily air temperature under the AV system was 0.21 °C lower throughout the day (Figure 5 (b)). Hence the air temperature tends to be stabilized under the AV system as the differences between night and daytime temperatures are smaller compared to the open field. Also, we observe that temperature differences increase with rising air temperatures. The decreased air temperature during the day could potentially be attributed to lower GHI under the AV system. Temperature increase during the night may be connected to the shelter effect, which is also observed in forests compared to clear-cut fields [19].

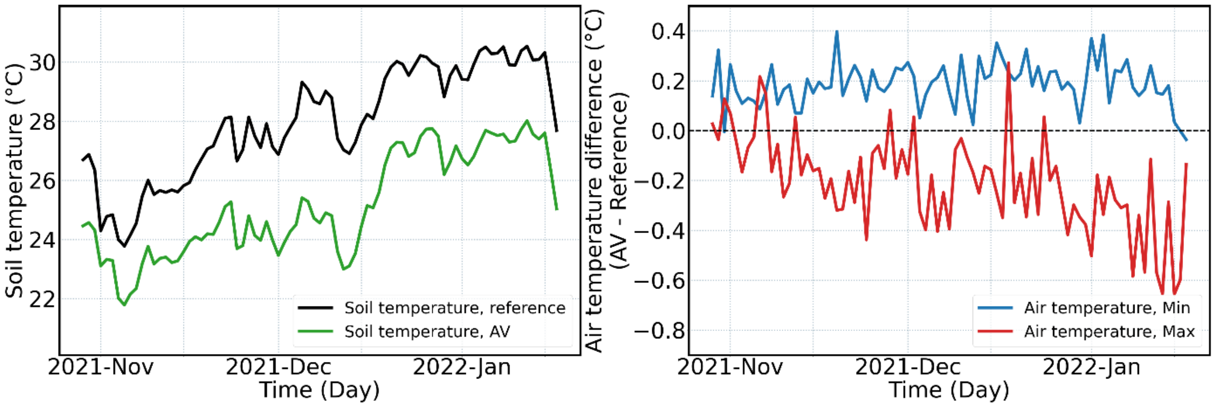

Figure 5. (a) Average daily soil temperature [°C] and (b) daily difference in minimum and maximum air temperature [°C]

4. Conclusion

We present data for microclimatic parameters measured during an 81-day period between November 2021 to January 2022 under an AV pilot and in reference conditions in the Metropolitan Region of Santiago, Chile: GHI under the AV system is on average 42% lower compared to the reference conditions. Based on measured data, we compute a diminution of PET and potential crop irrigation demand by 31%, mainly due to the reduction of GHI. In line with the computation of PET, measured soil moisture was on average 29% higher under the AV system compared to the reference conditions at equal irrigation quantities, thus validating the results of PET computation. Further, results show significantly lower soil temperatures under the AV pilot, and we observe a stabilized air temperature under the PV panels.

The results give valuable indications regarding the impact of AV over horticulture crops in a semi-arid climate. Further, in the context of challenges of Chilean agriculture in the face of climate change, the benefits of AV become apparent: First, presented results indicate the potential of AV to address the decrease of water availability by lowering evapotranspiration rates and herewith crop water demand. Second, in the context of extreme weather effects, the diminution of solar irradiation and resulting lower air and soil temperatures at midday may be beneficial to avoid sunburns and heat stress. Hence, considering the indicated crop-beneficial microclimatic changes, AV systems may allow replacing shading nets and foils long-term and thus fostering the transformation of agriculture towards more sustainable production systems.

Presented results are limited due to the absence of detailed documentation of the agricultural practices, specific irrigation parameters, and yield analysis. Also, the positioning of sensors, especially for irradiation, has an impact on the presented results and the calculation of evapotranspiration, as the shadow under the AV pilot presents heterogeneity. Further, the documented effects must be verified over a longer period to understand and interpret the impact of AV within seasonal and interannual climatical variations.

Finally, it is decisive to measure the microclimatic effects of AV in combination with other system designs within different agricultural fields such as fruticulture, annual crops, and grassland farming to evaluate the technology and its potential for climate change adaptation within the diverse Chilean agriculture.

Data availability statement

The measured data presented in this study can be made available by the corresponding author upon reasonable request.

Author contributions

D. Jung: Sensor Setup, Methodology, Data validation, Visualization, writing; F. Schönberger: Conceptualization, Methodology, Writing – review & editing; F. Spera: Data handling and analysis, Methodology

Competing interests

The authors declare that they have no competing interests.

Funding

The authors acknowledge the generous financial support provided by the Nacional Agency for Investigation and Development (ANID) under project 13CEI2-21803 and by the Regional Government of the Metropolitan Region of Santiago under the project FIC-R Met 2015, BIP code: 30449383-0.

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