Sonoran Desert Photovoltaics Laboratory and Growing Green: A networked regional approach to agrivoltaics citizen science

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Abstract — **This paper describes a multi-generational collaboration to create a networked approach to studying the benefits and challenges of small-scale agrivoltaics sites in the U.S. region of the Sonoran Desert. Supported by university collaborators, K-12 students and teachers design, build, care for, monitor, and report on garden beds with and without solar panels over the crops on school campuses and in community gardens. Early results show promise for the benefits of community-embedded installations of agrivoltaic systems.**

I. Introduction

A rapidly changing climate is putting pressure on energy and food production security around the globe. Therefore, it is important that citizens of all ages and from all walks of life begin emphasizing food-water-energy nexus needs in their local regions while addressing these environmental problems. Drylands, arid regions with water scarcity (e.g., Southwestern U.S., Mexico, North Africa, Southeast Asia), endure particularly significant challenges within agriculture due to extreme heat and little rainfall. Dryland farmers frequently grow non-drylands adapted food and, thus, rely heavily on irrigation, leading to a major problem of extreme water scarcity in these regions, e.g. [1]. As these regions become drier due to the effects of climate change, the demand for irrigation could skyrocket while food production plummets.

Many farms in dryland regions have started to convert land into drought-proof renewable energy development areas, designated for projects such as solar and wind systems, as the lack of water has made agriculture economically inefficient [1]. As such, photovoltaics (PV) is being widely adopted, especially in the drylands because of the abundance of sunlight. However, increasing temperatures negatively affect these PV systems and their efficiencies due to temperature derating effects [2-3]. Moreover, large solar systems have been shown to generate microclimates that warm the area under the panels, thereby creating a heat island effect [4] that can both further hinder the efficiency of solar and increase local temperatures, leaving a negative effect on the environment. One solution to PV systems overheating and the warming effect is agrivoltaics, in which crops are placed underneath solar panels to leverage the cooling effect from evapotranspiration.

Agrivoltaics have been of growing interest around the globe over the past few decades [5-6]. Agrivoltaic systems highlight the dual land usage of solar and farmland, especially in drylands, to increase economic viability, generate renewable energy, maximize water efficiency, and protect crops from heat stress [7]. Agrivoltaic projects differ in whether crops are grown alongside or under solar panels.

Overall, findings to date demonstrate that agrivoltaic systems can be an effective practice to combat climate change and food-water-energy nexus challenges [7]. For instance, studies have shown that leafy greens such as lettuce are more productive under agrivoltaic systems [e.g., 6]. Nonetheless, some location-specific risks should be considered. It is possible, for example, that agrivoltaics could lead to excess soil moisture, potentially damaging solar infrastructure. Barriers to wider adoption of agrivoltaic systems include concerns such as increased costs, interference with common agricultural machinery (tractors, harvesting systems), as well as negative social perceptions [8]. Our project addresses some of the current limitations and challenges of agrivoltaic system implementation, specifically for communities in the Sonoran Desert region.

B. Agrivoltaics in the Sonoran Desert

The interest of the current project is to identify the possible benefits and address the challenges of agrivoltaics in the Sonoran Desert. Although the Sonoran Desert region stretches across parts of the U.S. and Mexico, the project is currently limited to implementation in the U.S. Few studies have yet been conducted on agrivoltaics in the Sonoran Desert region specifically; however, early results show promise. One recent study conducted during a three-month summer season tested three different crops [6]. Chiltepin peppers thrived with three times the yield under solar panels, showing a 33% boost in CO_2 uptake. In contrast, jalapeños had 11% less CO_2 uptake in the agrivoltaic system but achieved a 157% increase in water use efficiency. Tomatoes had a 65% increase in CO_2 uptake and a 65% increase in water use efficiency; fruit production was doubled. There was a 3% increase in solar energy output during the months of May through July and a 1% increase annually attributed to the crops' transpiration underneath.

Another study focused on opportunities for agrivoltaics to help address the rising energy needs of a growing urban population in the Sonoran Desert region. Specifically, the study addresses the quickly rising demand for energy in the growing Phoenix metropolitan area. Analysis of panel distribution patterns showed that half-density panels on private lands can generate significantly more energy than needed by residential, commercial, and industrial sectors, suggesting that agrivoltaic systems in Phoenix can meet energy demands, save land, and

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protect farmland by generating clean electricity on agricultural lands [8]. More research has to be done to understand issues such as the effect of shading on crops in the Sonoran Desert.

III. A Community-based Approach to Citizen Science

Many systems being studied today are on larger-scale farms. However, research on small-scale off-grid installations may also help develop knowledge of agrivoltaics for regional communities. This paper describes preliminary results of collaborative cross-organizational efforts to conduct community-based research in small-scale agrivoltaic systems in the Sonoran Desert region. The project builds on the authors' collective experience facilitating teacher and youth engagement in similar projects e.g. [9-10]. The intergenerational author-researcher team, with members crossing age categories and education levels, reflects the team's commitments to engaging youth in the real work of contributing new knowledge about agrivoltaics in local communities. Two organizations collaborated on this research.

Growing Green is a youth-led organization dedicated to promoting, implementing, and researching technologies at the intersection of sustainability and agriculture while engaging and teaching the community. They were able to bring garden bed agrivoltaic systems to two community gardens in the region. Through these two systems, they have hosted workshops to help raise awareness among farmers, schools, and community members on agrivoltaics with the hopes of increasing adoption of this technology. From late summer to winter, experiments were conducted at the two agrivoltaic locations with different crops and successfully captured the attention of the community who were eager to participate in data collection, harvesting, and adoption in other areas.

The Sonoran Photovoltaics Laboratory (SPV Lab) is a network of students, teachers, scientists, engineers, and community partners who work collaboratively to engage K-12 students (elementary, middle and high school) in designing, building, caring for, monitoring, and reporting on agrivoltaics systems. SPV Lab research sites are hosted by 17 schools in which students work to achieve active engineering citizen science focused on agrivoltaics and solar energy.

Teachers involved in SPV Lab participate in a six-week summer program, creating curriculum and preparing to support their students in agrivoltaics citizen science. Thereafter, K-12 students and teachers explore symbiosis between plants and solar panels by maintaining twin garden beds on their school campuses or in community gardens, one shaded by solar panels and the other fully exposed. Working in collaboration with scientists and engineers, SPV Lab students actively participate in the construction of the garden beds and the design and construction of mobile PV racking systems before planting crops and deciding how to use the DC power generated by their solar panels. They monitor garden features like soil moisture, air temperature, and plant leaf size as well as the voltage produced by the panels at different times of the day. To conduct their research, students scan a QR code and complete data collection forms. Not only are they responsible for properly utilizing the tools provided to them, such as temperature and light meters, they are also encouraged to understand differences between the garden bed conditions based on collected data.

The Sonoran Desert climate affords both fall and spring growing seasons. Because these seasons align well with school schedules, this creates an opportunity for students to contribute to agrivoltaics research during multiple seasons. Students collect and analyze garden data and determine whether agrivoltaics addresses factors such as solar panel efficiency and garden growth, contributing to their experience as citizen scientists. They share their experience and results through a networked learning platform that connects the research sites and the university facilitators.

IV. Results

Each school and community-based research site operates differently regarding the implementation of the program based on the needs of their community. Rather than adhere to strict standardized protocols across school and community garden sites, each research site conducts its own protocols in consultation with university research faculty and students. Table 1 describes eight research sites to illustrate the variation in the installations and implementation. All panels faced south and were angled between 20 and 33 degrees.

TABLE I. Description of Eight Small-Scale Agrivoltaics Research Sites

	Site Description			
	Site description	***Season & crops***	***Data collected***[b]	***Overview of analysis***
Site 1	3 Exp, 3 Con 1.83mX.91m PV: 4 305W panels; rack height: .91m, Unistrut	Spring 2023: basil, peppers, tomatoes Fall 2023: cilantro, strawberry	microclimate: soil moisture/ temp/light/pH, plant health	Exp beds more hospitable Sept-Nov; basil healthier, strawberries longer lasting; Con spring crops healthier
Site 2	4 Exp, 4 Con 1.83mX.91m PV: 4 305W panels; rack height: 2.44m steel w/gabions	Fall 2023: cilantro, broccoli, tomatoes	microclimate: soil moisture/ temp/light/pH, plant health; electricity generated	Analysis in progress
Site 3	1 Exp, 1 Con 1.22mX1.22m PV: 2 50; rack height: 21.18m, PVC pipe	Spring 2022: peppers, basil, cilantro	microclimate: soil moisture/ temp/light/pH, plant health	Exp soil moisture more sustained; cilantro flowered later
Site 4	1 Exp, 1 Con 1.83mX.91m PV: 3 100W 25.4cm apart; rack height: 1.52m, wood	Fall 2023: spinach, cilantro	microclimate: soil moisture/ temp/light/pH, plant health	Analysis in progress

Site 5	3 Exp, 1 Con 1.10m X .88 PV: 1 100W per bed; heights vary for Exp beds:.59m, .62m, .65m, wood & PVC	Spring 2024 (Jan-Feb): radish, dill, broccoli	Plant growth, biomass; panel temperature; voltage and current produced	High Panel most efficient power. Con yielded most biomass; no sig. diff. in temp based on panel height
Site 6	1 Exp, 1 Con PV 2 100W 1.15m X .75m spaced; rack height: 1.524m; unistrut	Spring 2024: spinach	Plant growth, crop yield; voltage generated	Exp quicker growth of seedlings; Con produced slightly larger crops
Site 7[c]	1 Exp, 1 Con 2.35m x 1.18m PV: 1 400W; rack height: 1.83m, wood	Summer 2023, Fall-Winter 2023: kale, swiss chard	crop yield (weight), microclimate: soil moisture/ temp/light/pH, electricity generated	Exp lower crop yield; average power yield: 350 KWH Maximum output: 110W
Site 8	1 Exp, 1 Con PV: 1 400W Garden Bed: 2.35m x 1.18m Rack height: 1.83m, wood	Fall-Winter 2023: turnips, kale	crop yield (weight), microclimate: soil moisture/ temp/light/pH, plant health, electricity generated	Exp 9 lbs. of turnips and 1.2 lbs. of kale, Con 6.5 lbs. of turnips and no kale harvest

a. Exp=experimental condition (with solar panels) Con=control (no panels); height is at highest point

b. Time series data collected using Tomst; point-in-time data collected by hand using digital forms

c. Shaded cells = community garden research site; all others are school-based research sites

V. Discussion

Overall, preliminary results suggest that small-scale agrivoltaics systems can benefit communities, though comparison of crop production in the two conditions varied across sites. Data collection, analysis and interpretation are ongoing to further contribute to understanding the potential value of community implementation of this innovative approach to gardening in the Sonoran Desert.

Engaging youth in citizen science research increases understanding of the possible benefits of agrivoltaics while combining cutting edge technology application with educational opportunities and career readiness. The longer paper will share initial results from particular research sites and identify limitations in research protocols and practices. Some identified challenges include issues with irrigation, particularly in regards to monitoring standardization of watering across control and experimental garden beds. Beyond collection and analysis of data related to plants and panels, implementation of these small-scale garden bed systems has led to community members and farmers expressing interest in implementing agrivoltaics in their gardens and farms.

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