land

Article

Ecovoltaics: Maintaining Native Plants and Wash Connectivity inside a Mojave Desert Solar Facility Leads to Favorable Growing Conditions

Tamara Wynne-Sison *, Dale A. Devitt and Stanley D. Smith

School of Life Sciences, University of Nevada Las Vegas, Las Vegas, NV 89154, USA;
dale.devitt@unlv.edu (D.A.D.); stan.smith@unlv.edu (S.D.S.)
* Correspondence: wynne@unlv.nevada.edu

Abstract: The installation of solar facilities is increasing rapidly in the Mojave Desert USA, with the largest facility in North America (3227 ha) currently being built 30 km north of Las Vegas, NV. At the state level, Nevada (USA) has developed an energy plan to diversify its energy portfolio by 2030 with green energy representing 50% of the energy produced. Although solar is considered a clean energy, it does require significant amounts of land and as such may have negative consequences at the habitat and ecosystem levels. A multi-year study was conducted to assess the impact a photovoltaic facility in the Mojave Desert had on the growth and physiological response of two native shrubs (*Ambrosia dumosa* and *Larrea tridentata*) growing inside and outside the facility. These species were selected because they were the dominant species at the site and are representative of desert scrub communities throughout the Mojave Desert. At the time of construction, native plants and washes were left intact inside the solar facility. The solar panel arrays were separated at either 8 m or 10 m. Plants were selected for monitoring on the basis of location: at the panel drip line, below the panels, or midway between panel rows. Abiotic factors, including PAR, reference evapotranspiration, precipitation, soil water in storage, and infiltration, were monitored bi-monthly. The growth and physiological status of the plants were assessed by monitoring leaf water potential, chlorophyll index, canopy temperatures, non-structural carbohydrates in the roots and stems, leaf tissue ion concentrations, stem elongation, and seed production. Plants at the bottom edges of the panels received more precipitation due to runoff from the panels, which led to increased soil moisture in the long spacing but not the short spacing. The lower soil water in storage in the short spacing was related to greater growth and higher soil water extraction. Although the area under the panels provided shade in the summer and warmer temperatures in the winter, the incoming PAR was reduced by as much as 85%, causing plants growing under the panels to be spindly with lower canopy volume (*L. tridentata*, $p = 0.03$) and seed yield (*A. dumosa*, $p = 0.05$). *Ambrosia* plants remained green in color year-round (not going into winter dormancy) inside the facility and had elevated levels of starch in their roots and stems compared with plants growing at the outside control sites ($p < 0.001$). *Larrea* growing outside the facility had lower xylem water potentials compared with those inside the facility ($p < 0.001$), lower chlorophyll index ($p < 0.001$, *Ambrosia* as well), and lower stem elongation ($p < 0.001$), supporting the conclusion that both *Larrea* and *Ambrosia* performed better inside the facility. Shifts in δ^{13} C suggested greater water-use efficiency at the locations with the least amount of soil water in storage. Our results support the installation of solar facilities that minimize the impact on native plants and wash connectivity (ecovoltaics), which should translate into a reduced negative impact at the habitat and ecosystem levels. Basedon our results, energy companies that embrace ecovoltaic systems that take an engineering and biological approach should provide acceptable environments for desert fauna. However, corridors (buffers) will need to be maintained between solar facilities, and fences will need to have openings that allow for the continuous flow of animals and resources.

Keywords: soil moisture; photosynthetic active radiation; leaf water potential; chlorophyll index; stem elongation; seed yield; starch; photovoltaic systems

Citation: Wynne-Sison, T.; Devitt, D.A.; Smith, S.D. Ecovoltaics: Maintaining Native Plants and Wash Connectivity inside a Mojave Desert Solar Facility Leads to Favorable Growing Conditions. *Land* **2023**, *12*, 1950. https://doi.org/10.3390/land12101950

Academic Editors: Jianzhi Dong, Yonggen Zhang, Zhongwang Wei, Sara Bonetti and Wei Shangguan

Received: 30 September 2023
Revised: 13 October 2023
Accepted: 17 October 2023
Published: 21 October 2023

1. Introduction

Deserts exist as fragile and diverse ecosystems [1]. When a disturbance occurs, it can create disconnected habitats for wildlife [2–5]. Desert plants tend to recolonize very slowly after a disturbance, taking anywhere from decades [6] to centuries [7–9], indicating that long-term multiscale studies are needed to better understand disturbance [10].

New solar energy facilities are being built at an exponential rate in the western U.S. [11], especially in the Mojave Desert where high solar irradiance, low infrastructure, and few population centers exist [5,12,13]. The U.S. and other countries are turning to solar energy as an alternative renewable energy because it reduces greenhouse gases, provides greater energy independence, and does not produce significant noise or chemical pollutants [14]. Cameron et al. [15] calculated that the lower-conservation-value lands in the Mojave Desert, with slopes of less than one percent, could supply 180% of California's estimated renewable energy needs. Putting solar panels on already developed areas in California could meet the state's needs three to five times over [16] and decrease the fragmenting of native habitats [17]. Solar facilities typically remove vegetation and disturb the land in more area per gigawatt than coal mining or nuclear energy [14,18], creating environmental consequences (ecological footprint) that need to be addressed [13,19,20]. Hernandez et al. [21] in particular argued the need for an approach that merges technological and ecological systems, accounting for both uncertainty and variability.

The construction of solar energy facilities was reported by Parker et al. [22] to cause a downgrade in the conservation value of land in the Mojave Desert. This is significant because shrublands support a diversity of plants and animals, some listed as threatened or endangered, with some still having limited legal protection, especially on private land [23]. The development of utility-scale solar facilities can lead to habitat loss, fragmentation, and microclimate alteration [4,13]. Even when just the soil biocrust is disturbed, it can lead to erosion and heightened susceptibility to invasion by non-native grasses [9,24], which can then increase fire susceptibility [25]. An excellent review by Yavari et al. [26] describes the current science of minimizing the environmental impacts of large-scale solar facilities, with an emphasis on hydrology and stormwater management.

Recognizing that the construction of solar energy facilities can impact the habitat of desert fauna, the Bureau of Land Management (BLM) in California, under the Desert Renewable Energy Conservation Plan, set aside 1570 km^2 of land for solar, wind, and geothermal development and 17,000 km^2 for other conservation causes [22]. An important species of concern in this area is the desert tortoise (*Gopherus agassizii*), which is listed as a threatened species under the United States Endangered Species Act. Tortoise signs, such as scat, burrows, or the animals themselves, were reported by Hoff and Marlow [27] to not occur within 4000 m of busy roadways, while roads with less traffic had tortoise signs closer to the roads. Such reports indicate that the tortoise's habitat is affected by more than just the construction site. Some solar facilities have been reported to increase the ambient temperatures at night by 3 to 4 °C in Arizona [28] and as much as 8 °C down-gradient from a solar facility in southern Nevada [13]. Such temperature changes could affect desert tortoise eggs, whose gender is determined by incubation temperatures [29]. More research is needed to quantify the impact solar facilities might have on plants [10,24,30] and animals [31] at the local and ecosystem levels, especially the impact solar facilities might have on animal behavior [31].

Solar facilities have been shown to decrease plant biomass and diversity under solar panels compared with control areas [32]. The invasive grass *Schismus arabicus* and other exotics were reported to increase dramatically in the shade of simulated solar panels in a caliche pan habitat but not a gravelly soil habitat in the Mojave Desert [33]. Besides native plants, agricultural crops grown within solar panel facilities have also been studied [34], with Marrou et al. [35] reporting canopy temperatures increasing rapidly in the presence of solar panel shading. In Pahrump, Nevada (USA), a photovoltaic solar facility was constructed (Valley Electric Association). The facility left the majority of native plants and washes in place when installing the solar panels and kept openings in the fences for desert fauna to freely pass. Few studies have monitored native perennials inside a solar facility as part of habitat assessment, but those that have monitored them have reported increased soil moisture at the edge of solar panels [36,37], which should be beneficial to desert plants.

Our study identified how native plants in the Mojave Desert are affected by shade, higher temperatures, and rain displacement within a solar photovoltaic facility. The goal of our study was to understand the biotic and abiotic factors that influence the response of native shrubs when grown under the influence of solar panels and to compare that with plants growing in an adjacent unaltered landscape. As such, this study analyzed the impact solar panels have on the microenvironment (light, temperature, and moisture) and the changes in morphology and physiology of the plants in response to those altered microclimates. We hypothesized that plants inside the facility would exhibit less stress than plants outside the facility, identified by differences in ambient and canopy temperatures, leaf xylem water potential, photosynthesis, chlorophyll index, height, canopy volume, and stem elongation. We also hypothesized that plants growing under the solar panels would deplete starch levels in their roots and stems and decline in growth and overall health.

Finally, we wanted to confirm whether the Pahrump solar facility model of conserving plants with minimal soil surface disturbance positively or negatively affected the environment and vegetation in and around the solar facility. Positive plant responses would support a paradigm shift (ecovoltaics) in how solar facilities in the future should be constructed and operated in desert environments.

2. Methods

A field experiment was conducted to determine the impact a solar facility had on the growth and physiological status of creosote bush (*Larrea tridentata*) and white bursage (*Ambrosia dumosa*) growing inside and outside the facility. The experiment took place in Pahrump, NV (USA), at the Valley Electric Solar Facility (36°16′31.0″ N, 115°58′19.6″ W, 896 m elevation), which has approximately 0.25 km^2 of solar panels. The construction company did not grade the land before building the solar facility (2013) and kept the native plants and the small washes intact (there was some trimming of plants adjacent to the panels, and such plants were not selected for the study). Native plants were selected (18 *Ambrosia* and 18 *Larrea*) growing below the panels, at the panel drip line, and centrally located between panel rows (6 of each species at each plant location). In addition, the builders spaced the solar panels both at 8 m between rows on the north side and 10 m between rows on the south side of the facility. As such, half of the plants were selected in the 8 m and the 10 m spacing locations. Panels were 1.1 m off the ground at the low end (south side of panel) and 3.2 m at the high end (north side of panel). Modules were 3.6 m in length containing 72 solar panel cells per module, with each cell being 15.7 cm by 15.7 cm. All modules were positioned with a 30° south-facing slope. There were two control sites located outside of the solar facility, one on the east side and one on the west side; each had three *Larrea* and three *Ambrosia* plants selected for monitoring. Although the land was owned by the electric company, permitting required approval from both the Bureau of Land Management and the U.S. Fish and Wildlife Service. No restrictions or approvals associated with this study were required by these agencies.

Several abiotic factors inside and outside the solar facility were assessed. Photosynthetically active radiation (PAR) (Apogee, Logan, UT, USA) was measured at a site inside the facility, which captured all plant panel positions (drip, middle, and shade) in both the long and short row spacings. I-buttons (Maxim Integrated, San Jose, CA, USA) were placed in PVC ventilated towers to record the air temperature at 10 cm, 1 m, and 2 m heights above the soil surface, located at the same plant and panel positions (replicated three times). The soil volumetric water content at 10, 20, 30, 40, 60, and 100 cm was estimated with a theta probe (PR2, DeltaT, Cambridge UK) at all *Larrea* plant locations. A fiberglass access tube was placed in the ground to a depth of 100 cm, which allowed for the theta probe to be inserted for measurements. Infiltration was measured at all plant locations with a mini disk infiltrometer (Meter Group, Pullman, WA, USA). Sorptivity was determined by calculating the slopes between the square root of time and cumulative infiltration. Additional climatological information was obtained from four small weather stations (Hobo USB micro station data logger with temperature, wind speed, relative humidity, wind direction, and soil volumetric water content sensors; Onset, Bourne, MA, USA), two positioned in the short spacing and two in the long spacing areas inside the facility. Environmental demand was assessed using the Kimberly Penman equation [38] obtained from a Community Environmental Monitoring Program weather station in Pahrump, NV (36°13′16″ N, 115°59′43″ W).

Plant growth was assessed by measuring height, canopy volume, and stem elongation. Stem elongation was measured by placing a piece of tape at 10 cm from a randomly selected growth tip on all preselected plants in 2018 and thereafter, measuring monthly elongation. In the beginning, measurements were taken on 18 *Larrea* and 18 *Ambrosia* plants, but due to herbivory on the *Ambrosia*, measurements were continued only on Larrea. Plant physiological status was assessed by measuring leaf xylem water potential (Pressure Chamber, PMS Instruments, Albany, OR, USA), canopy minus ambient temperature (39800 Infrared Thermometer, Cole Palmer, Vernon Hills, IL, USA), photosynthesis and stomatal conductance (LI-COR 6400, LI-COR, Lincoln, NE, USA), and chlorophyll index (FieldScout CM1000 Chlorophyll Meter, Spectrum Technologies, Aurora, IL, USA) at midday on a bi-monthly basis. Total annual seed production (grams) was quantified for each plant that was monitored in the study (seeds harvested were cleaned of all debris and oven-dried at 70 °C for 48 h). Leaf area, length, and width were assessed with a LI-COR 3100 C leaf area meter. Leaf moisture content was quantified by weighing the fresh and dry weights of the leaves (48 h at 70 °C). Stomatal density was determined by taking fingernail polish impressions of the leaves and then securing the impressions on a glass slide. The density was assessed by counting the number of stomata impressions within the view of the eyepiece at 400× magnification. Leaf thickness was determined with calipers in the spring of 2019 and 2020.

Water use efficiency (WUE) was assessed by measuring the ratio of photosynthetic carbon assimilation to transpiration. Δ13 carbon was used as a proxy to assess the WUE of the plants [39–41]. In early spring of 2021, new leaves were sampled from both species at all plant locations. Leaf tissue samples were sent to the SIRFER lab (Salt Lake City, UT, USA) for δ^{15} Nitrogen, δ^{13} Carbon, and the carbon-to-nitrogen ratio. Ward Labs (Kearney, NE, USA) quantified the percentage of nitrogen, phosphorous, potassium, sulfur, calcium, and magnesium and the ppm concentration of zinc, iron, manganese, copper, molybdenum, and boron in the leaf tissue.

Non-structural carbohydrates were assessed in the roots and stems. Samples were processed using a modified method outlined in Landhäusser et al. [42]. Samples were dried and ground before weighing in 2 mL centrifuge tubes. Sugar was extracted using 80% ethanol and heated at 90 °C for 10 min. After centrifuging, 0.2 mL of the supernatant was pipetted into a new centrifuge tube. This sugar extract was saved for later analysis. The sugar extract was reacted with phenol-sulfuric acid to yield a yellow color, which was measured at 490 nm (UV spectrophotometer (UV-120-02, Shimadzu, Kyoto, Japan)). The remaining plant tissue sample was extracted twice more, then dried at room temperature for subsequent starch digestion. The starch digestion was performed on the remaining plant tissue first with α-amylase at 85 °C for 30 min and then with amyloglucosidase at 55 °C for 30 min. The extract was saved for starch analysis. The starch extract was reacted with a PGO color reagent solution followed by sulfuric acid, which had a stabilized pink color measured at 525 nm.

Plant density was quantified by counting the number of plants and measuring the distance between the plants inside the facility (6 random short- and long-panel rows) and in the east and west control areas (same width and length as inside the facility, center to fence). The annual plant cover and composition were surveyed inside the facility and at the east and west control sites in March 2019 and March 2020. This was performed with PVC pipe made into square frames (0.5 m by 0.5 m) that were placed at four random locations at the drip line, between panels, underneath panels, and at control sites outside the facility.

Percent cover was estimated visually, and plant identity was determined using a Jepson Manual [43].

The heat index was determined using i-buttons (Maxim Integrated, San Jose, CA, USA) at heights of 10 cm and 1 m, capturing the general height of the plants. The temperatures from each of these i-buttons were averaged on an hourly basis from ten-minute readings. This average temperature had 35 °C subtracted from it as a threshold. ((Air temperature at 10 cm − 35 degrees) + (air temperature at 1 m − 35 degrees)). The index was also assessed with thresholds of 25 °C and 30 °C but found greater statistical separation at 35 °C. Only positive values were considered in the calculations. The data were then summed for 24 h, divided by two, and multiplied each day by the ET$_{ref}$-Precipitation of that day. The values for each day were then summed for two weeks, only positive values were accepted, and the area under the curve (AUC) was found for the two-year data sets.

Equation (1). Heat Index =

$$\text{Area Under the Curve}\left(\sum_{\mathrm{i}=1}^{14\text{ days}} \frac{\left(\sum_{\mathrm{i}=1}^{24\text{ h}}((\mathrm{a}-35)+(\mathrm{b}-35))\right)}{2}\,(ETref-PPT)\right)$$

$$\text{Average Hourly Air Temp at 10 cm}_{\mathrm{i}} = a$$

$$\text{Average Hourly Air Temp at 1 m}_{\mathrm{i}} = b$$

One-year-old seedlings were transplanted into six rows of the solar facility to assess their survival over the monitoring period. *Encelia virginensis*, *L. tridentata*, and *A. dumosa* seedlings were planted in the short-spacing and long-spacing areas at all panel locations (replicated three times for each spacing). Plants were watered weekly (1 L) during a two-month establishment period and then received no additional water for the duration of the experiment. Survival was assessed on a quarterly basis. Data were analyzed using descriptive statistics, analysis of variance, and linear and multiple regression analysis (Sigmaplot 12.5, Systat Software, San Jose, CA, USA, and R Core Team [44]).

3. Results

3.1. Abiotic Factors

3.1.1. Precipitation

Precipitation in 2018 and 2020 was less (42% and 44%, respectively) than the historical average (12.45 cm, National Weather Service). However, in 2019, the precipitation was 38% higher than the average (Table 1). In 2020, a six-month dry period occurred (the longest in recorded history) with no rainfall from May to November. Environmental demand (ET$_{ref}$), as assessed with the Kimberly Penman equation, revealed very similar values for each of the three years in the study. The imbalance between ET$_{ref}$ and precipitation was quantified as an indicator of water availability and level of drought-induced stress. ET$_{ref}$ minus precipitation followed a similar shift each year, with the wetter 2019 value 13 cm lower than that in 2018 (Figure 1).

Table 1. The amount of precipitation, reference evapotranspiration (ETref), and ETref minus precipitation recorded for all three years of the study (cm).

Year	Precipitation	ETref	ETref−Precipitation
2018	7.3	190.8	183.5
2019	17.2	187.5	170.3
2020	7.0	187.0	180.0

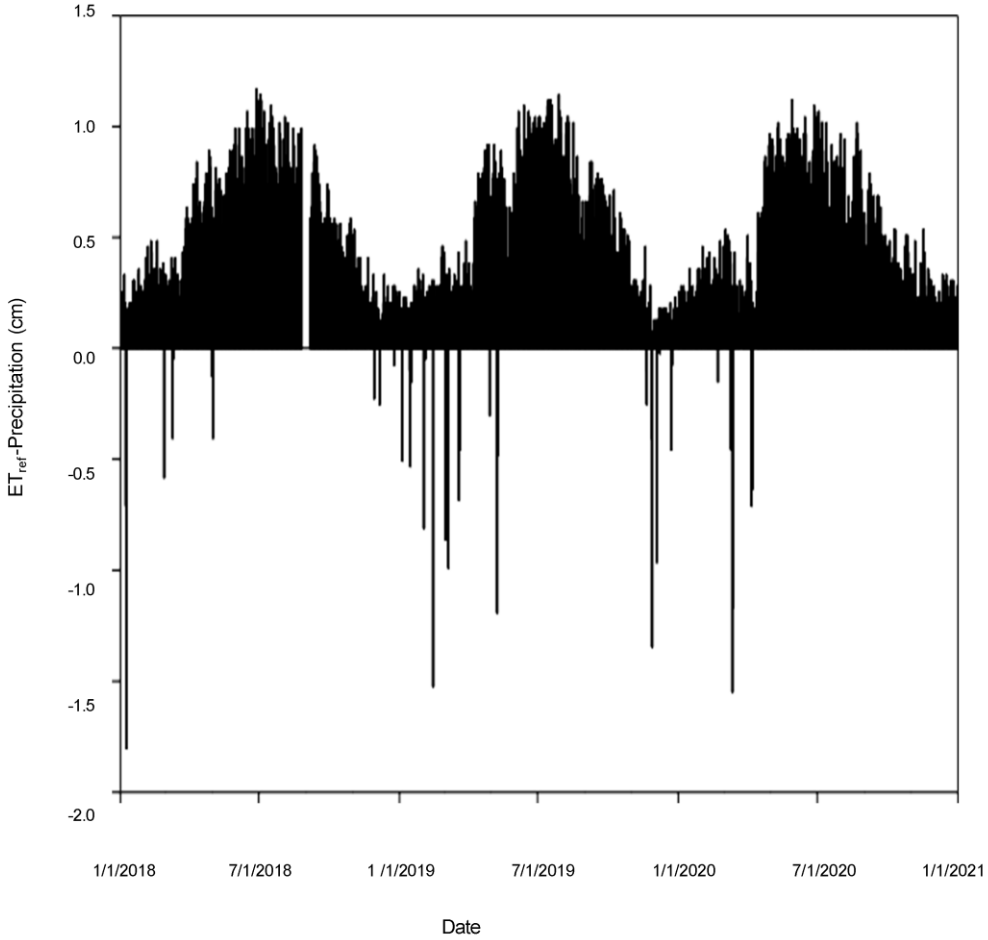

Figure 1. Reference evapotranspiration (ET_{ref}) minus precipitation throughout the three-year study (cm).

3.1.2. Soil Water in Storage

Soil water in storage was higher during the wetter winter periods in both 2019 and 2020 (Figure 2). However, the response was dependent on the panel spacing and the plant position relative to the panels. In the long spacing, the soil water in storage increased at the drip line of the panels more than underneath or between panels ($p = 0.006$). Water accumulated from across the panels to the low end of the panels and dripped down to the soil in a non-uniform fashion (personal observation). In the short spacing, underneath the panels had the highest soil water in storage compared with the drip line or between panels ($p = 0.02$). This may have been associated with higher wind turbulence based on greater variability in the relationship between wind gusts and wind speed (wind gusts vs. wind speed for short spacing $R^2 = 0.50$, $p < 0.001$; long spacing wind gusts vs. wind speed $R^2 = 0.65$, $p < 0.001$), which may have changed the rainfall distribution within the panels. Greater wind gusts were observed to be associated with lower wind speeds in the shorter panel spacing area. It is also possible that the actual evapotranspiration (ET) of the plants was higher in the shorter spacing, which would potentially decrease the amount of water in the soil. Such ET estimates would have required the quantification of run-on, run-off, change in soil water in storage, and deep drainage, which was not assessed. However, greater growth (later section) was reported in the short spacing, which may have led to a decrease in the amount of water in the soil.

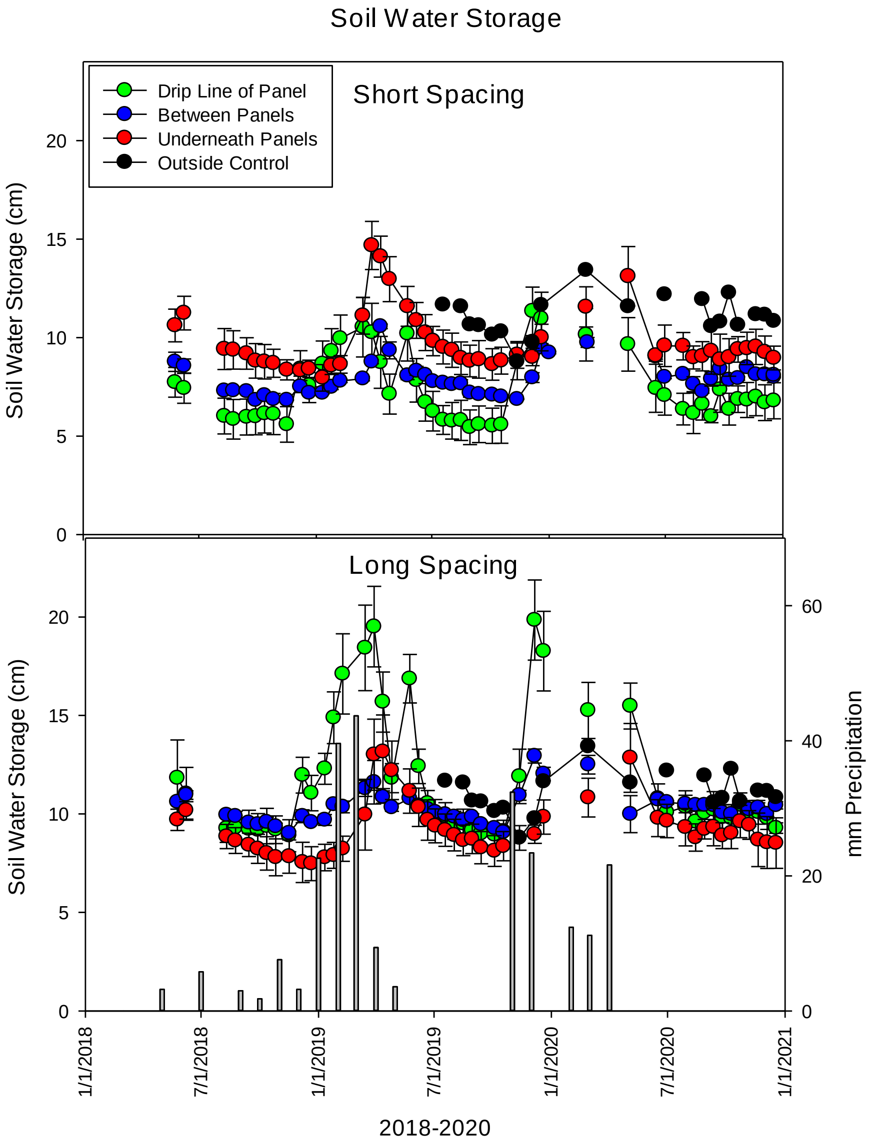

Figure 2. The soil water in storage measured biweekly at different locations throughout the solar photovoltaic facility. Vertical bars indicate precipitation events.

3.1.3. Infiltration

Cumulative infiltration was assessed as a function of the square root of time at all plant panel positions. A two-way analysis of variance on sorptivity revealed significantly different values based on the position relative to the panels (drip 0.047, SEM 0.014, middle 0.076, SEM 0.014). The sorptivities were low and not significantly different for the drip and middle row positions ($p > 0.05$). The sorptivity values were statistically higher ($p < 0.05$) under the panels (0.133, SEM 0.014). However, the control areas had the highest values (0.192, SEM 0.02), which were statistically different from all other locations ($p < 0.001$), indicating that the control areas were the least impacted by construction. Even though great care was taken to preserve the immediate area surrounding the solar panels, there appeared to be a legacy effect on infiltration associated with panel array construction. Higher infiltration underneath the panels may have contributed to the higher soil water in the storage estimates in the short panel spacing location, but further research is needed to fully understand the differences/inconsistencies.

3.1.4. Photosynthetically Active Radiation

In the solar facility, photosynthetically active radiation (PAR) sensors were placed on the soil surface at the drip line, underneath the panel, and between the panels in both the long and short spacing. Panels were spaced in such a way that one row of panels would not shade the next row of panels. Without an outside control sensor (vandalism), the long-spacing drip sensor was used to compare the other locations since there was no panel shading and no panel reflection at that location. The panels were approximately 100 cm above the soil surface but varied according to the topography, with an average soil slope of 9.0% (Table 2). The PAR in the long spacing was similar at the drip line of the solar panels and between the panels ($p = 0.98$) but revealed an 83–85% reduction under the panels, which was statistically different from all other locations (Table 3, $p < 0.001$). The amount of sunlight that reached the ground varied on an hourly basis and by time of year (Figures 3 and 4) and by panel row position. PAR values at midday reached 1000 μmol $m^{-2}s^{-1}$ near the winter solstice but approached 2000 μmol $m^{-2}s^{-1}$ near the summer solstice. Deviations in the hourly PAR values (not including the shade location) occurred during the morning and early evening hours. Well-defined spikes in PAR occurred throughout the day, reflecting light penetration between the panel mounts.

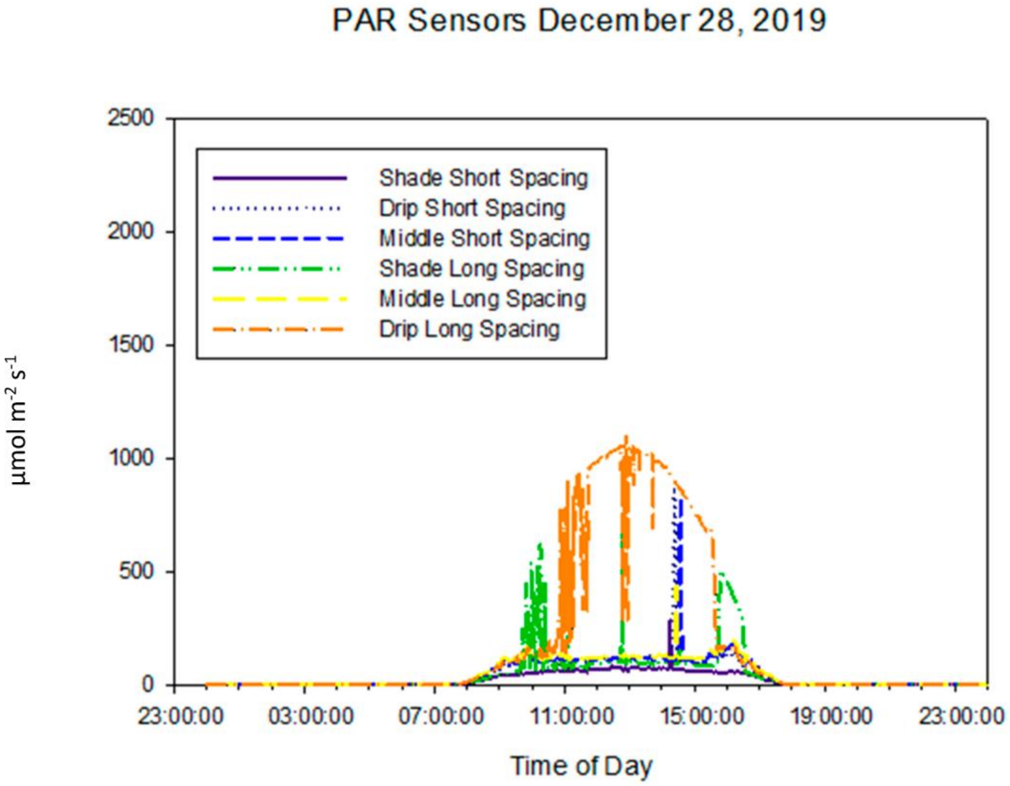

Figure 3. The amount of photosynthetic active radiation (PAR) captured by sensors on the ground at different locations inside the solar photovoltaic facility throughout one day in December 2019. Shade is underneath the panels, drip is at the dripline, and middle is located between panel rows.

Table 2. Height of panels above the soil surface ($n = 36$), slope of the panels facing south ($n = 38$), and slope of the soil surface measured near all plant locations ($n = 54$).

Parameter	Mean+/−SE
Panel Height above the Soil	99.1+/−19.1 cm
Panel Slope	29.4+/−1.3%
Soil Slope	9.0+/−6.1%

Table 3. Reductions in yearly photosynthetic active radiation (PAR) measured at the soil surface, based on position relative to values at the middle row position in the long spacing. Shade is underneath the panels, drip is at the dripline, and middle is between panel rows.

Position	Long Spacing	Short Spacing
Drip Line	0% reduction	11%
Middle of the Row	16%	20%
Under the Panel	83%	85%

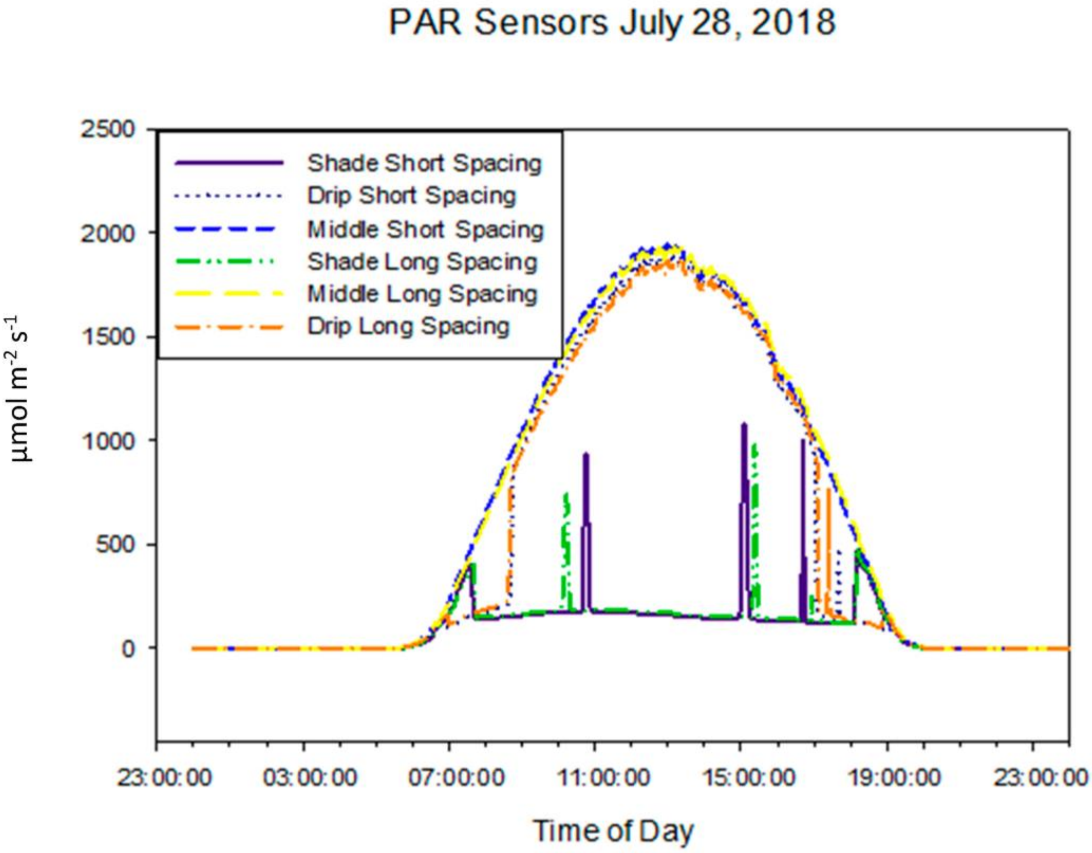

Figure 4. The amount of photosynthetic active radiation (PAR) captured by sensors on the ground at different locations inside the solar photovoltaic facility throughout one day in July 2018. Shade refers to underneath the panels, drip is at the dripline, and middle is between panel rows.

3.1.5. Temperature

Within the solar facility, air temperature was assessed using i-buttons at 10 cm, 1 m, and 2 m heights. The i-button data set revealed significant temperature differences between the 2 m and 10 cm heights at the long and short spacing locations ($p < 0.05$). Underneath the panels in the short spacing, the 2 m i-buttons recorded temperatures as much as 6 °C higher than at the 10 cm height during midday (June, $p < 0.001$, Figure 5), whereas at the middle location, temperatures were as much as 5 °C higher at the 10 cm i-button height compared with the 2 m height at midday ($p < 0.001$, Figure 6). These higher temperatures at the 2 m height under the solar panels were directly related to the solar panels radiating heat from the underside of the panels (sensible heat). The temperatures of the surface of the top of the panels averaged 7.9 °C lower than the temperature of the surface of the bottom of the panels ($p < 0.001$. Figure 7). The soil temperatures taken at the drip line were as much as 25 °C cooler than the temperatures at the bottom of the panels (winter, $p < 0.001$). The panels also warmed the air during the winter (October to March), generating fewer freezing temperatures associated with the panels at the 10 cm height than at the middle row locations ($p < 0.001$, Figure 8). Such warmer temperatures in closer contact with the panels provided reduced freezing conditions for both plant species during the winter months.

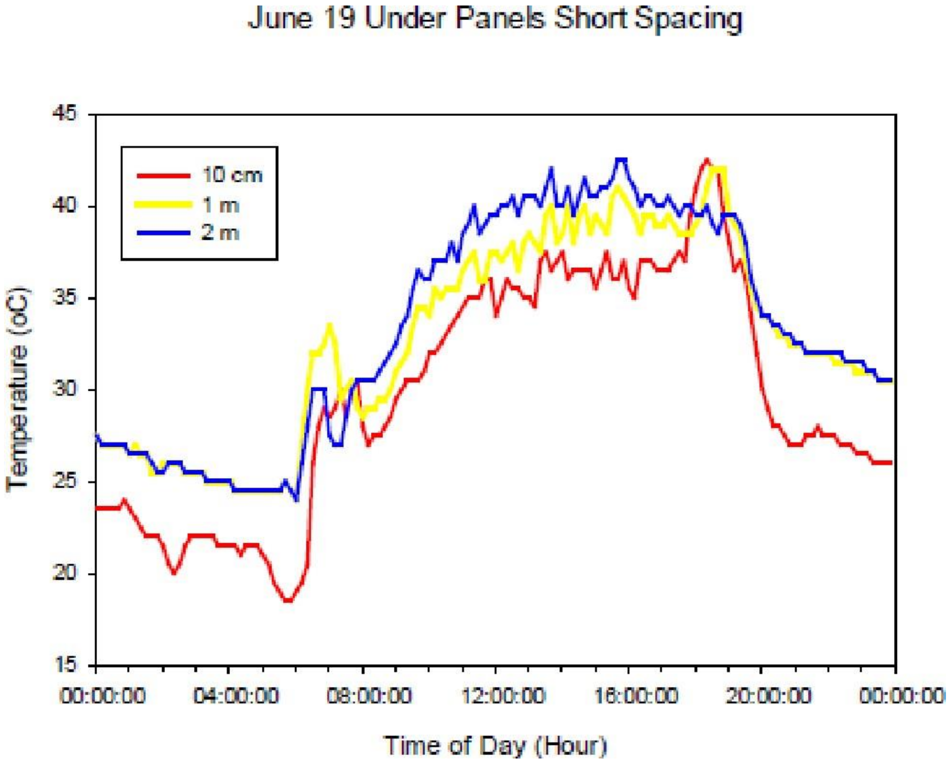
June 19 Under Panels Short Spacing

Figure 5. Air temperature measurements at an i-button tower located underneath the solar *panels* in the short spacing.

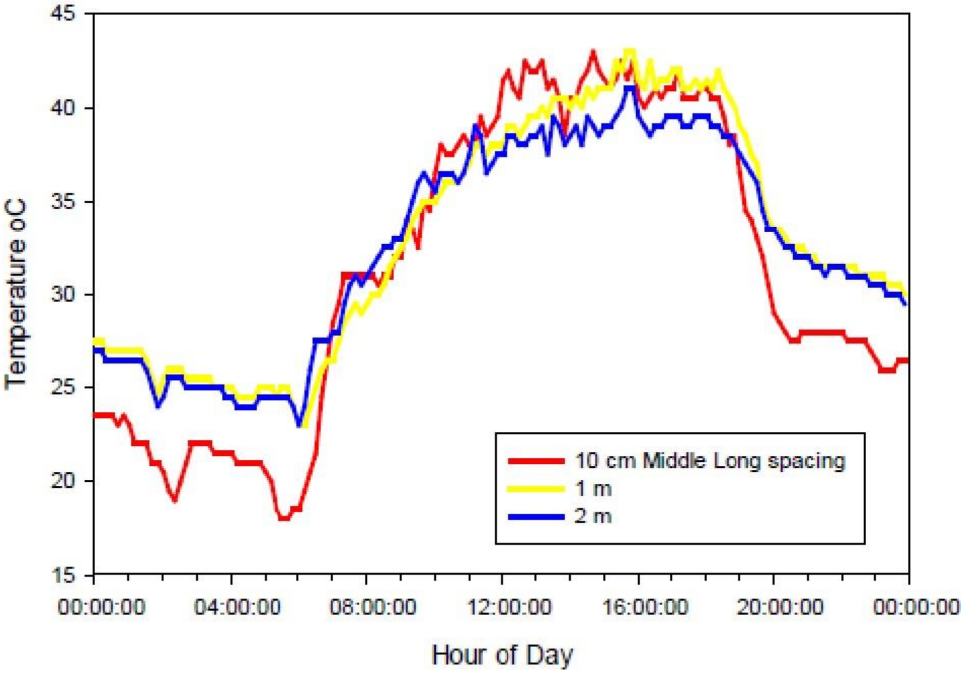

Figure 6. Air temperature readings at an i-button tower between the solar panels in the long spacing.

3.1.6. Heat Index

The heat index revealed that plants growing between the panels in the short spacing experienced a higher heat index than those in other locations on 5 April 2020 ($p < 0.001$)

and almost all locations on 5 October 2019 ($p = 0.01$, Figure 9). The heat indexes underneath the panels in the short and long spacing were the lowest compared with other locations ($p < 0.001$) during most of the period between June to October of both 2019 and 2020. Although 2020 was a dry year vs. 2019, the heat index moved off the baseline at about the same time, but the heat index began to separate earlier in 2020. In 2020, the heat index returned to baseline two weeks later, with higher values (>900) during peak summer.

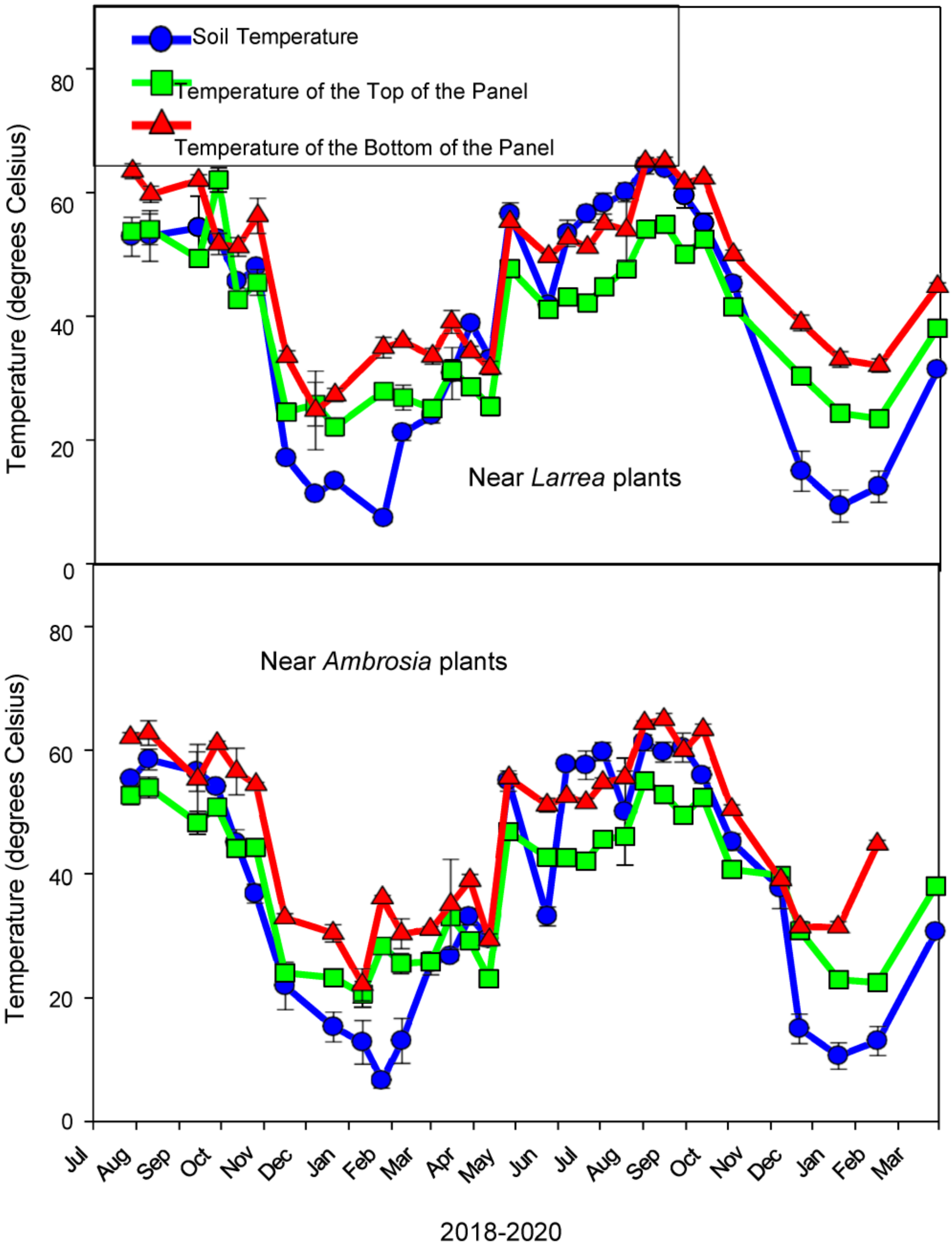

Figure 7. Temperatures of the top and bottom of solar panels as well as the soil temperature at the drip line, all significantly different at $p < 0.001$. Values are means plus or minus one standard error.

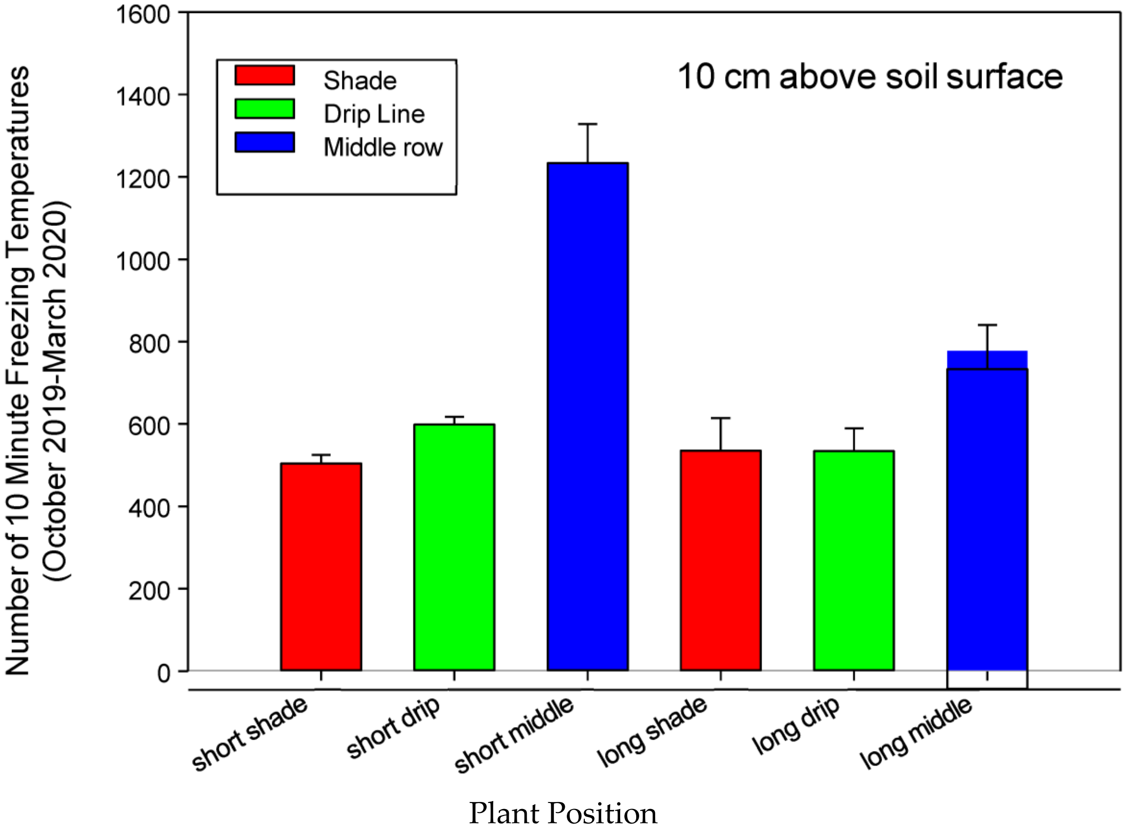

Figure 8. The number of times the i-buttons reached a freezing temperature during 10-min periods at different locations throughout the solar facility from October 2019 through March 2020. Middle-row positions had a significantly higher ($p < 0.001$) number of freezing temperatures during the winter of 2019–2020.

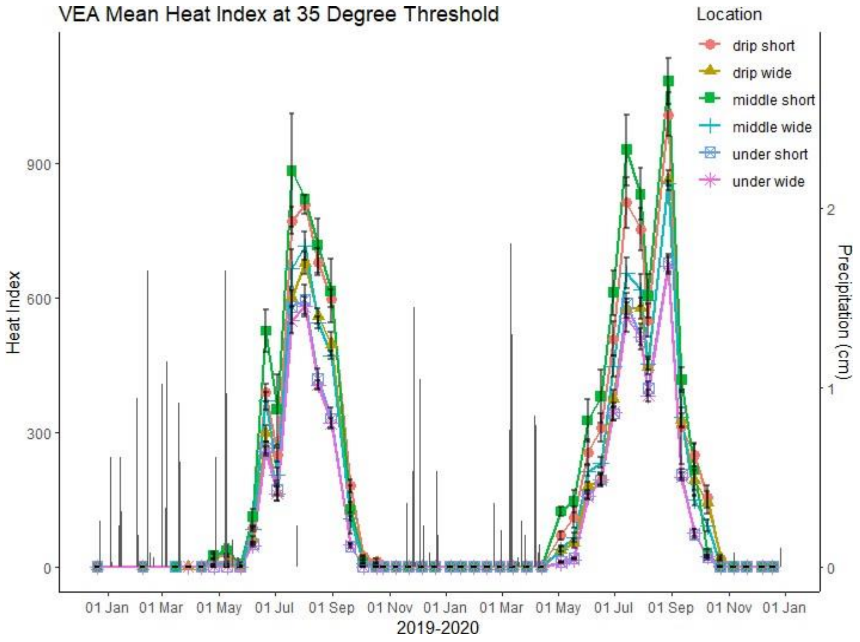

Figure 9. Heat index calculated with a 35-degree threshold for the two-year period of 2019 and 2020 at different locations throughout the solar facility. Precipitation values are included, which were obtained from a central weather station located in the solar photovoltaic facility.

Ambrosia dumosa's δ^{13} Carbon in the leaf tissue and seed weight was correlated with the area under the curve (AUC) of the heat index taken for the research locations within the facility ($p < 0.001$, $R^2 = 0.53$; $p < 0.001$, $R^2 = 0.51$). *Larrea*'s morphological and physiological attributes revealed poor correlations with the AUC of the heat index, with the exception of leaf thickness of *L. tridentata*, which revealed a significant correlation with the AUC of the heat index ($p = 0.02$ $R^2 = 0.33$) with lower leaf thickness associated with higher heat index values.

3.2. Biotic Responses

3.2.1. Leaf Xylem Water Potential

Leaf xylem water potential (l_{xwp}) can be a good indicator of plant water status, with more negative values representing greater water deficits. The l_{xwp} of *L. tridentata* was significantly higher inside the facility than at outside control locations ($p < 0.001$) during July 2018–December 2019. All *L. tridentata* plants outside were also significantly lower in l_{xwp} (<-6 MPa) compared with plants inside the facility (>-4.5 MPa) in December 2020, except the plants in the long spacing between panels (-3.9 ± 1.5 MPa). *A. dumosa* plants went dormant outside the facility during the winter months, whereas inside the facility, the plants stayed green and active for 12 months out of the year (although reduced in activity during winter months). During the active growing period, there were no statistical differences in the l_{xwp} of *A. dumosa* based on location ($p > 0.05$). The mean ± standard deviation of *A. dumosa* l_{xwp} during the active growing period was -2.7 ± 2.3 MPa.

3.2.2. Stored Sugars and Starch

At the end of the three-year monitoring period (spring), stem and root tissue was harvested from all test plants inside and outside of the solar facility for starch and sugar analysis. No statistical differences were found in the starch and sugar contents of the plant parts; as such, stems and roots were combined for statistical analysis. *Ambrosia dumosa* growing inside the facility that remained active year-round had greater amounts of stored starch in the stems and roots than the plants outside the facility, which were dormant for 56% of the experimental period (Figure 10, $p = 0.04$)). *L. tridentata* did not show significantly higher starch based on position or when compared with *A. dumosa* (Figure 10, $p > 0.05$), with the exception of the control plants. Differing from the starch, the sugar contents (glucose, fructose, and galactose) of the stems and roots were not significantly different for *A. dumosa* or for *L. tridentata* at the various locations.

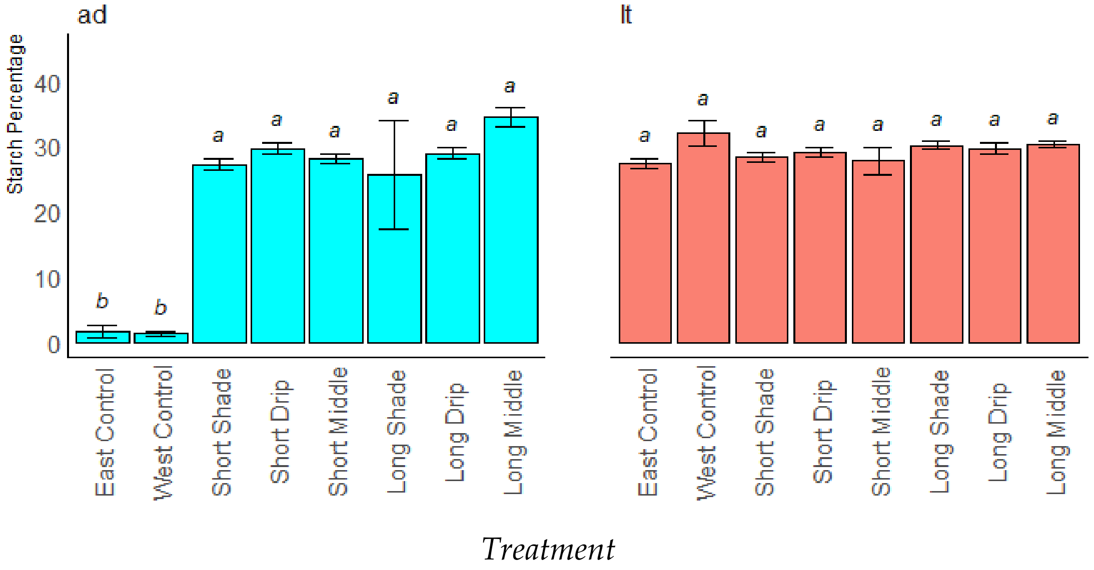

Figure 10. *Ambrosia dumosa* (ad) and *Larrea tridentata* (lt) starch content of both stems and roots combined inside the solar facility at various locations and outside the facility at the control sites. Letters denote significant differences at the $p < 0.05$ level.

3.2.3. δ^{13} Carbon

Carbon isotope data were used to indirectly assess water use efficiency (WUE, 40), which was higher (the water stress was greater) outside the facility than inside the facility (*A. dumosa* $p < 0.001$, *L. tridentata* $p = 0.02$). Both *L. tridentata* and *A. dumosa* had the most negative δ^{13} C values in the tissue of the plants growing in the shade underneath the panels, suggesting that the plants were the least water efficient in the shade where there was less water stress. In the fall of 2020, WUE measurements assessed using the LI-COR 6400 (photosynthesis/conductance) were found to be highly correlated with δ^{13} C values ($R^2 = 0.72$, $p = 0.02$), as were stomatal conductance values with δ^{13} C ($R^2 = 0.47$, $p < 0.001$). Species also differed in the amount of δ^{13} C, with *Larrea* having higher (more positive) values (−32 to −27) than *A. dumosa* (−34 to −28) ($p < 0.001$).

The percentage of carbon in the tissue varied by plant position ($p < 0.001$). *L. tridentata* growing between panels (middle) had the highest percent carbon (48%), associated with higher PAR.

3.2.4. Chlorophyll Index

Chlorophyll index values for *L. tridentata* in August 2019–January 2020 inside the facility were significantly higher than the east and west control plants (p-value < 0.001), except in the short spacing underneath the panels (Figure 11). Low light under the panels may have altered the readings; (under controlled conditions we measured a 6% increase in values on plants growing in the shade vs. the same plants in direct light) we report the values with this limitation. During the winter months, *L. tridentata* inside the facility appeared greener (Figure 12), whereas outside the facility, plants lost most of their spring green color, and the leaves appeared brown in color. This was reflected in the chlorophyll index that was measured (Figure 11). Few *L. tridentata* chlorophyll index values of control plants or shade plants exceeded 150, which was chosen as a reference level. In contrast, plants near the drip line or in the middle row positions had values consistently over 150. *Ambrosia dumosa* plants outside the facility were dormant during the winter and did not possess leaves during this period (Figure 13). *Ambrosia* has a lighter color green and only reached chlorophyll index values of 150 during spring. *Ambrosia dumosa* east and west control plants had chlorophyll index values that were significantly lower during the summer of 2019 than at all other locations (p-value < 0.001). *A. dumosa* chlorophyll index values (Figure 14) measured between panel rows and at the drip position in the short and long spacing, were significantly higher than values measured on plants underneath the panels (June–December 2019, $p < 0.05$).

Canopy Temperature Minus Ambient Temperature

Temperature differences between the canopy and ambient air (t_c-t_a) reflect the extent of leaf/canopy cooling via transpiration. Usually, a higher canopy temperature than ambient air suggests that the plants have low transpiration and are under increased levels of water stress. *Larrea tridentata* did not reveal statistical differences in t_c-t_a between plants growing outside and inside the facility ($p = 0.14$), with the majority (93%) of values ranging from −5 to +5 °C. *Ambrosia* plants sometimes had a t_c-t_a greater than 10 °C, although the majority (90%) were between −5 and +5 °C. *Ambrosia* plants growing underneath the panels had statistically higher t_c-t_a values ($p < 0.05$) compared with plants located in the middle of the row.

Stem Elongation

Stem elongation was measured only on *L. tridentata* plants because of herbivory on *A. dumosa* plants, with significantly lower elongation in control plants compared with plants growing inside the facility ($p < 0.001$). The greatest growth was observed in the shorter spacing at all plant panel positions and in the long spacing underneath the panels (Figure 15). The higher elongation associated with the shade locations suggested etiolation as a factor, whereas stem elongation declined between and at the drip line in the wider spacing ($p = 0.05$). Stem elongation for the short spacing averaged greater than 30 cm, while the control plants averaged under 5 cm during the study period ($p < 0.001$).

Stomatal Density

Stomata density was measured only in *L. tridentata* plants because of difficulties in obtaining flat impressions of *A. dumosa* stomata. The lowest stomatal densities of *L. tridentata* plants were in plants growing at the control sites; however, only the west control plants had a significantly lower number of stomata than plants growing inside the solar facility ($p < 0.001$).

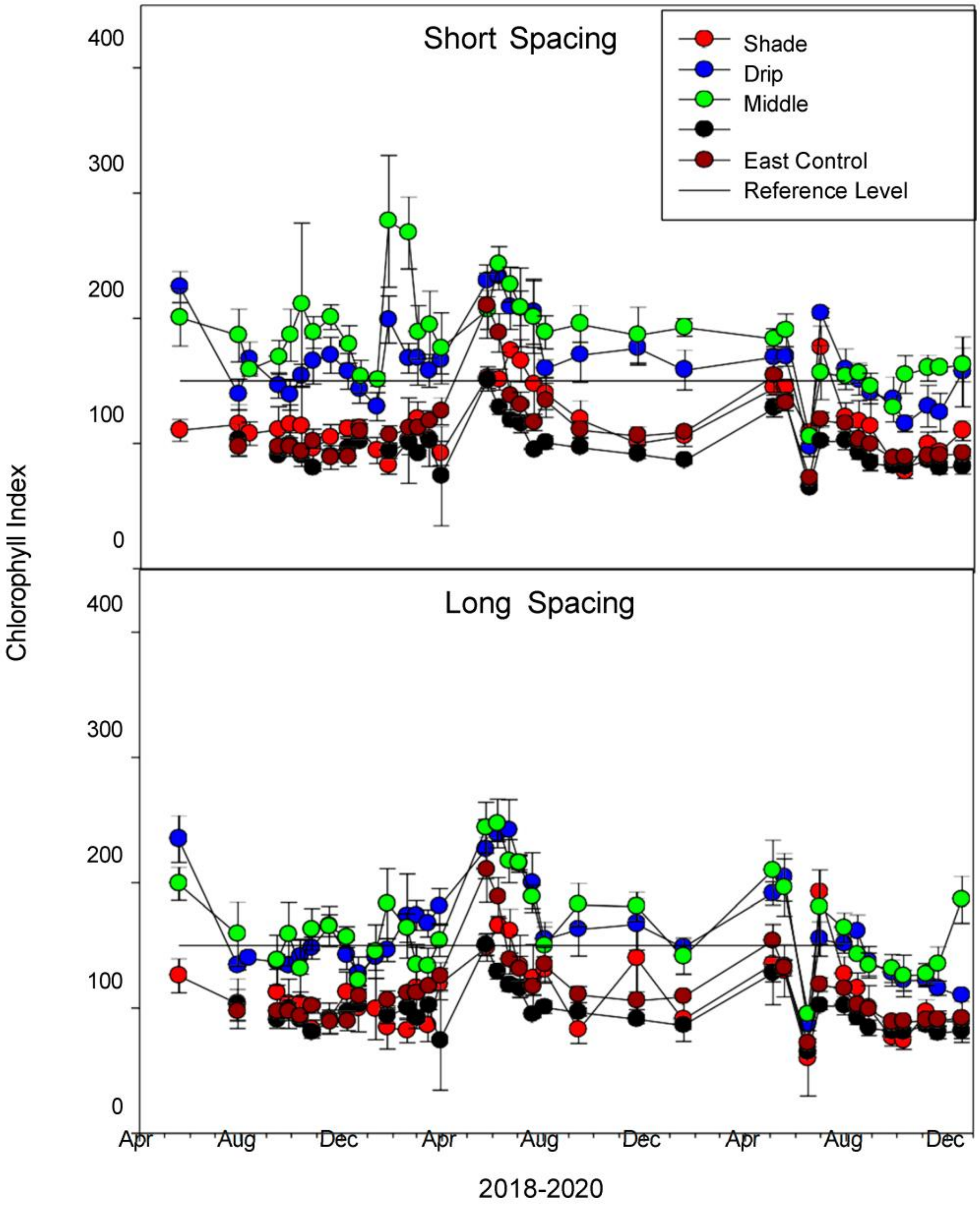

Figure 11. Chlorophyll index for Larrea tridentata at multiple locations inside and outside the solar facility. Y = 150 was marked as a reference line for other measurements. Points are means with plus or minus one standard error.

Figure 12. Larrea tridentata outside (**left**) and inside (**right**) of the solar facility in December 2019.

Figure 13. Ambrosia dumosa outside (**bottom**) and inside (**top**) of the solar facility in December 2019.

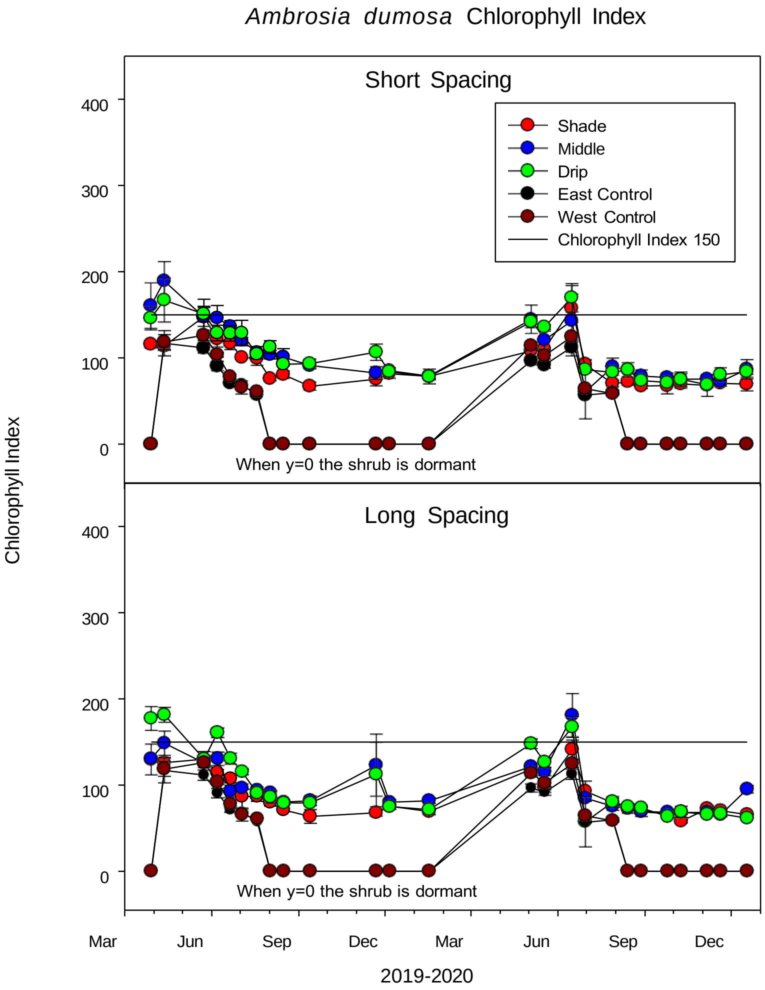

Figure 14. Chlorophyll index for Ambrosia dumosa at multiple locations inside and outside the solar facility. Y = 150 was marked as a reference line for other measurements. Points are means with plus or minus one standard error.

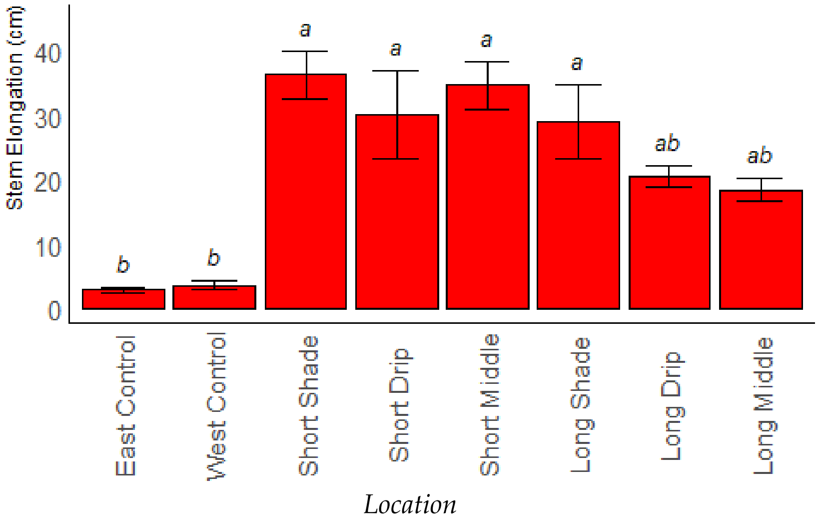

Figure 15. Growth of stems of Larrea tridentata over the two-year monitoring period separated by panel spacing and plant position. All plants inside the facility had significantly more stem elongation than the control plants, except for long drip and long middle ($p < 0.001$). Letters denote significant differences at the $p < 0.05$ level.

Seed Yield

Ambrosia dumosa seed weights were lowest underneath the panels and at the adjacent undisturbed control locations ($p = 0.05$). *Ambrosia dumosa* had higher seed weights at the drip line and between panel row positions in the short spacing compared with all other locations ($p < 0.05$). However, with *L. tridentata*, the average seed yield had no statistical difference between the plants within the facility vs. those at control locations ($p > 0.05$).

Tissue Ion Concentrations

Larrea tridentata leaf tissue ion concentrations were statistically lower than *A. dumosa* tissue ion concentrations ($p < 0.001$, except for Mn at $p = 0.04$). *Larrea* showed statistical differences in leaf tissue concentrations of Mn, Mo, and Zn when comparing control plants with plants growing inside the facility at panel positions (lower concentrations in control plants). In *A. dumosa*, N, K, S, Mg, Zn, Fe, and Mo were statistically different ($p < 0.001$) depending on plant position, with N, K, S, Mg, and Mo having lower concentrations in the tissues of the control plants. *Ambrosia* had higher Fe concentrations in control plants than in other plant positions ($p < 0.001$), whereas Zn revealed higher concentrations in plants located below the panels ($p < 0.001$).

Multiple regression analysis revealed that most macro- and micronutrient concentrations could be described by a combination of other macro- and micronutrients (restricting the number of nutrients in the equations to 4, with no co-correlation (VIF < 2.0, Table 4)). For example, in the case of *A. dumosa,* all but Ca and B had R^2 values between 0.52 and 0.78 ($p < 0.001$), such as $\%N = 0.71 + 5.48P + 5.03S - 0.005B$ ($R^2 = 0.78$, $p < 0.001$). Multiple regression equations for *L. tridentata* had R^2 values that ranged from 0.38 to 0.51 (p ranging from <0.001 to 0.03), such as $\%N = 1.02 + 10.13P$ ($R^2 = 0.51$, $p < 0.001$). It should be noted that the highest correlations between nutrient concentrations for *L. tridentata* included P, whereas in *A. dumosa*, it included B.

Table 4. Leaf tissue nutrient correlations.

Variable	**Species**
Seed Weight	*L. tridentata* $Y = 9.76 + 0.027Fe - 1.36\ Cu$ $R^2 = 0.49$ $p < 0.001$
	A. dumosa $Y = 138.2 - 40.4K - 8.03Ca + 151.7Mg + 1.71Mn$ $R^2 = 0.56$ $p = 0.004$
Δ Height	*L. tridentata* $Y = 39.84 - 7.34$ position $- 127.2S + 76.1Mg$ $R^2 = 0.58$ $p < 0.001$
Δ Height	*A. dumosa* $Y = -15.16 + 0.56Zn + 12.58Mo$ $R^2 = 0.59$ $p < 0.001$
Stem Elongation	*L. tridentata* $Y = 51.88 - 9.10$ position $- 13.9K + 0.27Mn$ $R^2 = 0.70$ $p < 0.001$
Species Effect	*A. dumosa* Concentrations of all macro and micronutrients were higher inside facility ($p < 0.001$)
Position Effect	
Nutrient concentrations *A. dumosa* lower in the outside control plants; N, K, S, Mg, and Mo ($p < 0.001$)	
Correlations between nutrient concentrations. Highest three R^2 values for each species.	
L tridentata $\%N = 1.02 + 10.13P$, $R^2 = 0.51$, $p < 0.001$	
L. tridentata $\%P = -0.0004 + 0.0524\ N$, $R^2 = 0.51$, $p < 0.001$	
L. tridentata Mo (ppm) $= 1.024 + 10.129P$ $R^2 = 0.51$, $p < 0.001$	
A. dumosa $\%K = -0.373 + 0.85N - 0.006B + 0.543Mo$, $R^2 = 0.84$, $p < 0.001$	
A. dumosa $\%N = 0.71 + 5.48P + 5.03S - 0.005B$ $R^2 = 0.78$, $p < 0.001$	
A. dumosa $\%S = -0.027 + 0.81K + 0.001B$ $R^2 = 0.77$, $p < 0.001$	

The regression analysis revealed that some nutrients were correlated with growth, spacing, and position. Seed weight for *L. tridentata* was correlated with position ($R^2 = 0.35$, $p = 0.004$) and based on Fe and Cu ($R^2 = 0.49$, $p < 0.001$), whereas seed weight was poorly correlated with a change in height, canopy volume, and stem elongation. *L. tridentata* nutrient concentrations were highly correlated with a change in height ($R^2 = 0.58$, $p < 0.001$), change in canopy volume ($R^2 = 0.56$, $p < 0.001$), and stem elongation ($R^2 = 0.70$, $p < 0.001$). However, with *A. dumosa,* plant seed weight did not correlate with spacing or position. *Ambrosia* seed weight was, however, correlated with macro- and micronutrients, with higher seed weight associated with higher Mg and Mn concentrations ($R^2 = 0.56$, $p = 0.004$) and with positive changes in Zn and Mo ($R^2 = 0.59$, $p < 0.001$). In *Larrea*, only Mg in combination with position was found to be linearly correlated with a positive change in height ($R^2 = 0.58$, $p = 0.001$).

Survival of Transplants

Seedlings of *L. tridentata*, *A. dumosa*, and *Encelia virginensis* were established at panel/spacing locations within the study area of the solar facility. The survival of the transplanted seedlings varied depending on the species and the spacing ($p < 0.05$, Figure 16). Herbivory was observed on *E. virginensis* and *A. dumosa, which led to the death of plants in the short spacing. Ambrosia dumosa* had 67 percent survival in the long spacing, whereas *E. virginensis* had 0 percent survival in the short spacing three years after transplanting. Such results may have been related to predator–prey relationships, as dead rabbits were found in the long spacing but not in the short spacing, suggesting that the shorter spacing provided more visual cover for prey from carnivores such as coyotes, leading to greater herbivory.

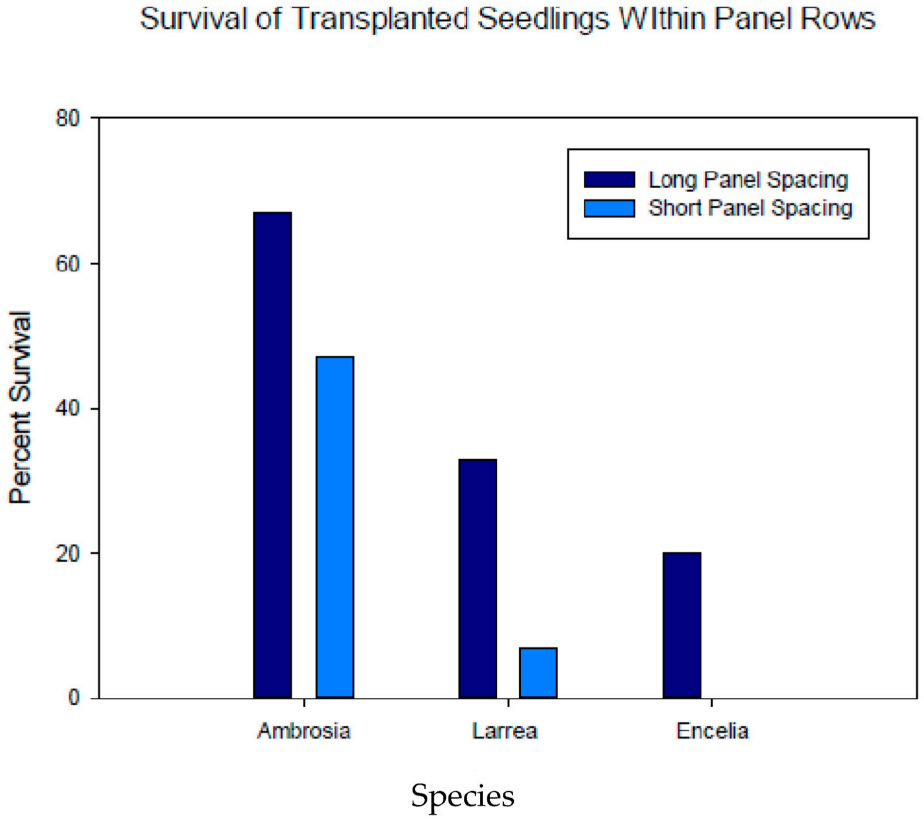

Figure 16. Percentage survival for three species of plants Ambrosia dumosa (Ambrosia), Larrea tridentata (Larrea), and Encelia virginensis (Encelia) assessed over the monitoring period. Data were combined on the basis of species, not panel spacing location.

4. Discussion

Minimizing the impact of solar photovoltaic facilities on desert ecosystems requires an integrated biological approach [21,24,45], such as through conserving native plants while also maintaining wash connectivity [13]. This multiyear study monitored the growth and physiological status of the desert shrubs *L. tridentata* and *A. dumosa* growing inside and outside of a solar photovoltaic facility, that left plants in place and minimized the impact on the structural integrity of washes flowing inside the facility (ecovoltaic system). Larrea and Ambrosia plants were selected because they were the dominant plants at the site and because they represent the dominant plant community in the Mojave Desert, providing the majority of cover for smaller animal life. The results of this study support a paradigm shift in how solar facilities in the desert should be built in the future. However, the actual position of plants relative to the panels and spacing was shown to have a significant impact on plant responses, especially on the plants located below panels, where they did not fare as well. Photos capturing the growth response of both species inside and outside of the solar facility provided powerful documentation of the overall positive effect the solar panels had on both species. Although the area under the panels provided shade in the summer and warmer temperatures in the winter, as also reported by Armstrong [32] and Yue [46], the PAR was reduced by as much as 85%, causing the plants growing under the panels to be spindly, with lower canopy volumes (*L. tridentata*, $p = 0.03$) and seed yields (*A. dumosa*, $p = 0.05$). However, others [34,35] have documented shade tolerance with some species, with increased light-use efficiency of wheat and improved radiation interception efficiency and increased leaf area of lettuce under the shade of solar panels, while Armstrong [32] reported that certain forbs and grasses fared better under solar panels.

Ambrosia dumosa remained green in color year-round inside the facility. The *A. dumosa* plants growing in the facility stored more starch in the stems and roots compared with the plants growing at the outside control sites. These higher starch levels were directly related to the retention of leaves and continued photosynthesis on a year-round basis inside the solar facility. This negates one of our hypotheses that inside the facility, both species would deplete stored starch and decline in health when the plants were in highly shaded locations. The plants growing under the panels were smaller in stature, but they did not have lower levels of starch. The long-term effects of the functionally evergreen status of *A. dumosa* associated with a solar facility need to be studied in greater detail.

Larrea tridentata plants growing outside the facility had lower xylem water potentials compared with those inside the facility, a lower chlorophyll index (*A. dumosa* as well), and lower stem elongation, supporting the conclusion that both *L. tridentata* and *A. dumosa* performed better inside the facility than outside. A positive plant response inside the solar facility was also related to rainwater harvesting from the panels, combined with reduced solar radiation striking the soil surface under the panels. The washes were irregular in shape and depth, with some running parallel to the panels and other washes cutting below multiple panel rows. The results of this study are in agreement with Schwinning et al. [47] and Devitt et al. [13], which found that washes play a critical role in maintaining the overall health of desert habitats and ecosystems.

A shift in the δ^{13} C suggested greater water use efficiency at the locations with the least amount of soil water storage. Water use efficiencies were shown by Wright et al. [48] to be influenced by leaf morphological changes associated with light reception or water availability, factors that would be highly variable within solar facilities. Ehleringer and Cooper [39] reported higher water use efficiencies for *A. dumosa*, *E. virginensis*, and *A. salsola* at locations with less available water (wash, upland vs. slope). Contrary to our results, models in other studies suggested that shade would reduce transpiration and thus increase water use efficiency [34]. Our results are more in agreement with Schulz et al. [49], who reported that increased soil water would reduce plant water stress, leading to lower water use efficiency.

Plants at the drip line that received more precipitation due to runoff from the panels had increased soil moisture in the long spacing but not the short spacing. Other studies identified increased soil moisture at the edge of solar panels [36,37,50]. The short spacing inconsistency was associated with lower infiltration rates, leading to greater water runoff at the drip line and greater accumulation of water underneath the panels, all dependent on wash location. At the same time, plants in the shorter spacing (drip and mid-panel locations) had higher stem elongation and growth, which are typically associated with greater plant water use, which most likely played a significant role in reducing soil water in storage associated with the short panel locations (drip and mid-panel). More research is needed to quantify the dynamic environment in and around the panels, which could greatly influence environmental demand and plant water use [50]. Assessments of soil compaction and aggregate stability [51] also need to occur in association with the construction of solar facilities, as they will have long-term legacy effects, stressing the need for long-term monitoring.

Ambrosia dumosa plants growing inside the facility had higher N, K, S, and Mo in their leaves than plants growing outside the facility. Unlike Wright et al. [48], plants in the less stressful environment had higher N, suggesting that the plants inside the facility acquired the nutrients at a higher rate than plants outside the facility. These larger plants inside the facility may have acquired more nutrients through the development of larger root systems to enhance nutrient acquisition within a larger root zone, an unexplored research topic. Clearly, the plant response in this study cannot be explained by a single biotic or abiotic factor; instead, the responses were dynamically linked to many factors, such as PAR reduction, heat transfer, rainwater harvesting, panel row spacing, plant location, and species.

Marrou et al. [35], reported higher plant canopy temperatures during the morning in their solar array shaded treatments compared with outside controls. The higher temperatures in the shade in the winter in our study were associated with heat and longwave radiation that was transferred from the underside of the panels to the ambient air and soil surface underneath the panels, driving higher air temperatures. The average lower surface panel temperatures were 7.9 °C warmer than the upper surface panel temperatures. Other studies [52] have quantified that as much as 63% of incoming solar energy is transmitted through the panels, and this energy can be moved into adjacent plant communities [13,28].

The Marrou et al. study [35] reported higher temperatures under the panels at night but lower mean daytime temperatures in the shade. The heat index in our study showed that temperatures in the short spacing, especially between the panels, were hotter than those in other locations in the facility ($p < 0.001$).

Ideally, solar facilities will be placed on already disturbed land [15,16,24], such as brownfields [5] where native plants could be used to restore the disturbed areas within the facilities, reestablishing ecosystem services, even if diminished [24]. At our study site, *A. dumosa* would be recommended over the other species, but a mixed planting approach could be selected by adjusting the number of transplants of each species. Desert perennial grasses could also be good candidate restoration species.

The Pahrump Solar facility had desert tortoises that moved in and out of the site (personal observation). Rabbits, birds, and coyotes were also observed within the facility. Although Hoff and Marlow [27] reported desert tortoises avoiding roads, even dirt roads, they also reported that traffic was an important factor that must be considered. Traffic at our site was minimal, with very few vehicles observed during the three-year study. These observations are in contrast to a utility scale photovoltaic facility (~2.6 km^2) in Eldorado Valley (NV, USA), in which no plant or animal life was observed inside the panel rows during a multi-year study [13].

At a new facility in southern Nevada, which will become the largest solar facility in North America, native plants will be left intact but mowed at different heights with no relocation of desert tortoise during the construction phase (personal communication). Research is needed to compare the results from different solar facilities that differ significantly on a spatial scale to determine what information is transferable, especially when dealing with long-lived shrubs such as Larrea tridentata (~300 years in the Sonoran Desert [53]) and animals such as the desert tortoise (15–50+ years [54]).

5. Concluding Comments

The results from this study will contribute to a shift in how solar facilities are constructed and maintained in arid regions. Solar development should occur only within desert ecosystems that are not fragile and sensitive to change [15,16,24,45]. When possible, restoration within solar facilities should also occur with the transplanting of native species between the panel rows but not under the panels, unless the panels are part of a solar tracking system. Our results support the installation of solar facilities that minimize the impact on native plants and wash connectivity, which should translate into reduced impact at the habitat and ecosystem level. Research by Devitt et al. [13] quantified the impact of decoupling a wash system, leading to declines in soil moisture, canopy level NDVI, and plant water status. Because the shorter spacing panels provided better growing conditions for both plant species at our research site, a recommendation would be for the shorter spacing, which should lead to greater profitability with the placement of more panels per unit area.

Deserts provide ecosystem services that are not always fully recognized [19]. If unrecognized, cost–benefit analysis would not provide a fair assessment [55]. Optimizing energy production while also protecting habitats and ecosystems is possible if site selection, construction, and maintenance embrace both biological and engineering solutions [20,45].

Where water is available (precipitation and irrigation), agrivoltaic systems [56,57] have been shown to increase overall land productivity. However, in Southern Nevada, which receives only about 10 cm of precipitation per year and where water is a limited resource, agrivoltaics may not be appropriate, but ecovoltaic systems, such as the one reported on in this study, would be a viable option, as they would provide acceptable habitat compared with unaltered control sites based on plant response, microenvironments, and water redistribution. For energy companies that embrace ecovoltaic systems and thus do not require the sacrifice (clearing) of large tracts of land for energy development, the permitting process should be streamlined with fewer restrictions if the systems provide renewable energy without the loss of ecosystem services.

Author Contributions: Conceptualization, D.A.D.; Methodology, T.W.-S. and D.A.D.; Formal Analysis, T.W.-S. and D.A.D. Writing, T.W.-S., D.A.D. and S.D.S.; Review and editing, D.A.D., T.W.-S. and S.D.S. All authors have read and agreed to the published version of the manuscript.

Funding: Valley Electric Association of Pahrump, NV.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Scheffer, M.; Carpenter, S.; Foley, J.A.; Folke, C.; Walker, B. Catastrophic shifts in ecosystems. *Nature* **2001**, *413*, 591–596. [CrossRef]
2. Andrews, A. Fragmentation of Habitat by Roads and Utility Corridors: A Review. *Aust. Zool.* **1990**, *26*, 130–141. [CrossRef]
3. Fahrig, L. Effects of Habitat Fragmentation on Biodiversity. *Annu. Rev. Ecol. Evol. Syst.* **2003**, *34*, 487–515. [CrossRef]
4. Lovich, J.E.; Ennen, J.R. Wildlife Conservation and Solar Energy Development in the Desert Southwest. *USA Biosci.* **2011**, *61*, 982–991. [CrossRef]
5. Devitt, D.A.; Young MHPierre, J.P. Assessing the potential for greater solar development in West Texas, USA. *Energy Strategy Reviews* **2020**, *29*, 100490. [CrossRef]
6. Bolling, J.D.; Walker, L.R. Plant and Soil Recovery along a Series of Abandoned Desert Roads. *J. Arid. Environ.* **2000**, *46*, 1–24. [CrossRef]
7. Vasek, F.C.; Johnson, H.B.; Brum, C.D. Effects of power transmission lines on vegetation of the Mojave Desert. *Madrone* **1975**, *23*, 114–130.
8. Webb, R.H.; Wilshire, H.G. *Environmental Effects of Off-Road Vehicles: Impacts and Management in arid Regions*; Springer Series on Environmental management; Springer: New York, NY, USA, 1983.
9. Lovich, J.E.; Bainbridge, D. Anthropogenic Degradation of the Southern California Desert Ecosystem and Prospects for Natural Recovery and Restoration. *Environ. Manag.* **1999**, *24*, 309–326. [CrossRef] [PubMed]
10. Liu, Y.; Zhang, R.Q.; Huang, Z.; Cheng, Z.; López-Vicente, M.; Ma, X.R.; Wu, G.L. Solar photovoltaic panels significantly promote vegetation recovery by modifying the soil surface micro habitats in an arid sandy ecosystem. *Land Degrad. Dev.* **2019**, *30*, 2177–2186. [CrossRef]
11. Moriarty, P.; Honnery, D. Ecosystem maintenance energy and the need for a green EROI. *Energy Policy* **2019**, *131*, 229–234. [CrossRef]
12. Northrup, J.M.; Wittemyer, G. Characterising the impacts of emerging energy development on wildlife, with an eye towards mitigation. *Ecol. Lett.* **2012**, *16*, 112–125. [CrossRef]
13. Devitt, D.A.; Apodaca, L.; Bird, B.; Dawyot, J.P.; Fenstermaker, L.; Petrie, M.D. Assessing the Impact of a Utility Scale Solar Photovoltaic Facility on a Down Gradient Mojave Desert Ecosystem. *Land* **2022**, *11*, 1315. [CrossRef]
14. Tsoutsos, T.; Frantzekaki, N.; Gekas, V. Environmental Impacts from the Solar Energy Technologies. *Energy Policy* **2005**, *33*, 289–296. [CrossRef]

15. Cameron, D.R.; Cohen, B.S.; Morrison, S.A. An Approach to Enhance the Conservation-Compatibility of Solar Energy Development. *PLoS ONE* **2012**, *7*, 38437. [CrossRef] [PubMed]
16. Hernandez, R.R.; Hoffacker, M.K.; Field, C.B. Efficient use of land to meet sustainable energy needs. *Nat. Clim. Change* **2015**, *5*, 353–358. [CrossRef]
17. Hernandez, R.R.; Hoffacker, M.K.; Murphy-Mariscal, M.L.; Wu, G.C.; Allen, M.F. Solar energy development impacts on land cover change and protected areas. *PNAS* **2015**, *112*, 13579–13584. [CrossRef] [PubMed]
18. Fthenakis, K. Land Use and Electricity generation: A life-cycle analysis. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1465–1474. [CrossRef]
19. McClung, M.R.; Moran, M.D. Minimizing impacts of future renewable energy development on the worlds desert ecosystems. *Front. Sustain.* **2022**, *3*, 900468. [CrossRef]
20. Hernandez, R.R.; Cagle, A.E.; Grodsky, S.M.; Exley, G.; Jordan, S.M. Comments on: Land use for United States power generation: A critical review of existing metrics with suggestions for going forward. *Renew. Sustain. Energy Rev.* **2021**, *143*, 110911.
21. Hernandez, R.R.; Armstrong, A.; Burney, J.; Ryan, G.; Moore-O'leary, K.; Diédhiou, I.; Grodsky, S.M.; Saul-Gershenz, L.; Davis, R.; Macknick, J.; et al. Techno–ecological synergies of solar energy for global sustainability. *Nat. Sustain.* **2019**, *2*, 560–568. [CrossRef]
22. Parker, S.S.; Cohen, B.S.; Moore, J. Impact of solar and wind development on conservation values in the Mojave Desert. *PLoS ONE* **2018**, *13*, e0207678. [CrossRef] [PubMed]
23. Popcewicz, J.A.; Copeland, H. Potential impacts of energy development on shrublands in western North America. *Nat. Resour. Environ.* **2011**, *17*, 93–97.
24. Grodsky, S.M.; Hernandez, R.R. Reduced ecosystem services of desert plants form ground-mounted solar energy development. *Nat. Sustain.* **2020**, *3*, 1036–1043. [CrossRef]
25. Rao, L.E.; Allen, E.B. Combined effects of precipitation and nitrogen depositon. *Oecologia* **2010**, *162*, 1035–1046. [CrossRef] [PubMed]
26. Yavari R., D.; Zaliwciw, D.; Cibin, R.; McPhillips, L. Minnimizing environmental impacts of solar farms: A review of current science on landscape hydrology and guidance on stormwater management. *Environ. Res. Infrastruct. Sustain.* **2022**, *2*, 032002. [CrossRef]
27. Von Seckendorff Hoff, K.; Marlow, R.W. Impacts of Vehicle Road Traffic on Desert Tortoise Populations with Consideration of Conservation of Tortoise Habitat in Southern Nevada. *Chelonium. Conserv. Biol.* **2002**, *4*, 449–456.
28. Barron-Gafford, G.A.; Minor, R.L.; Allen, N.A.; Cronin, A.D.; Brooks, A.E.; Pavao-Zuckerman, M.A. The Photovoltaic Heat Island Effect: Larger solar power plants increase local temperatures. *Sci. Rep.* **2016**, *6*, 35070. [CrossRef] [PubMed]
29. Hulin, V.; Delmas, V.; Girondot, M.; Godfrey, M.H.; Guillon, J.M. Temperature-dependent sex determination and global change: Are some species at greater risk? *Oecologia* **2009**, *160*, 493–506. [CrossRef]
30. Graham, M.; Ates, S.; Melathopoulos, A.P.; Moldenke, A.R.; Debano, S.J.S.; Bes, L.R.; Higgins, C.W. Floral abundance during the late=season pollinators in a dryland, agrivoltaic ecosystem. *Sci. Rep.* **2021**, *11*, 7452. [CrossRef]
31. Chock, R.Y.; Clucas, B.; Peterson, E.K.; Blackwell, B.F.; Blumstein, D.T.; Church, K.; Fernández-Juricic, E.; Francescoli, G.; Greggor, A.L.; Kemp, P.; et al. Evaluating potential effects of solar power facilities on wildlife from an animal behavior perspective. *Conserv. Sci. Pract.* **2021**, *3*, e319. [CrossRef]
32. Armstrong, A.; Ostle, N.J.; Whitaker, J. Solar park microclimate and vegetation management effects on grassland carbon cycling. *Environ. Res. Lett.* **2016**, *11*, 074016. [CrossRef]
33. Tanner, K.E.; Moore-O'Leary, K.A.; Parker, I.M.; Pavlik, B.M.; Hernarndez, R.R. Simulated solar panels create altered microhabitats in desert landforms. *Ecosphere* **2020**, *11*, e03089. [CrossRef]
34. Dupraz, C.; Marrou, H.; Talbot, G.; Dufour, L.; Nogier, A.; Ferard, Y. Combining solar photovoltaic panels and food crops for optimizing land use: Towards new agrivoltaic schemes. *Renew. Energy* **2011**, *36*, 2725–2732. [CrossRef]
35. Marrou, H.; Wery, J.; Dufour, L.; Dupraz, C. Productivity and radiation use efficiency of lettuces grown in the partial shade of photovoltaic panels. *Eur. J. Agron.* **2013**, *44*, 54–66. [CrossRef]
36. Hassanpour, A.E.; Selker, J.S.; Higgins, C.W. Remarkable agrivoltaic influence on soil moisture, micrometeorology and water use efficiency. *PLoS ONE* **2018**, *13*, e0203256. [CrossRef] [PubMed]
37. Choi, C.S.; Cagle, A.E.; Macknick, J.; Bloom, D.E.; Caplan, J.S.; Ravi, S. Effects of Revegetation on Soil Physical and Chemical Properties in Solar Photovoltaic Infrastructure. *Front. Environ. Sci.* **2020**, *8*, 140. [CrossRef]
38. Wright, J.L. New Evapotranspiration crop coefficients. *J. Irrig. Drain. Eng. Div.* **1982**, *108*, 57–74. [CrossRef]
39. Ehleringer, J.R.; Cooper, T.A. Correlations between carbon isotope ratio and microhabitat in desert plants. *Oecologia* **1988**, *76*, 562–566. [CrossRef]
40. Ehleringer, J.R. Variation in leaf carbon isotope discrimination in *Encelia farinosa:* Implications for growth, competition, and drought survival. *Oecologia* **1993**, *95*, 340–346. [CrossRef]
41. Devitt, D.A.; Smith, S.D.; Neuman, D.S. Carbon isotope discrimination in three Landscape species growing in an arid environment. *J. Arid. Environ.* **1997**, *36*, 249–257. [CrossRef]
42. Landhäusser, S.M.; Chow, P.S.; Dickman, L.T.; E Furze, M.; Kuhlman, I.; Schmid, S.; Wiesenbauer, J.; Wild, B.; Gleixner, G.; Hartmann, H.; et al. Standardized protocols and procedures can precisely and accurately quantify non-structural carbohydrates. *Tree Physiol.* **2018**, *38*, 1764–1778. [CrossRef]
43. Hickman, J.C.; Jepson, W.L. *The Jepson Manual: Higher Plants of California*; University of California Press: Berkeley, CA, USA, 1993.

44. R Core Team 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available online: https://www.R-project.org/ (accessed on 10 October 2020).
45. Jordan, S.M.; Lee, J.; McClung, M.; Moran, M. Quantifying the ecosystem services values of electricity generation in eh US Chihuahuan Desert: Life cycle perspective. *J. Indus. Ecol.* **2021**, *25*, 1089–1101. [CrossRef]
46. Yue, S.; Guo, M.; Zou, P.; Wu, W.; Zhou, X. Effects of photovoltaic panels on soil temperature and moisture in desert areas. *Environ. Sci. Pollut. Res.* **2021**, *28*, 17506–17518. [CrossRef]
47. Schwinning, S.; Hooten, M.M. *Mojave Desert Root Systems. The Mojave Desert: Ecosystems Processes and Sustainability*; University of Nevada Press: Reno, NV, USA, 2009; pp. 278–311.
48. Wright, J.I.; Reich, P.B.; Westoby, M. Strategy Shifts in Leaf Physiology, Structure and Nutrient Content between Species of High-and Low-Rainfall and Higher- and Low-Nutrient Habitats. *Funct. Ecol.* **2001**, *15*, 423–434. [CrossRef]
49. Schulz, E.D.; Turner, N.C.; Nicolle, D.; Schumacher, J. Leaf and wood carbon isotope ratios, specific leaf areas and wood growth of Eucalyptus species across a rainfall gradient in Australia. *Tree Physiol.* **2006**, *26*, 479–492. [CrossRef] [PubMed]
50. Wu, C.; Liu, H.; Yu, Y.; Zhao, W.; Liu, J.; Yu, H.; Yetemen, O. Ecohydrological effects of photovoltaic solar farms on soil microclimates and moisture regimes in arid northwest China: A modeling study. *Sci. Total Environ.* **2022**, *802*, 149946. [CrossRef] [PubMed]
51. Lambert, Q.; Bischoff, A.; Cluchier, A.; Cueff, S.; Gros, R. Effects of solar park construction and solar panels on soil quality, microclimate, CO_2 effluxes and vegetation under a Mediterranean climate. *Land Degrad. Dev.* **2021**, *32*, 5190–5202. [CrossRef]
52. Levis, S.; Meehl, G.A.; Han, W.; Washington, W.M.; Oleson, K.W.; van Ruijven, B.J.; Strand, W.G. Impact of solar panels on global climate. *Nat. Clim.* **2016**, *6*, 290–294.
53. Bowers, J.E. Effects of drought on shrub survival and longevity in the northern Sonoran Desert. *J. Torrey Bot. Soc.* **2005**, *132*, 421–431. [CrossRef]
54. Curtin, A.J.; Zug, G.R.; Medica, P.A.; Spotila, J.R. Assessing age in the desert tortoise Gopherus agassizii: Testing skeletochronology with individuals of known age. *Endanger. Species Res.* **2008**, *5*, 21–27. [CrossRef]
55. Moore-O'Leary, K.A.; Hernandez, R.R.; Johnston, D.S.; Abella, S.R. Sustainability of utility-scale solar energy- critical ecological concepts. *Front. Ecol. Environ.* **2017**, *15*, 385–394. [CrossRef]
56. Mamun, A.M.A.; Dargusch, P.; Wadley, D.; Zulkarnain, N.A.; Aziz, A.A. A review of research on agrivoltaic systems. *Renew. Sustain. Energy Rev.* **2022**, *161*, 112351. [CrossRef]
57. Elamri, Y.; Cheviron, B.; Lopez, J.-M.; Dejean, C.; Belaud, G. Water budget and crop modelling for agrivoltaic systems: Application to irrigated lettuces. *Agric. Water Manag.* **2018**, *208*, 440–453. [CrossRef]