AN ABSTRACT OF THE THESIS OF

Maggie Graham for the degree of Master of Science in Water Resources Science presented on May 13, 2020.

Title: Pollinator-Focused Solar: Observations of Plant-Pollinator Interactions in the Agrivoltaic Understory.

Abstract approved:

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Chad Higgins

Habitat for pollinating insects is declining, which is a concern for agricultural communities that rely on pollination services. Meanwhile, solar energy development is increasing as communities seek to source energy renewably. Land under solar panels is traditionally unused, so some communities are planting pollinator habitat under solar panel canopies to maximize land-use efficiency. However, there are currently no published, peer-reviewed data on whether pollinators use habitat in this solar panel understory. We present a case study of plant-pollinator interactions at a solar energy generation site in southwestern Oregon, a water-limited, dryland ecosystem. Results show no difference in visitation rates of insects to flowers located inside versus outside the solar array. Panel shading did offset the bloom timing for some species, and flowers partially shaded under solar panels produced more blooms during the late season, a time when forage is typically low in this water-limited environment. These data can inform agriculture and pollinator health advocates as they seek land for pollinator habitat restoration in target areas, as well as local solar developers and homeowners deciding how to manage land beneath solar arrays.

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Pollinator-Focused Solar:
Observations of Plant-Pollinator Interactions
in the Agrivoltaic Understory

by
Maggie Graham

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APPROVED:

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Director of the Water Resources Graduate Program

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Maggie Graham, Author

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CONTRIBUTION OF AUTHORS

Dr. Chad Higgins assisted with conceptual design. Dr. Serkan Ates and Dr.Andony Melathopoulos assisted with experimental design and statistical analysis. Dr. Andy Moldenke assisted with insect species identification.

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DEDICATION

This thesis is dedicated in honor of my grandfather, Frank Bauman, an avid gardener, beekeeper, and science enthusiast.

1. Introduction

Pollinator habitat is declining. Pollinating insects are a cornerstone species of natural and agricultural ecosystems, providing pollination services to over 75% of the world's flowering plants[1], including 35% of global crops[2]. In the US alone, pollination services to agriculture are valued at over $14 billion annually[3]. Pollinator habitat is declining globally as a result of land use change, attributed in part to urbanization, agricultural intensification[4], and in some cases, energy development[5, 6].

During pollination, insects transfer pollen grains between flowers, facilitating plant reproduction. Ideal pollinator habitats are composed of a variety of flowering species with different shapes and colors that bloom during different seasons, creating a diverse array of forage options which extend over a long period of time [7]. As summers become warmer and dryer, drought conditions can impact floral abundance, decreasing the available forage for pollinators[8].

Solar energy development is increasing, while the understory is unused. Over the past decade, solar photovoltaic (PV) installation has increased by an average of 48% per year, and current capacity is expected to double again over the next five years[9]. PV can be installed on a variety of surfaces including built structures and open land or water, with sizes ranging from small, backyard residential sites to multi-acre utility-scale solar energy (USSE) systems. Installations on existing rooftops, parking lots, or degraded lands can minimize the conversion of undeveloped land in land-limited environments[10].

When vegetated land surfaces are used for installations (e.g. backyards, agricultural fields, deserts, rangelands), the land beneath the panels is traditionally managed to limit plant growth since tall plants would block sunlight, decreasing energy generation. This management may include removing the existing vegetation, then covering with gravel or turf grass[11]. Rarely is the understory space used as productive land.

Potential for mutual solar-agricultural benefit. Recent literature documents a variety of possible synergies between solar-agricultural systems[12], including pairing utility-scale solar sites with wildlife habitat to increase ecosystem services, notably pollination[6]. In 2018, 9% of all existing and planned USSE were within the insect foraging range (1.5 km) of croplands that could benefit from pollination services, amounting to 3,528 km^2 of agricultural land[11]. Concerns of zoning, aesthetics, and cultural preservation of agricultural lands have generated resistance to this idea in Oregon[13]. Meanwhile other states, such as Minnesota, North Carolina, Maryland, and Vermont, have embraced the concept of agrivoltaics (agriculture combined with solar photovoltaics[14]), developing incentives and guidelines to promote filling sub-panel real estate with forage for wild and managed pollinators[11].

Data gap in pollinator responses to solar. Despite a recent surge in pollinator-focused solar installations, there are no peer-reviewed data on how solar panel canopies impact pollinators and the flowers they pollinate. Recent studies document the response of forage grasses[15], vegetables[16, 17], and other crops to solar panel canopies, yet none have addressed floral abundance or insect populations. In dryland ecosystems, panel shading alters sunlight and soil moisture levels, creating a variety of microclimates within the solar understory[15]. Sunlight, water, and nutrients drive plant growth, which then impacts floral abundance and timing. Floral abundance and shade influence pollinator community structure[18, 19]. However, the relationship between shade, plants, and pollinators has not been formally documented within a solar array.

To address this knowledge gap, we present the first observational case study of plant-pollinator interactions within a ground-mounted photovoltaic solar energy generation site. During the summer of 2019, we documented the species abundance, richness, and diversity of floral blooms and pollinating insects at three locations within a restored native prairie planted beneath a solar array in a predominantly agricultural region of southern Oregon. The objectives of our study were to document the composition of pollinator and plant communities and to compare pollinator use of floral resources within and outside of the solar array. We hypothesized that while the plant species composition and bloom timing might differ among treatments, pollinators would forage indiscriminately on available floral resources.

2. Methods

Site Location. We conducted this study at the Eagle Point Solar Plant in Jackson County, Oregon (42°24' N, 122°50' W; Figure 1). This 40 acre site is located in the Rogue River Valley, west of the Cascade Mountains, and east of the Oregon Coast Range, within the traditional land of the Takelma peoples. The Rogue Valley is a predominantly agricultural region. Popular crops include wine grapes, pears, and other tree fruits. Site soils are composed of Coker clay (33A), Padigan Clay (139A), and Phoenix Clay (141A) soils, all of which are Non-irrigated Class 4w soils[20] (Web Soil Survey, 2020).

Local Climate. At 412m (1350 ft) of elevation, the site receives an average of 485mm[21] (19 in) of precipitation annually, and is considered a dryland, Mediterranean climate. The average growing season is from April 29th (last freeze) to October 17th (first frost) [22] with average monthly high and low temperatures ranging from 8 - 0°C (46 - 31°F) in January to 32 - 13°C (90 - 55°F) in July[21].

Solar Technology. The Eagle Point Solar Plant is a 10MW commercial solar generation site constructed in the fall of 2017 (Figure 2). The array consists of monocrystalline panels mounted on 3 m high racking with tracking systems. Light sensors in the trackers cause the panels to rotate, following the sun throughout the day. Rows of panels are oriented along a north-south gradient, with panels tracking from east to west. At the steepest angle of rotation (early morning, late evening), the lowest edge of the panel is approximately 1 m above the ground. When parallel with the ground (mid-day, sun overhead), the lowest edge of the panel is approximately 3 m above the ground.

Site Establishment. Prior to solar development, the site was used primarily for cattle grazing[23]. Site vegetation primarily consisted of non-native rhizomatous grasses. Small numbers of native and non-native forbs were also present at the site. The soils were highly compacted. During installation, all surface vegetation was removed, and surface soils were disturbed. In May 2018, clethodim was applied at 6 ounce/acre to portions of the site already occupied by native forbs, the remainder of the site was treated with glyphosate, applied at the manufacturer recommended rate. Additionally, bindweed was spot sprayed with glyphosate in June 2018. Manual removal of the highly invasive yellow starthistle (*Centaurea solstitialis*) occurred throughout the site in 2018 and 2019.

In October 2018, the site was restored with native vegetation to provide habitat for both wild and managed pollinators. The restoration species mix included a variety of annual and perennial forbs[23] (Appendix A), many grown from seed collected onsite or nearby. Apart from *Festuca roemeri*, native grass species were not introduced during the initial planting to allow for continued grass-specific herbicide use, but were planned for future installation. Additionally, an active apiary with 52 colonies was located along the southwest corner of the site, within flight distance of all survey locations (Figure 2).

Experimental Design. We collected observational data on pollinator and plant populations during seven field surveys in 2019, each spanning 2 days (June 11-12, July 2-3, July 14-15, July 30-31, August 13-14, August 27-28, and September 20-21). Field surveys started after peak bloom (late-April to mid-May) in early June, and continued through late September. We established the survey as a complete randomized block design, with three replicates positioned in representative locations within the site. Each replicate consisted of three adjacent 100 m^2 plots, with shading as the treatment effect. Shade intensity was determined by location within the solar array. Shade treatments included: fully shaded (5% full sun) "full shade" plots, partially shaded (75% full sun) "partial shade" plots, and unshaded (100% full sun) "full sun" plots (Figure 3, 4). The individual width to length ratio of the 100 m^2 full sun plots varied based on the configuration of available land (Figure 2). We selected block locations within the array based on the availability of suitable full sun plots (areas within the restored area, not shaded by the solar panels, and greater than 100 m^2).

Figure 3: General site location in southern Oregon's Rogue River Valley.

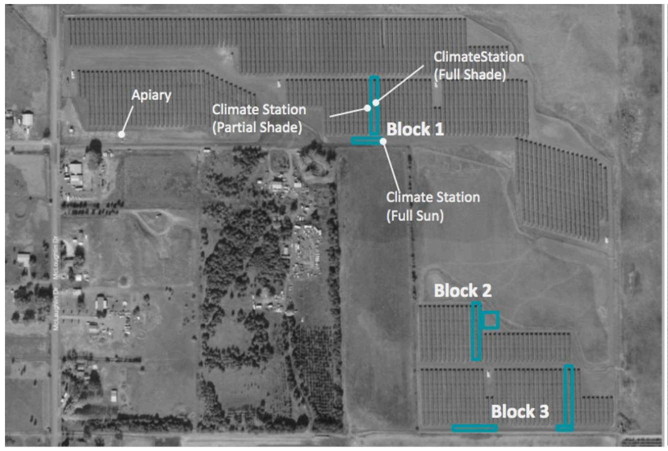

Figure 1: Aerial view of the Eagle Point Solar Plant. Replicates are arranged in a randomized block design. Climate monitoring stations are positioned in Block 1. An apiary is located along the southwestern arm of the site. Imagery: Google Earth, 2020.

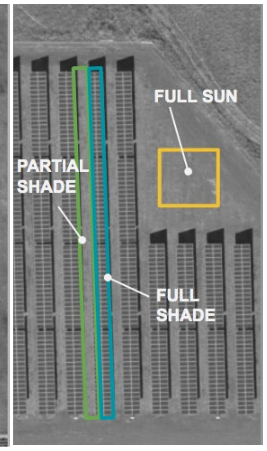

Figure 2: Aerial view of Block 2. Each replicate contains three treatments: full sun, partial shade, and full shade. Imagery: Google Earth, 2020.

Microclimate Data.

We collected climate data at three monitoring stations to provide context for the study. We collected net radiation (PYR Decagon Devices), air temperature (VP-3 Decagon Devices), and relative humidity (VP-3 Decagon Devices) at 15 minute intervals at a height of 1.4 m. Soil moisture and soil temperature (GS-3 Decagon Devices) were also measured at 15 minute intervals at a depth of 15 cm. We separated measurements by treatment when possible. Hourly and daily averages are reproduced below (Figure 5, Figure 6).

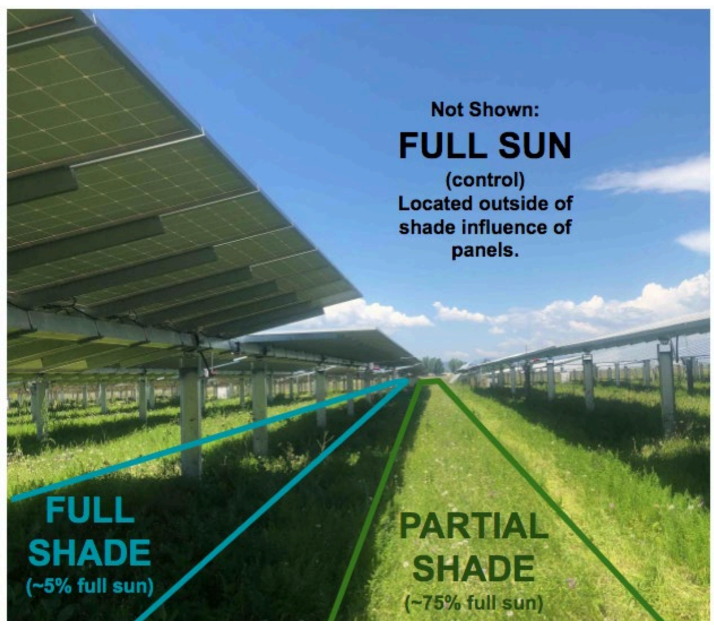

Figure 4: Side view of a block with shade treatments. Partial shade treatments are located between rows of panels. Full shade treatments are directly underneath panels. Full sun treatments are located outside of the shade influence of the panels, and are not pictured here.

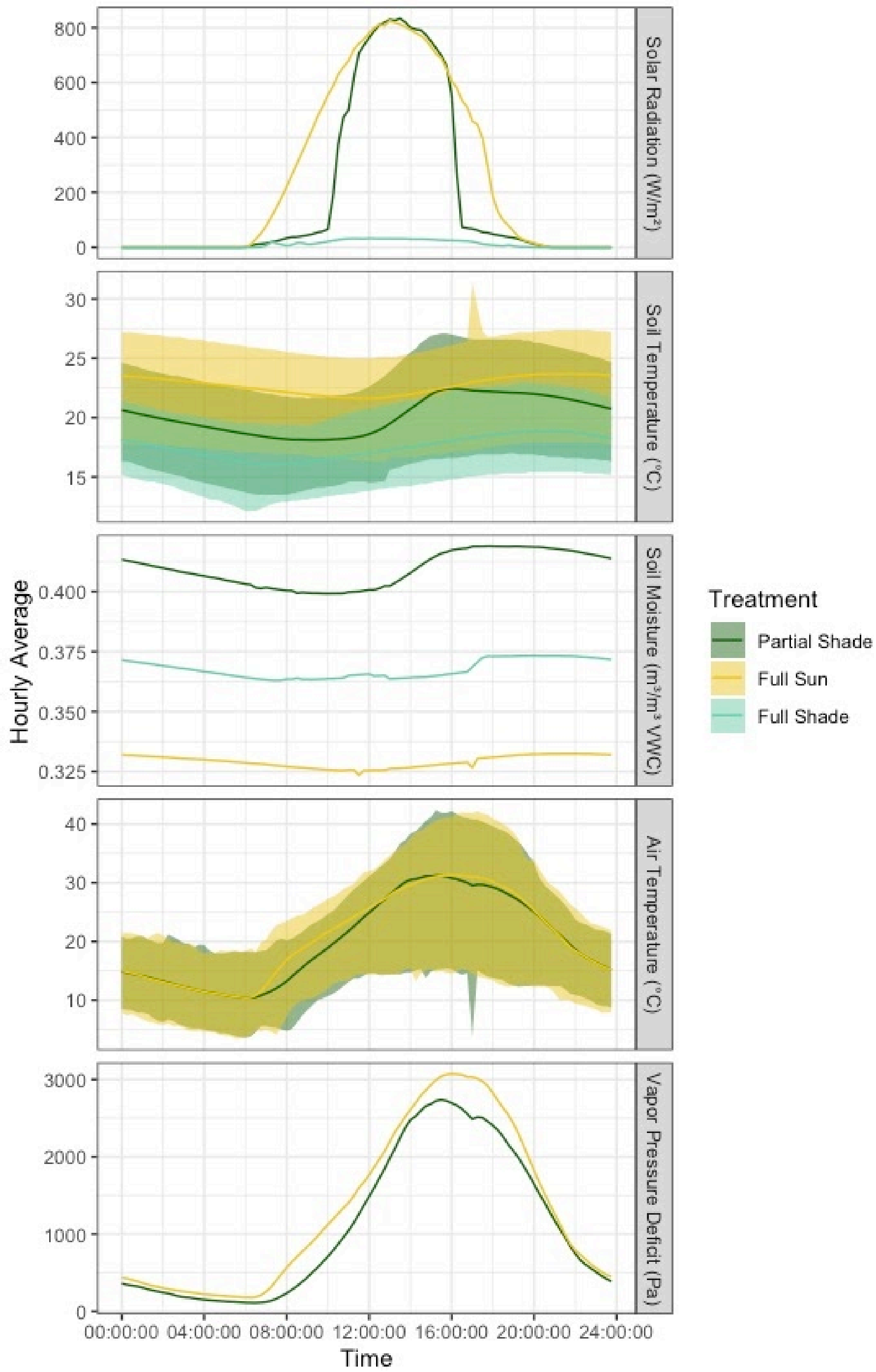

Figure 5: Diurnal flux of climate variables. Solar radiation, soil temperature, soil moisture, air temperature, and vapor pressure deficit, were recorded at three climate stations located in Block 1. Measurements were taken at 15 minute intervals, and averaged over each hour throughout the sampling season. Shaded regions show the range of daily minimum and maximum temperatures.

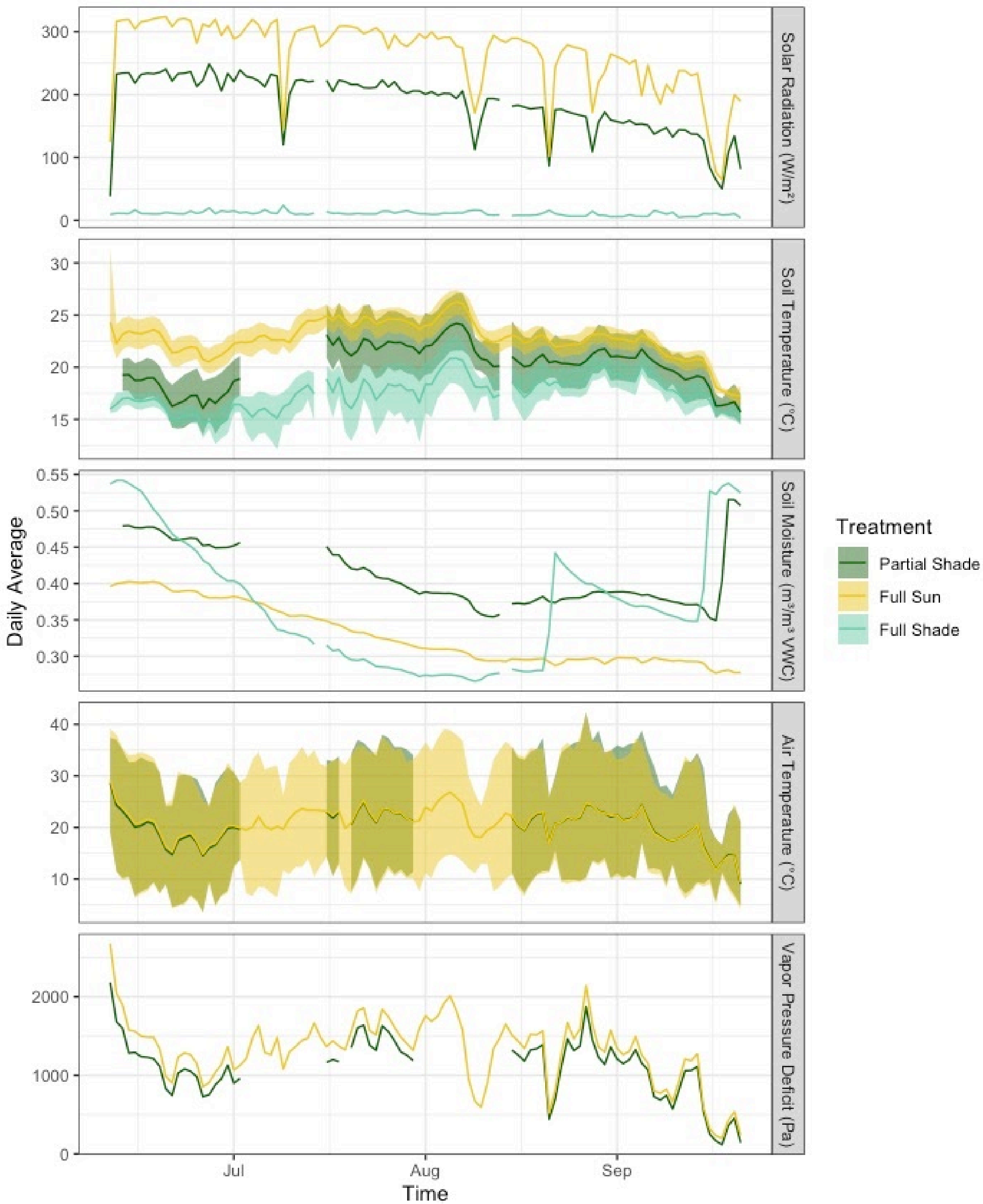

Figure 6: Daily averages of climate variables. Solar radiation, soil temperature, soil moisture, air temperature, and vapor pressure deficit, were recorded at three climate stations located in Block 1. Measurements were taken at 15 minute intervals, and averaged over each day. Shaded regions show the range of daily minimum and maximum temperatures.

Vegetation Data. We used the line point intercept method to inventory botanical composition [24]. In each sample unit, 100 data points were collected across five, 2 m transects at 10 cm intervals. We selected the starting point of transects at random before each sampling event. At each point intercept, we documented the species of the stem and the number of flowers in bloom per stem.

Flower morphology, notably the number and arrangement of inflorescences in flowers, varies between plants. In this study, we are interested in the relative difference between treatments, not individual species. We defined "bloom" in a way that was practical for field survey of each plant. For plants with stems of clustered flowers (e.g. *Castilleja*, *Vicia*, *Brassica*, thistles), we considered individual flowers a bloom unit (Figure 7a). For plants with distinct composite flowers (e.g. *Asteraceae*), we considered each capitulum a bloom unit (Figure 7b). For plants with distinct, unclustered flowers (e.g. *Clarkia, Brodiaea*), we considered each flower a bloom unit (Figure 7c). For plants with flowers composed of small, tight inflorescences (e.g. *Daucus*, *Achillea*) it was not practical to distinguish between inflorescences, so we considered each flower head a bloom unit [25] (Figure 7d).

Figure 7: Definition of bloom units. Bloom units are defined in a way that is practical for field measurement and conscious of flower morphology. A bloom unit is an individual flower for (a) stems of clustered flowers, a capitulum for (b) distinct composite flowers, an individual flower for (c) distinct unclustered flowers, and a flower head for (d) small, tight inflorescences.

Pollinator Data. We used hand nets to survey insects visiting flowers in transects during 30 minute sampling events (Figure 8a). We sampled transects continuously between 9 am and 4 pm, on warm (>16°C), calm (<20 km/h wind) days. We collected all insects observed touching the reproductive parts of flowers (Figure 8b), excluding individuals from the family

Miridae, which were found in large quantities on stems, leaves, and flowers of some plants. After netting, we placed insects in ethyl acetate jars and froze for later identification. In the lab, we pinned, sexed, and identified specimens to species or the lowest taxonomic group possible (Figure 8c). A taxonomist (Dr. Andy Moldenke) confirmed identifications and checked with voucher specimens at the Oregon State Arthropod Collection, at Oregon State University in Corvallis, OR.

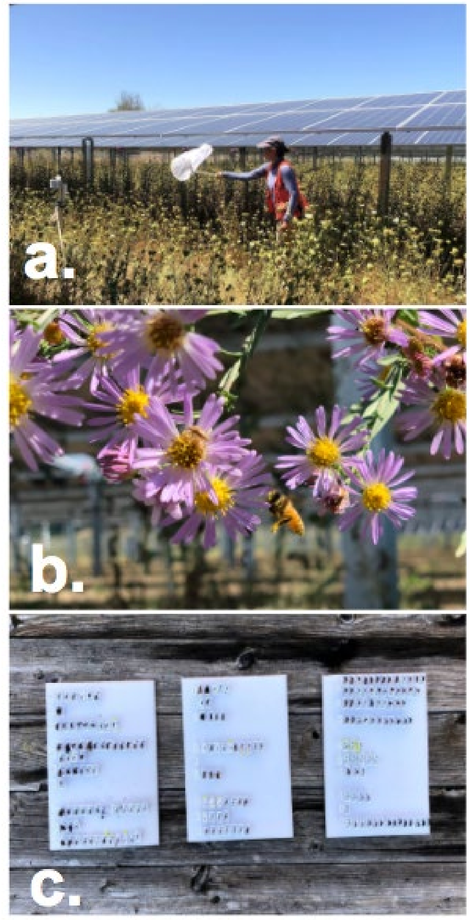

Figure 8: Pollinator data collection methods included using (a) hand nets to capture (b) insects touching reproductive parts of flowers, then (c) pinning and identifying specimens.

Statistical Analysis. To test the hypothesis that pollinators use floral resources both within and outside of the solar array, we compared the relative insect visitation rate for each treatment. Visitation rate is defined as the ratio of insect abundance per minute, adjusted for the abundance of blooms. This estimates insect use of floral resources relative to the number of resources available in each treatment, illuminating differences from factors other than floral abundance. We tested the assumptions for the model by visually examining the distribution and standard deviation of the data. We checked for differences among variables using a one-factor ANOVA with repeated measures. We used a paired t-test with Bonferroni correction to compare means. We performed statistical analyses in R version 3.6.1[26]. We calculated species diversity using the vegan[27] package. Code is provided in Appendix B.

Prior to statistical analysis, we log transformed counts of both flowers and insects (Log(x+1)) to improve normality and preserve extreme values. We did not remove zero values (i.e., plots with no insects or no flowers), as these are important to the survey objectives. We calculated species abundance and diversity, using both richness and Shannon's diversity index, for all species of plants and insects[24]. We calculated visitation rate using (log (insects +1)/(log(blooms + 1)) per 30 minutes. Units without any insects and/or any flowers were assigned a value of zero.

3. Results

Visitation Rate. Visitation rate did not differ among treatments ($p = 0.184$) nor over time ($p=0.445$).

Vegetation Data. We found an average of 4% more blooms per 100 m² in partial shade than in either full sun ($p = 0.008$) or full shade ($p = 0.019$, Figure 9). Neither richness nor diversity of flowers differed among treatments ($p = 0.11$, $p = 0.12$ respectively), though both differed throughout time ($p < 0.001$, $p = 0.01$ respectively).

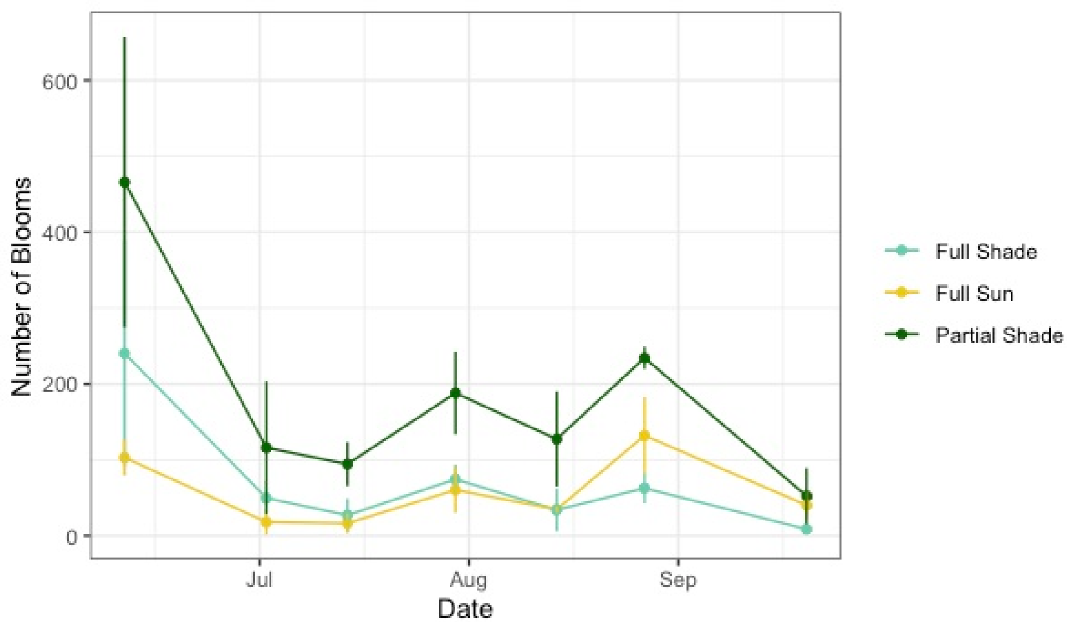

Figure 9: Abundance of flowers per 100m², surveyed from June to September .The mean and standard error is shown for each date. On average, 4% more blooms were found in partial shade than full sun or full shade.

Over the course of the study, we collected 6,300 data points from 48 different plant species. Of these, 900 data points (14%) were from stems of plants blooming at the time of the survey, representing 26 different flowering species. The percent composition of flowers by functional group is shown in Figure 10.

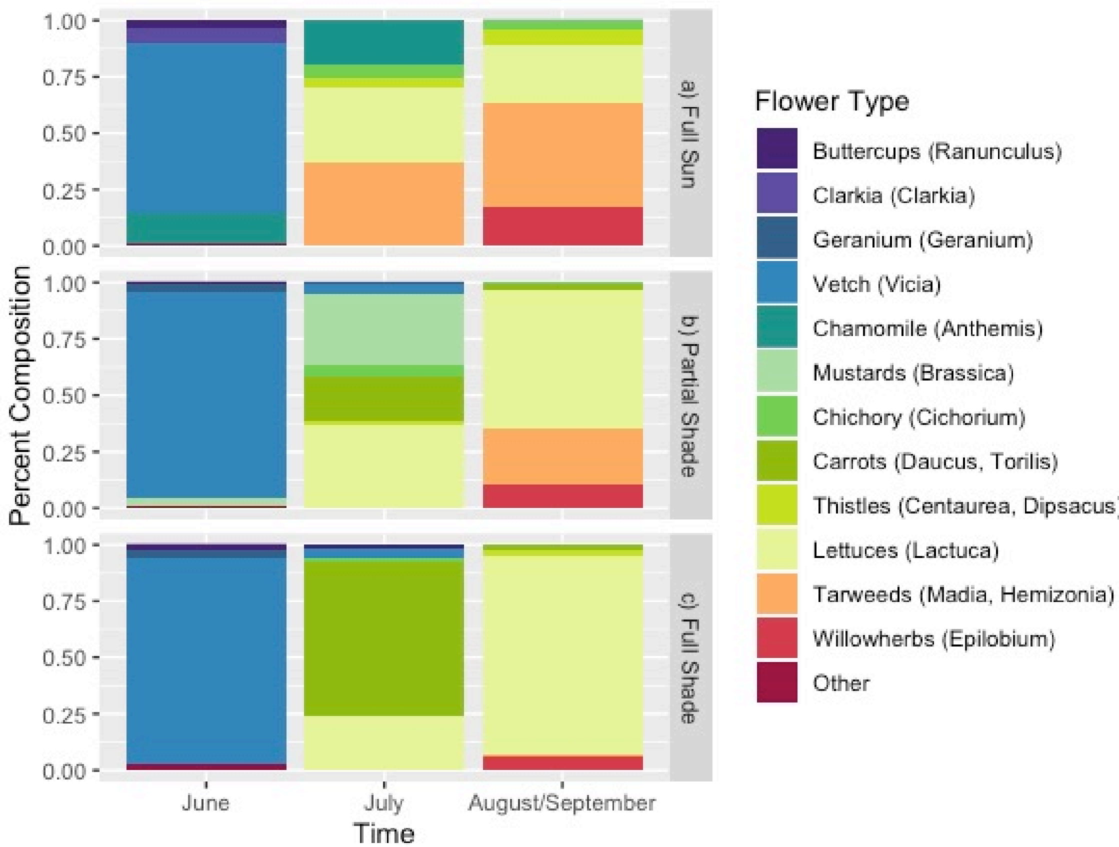

Figure 10: Percent composition of flowers sampled in each treatment (a. full sun, b. partial shade, c. full shade) by month. Species are displayed by functional group.

In June, species composition across all treatments was dominated by vetch (*Vicia*), with smaller amounts of clarkia (*Clarkia*), buttercup (*Ranunculus*), chamomile (*Anthemis*), and geranium (*Geranium*).

In July, the full sun was dominated by chamomile, lettuces (*Lactuca*), and tarweeds (*Madia, Hemizonia*). Tarweeds were not yet blooming in partial shade or full shade treatments. The partial shade was dominated by lettuces, mustards (*Brassica*), and carrots (*Daucus, Torilis*). The full shade was dominated by lettuces and carrots. In July, both vetch and geranium were still blooming in partial shade and full shade plots, though not in full sun plots.

In August/September, blooms in the full sun and partial shade were dominated by tarweeds, lettuces, and willowherbs. Bloom in the full shade were dominated by lettuces.

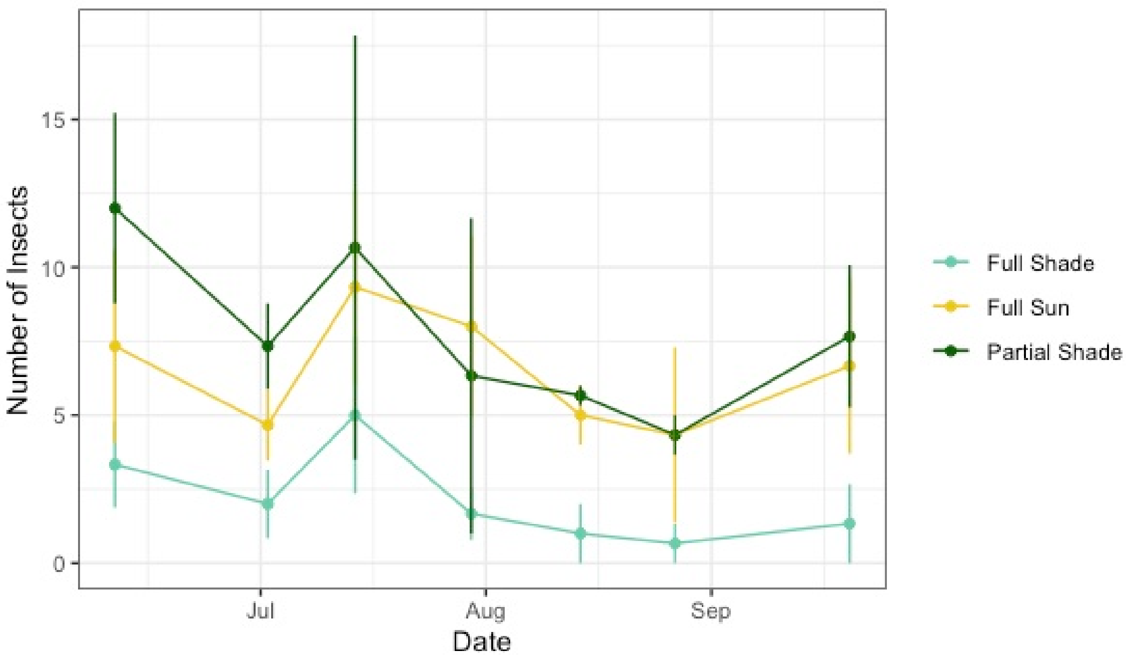

Figure 11: Abundance of pollinators per 30 minutes per $100m^2$, surveyed from June to September .The mean and standard error is shown for each date. On average, 3% more blooms were found in full sun and partial shade than in full shade.

Pollinator Data. We found an average of 3% more insects per $100m^2$ found in partial shade and full sun than in full shade treatments ($p < 0.001$, $p < 0.001$ respectively, Figure 11). Insect species richness was higher in partial shade and full than in full shade ($p < 0.001$, $p < 0.001$ respectively; Figure 12), as was species diversity ($p = 0.001$, $p < 0.001$ respectively; Figure 13).

We collected 342 pollinating insects over the course of the study, representing 65 different insect species. Of these individuals, 200 were bees, representing 21 different bee species. Community composition by functional group is detailed in Figure 14.

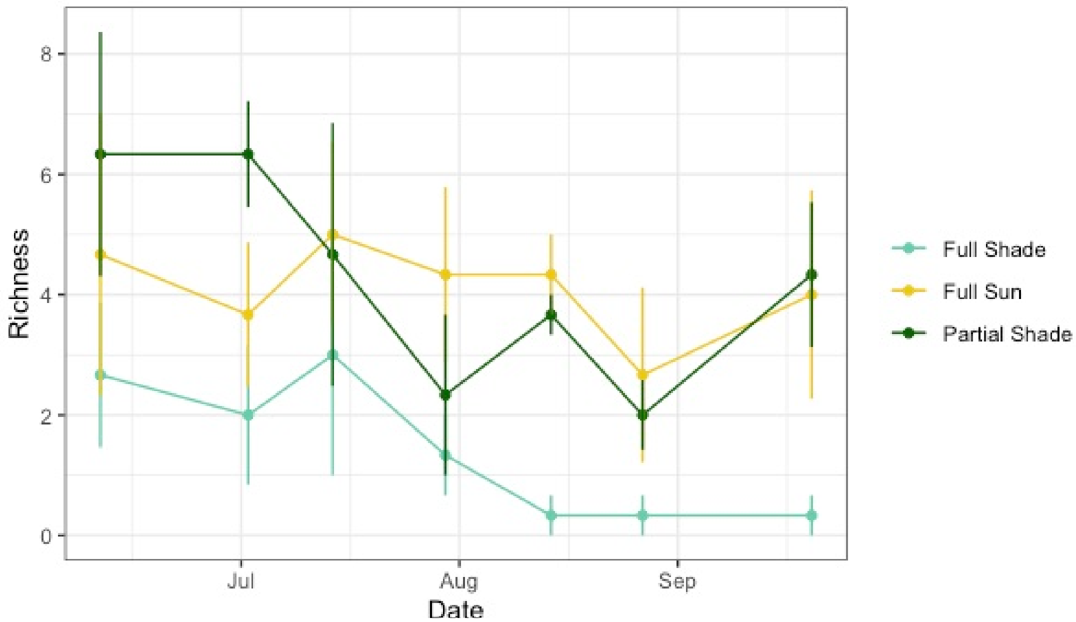

Figure 12: Richness of pollinators per 30 minutes per 100m², surveyed from June to September. The mean and standard error is shown for each date. Partial shade and full sun exhibited higher species richness than full shade.

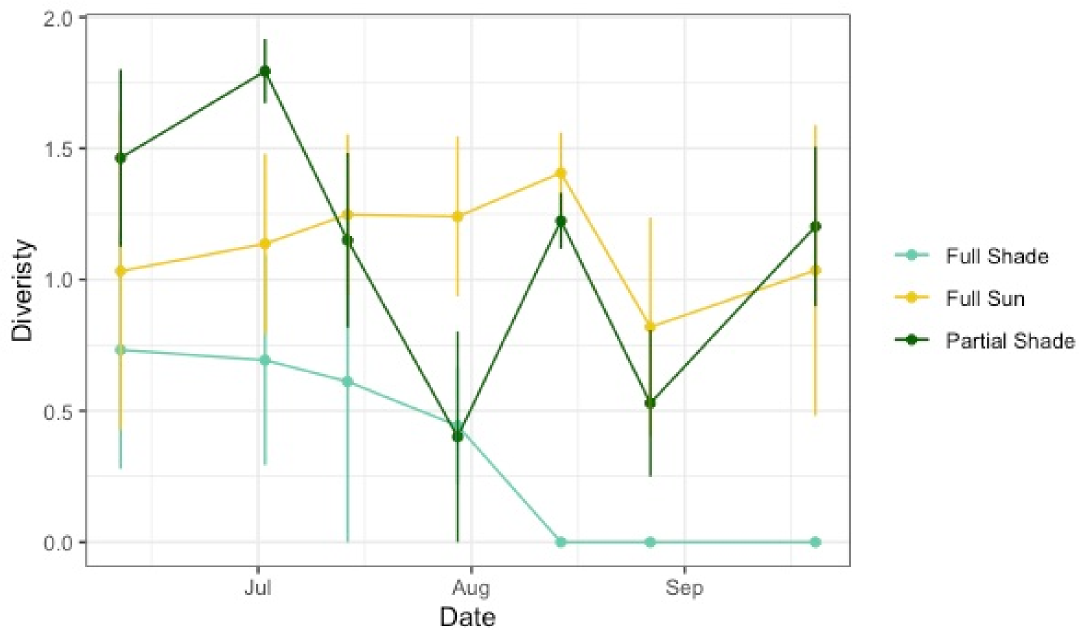

Figure 13: Diversity (Shannon-Weiner Index) of pollinators per 30 minutes per 100m², surveyed from June to September .The mean and standard error is shown for each date. Partial shade and full sun exhibited higher species diversity than full shade.

In June, pollinators in full sun were dominated by mason bees (*Osmia*) and beetles (Coleoptera). Pollinators in partial shade were dominated by mason bees, honey bees (*Apis mellifera*), and flies (Diptera). Pollinators in full shade were dominated by bumblebees (*Bombus*) and flies.

In July, species composition in all three treatments included sweat bees (*Halictus*, *Lasioglossum*), honey bees, flies, and beetles. In August/September, all treatments were dominated by sweat bees and flies, with some other native bees and wasps observed in full sun and partial shade.

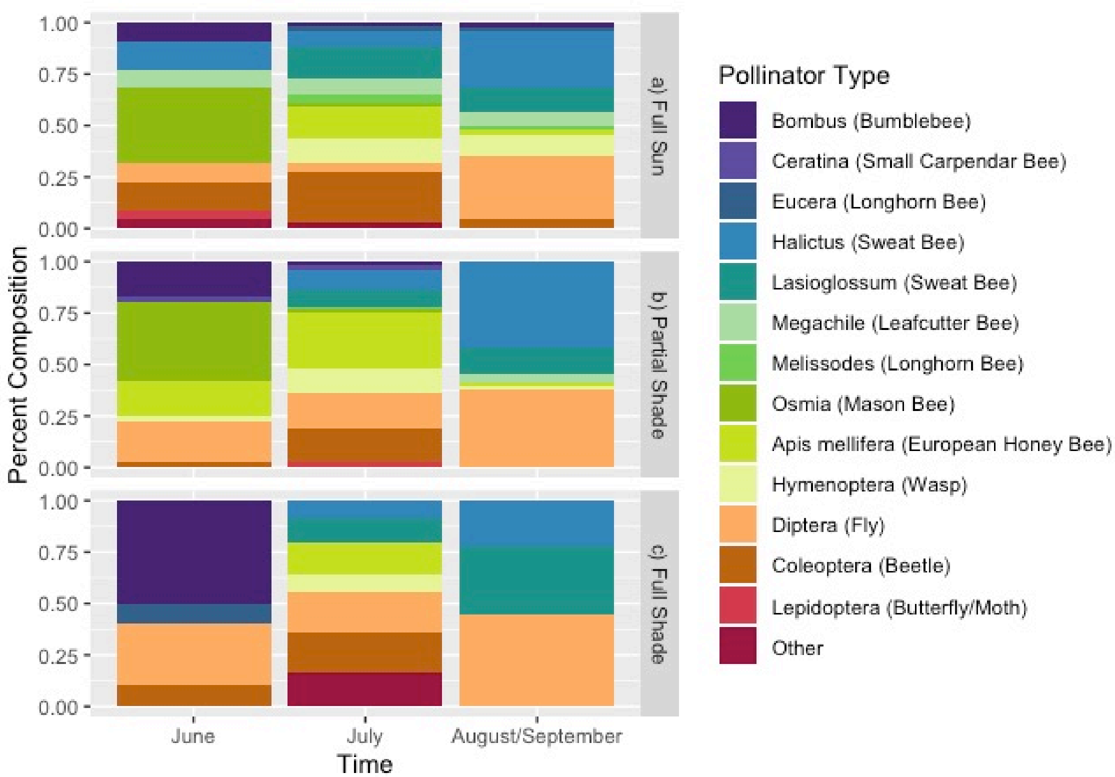

Figure 14: Percent composition of pollinators sampled in each treatment (a. full sun, b. partial shade, c. full shade) by month. Species are displayed by functional group: native bees by genus, honey bees by species, and non-bees by order.

4. Discussion

The results supported our hypotheses. Visitation rates did not differ across treatments, implying that pollinators will forage on flowers that grow under solar arrays as they would forage on any other flowers. Both the plant community and the pollinator community differed among treatments, showing that changes in shading throughout the array are linked to plant and pollinator community structure.

Plant Community. Floral abundance differed among treatments, implying that panel shading impacted plant physiology and morphology. At this site, partial shade conditions yielded more blooms than full sun or full shade conditions. This could be because the increased soil moisture reduced water stress on the plant, allowing it to dedicate more resources to reproduction (making flowers). Or it could also be the effect of increased heat stress, which can quicken floral bloom. However, since soil in the partial shade was cooler and wetter than in full sun, we can assume that the increase in flowering was a result of decreased stress and an increase in resource allocation to reproduction.

Floral richness and diversity did not differ among treatments. As seen in Figure 10, this does not mean that treatments did not contain different species, but rather that the number and evenness of species types was not different.

For some species, bloom timing extended later into the growing season in partial and full shade treatments than in full sun. In July, vetch and geranium were still blooming in partial shade and full shade, although bloom had already finished in full sun. We also see that bloom starts earlier in full sun for some species, like tarweeds which started blooming in July in the full sun, but not until August/September in the partial shade. This shows that variable shading in the solar array has the potential to extend the flowering period for a particular species.

Many of the species included in the restoration seed mix (Appendix I) were not documented in this survey, but that does not mean they were not present on the site. During our two weeks of survey design in late May, we observed many species from the mix in bloom at the site, including *Amsinckia menziesii*, *Collinsia grandiflora*, *Lupinus* sp., *Navarretia intertextata*, and *Achyrachaena mollis*, among others. The peak bloom of the seed mix was in late April to early May, so most early and mid-season species had finished blooming by the start of this survey in early June. Some late-blooming species such as *Madia elegans*, *Helianthus bolanderi*, and *Achillea millefolium* were present throughout the site and seemed to attract many pollinators, though they may not have been surveyed in our plots. Results from this survey should not be used to evaluate the success of the restoration seed mix, as the duration and spatial replication are too limited for that purpose.

Pollinator Community. Pollinator abundance, richness, and diversity were higher in full sun and partial shade than in full shade, implying that we can expect to find differences in the pollinator community based on location (and shading) with the solar array. Since visitation rates did not differ among treatments, but floral abundance did differ among treatments, variations in pollinator abundance can be attributed in part to differences in the plant community. There may be additional environmental factors (soil moisture, wind, temperature) impacting pollinator populations, which could be researched by future studies.

Climate Trends. Climate observations in partial shade and full sun treatments were as expected, with partial shade plots experiencing reduced temperatures, reduced sunlight, and elevated soil moisture than full sun plots (Figure 5, Figure 6). Hourly trends show that partial shade plots received approximately 4 fewer hours of sunlight per day than full sun plots (roughly 10am to 4pm versus 8am to 8pm, Figure 5). However, full shade treatments behaved differently than expected. During much of July and August, soil moisture was lower in fully shaded plots than in partial shade or full sun, although it was greater than these areas in the early summer and again after the first fall rains. We saw steep spikes in moisture levels over very short intervals on August 21 and September 15 that are not observed in other treatments. It is possible that the sensor was located near a soil crack or other non-uniformity that may have influenced the data.

Agrivoltaic Parallels: Past research also documents physiological and morphological differences between plants in agrivoltaic systems, though these differences manifest in various ways depending on the crop and observation methods. Hassanpour et al. found that forage grasses had a greater biomass in the full shade regions of a fixed array in Oregon's Willamette Valley[15] (Hassanpour, 2018). This was both in a wetter climate, and under a different panel arrangement (fixed, lower height), and earlier in the growing season (wetter). Studies by Marrou et al. found that lettuces had fewer, larger leaves in the partial shade of their array in Montpellier, France[16], also with a different climate and panel arrangement. Meanwhile in Arizona, Barron-Gafford et al. found that some varieties of peppers and tomatoes preformed best (greater fruit weight) in the partial shade, while others preferred full sun[17]. All show that panel shading is correlated with plant physiology and morphology, thus optimization depends on local conditions and plant preferences.

Inferences. Our observation of visitation rate shows that pollinators will use flowers despite proximity to solar panels, and that pollinator and plant communities will vary along with differences in shading throughout the array. These qualities are transferable, and we expect to see changes in visitation rate, insect abundance and composition, floral abundance, and bloom timing at other agrivoltaic sites regardless of local climate, species mix, or panel arrangement. Observations of species-based performance are limited to sites with the same climate, species mix, and panel arrangement to that of the Eagle Point Solar Plant. Our results make sense for a dryland, water-limited ecosystem but may differ from wetter systems, especially those that are light-limited. Our site contained plant species with various levels of shade-tolerance. Observations may differ in systems with an abundance of shade-loving or shade-intolerant species. This site was designed specifically to facilitate the collocation of solar with an active worksite, meaning panels were spaced such that a full size tractor could move between the rows. Panel arrangement (e.g. orientation, height, row spacing, tracking versus fixed) may also impact diurnal shade patterns and general microclimate, and thus the plant and pollinator communities.

Future Studies. Since research on pollinator-focused solar is just emerging, opportunities for future study abound. This study could be replicated across different climatic regions, with a variety of panel arrangements, and over a broader range of time to capture increased seasonal variation. It would be particularly helpful to conduct species-specific observations starting at first floral emergence, then continue through peak bloom, past first frost until all blooms have ceased, to gain a more detailed account of how panel design influences bloom timing for particular species.

Combined with pollen and nectar analysis, this could highlight which flower species are most attractive to insects in particular seasons, climates, and treatments, helping restoration professionals decide which species will be most beneficial to pollinators in the solar panel understory. In addition, research could be expanded to examine effects of solar panels on integrative pest management in agricultural systems, as there are many other types of insects that are impacted by changes in habitat complexity[28] such as that created by the solar panels.

The cost of pollinator-focused solar is not studied here, although critical to the paper's audience. The cost of establishing and maintaining traditional solar panel understories (e.g. gravel, turf grass) could be compared to pollinator habitat restoration, taking into account financial implications of the cooling effect of vegetation on panel efficiency[29, 30], the effect of pollinator abundance on agricultural yields[11], and possible effects on water quality and groundwater recharge[31] (Zhang et al., 2016), as well as any panel design alterations (e.g. elevated height) that may be necessary.

Conclusion: Our results show that pollinating insects use habitat under solar arrays. The plant and pollinator communities may differ along shade gradients within a solar array, but pollinators will visit blooming flowers despite their location within the array. This information can help inform agricultural communities and pollinator health advocates considering solar arrays as opportunities for habitat development, as well as solar developers, homeowners, and policy makers looking to maximize land use efficiency and biodiversity at solar PV sites.

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APPENDICES

Appendix A. Seed Mix

Seed mix provided curtesy of Lomakatsi Restoration Project.[32]

Species	Type	Amount (lbs)
Amsinckia menziesii	Annual forb	3
Clarkia purpurea	Annual forb	12
Collinsia grandiflora	Annual forb	5
Daucus pusillus	Annual forb	10
Gillia capitata	Annual forb	7.5
Hemizonia fitchii	Annual forb	0.5
Helianthus bolanderi	Annual forb	0.5
Lupinus bicolor	Annual forb	0.5
Madia elegans	Annual forb	3
Navarretia intertextata	Annual forb	1
Plagiobothrys figuratus	Annual forb	7
Festuca roemeri	Grass	130
Carex densa	Sedge	6
Carex pachystachya	Sedge	4
Carex tumulicola	Sedge	4
Juncus tenuis	Rush	0.5
Achillea millefolium	Perennial forb	5
Agoseris grandiflora	Perennial forb	3
Asclepias fascicularis	Perennial forb	10
Camassia quamash	Perennial forb	1
Cynoglossum grande	Perennial forb	0.5
Eriophyllum lanatum	Perennial forb	18
Grindelia nana	Perennial forb	20
Lomatium utriculatum	Perennial forb	0.5
Lupinus microcarpus	Perennial forb	5
Lupinus adsurgens	Perennial forb	5
Ranunculus austrooreganus	Perennial forb	0.5
Wyethia angustifolia	Perennial forb	1

Appendix B. Code

```
##Appendix C. Code
##This file provides calculations of repeated measures ANOVA and paired t-test used
in data analysis.

##Import data and packages
library(ggplot2)
polsol <- read.csv("~/Desktop/R_files/Overview_4.27.20.csv", header=TRUE)
View(polsol)

##Set time as a factor
polsol$time <- as.factor(polsol$time)
#class(polsol$time)

##Select data for analysis
polsol$testdata <-polsol$attractivenesslog10
#polsol$testdata <-polsol$log10blooms
#polsol$testdata <-polsol$log10insects
#polsol$testdata <-polsol$richness_bl
#polsol$testdata <-polsol$richness_ins
#polsol$testdata <-polsol$diversity_shan_bl
#polsol$testdata <-polsol$diversity_shan_ins
head(polsol$testdata)

##Check Assumptions
##(1)Normal distribution? (histogram)
qplot(testdata, data=polsol, geom="histogram", bins = 25, main = "Distribution of
Data") +
  facet_grid(treatment ~ .)
##(2)Equal std deviation? (boxplot)
ggplot(data=polsol, aes(x=treatment, y=testdata)) +
  geom_boxplot() +
  facet_grid(.~ time) +
  stat_summary(fun.y=mean, geom="point", shape=3, size=3)+
  theme_bw()+
  labs(title = "Standard Deviation of Data", legend = "Treatment")

##Are there differences?
##One-factor ANOVA with repeated measures (time), with varible selected above.
rm.aov <- aov(testdata~Error(replicate)+treatment*time, data=polsol)
summary(rm.aov)

##Which treatments are different?
##Paired t-test
```

```
t.test(formula = testdata ~ treatment,
       data = polsol,
       subset = treatment %in% c( 'Full Sun', 'Partial Shade'),paired=TRUE,
var.equal=TRUE)
t.test(formula = testdata ~ treatment,
       data = polsol,
       subset = treatment %in% c('Full Sun', 'Full Shade'),paired=TRUE,
var.equal=TRUE)
t.test(formula = testdata ~ treatment,
       data = polsol,
       subset = treatment %in% c('Partial Shade', 'Full Shade'), paired=TRUE,
var.equal=TRUE)

##Bonferroni correction
pairwise.t.test(polsol$testdata, polsol$treatment, p.adj = 'bonferroni')

##Calculate means and sd for each treatment
aggregate(testdata~treatment, data=polsol, FUN=mean)
aggregate(testdata~treatment, data=polsol, FUN=sd)
```