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The influence of solar power plants on microclimatic conditions and the biotic community in Chilean desert environments

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ABSTRACT

The renewable energy sector is growing at a rapid pace in northern Chile and the solar energy potential is one of the best worldwide. Therefore, many types of solar power plant facilities are being built to take advantage of this renewable energy resource. Solar energy is considered a clean source of energy, but there are potential environmental effects of solar technology, such as landscape fragmentation, extinction of local biota, microclimate changes, among others. To be able to minimize environmental impacts of solar power plants, it is important to know what kind of environmental conditions solar power plants create. This study provides information about abiotic and biotic conditions in the vicinity of photovoltaic solar power plants. Herein, the influence of these power plants as drivers of new microclimate conditions and arthropods diversity composition in the Atacama Desert was evaluated. Microclimatic conditions between panel mounts was found to be more extreme than in the surrounding desert yet beneath the panels temperature is lower and relative humidity higher than outside the panel area. Arthropod species composition was altered in fixed-mount panel installations. In contrast, solar tracking technology showed less influence on microclimate and species composition between Sun and Shade in the power plant. Shady conditions provided a refuge for arthropod species in both installation types. For example, *Diptera*ns were more abundant in the shade whereas *Solifugae*s were seldom present in the shade. The presented findings have relevance for the sustainable planning and construction of solar power plants.

Keywords: Arthropod Species Composition; Atacama Desert; Environmental Effect; Microclimate; Photovoltaic Power Plant.

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1. INTRODUCTION

Chile depends on fossil fuels to satisfy its energy needs (Ortega et al. 2010, Jiménez-Estévez et al. 2015) but lacks significant reserves of its own (Corral et al. 2012). Chilean energy consumption is projected to grow 5.4% annually until 2030. Especially current inland production will need to be increased (Tokman 2008). In addition, Chile has set a mandatory quota that 20% of produced electricity has to come from renewable energy sources by 2025 (Ortega et al. 2010). Therefore, to reach this level of supply, renewable energy sources are being promoted nationally (Fthenakis 2009, Hernández et al. 2014)

Solar radiation intensity in the North of Chile is one of the best worldwide, with an annual average Direct Normal Irradiation (DNI) of 9-10 kWh / (m^2 day) (del Sol & Sauma 2013). Such potential makes the Atacama Desert an attractive location for large-scale solar power plant projects (Corral et al. 2012, Jiménez-Estévez et al. 2015, Salazar 2015). Nevertheless, the use of solar energy is in its initial phase in Chile (Ortega et al. 2010). In 2015, only 3 % of total electricity was produced by solar energy in the country (Ministry of Energy, Chile 2015). However, the amount is growing because several solar power projects are in the works. These include photovoltaics (PV), concentrated solar power, and thermal solar plants (Escobar et al. 2014).

Solar energy is a clean and safe energy source compared to fossil fuel energy sources (Tsoutsos et al. 2005) although it requires a large-scale landscape transformation (Chiabrando et al. 2009). Landscape fragmentation, the elimination of existing flora and fauna, changes in microclimate and changes in surface albedo are some of the main environmental impacts (Turney & Fthenakis 2011, Wu et al. 2014). Furthermore, rapid growth in renewables in recent years has meant that management planning for solar installations is lagging behind (Lovich & Ennen 2011). Consequently, there is a lack of studies on this subject in Chile, and existing studies usually focus on the technical factors, resource measurement, and economic impacts of installing solar power plants (del Sol & Sauma 2013, Escobar et al. 2014, Ferrada et al. 2015).

Areas with high solar energy potential are often easily disturbed fragile ecosystems, which exhibit difficulties in recovery (Stoms et al. 2013). For example, biological soil crusts take several years to recover from disturbance (Callison et al. 1985, Johansen & St. Clair 1986). Solar power plant construction can alter the soil conditions because the area might be scraped to bare ground, and herbicides are commonly used (Tsoutsos et al. 2005, Turney & Fthenakis 2011). Consequently, these modifications might alter the local flora and fauna (Wu et al. 2014). However, impacts on biodiversity can also be positive as the panels can create beneficial microclimate for new species (Tsoutsos et al. 2005). For instance, in the Chilean semiarid desert, the microclimate beneath the shrub canopy can be favorable; contributing to species dispersion (Tracol et al. 2011), an effect that might be mimicked by solar panels. According to Wu et al. (2014), solar panels can increase soil humidity, which generates favorable conditions for biota.

The Atacama Desert is characterized by highly endemic lineages, monotypic taxa and species with restricted distribution (Agusto et al. 2006, Ferrú & Elgueta 2011, Hughes & Eastwood 2006, Pennington 2010, Pizarro-Araya et al. 2008, Pizarro-Araya & Jerez 2004, Roig-Juñet & Flores 2001, Taucare-Ríos & Sielfeld 2013, Toro-Núñez et al. 2015). This particular biota is the result of a complex history of geomorphological and climatic events, which promoted diverse environmental conditions and a gradient of abiotic conditions (e.g. temperature and aridity) as a function of latitude and altitude (Luebert & Pliscoff 2006, Rundel et al. 1991).

In the Atacama Desert, arthropods are one of the most abundant and diverse group of animals (Pizarro-Araya et al. 2008). They are capable of maintaining vertebrate populations (Gantz et al. 2009, Guzmán-Sandoval et al. 2007, Vidal et al. 2011) and are the keystones of many food webs (Samways 2005). Moreover, in desert systems, arthropods take over functional roles that are occupied by annelids and other invertebrates in mesic environments (Whitford 2000). The latter stems from fewer restrictions due to low water availability and extreme temperature conditions in comparison to other animal groups (Whitford 1991).

Some of the other studies have focused on microclimate changes of solar facilities (Chiabrando et al. 2009, Kayguzus 2009, Lovich & Ennen 2011, Turney & Fthenakis 2011). Nevertheless, only a few hypothetical schemes assume that changed microclimate conditions could have a beneficial effect on biota (Tsoutsos et al. 2005, Wu et al. 2014). Despite of a few studies (Turney & Fthenakis 2011, Wu et al. 2014) the impacts between solar power plants and their surrounding environments have not yet been addressed comprehensively in literature. Therefore, it is crucial to understand what potential ecological impacts and environmental issues solar power plants have, related to the growing installation of solar power plants in Chile. Moreover, it would be beneficial to know the most sustainable way to construct solar power plants into the Atacama Desert.

In the present study, a preliminary spatio-temporal evaluation of the biodiversity (e.g. arthropods) and abiotic parameters, temperature, relative humidity (hereinafter humidity), and dew point, associated with micro-environments (beneath and between panels) was performed. Two solar power plants were included in the study: “Photovoltaic Solar Plant Subsole” (PSPS) was built in 2012 and “Pozo Almonte Solar III” (PAS3) in 2013. Considering the large daily thermal oscillations and humidity condensation beneath the solar panels, it is expected that these areas might create favorable environmental conditions for arthropod assemblages and therefore act as refuges. This may lead to significant changes in arthropod assemblages and abiotic conditions among the study sites. Differences in environmental conditions between the solar plants and the outer zone, and among sampling times may be significant.

The objectives of the study were to: 1) describe the variation in temperature, humidity, and dew point within the two different solar power plants; 2) evaluate the spatio-temporal effects of solar plants on diversity and taxonomic composition of arthropods; 3) evaluate and link the arthropod distribution patterns with abiotic variables and biotic interactions; and 4) propose guidelines for sustainable construction of solar power plants for decision makers, engineers and environmental specialist.

2. MATERIAL AND METHODS

2.1. Study sites

The two PV plants, PSPS and PAS3 situated in northern Chile, differ in their mount technologies. PSPS consists of six arrays of fixed mounts. Panel mounts are north-facing and they cover an area of 1.0 ha with 0.5 ha of arrays with a total of 42 panels (Fig. 1). PSPS has a power output of 0.3 MW and it is located at the interior of Copiapó Valley in the Atacama region (27° 44.11' S, 70° 11.45' W). The vegetation is semi-desert scrub (Moreira-Muñoz 2011). Annual rainfall is 10-50 mm and coastal fog brings humidity to the area (Moreira-Muñoz 2011). Raining season is from June to August (Agroclima 2016). The plant was built on former agricultural land beside the river Copiapó and has an elevation of approx. 773 m.

The PAS3 consists of 58,560 panel mounts with 102 solar trackers, allowing the array to follow the Sun. This plant covers an area of 126 ha with 33 ha of arrays installed facing East in the morning and turning towards West during the day. PAS3 output power is 16 MW and produced electricity is used for mining processes (Solar Pack 2013). The plant is located near Pozo Almonte city in Tarapacá region (20° 15.37' S, 69° 44.82' W). The area is situated in the central desert with an elevation of 1,030 m. Annual rainfall at Pozo Almonte is below 10 mm and vegetation is very scarce (Moreira-Muñoz 2011). Raining season in the Andes is from January to March, which might cause floods to the study area.

During the study period, PSPS was 1 year old and PAS3 was built only 5 months before this study. Geographic distance of the two power plants is almost 800 km. The two studied PV technologies vary in their shading conditions for two reasons. First, mounts have different orientation to the sun (Fig 1), and second, solar tracking makes the shade change its position at PAS3. Fixed panels have longer periods of shade beneath the mounts than solar tracking panels. Fixed panels allow the sunshine to enter under the mounts very short moments during the sunrise and sunset. By contrast, moving panels shift from East to West during the day allowing direct sunlight to shine longer periods under the mounts. Therefore, the moving panels create more temporary shading conditions than the fixed panels.

Study periods were chosen according to water availability to obtain richer arthropod activity. Therefore, PSPS was studied during September and November 2013, and PAS3 during January and February 2014. At PAS3, abiotic data were supplemented with data from 2015. Sampling units of the experimental design considered three different environmental conditions. They were called Sun, Shade, and Reference. Units were named according to mid-day sun conditions. Sun units were between the panels having sunny conditions during the hottest hours of the day. Shade sampling units were below the solar panels and were shaded at least during the mid-day. Finally, Reference units were outside the panel area.

2.2. Measurements of abiotic variables

Abiotic variables, temperature, humidity, and dew point were recorded with 16 data loggers (Lascar, EL-USB-1-LCD) during a six-day period at PSPS and during one month at PAS3. Loggers were placed 10 cm above ground and protected from solar radiation with white mesh (as suggested in, e.g., Tracol et al. 2011). Loggers were divided into Sun and Shade sampling unit locations at the sites as explained above. The Reference area had two loggers for two days at PSPS and for 30 days at PAS3. Temperature, humidity, and dew point were measured with one-minute intervals at PSPS, and every five minutes at PAS3. To detect correlations between abiotic variables and distinct parts of the solar plants, arrays were numbered starting from the northern edge of the solar plants (Fig 1). Six arrays of the PSPS plant were observed for small-scale abiotic variables correlations, whereas at PAS3 it was possible to study large-scale correlations between panel groups. The first panel grouping of PAS3 (upper left corner of the plant, see Fig 1) was divided into 12 rows according to the sun tracking array groups.

2.3. Arthropod collection and identification

Arthropods were sampled with same method using 30 sampling units at both study sites. However, since the solar panels can drastically modify abiotic conditions at small scale, 10 sampling units were installed between the panel mounts (Sun) and 10 beneath the panels themselves (Shade). On the north side of the perimeter fence, 10 sampling units were placed and used as a reference. Sampling protocol proposed by Cepeda-Pizarro et al. (2005b) was used in which each unit consisted of six interception traps in a grid of 1 ´ 2 meters. Traps were plastic recipients with diameter of 8.5 cm and height 10 cm and were buried at ground level and were filled 1 / 3 with propylene glycol as the preserving liquid. Locations of the sampling units were randomized. Reference sites were the same type of terrain as the solar power plant areas themselves. Traps were operating for four full days at both power plants; the contents of each trap were labeled and preserved in an 80% ethanol solution for taxonomic determination and counting. Arthropods were identified afterwards. For taxonomic nomenclature Snelling & Hunt (1975), Aguilera & Casanueva (2005), Ferrú & Elgueta (2011), Taucare-Ríos & Sielfeld (2013), among others were followed.

2.4. Statistical analyses

Because of different locations and technologies, panel design, and sampling times, the studied solar power plants were not directly comparable. Therefore, all the statistical analyses were performed separately.

2.4.1. Abiotic variables

For the characterization of abiotic variables, Sun conditions were divided into Sun-front (arrays 1-2, Fig 1) and Sun-back at PSPS (arrays 3-6, Fig 1). Division was done because of high temperature differences among the Sun sampling units. To study spatial and temporal differences in abiotic variables, Linear Mixed-Effects models (LME) were used in the R package “nlme” (Pinheiro et al. 2015) using the protocol of Zuur et al. (2009). Further interactions were analyzed using the pairwise argument of “testInteractions” function in “phia” package (De Rosario-Martinez 2015) (Online Resources 1-3). To understand correlations between abiotic variables and the arrays / array groups, Kendall’s tau correlation analyses (Kendall 1938) were used (Online Resource 4). Visual interpretations of abiotic variables with significant spatial correlation were created with spatial interpolation method inverse distance weighting (IDW) programmed with Python (Ascher et al. 2001) (Online Resources 5-6).

2.4.2. Biotic data and abiotic variables

Obtaining the overall understanding how the biotic data was distributed at the two sites univariate and multivariate analyzes were performed to the arthropod data. To summarize the arthropod assemblages, for each sampling unit within each sampling time, richness (S), abundance (N) and species composition were estimated. A Euclidean distance matrix of differences between every pair of observations was calculated to assess richness and abundance. To analyze the arthropods composition, the species abundances data were transformed with square root and a Bray-Curtis (Clarke et al. 2006) similarity matrix was generated. To visualize and detect the main sources of variation in assemblage structure, a non-metric multi-dimensional scaling (nMDS) was performed as an ordination method (Kruskal 1964). The effects of environmental conditions and sampling time on arthropods biodiversity and species composition were analyzed with permutational multivariate analysis of variance (PERMANOVA, Anderson 2001a). Analyses were performed with PRIMER v6.1.12 (Clarke & Gorley 2006) and PERMANOVA+ v1.0.2 add-on software (Anderson et al. 2008). In cases of significant differences, pair-wise tests for all combinations of factors were conducted using the t-statistic (pseudo t-test) (Anderson & Robinson 2003). The statistical significances of variance components were tested using 10,000 permutations of residuals under a reduced model and type III sums of squares (Anderson 2001b). To test the effect of the taxonomic resolution, the RELATE routine (Clarke & Ainsworth 1993) was performed.

After finding out that there were significant differences among the environmental conditions with PERMANOVA, similarity percentages routine (SIMPER, Clarke 1993) was performed to identify which arthropod orders were causing the differences. Further, to determine the best combination of abiotic variables that explained the overall multivariate arthropods pattern, the BIO-ENV (Clarke et al. 2008) routine was used. Subsequently, to understand how species composition was structured among abiotic variables, linkage tree analysis (LINKTREE, Clarke et al. 2008) in conjunction with similarity profile test was performed (SIMPROF, Clarke et al. 2008) to settle the terminal nodes statistically.

Finally, to evaluate our prediction of solar panels acting as refuge in each study site, for each arthropod species the degree of nestedness was estimated with the NODF index (Almeida-Neto et al. 2008). Furthermore, due to possible biotic interactions, the co-occurrence pattern was evaluated to test the species aggregation/segregation among environmental conditions using modified C-score index (Ulrich & Gotelli 2013) as proxy. These analyses (i.e. nestedness and aggregation/segregation) were performed using the programs NODF v2.0 (Almeida-Neto & Ulrich 2011) and TURNOVER v1.1 (Ulrich & Gotelli 2013), respectively.

3. RESULTS

3.1. Abiotic conditions

3.1.1. Characterization of abiotic variables

Temperature, humidity, and dew point were affected by sampling month, environmental conditions, and day / night interaction according to all LME models (Table 1). In pair wise analyses, temperature did not differ between Shade and Sun-front arrays during the day time at PSPS (Fig 2 a). In contrast, Sun-back were warmer than other environmental conditions (Fig 2 a). At PAS3, Sun, Shade and Reference had unique microclimates during the day time. Shade had higher temperature than Sun during the morning and late afternoon hours (Fig 2 b). Shade humidity conditions were higher than Sun or Reference during the day time from 8:00 to 18:15 (Fig 2 c) at PSPS. This was also true at PAS3, however, only between 10:11 and 16:30 (Fig 2 d).

PSPS Reference dew point was significantly different from Shade or Sun conditions during the day time (Fig 2 e). Reference had a high peak in the morning meaning that temperature increased faster at the Reference than in the panel area. At PSPS, night time microclimate conditions did not differ (Fig 2 a and c) except References' dew point was significantly lower (Fig 2 e). The same was true at PAS3 (Fig 2 f). Nevertheless, diurnal dew point at PAS3 did not show statistical differences between environmental conditions (Fig 2 f). Reference was significantly cooler and more humid during the night compared to panel area while Sun and Shade did not differ (Fig 2 b and d). Abiotic conditions changed with delay in the solar power plant areas. For example, temperature values stayed at high levels longer during the morning hours and heat lingered longer in the afternoon compared to Reference (Fig 2 a-f).

Table 1. Results of LME models for abiotic response variables (temperature, humidity, dew point) in both study sites. Abbreviation Env. stands for environmental condition (Sun, Shade, Reference).

	Temperature		Humidity		Dew Point	
	F-value		*F*-value		*F*-value	
PSPS						
Intercept	40.34	***	23.30	***	219.22	***
Month	0.02		0.13		107.41	***
Env.	6.86	***	0.29		4.53	*
Day / Night	1055.21	***	465.90	***	281.12	***
Month × Env.	0.19		0.03		10.21	***
Env. × Day / Night	8.45	***	2.33		1.50	
Month x Env. × Day / Night	24.65	***	19.23	***	37.25	***
PAS3						
Intercept	2723.60	***	3313.60	***	6637.15	***
Month	13.14	***	6.96	*	75.86	***
Env.	9.26	***	11.55	***	3.75	*
Day / Night	6021.20	***	4592.93	***	102.86	***
Month × Env.	0.45		2.55		0.17	
Env. × Day / Night	18.39	***	11.83	***	4.30	*
Month x Env. × Day / Night	9.03	***	3.34	**	4.94	**

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

3.1.2. Correlations of abiotic variables

Statistically significant Kendall's correlation was observed between the mean temperatures and the array numbers in Sun ($z = 2.07$, $p = 0.039$, t = 0.41) and Shade ($z = 2.04$, $p = 0.042$, t = 0.42) (Fig. 3 a) sampling units at PSPS in 2013. The mean humidity (Fig. 3 b) had a significant negative correlation ($z = -2.27$, $p = 0.023$, t = -0.46) with the array numbers. Thus, the maximum temperatures strongly correlated with the array numbers ($z = 4.40$, $p < 0.001$, t = 0.84) (Fig. 3 c), showing the same pattern as mean temperature. Temperature rose extremely high in the back arrays of PSPS plant, reaching 52 °C, which may cause reduction of efficiency of the PV panels (Krauter 2004). At PAS3, there were no significant correlation among abiotic variables among array groups (Fig. 3 d).

3.2. Biotic conditions

3.2.1. Diversity and taxonomic composition

1,364 individuals belonging to 18 orders of terrestrial arthropods with 87 morphospecific taxa were collected. Of these, 53 morphospecies (n = 952) were found at PSPS and 45 morphospecies (n = 412) at PAS3. The most abundant taxa can be seen in Table 2.

Table 2. Percentages and counts of most abundant taxa.

	PSPS		PAS3	
	%	*n*	%	*n*
Araneae	6.9	66		
Diptera	6.5	62	45.4	187
Coleptera	22.5	214	6.3	26
Orthoptera	22.3	212		
Hymenoptera	16.5	157	6.3	26
Hemiptera			23.3	96
Trichoptera			12.6	52
Total		952		412

The main difference in species richness was among environmental conditions at PSPS, but at PAS3 depended on both environmental conditions and the sampling month (Table 3). In addition, abundances only showed temporal differences at PAS3 (Table 3). However, the spatial diversity patterns depend on intrinsic local conditions, both environmental (Fig. 4 a and b) and temporal (Fig. 5). For instance, the number of morphospecies (S) at PSPS was higher in Shade compared to Sun (Fig. 4 a, Table 4). Opposite pattern was observed in the richness (S) at PAS3 (Fig. 4 b), Shade did not differ significantly from Sun (Table 4). Both sites show no abundance differences among environmental conditions (Table 4). In temporal terms, abundances (N) and richnesses (S) were the same at PSPS (Table 3). The opposite was observed at PAS3, where the first sampling time was higher on richness and abundance (Fig. 5).

Arthropod assemblages were statistically dissimilar among environmental conditions and the sampling times at both sites (Table 3). However, the taxonomic composition of PAS3 did not indicate variation in the community assembly between Sun and Shade. PSPS presents differences between areas beneath solar panel and Reference / Sun areas (Table 4). Figure 6 shows the nMDS ordering of the spatial and temporal components of both places. A strong correlation between full species dataset and the order-taxon matrix for multivariate community patterns was observed (RELATE: PSPS: $\rho = 0.68$, $p < 0.001$ and PAS3: $\rho = 0.63$, $p < 0.001$). The spatial and temporal variations, observed in PERMANOVA pairwise tests, were associated with different orders of arthropods (Table 5). For example, the spatial structuring was based on eight orders that contributed over 91%; the most important were *Solifugae*, *Coleoptera* and *Orthoptera* to PSPS, and *Diptera*, *Hemiptera* and *Trichoptera* to PAS3. *Solifugae* and *Diptera* explained the main dissimilarities at PSPS between Shade and the sunny (Sun / Reference) environments. In terms of temporal structuring, six orders contributed over 90% to the observed structure at PSPS; even though taxa contributions are similar, *Hymenoptera* presents higher abundances in October. *Trichoptera* was the most dominant order at PAS3 Reference, whereas *Diptera* in the panel area (Sun / Shade). Finally, four orders, including *Hymenoptera*, contributed over 93% to temporal structuration at PAS3. All taxa increased their abundances in the second sampling time, except for *Trichoptera*, which decreased (Table 5).

Table 3. Results of PERMANOVA main test among environmental conditions and sampling times. Abbreviation Env. stands for environmental condition (Sun, Shade, Reference), and S. time for sampling time.

		Community Parameters				Taxonomic Composition	
		Richness (S)		Abundance (N)		Bray-Curtis	
Source	df	Pseudo-F	P (perm)	Pseudo-F	P (perm)	Pseudo-F	P (perm)
PSPS							
Env.	2	6.14	0.003	1.81	0.176	5.81	< 0.001
S. time	1	3.42	0.069	0.03	0.882	3.69	< 0.001
Env. × S. time	2	0.71	0.493	0.35	0.713	0.63	0.884
Residuals	54						
Total	59						
PAS3							
Env.	2	4.33	0.008	0.49	0.620	2.33	0.002
S. time	3	21.74	< 0.001	8.97	< 0.001	7.54	< 0.001
Env. × S. time	6	2.40	0.031	1.79	0.104	1.31	0.523
Residuals	99						
Total	110						

Table 4. Summary of paired t-tests among environmental conditions. Results of pairwise comparisons between environmental conditions at PAS3 and at PSPS are above and below the main diagonal, respectively.

	Community Parameters			Taxonomic Composition		
	Richness (S)			Bray-Curtis		
	Shade	Sun	Ref.	Shade	Sun	Ref.
Shade		0.19	2.95**		1.15	1.55*
Sun	2.67*		2.72**	2.33***		1.87***
Ref.	2.94**	0.10		2.92***	1.77	

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

Table 5. Results of the analysis of similarity percentage with all taxa grouped by order (SIMPER), according to the groups noted significant in the PERMANOVA pairwise tests.

	Environmental Condition				Sampling time			
	PSPS		PAS3		PSPS		PAS3	
Average Similarity (%)	Ref./Sun (53.25)	Shade (52.60)	Ref. (35.53)	Sun/Shade (38.33)	September (50.14)	October (49.58)	January (46.65)	February (25.68)
	Contribution (%)							
Araneae	7.33	13.24			15.09	5.66		
Coleoptera	27.11	39.82			34.78	30.32		
Diptera		15.57	29.55	60.32	7.08	8.2	50.14	54.27
Hemiptera			31.88	17.29			19.31	24.55
Hymenoptera	6.95	10.94				10.9		8.53
Orthoptera	17.69	11.59			15.94	17.22		
Solifugae	32.77				17.86	17.96		
Trichoptera			37.50				23.71	6.67
Total Contribution	91.84	91.16	98.93	77.61	90.76	90.27	93.16	94.03
Total Orders	5	5	3	2	5	6	3	4

3.2.2. Linkages among arthropod assemblages and abiotic variables

The BIO-ENV test showed a significant link between global arthropod assemblages and statistical descriptor values calculated from a suite of environmental variables at both sites. For instance, five of the studied variables, temperature (minimum and standard deviation), and humidity (standard deviation, range, and mode) best explained the overall species arrangement at PSPS (BEST: Spearman's $\rho = 0.238$, $p < 0.004$). However, variables related to temperature (minimum, maximum and mode) explained the global biotic pattern at PAS3 (BEST: Spearman's $\rho = 0.325$, $p = 0.020$). The divisive cluster algorithm did not find an effective way to describe the species-environment relationships at PSPS. In contrast, the resulting linkage at PAS3 had one division based on inequalities in minimum temperatures (Fig. 7). In this case, the abiotic variables explained the biotic structure mostly according to sampling times (i.e. January and February). In a broad sense, it was noticed that the variation in abiotic variables was not evident from the spatial clustering of morphospecies (i.e. according to PERMANOVA tests).

3.2.3. The role of shade as refuges and co-occurrence patterns

At both sites, there was evidence of nestedness in co-occurrence patterns in the arthropods distribution and significant nestedness among sampling units and morphospecies independently (NODF-values in Table 6). On the other hand, a higher C-score value than expected by chance was evidence for a segregated pattern of species among environmental conditions at PSPS. There was no significant pattern of morphospecies aggregation nor segregation at PAS3, indicating that morphospecies are distributed independently of each other (Table 6).

Table 6. Co-occurrence analysis of morphospecies by sampling unit dataset of PSPS and PAS3 arthropods. Term 'sites' refers to sampling units in this table.

	PSPS		PAS3	
	Observed	Simulated	Observed	Simulated
NODF	28.48^{***}	23.22 (20.93 - 25.72)	29.17^{***}	16.61 (13.56 - 20.12)
$NODF_c$ (sites)	34.31^{**}	28.91 (25.49 - 32.66)	35.42^{***}	19.72 (14.89 - 25.39)
$NODF_r$ (species)	21.00^{***}	15.91 (13.60 - 18.36)	21.13^{***}	12.6 (9.73 - 16.11)
C-score	0.01672^{***}	0.01562 (0.0148 - 0.0162)	0.0066	0.0065 (0.0058 - 0.0071)

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

4. DISCUSSION AND CONCLUSIONS

4.1. Abiotic environment of solar power plants

The studied PV technologies created different microclimatic conditions. Shading and energy intake by the panels changes the energy balance of soil and affects the temperature (Wu et al. 2014). This was seen in both studied solar power plants. Fixed mounts create a shade where the temperature is cooler and humidity is higher than in the sun conditions throughout the day. In contrast, solar tracking creates temporally varying shading conditions.

The conditions at sun areas between arrays were more extreme than on the desert around it. Wind environment is affected by the solar power plants (Wu et al. 2014) and this is most likely the case also on the studied PV installations. Altered wind speed would explain why microclimatic changes in fixed mount structure occur already in a small-scale solar plant and maximum temperature rises by the increasing array number in Shade and in Sun conditions. In the night time, big scale power plant creates a warmer and dryer microclimate than on the surrounding desert whereas the effect of a small scale solar plant is not clearly seen.

4.2. Biotic environment of solar power plants

The type of PV power plant seems to be an important factor when considering the plants' effects on biodiversity. The results presented showed a clear spatio-temporal effect on richness and taxonomic composition. However, Sun and Shade have a differing effect on the number of morphospecies. There were no taxonomic composition differences in environmental conditions (i.e. Sun and Shade) within the studied solar tracking technology plant (PAS3), and only Shade conditions differed in the fixed-mount technology plant (PSPS).

In general, most of the studies have focused on microclimate impacts of solar facilities' design (e.g. Chiabrando et al. 2009, Lovich & Ennen 2011, Turney & Fthenakis 2011), and only a few hypothetical schemes assume beneficial effect on microclimate and biota by the shade conditions under the solar panels (Tsoutsos et al. 2005, Wu et al 2014). In fact, this study should reach the same conclusions, since greater humidity conditions beneath panels could be beneficial to biota showing as increased number of species. However, analyses in this study showed no explicit linkage between abiotic conditions and spatial biota arrangement. According to this study, there were no benefits on biota because of microclimatic conditions. This is a paradoxical result, since microclimate conditions beneath fixed-tables were more stable, and a significant nested co-occurrence pattern was observed at PSPS.

Fixed mounts could act as refuges for biodiversity (e.g. *Araneae*, *Coleoptera*, *Diptera* and *Hymenoptera*), because biotic segregate pattern was observed with differences of arthropod species distributions. Accordingly, *Solifugae* inhabited only Sun / Reference and *Diptera* Shade conditions. Moreover, there is a possibility of microhabitat selection regardless of the microclimatic conditions. For example, some spider species might consider solar panels as discrete habitat patches, and web spiders at habitat edges are expected to increase because of the facilitation to build webs in anthropic environments and to improve their fitness (Wise 2006). As a result from the increase in edge habitation, there were changes in species interactions which may be beneficial or detrimental to edge organisms depending on their intrinsic ecological traits (Cobbold & Supp 2012). The latter supports the idea that the structure of fixed-mounts determined the spatial assemblage pattern rather than abiotic conditions.

Although a nestedness pattern was observed at PAS3 as well, it cannot be asserted that solar tracking panels act as a refuge to biodiversity. Contrary to the findings in fixed-mount technology (PSPS), the pattern observed at PAS3 was due to a temporal factor, which modulated the abiotic parameters. Seasonal changes in arthropod composition were seen especially at PAS3 where the abundance of the second sampling time was lower. In this case, the main structuration source was dew point, which acted as an environmental filter. Thereby, during the first sampling time (January) dew point was significantly higher than on the second sampling time (February). In other words, when comparing the first and the second sampling times, increase in dew point made less condensed water available at higher temperatures that explained why both community parameters and taxonomic composition varied between the sampling times.

Solar tracking panels had no spatial assemblage differences among environmental conditions inside the panel area. Considering that PAS3 facilities are bigger than the ones at PSPS, the impact of disturbance is thought to be greater. However, the effect of disturbance relies on their frequency and intensity (Connell 1978). It should be noted that PAS3 was built quickly because terrain conditions were easy to modify. Unstable communities are often known to be the most resilient, so unstable communities are more likely to return to their previous composition and structure following some kind of disturbance (Holling 1973). Seemingly, the solar tracking panels at PAS3 generate an unstable environment beneath them because shadows are constantly moving during the day, and they prevent the direct sunlight only partially. This explains how assemblages within the solar plant had no differences in their taxonomic composition. Solar panel area's species composition was different from the Reference which was understandable because the solar power plant was recently installed. In addition, soil at PSPS is heavily used and development of biological crust has not been possible. On the contrary, PAS3 Reference was untouched ground. Therefore, the existence of biological crust could explain differences between the solar panel area and Reference.

4.3. Guidelines for enhancing sustainability of solar power plants

This preliminary study showed that PV power plant technology modifies microclimatic and biota conditions, but the way and magnitude of the effects depend on local conditions and power plant's scale. In this sense, it is important to consider the high level of endemism and heterogeneous ecosystems within Atacama Desert in Chile as others have suggested (Jerez 2000). Given the geographic distance between the sites in this study and the terrain differences, these results are not comparable. The effects of solar power plants described earlier suggest that the evaluation of solar panels' impacts on biota cannot be extrapolated to larger scales (i.e. regional, global). Because of scarcity of information and the limited focus of the present study, we recommend that both spatial short-term and long-term scale environmental studies are conducted at solar power plants.

The design and arrangement of solar panels is especially important in the case of fixed mounts; for instance, at PSPS, during the construction of the solar plant, distances between mounts were not considered. Having more space between the mounts, like there is at PAS3, could allow the cool air to get inside the solar power plant and the extreme abiotic conditions could be prevented. The terrain type should also be considered during the construction of solar power plants. Construction of solar power plants necessarily demands soil modifications (Chiabrando at al. 2009) and might alter local biota (Wu et al. 2014), but if construction is done quickly, desert arthropod species might have better resilience.

The studied reference areas represent a small fraction of Atacama Desert and the impact of different technologies on distinct type of desert ecosystems can be very different. This is important if the landscape heterogeneity of northern Chile is considered (Luebert & Pliscoff 2006), especially in the flowering desert area (Moreira-Muñoz 2011). The technology and design used at PAS3 seems to have a smaller impact on biota, because this plant did not have a significant impact on arthropod composition inside the panel area. Nevertheless, new studies are required to rule out an effect of the different types of desert ecosystems. Finally, this study highlighted the importance of evaluating the impact of solar plants considering the interaction of biotic and abiotic components as the first step. Thus, decision makers, engineers and environmental specialist should also focus on the proposed ecological aspects and changes in physical environment observed in this study. Although the solar power plants are considered to have a small impact compared to conventional energy production methods (Lovich & Ennen 2011, Tsoutsos et al. 2005) it is still better to decrease the impacts of solar power plant construction if it is possible.

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Figures

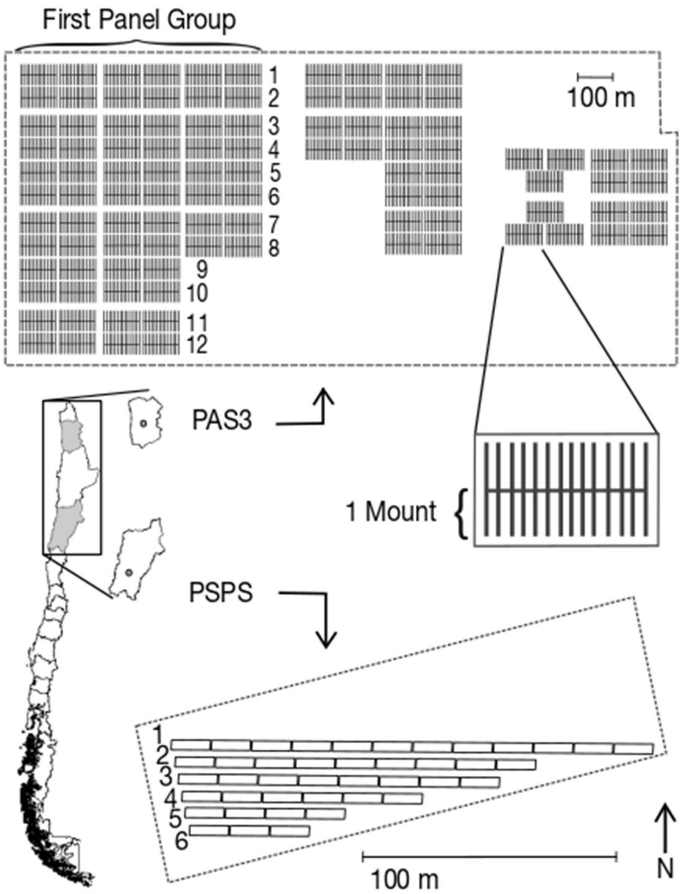

Fig. 1 Location and structure of solar power plants PAS3 (above) and PSPS (below). PAS3 is divided into three array groups and the first group is numbered according to the arrays, each including 30 mounts. Numbers 1-6 in PSPS indicate arrays. Dashed lines around the panel areas indicate perimeter fences. 129 x 174

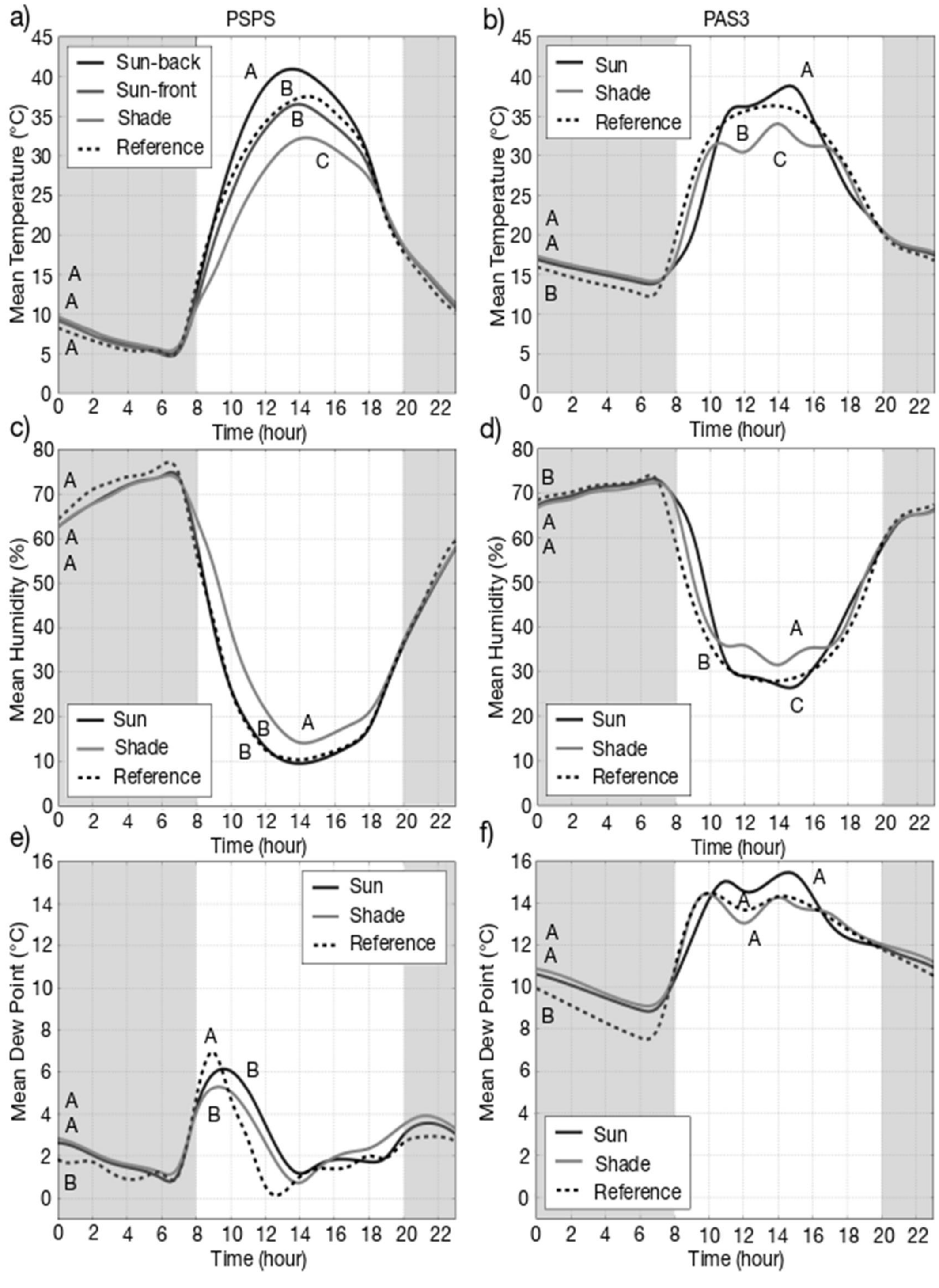

Fig. 2 Plots of a-b) mean temperature, c-d) mean humidity and e-f) mean dew point at PSPS on the left and PAS3 on the right. Nights are denoted with a grey background. Letters A-C in the figures indicate significant contrast between environmental conditions during the night or day time.174x234

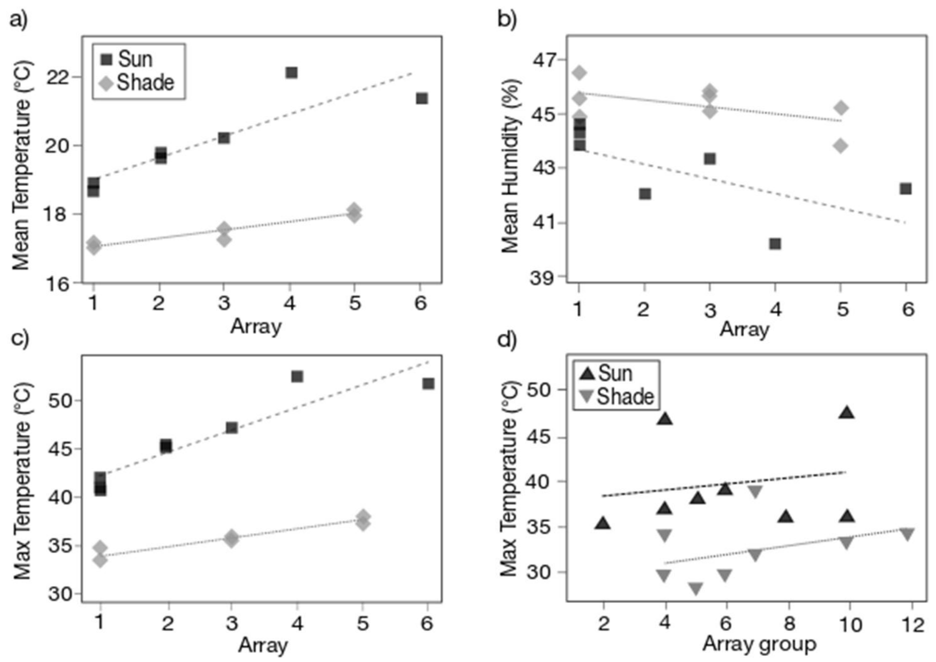

Fig. 3 Scatterplots of a) average temperature b) average RH, and c) maximum temperature among array numbers in PSPS, and d) maximum temperature among array groups in PAS3.129x129

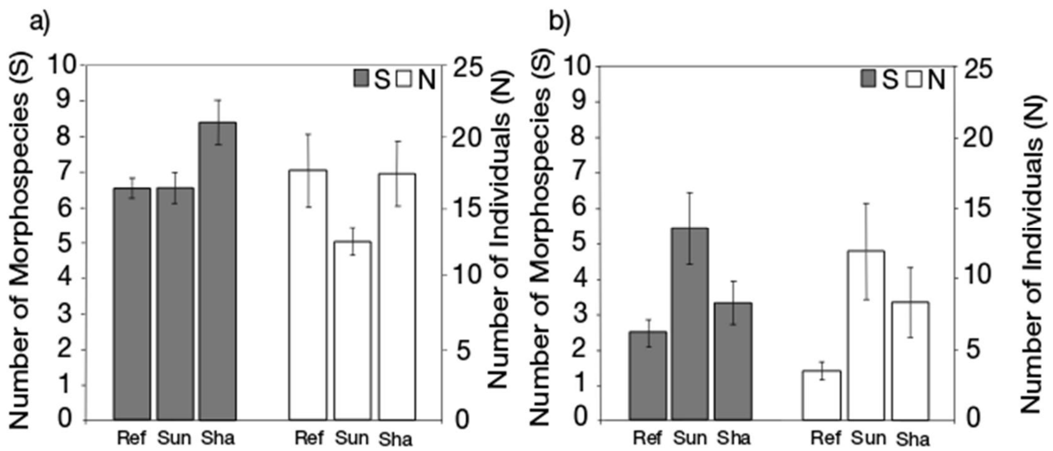

Fig. 4 Species richness (S), and abundance (N) among environmental conditions a) in PSPS and b) in PAS3. Vertical lines show standard error.129x84

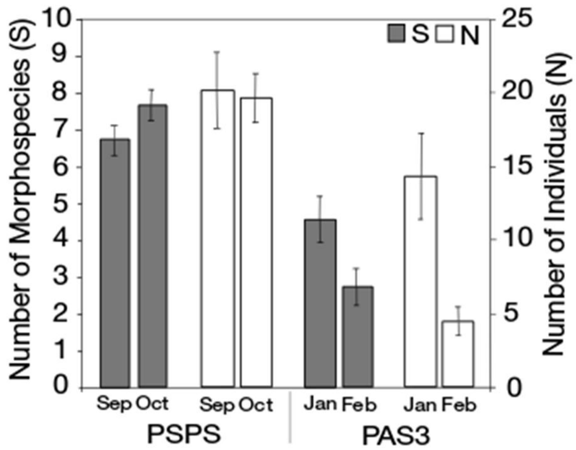

Fig. 5 Temporal averages of richness (S), and abundance (N). Vertical lines show standard error. 84x84

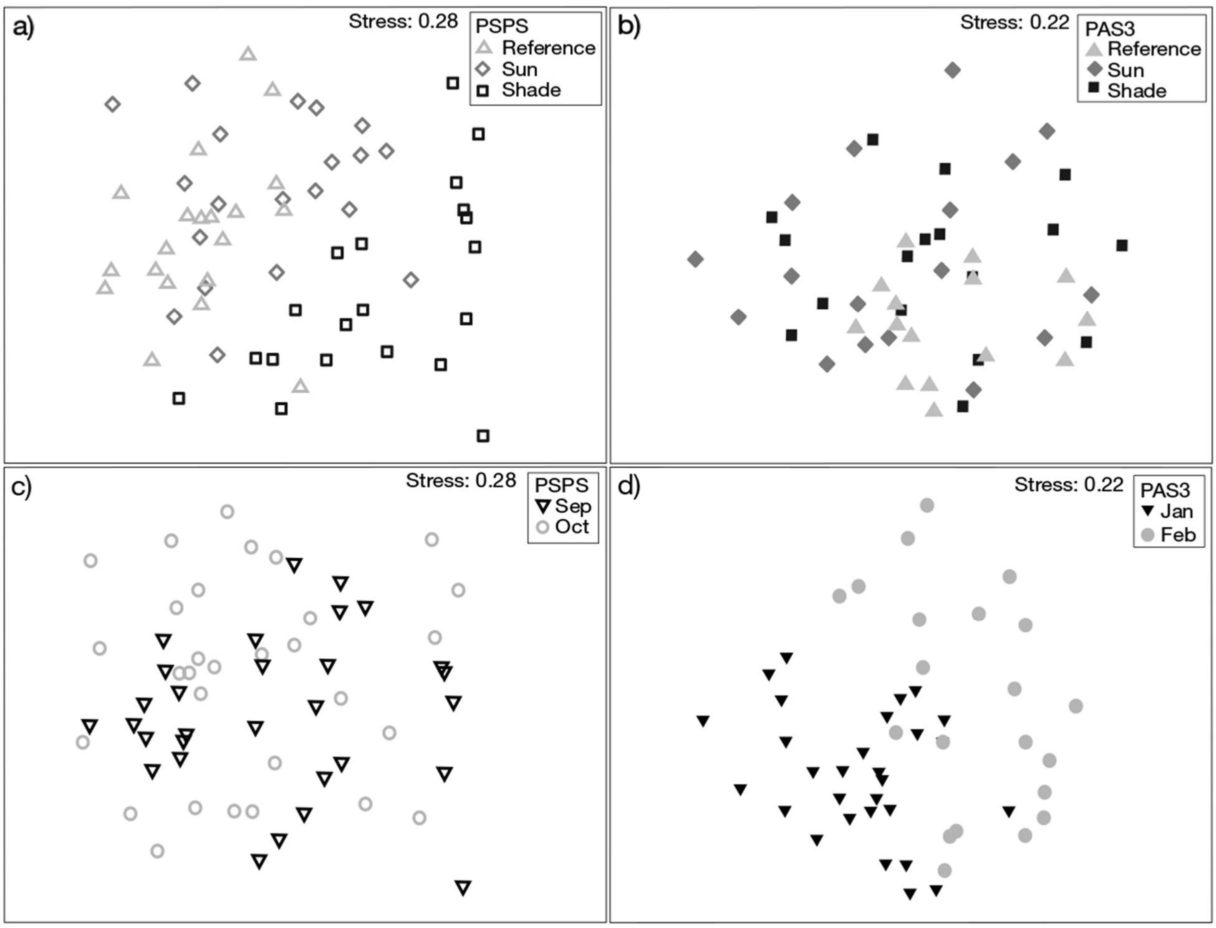

Fig. 6 Ordination of observed arthropod species composition by non-metric multidimensional scaling (nMDS) based on square root transformed Bray-Curtis similarities between environmental conditions a) at PSPS and b) at PAS3, and sampling times c) at PSPS and d) at PAS3 with 50 restarts.174x174

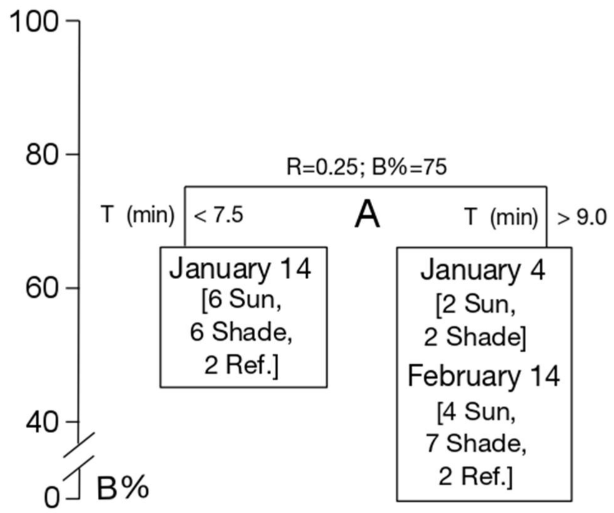

Fig. 7 Linkage tree analysis (LINKTREE) at PAS3 showing clustering of sampling units based on morphospecies composition constrained by abiotic variables. For each split, R is the optimal ANOSIM R value (relative subgroup separation). The B% statistic shows the absolute measure of group differentiation, and considers the ranks from the original resemblance data. The significant environmental variable(s) (SIMPROF, $p < 0.05$) that define each division are listed at the branching point (A). T stands for temperature. 84x84

The influence of solar power plants on microclimatic conditions and the biotic community in Chilean desert environments

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Online Resource 1

Contrast-based pair-wise LME test result among environmental conditions of temperature, humidity and dew point using hourly data of day time 8 a.m. - 8 p.m. in September and October at PSPS 2013 and in January and February at PAS3 2015.

Pair wise test by environmental conditions				PSPS (September-October)			PAS3 (January-February)		
				Temperature	Humidity	Dew point	Temperature	Humidity	Dew point
	N PSPS (PAS3)		*N*	χ^2	χ^2	χ^2	χ^2	χ^2	χ^2
Sun	8 (6)	Reference	2		0.73	13.5 ***	25.09 ***	6.44 ***	0.4
Shade	8	Reference	2	6.73 *	3.15	14.8 ***	63.32 ***	14.84 ***	0.36
Sun	8 (6)	Shade	8		6.9 *	0.06	168.12 ***	2.51 *	<0.01
Sun-back	3	Reference	2	10.54 **					
Sun-front	5	Reference	2	0.11					
Sun-front	5	Sun-back	3	8.54 *					
Shade	8	Sun-front	5	8.51 *					
Shade	8	Sun-back	3	34.12 ***					

Standard errors and number of data	SE	N	SE	N	SE	N	SE	N	SE	N	SE	N
Reference	1.31	39	2.92	39	0.44	39	0.38	297	0.62	297	0.15	297
Shade	1.14	39	2.98	39	0.40	40	0.29	297	0.53	297	0.14	297
Sun			2.88	39	0.42	38	0.40	297	0.63	297	0.15	297
Sun-back	1.57	39										
Sun-front	1.32	39										

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

Online Resource 2

Contrast-based pair-wise LME test result among environmental conditions of temperature, humidity and dew point using hourly data of night time 9 p.m. - 7 a.m. in September and October at PSPS 2013 and in January and February at PAS3 2015.

Pair wise test by environmental conditions				PSPS (September-October)			PAS3 (January-February)		
				Temperature	Humidity	Dew point	Temperature	Humidity	Dew point
	N PSPS (PAS3)		*N*	χ^2	χ^2	χ^2	χ^2	χ^2	χ^2
Sun	8 (6)	Reference	2		1	13.5 ***	25.65 ***	13.22 ***	5.52 *
Shade	8	Reference	2	1.74	0.88	2.05	12.43 ***	28.13 ***	11.3 **
Sun	8 (6)	Shade	8		1	5.17 *	2.37	2.78	1.02
Sun-back	3	Reference	2	1.03					
Sun-front	5	Reference	2	1.18					
Sun-front	5	Sun-back	3	<0.01					
Shade	8	Sun-front	5	0.06					
Shade	8	Sun-back	3	0.09					

Standard errors and number of data	SE	N	SE	N	SE	N	SE	N	SE	N	SE	N
Reference	0.83		2.68	28	0.33	28	0.25	291	0.55	291	0.21	291
Shade	0.72		2.46	28	0.26	27	0.21	291	0.48	291	0.18	291
Sun			2.61	28	0.36	39	0.22	291	0.52	291	0.18	291
Sun-back	0.72	28										
Sun-front	0.74	28										

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

Online Resource 3

Contrast-based pair-wise LME test results among day and night data of temperature, humidity and dew point using hourly data from September and October in PSPS 2013 and January and February in PAS3 2015.

	PSPS			PAS3		
Pair wise test by month	Temperature	Humidity	Dew point	Temperature	Humidity	Dew point
Day	0.22	0.39	218.9 ***	125.92 ***	272.00 ***	107.40 ***
Night	0.69	0.06	213.7 ***	13.46 ***	31.33 ***	0.70

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

Online Resource 4

Kendall´s tau correlation test of temperature, humidity, and dew point among rows in PSPS during September and October 2013 and among mount groups in PAS3 during January and February 2015.

	Temperature				Humidity				Dew Point			
	Sun		Shade		Sun		Shade		Sun		Shade	
	z	*tau*	*z*	*tau*	*z*	*tau*	*z*	*tau*	*z*	*tau*	*z*	*tau*
PSPS												
Average	2.07*	0.41	2.04*	0.42	-2.27*	-0.46	-1.75	-0.37	0.94	0.19	1.02	0.22
Max	4.20***	0.84	1.94	0.41	-1.04	-0.21	-1.21	-0.25	-0.14	-0.03	0.58	0.12
Min	0.78	0.17	-0.4	-0.09	-1.74	-0.37	0.05	0.01	-0.09	-0.02	1.11	0.23
PAS3												
Average	0.55	0.11	1.25	0.24	-0.37	-0.07	-1.52	-0.3	0.79	0.16	-0.09	-0.02
Max	0.66	0.13	0.83	0.16	-0.51	-0.1	-0.14	-0.03	-0.28	-0.05	-0.46	-0.09
Min	0.61	0.12	0.95	0.19	0.19	0.04	-0.23	-0.05	1.29	0.25	0.79	0.16

* $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

The influence of solar power plants on microclimatic conditions and the biotic community in Chilean desert environments

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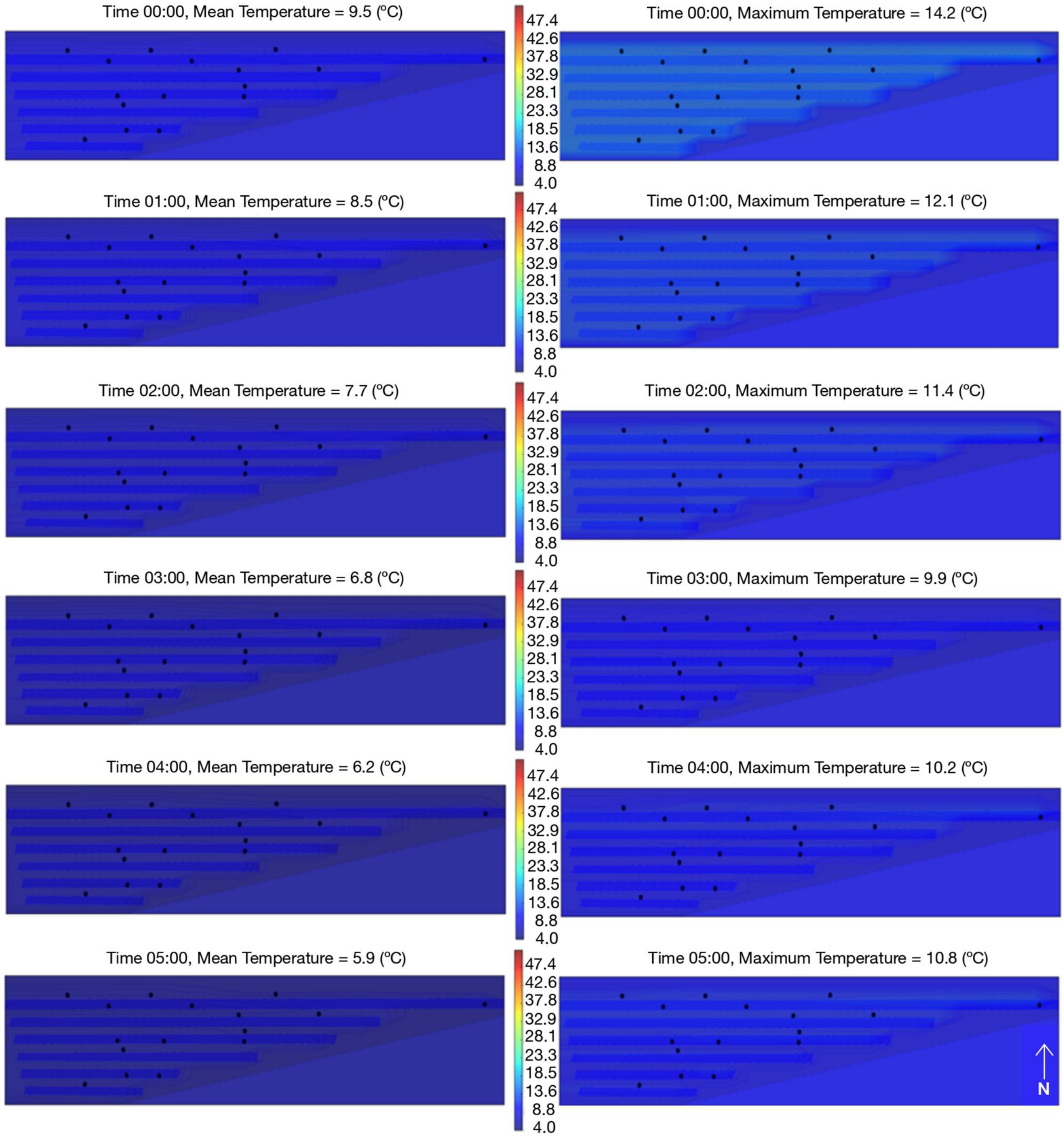
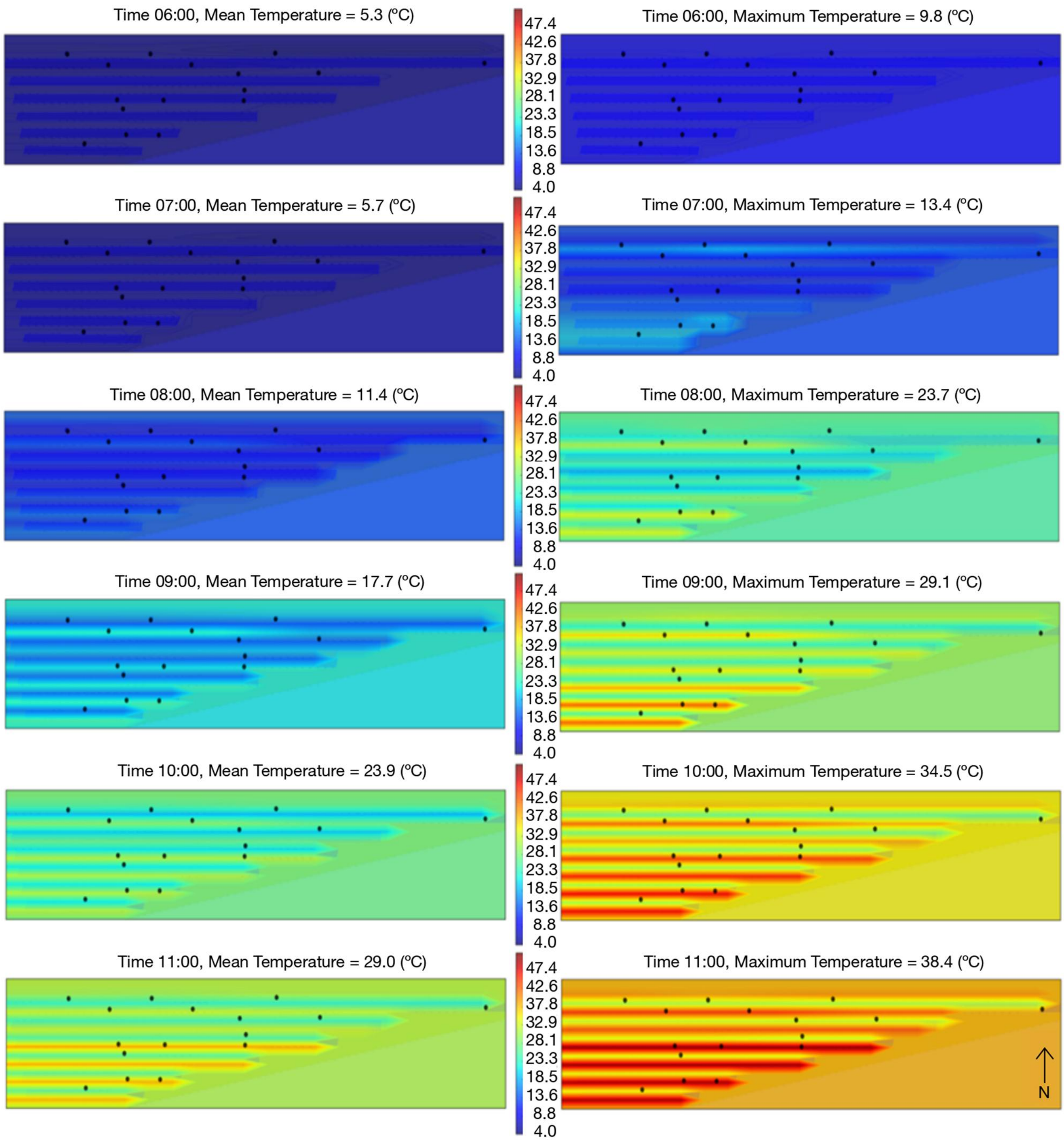
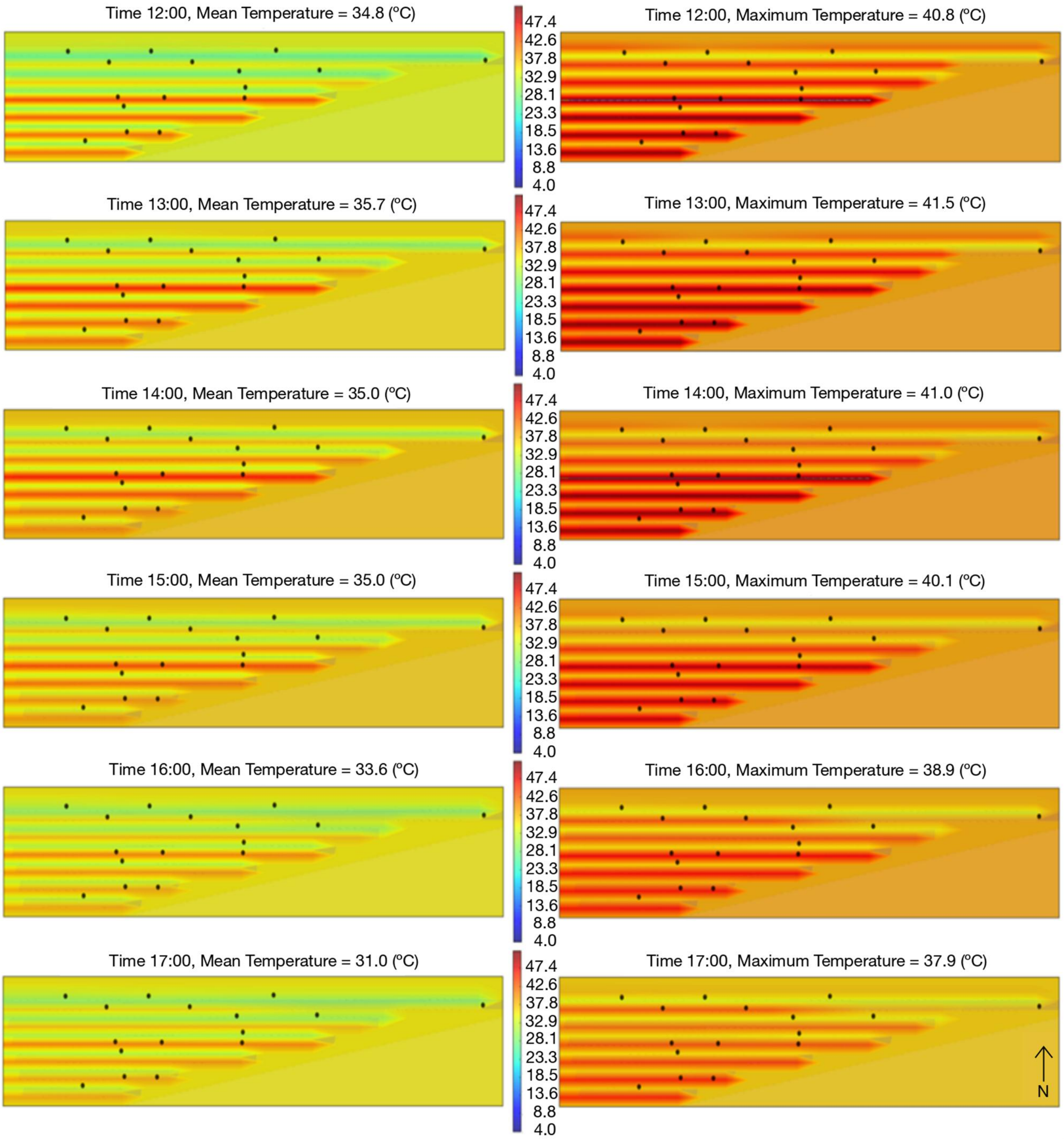
Online Resource 5

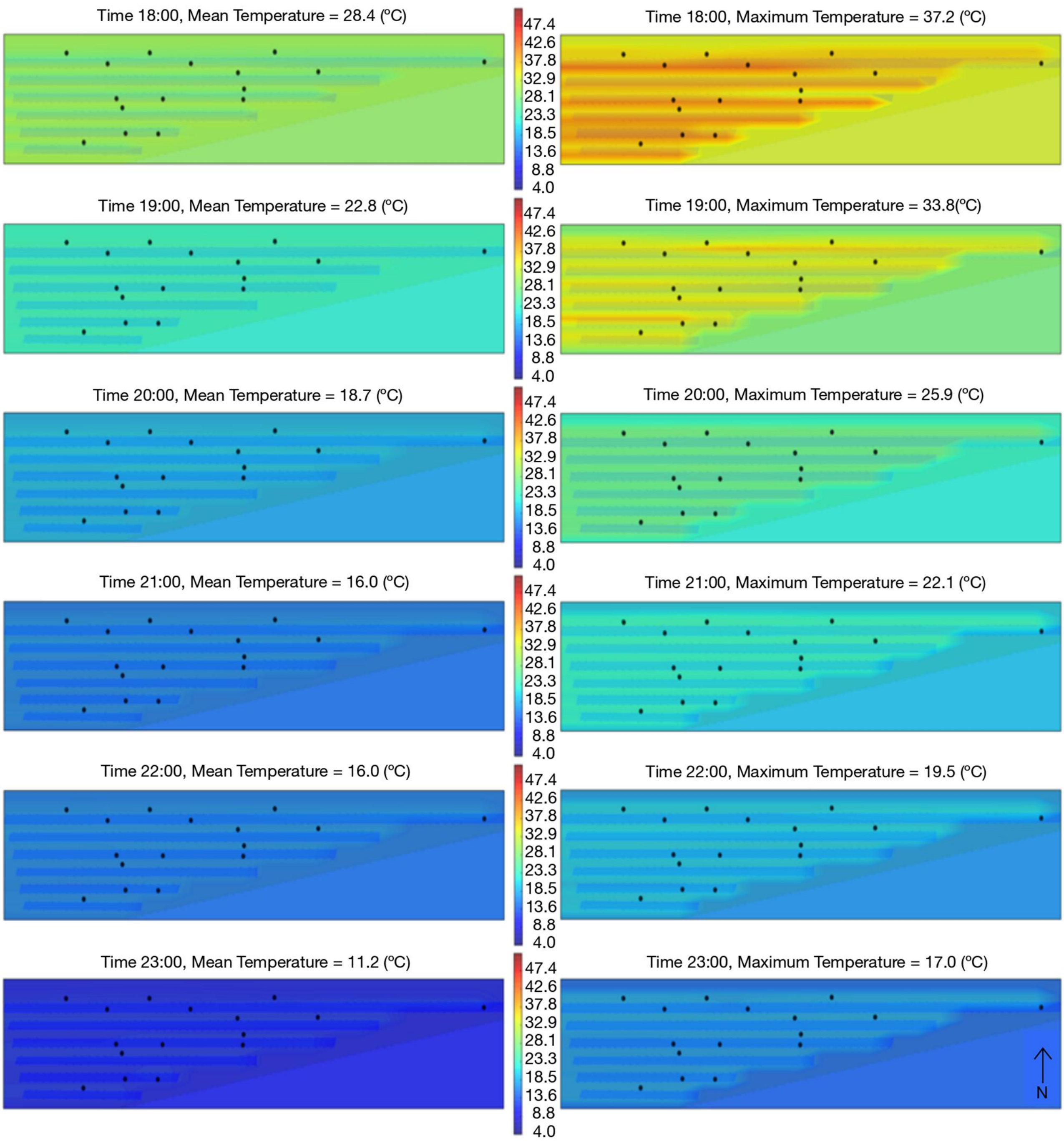
Interpolated hourly temperature means (on the left) and maximum hourly temperature (on the right) starting from midnight during September and October 2013 in PSPS. Black dots indicate the locations of 16 data loggers and the arrow at the bottom-right image marks the North direction. Solar power plant is displayed from above. Reference area's data loggers were on the northern side of the solar power plant so the interpolation in right bottom corner of the images is not reliable.




Time 06:00, Mean Temperature = 5.3 (ºC)
Time 06:00, Maximum Temperature = 9.8 (ºC)
Time 07:00, Mean Temperature = 5.7 (ºC)
Time 07:00, Maximum Temperature = 13.4 (ºC)
Time 08:00, Mean Temperature = 11.4 (ºC)
Time 08:00, Maximum Temperature = 23.7 (ºC)
Time 09:00, Mean Temperature = 17.7 (ºC)
Time 09:00, Maximum Temperature = 29.1 (ºC)
Time 10:00, Mean Temperature = 23.9 (ºC)
Time 10:00, Maximum Temperature = 34.5 (ºC)
Time 11:00, Mean Temperature = 29.0 (ºC)
Time 11:00, Maximum Temperature = 38.4 (ºC)
47.4
42.6
37.8
32.9
28.1
23.3
18.5
13.6
8.8
4.0
N

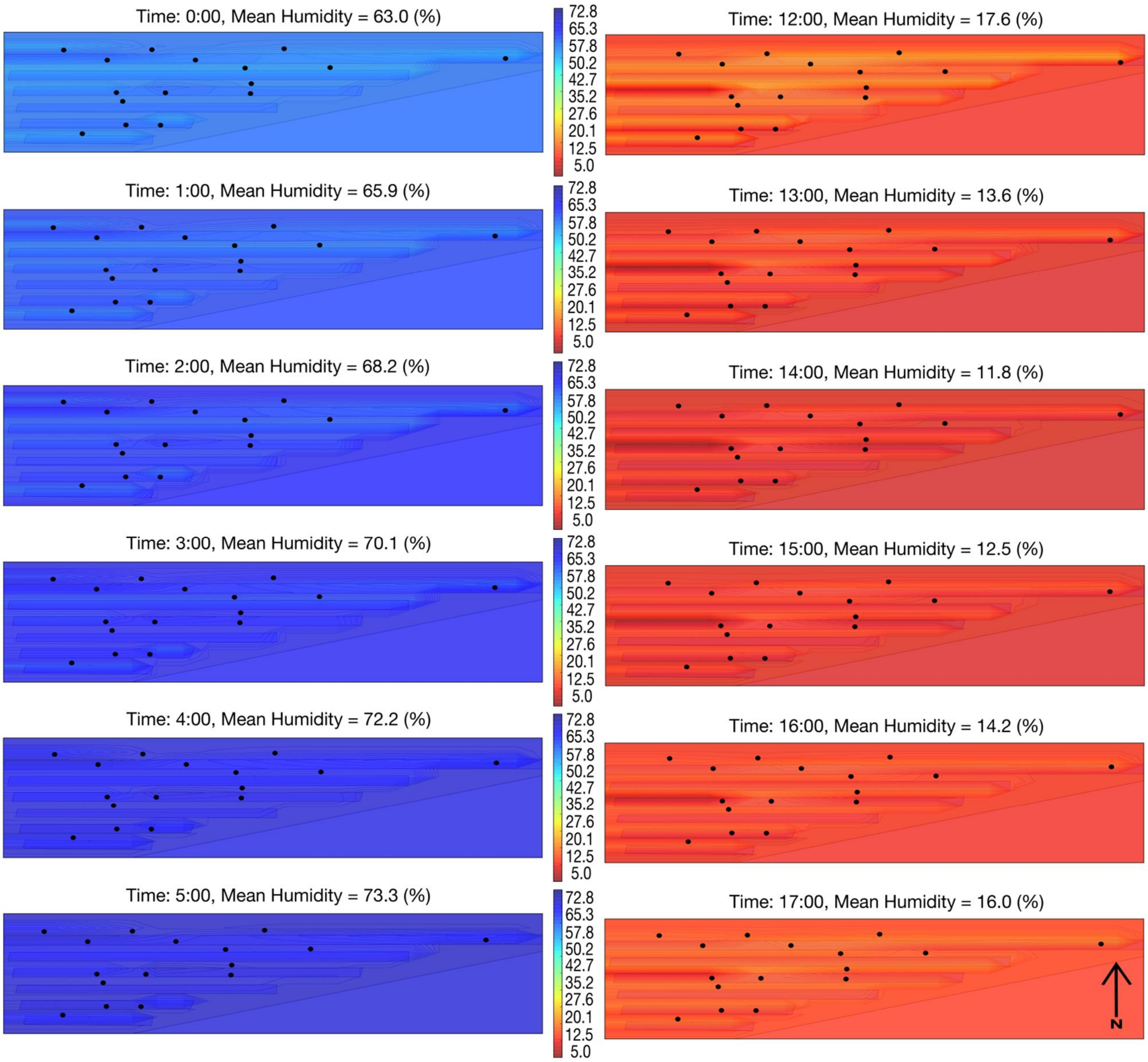


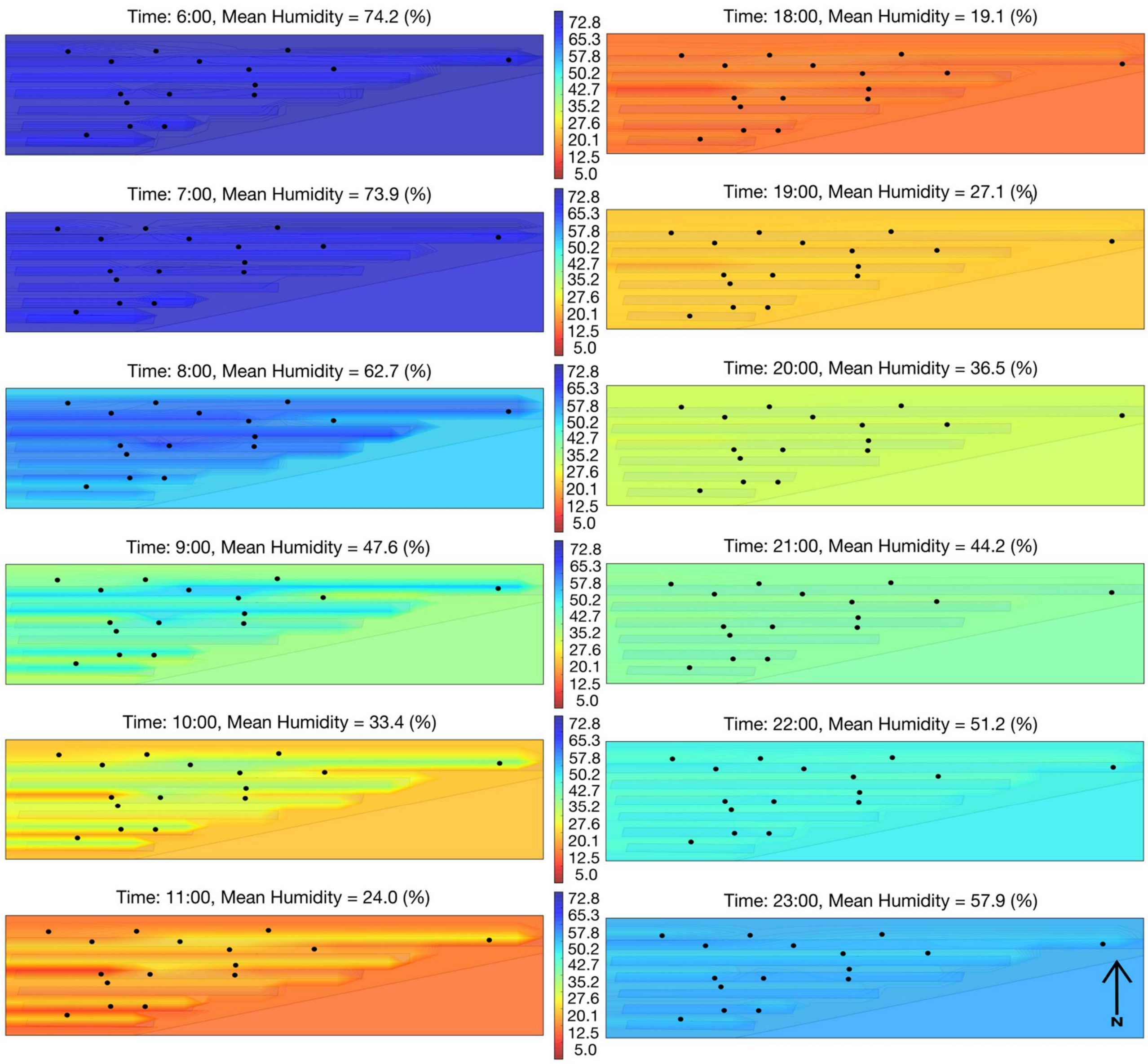
Time 12:00, Mean Temperature = 34.8 (ºC)
Time 12:00, Maximum Temperature = 40.8 (ºC)
Time 13:00, Mean Temperature = 35.7 (ºC)
Time 13:00, Maximum Temperature = 41.5 (ºC)
Time 14:00, Mean Temperature = 35.0 (ºC)
Time 14:00, Maximum Temperature = 41.0 (ºC)
Time 15:00, Mean Temperature = 35.0 (ºC)
Time 15:00, Maximum Temperature = 40.1 (ºC)
Time 16:00, Mean Temperature = 33.6 (ºC)
Time 16:00, Maximum Temperature = 38.9 (ºC)
Time 17:00, Mean Temperature = 31.0 (ºC)
Time 17:00, Maximum Temperature = 37.9 (ºC)
47.4
42.6
37.8
32.9
28.1
23.3
18.5
13.6
8.8
4.0
N


Time 18:00, Mean Temperature = 28.4 (ºC)
Time 18:00, Maximum Temperature = 37.2 (ºC)
Time 19:00, Mean Temperature = 22.8 (ºC)
Time 19:00, Maximum Temperature = 33.8(ºC)
Time 20:00, Mean Temperature = 18.7 (ºC)
Time 20:00, Maximum Temperature = 25.9 (ºC)
Time 21:00, Mean Temperature = 16.0 (ºC)
Time 21:00, Maximum Temperature = 22.1 (ºC)
Time 22:00, Mean Temperature = 16.0 (ºC)
Time 22:00, Maximum Temperature = 19.5 (ºC)
Time 23:00, Mean Temperature = 11.2 (ºC)
Time 23:00, Maximum Temperature = 17.0 (ºC)
47.4
42.6
37.8
32.9
28.1
23.3
18.5
13.6
8.8
4.0
N

Online Resource 6

Interpolated hourly means of humidity starting from midnight. during September and October 2013 in PSPS black dots are 16 data loggers and the arrow at the bottom-right image marks the North direction. Solar power plant is displayed from above. Reference areas data loggers were on the northern side of the solar power plant so the interpolation in right bottom corner of the images is not reliable.





Time: 6:00, Mean Humidity = 74.2 (%)
Time: 7:00, Mean Humidity = 73.9 (%)
Time: 8:00, Mean Humidity = 62.7 (%)
Time: 9:00, Mean Humidity = 47.6 (%)
Time: 10:00, Mean Humidity = 33.4 (%)
Time: 11:00, Mean Humidity = 24.0 (%)
Time: 18:00, Mean Humidity = 19.1 (%)
Time: 19:00, Mean Humidity = 27.1 (%)
Time: 20:00, Mean Humidity = 36.5 (%)
Time: 21:00, Mean Humidity = 44.2 (%)
Time: 22:00, Mean Humidity = 51.2 (%)
Time: 23:00, Mean Humidity = 57.9 (%)
72.8
65.3
57.8
50.2
42.7
35.2
27.6
20.1
12.5
5.0
N