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Anna Suuronen

Ecological and Social Impacts of Photovoltaic Solar Power Plants and Optimization of their Locations in Northern Chile

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ABSTRACT

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Large scale photovoltaic (PV) solar power plants are gaining popularity in Chile. Solar energy potential in northern Chile is one of the best worldwide and true deserts are considered ideal environments for solar power plant projects. Atacama Desert is one of the driest places on earth. Nevertheless, northern Chile is home for many endemic species with 40 different vegetation types. The thesis presents studies of ecological effects (I-II) and location optimization of PV solar power plants in northern Chile (III). For ecological impacts two types of PV solar power plant technologies were studied: fixed mount solar plant and solar-tracking mounts. Study units were placed below the mounts or between the panels. Reference area was outside the panel area. Arthropod species composition was altered between shade and sun conditions at fixed mount power plant and, for example, dipterans were more common in shade conditions. Fixed mount solar power plants' shade conditions can act as refuge to some arthropod groups, but for vegetation, shade conditions can disturb their florescence. Abiotic conditions limited local spider species habitat selection, but invasive spider species *Lactrodectus geometricus* could colonize mount legs of entire plant. Precaution should be taken when planning PV projects in areas with sensitive nature. Northern Chile is an ideal place for solar power plant projects because of its high solar energy potential but environmental and social aspects of site selection should be considered. Ideal places with low environmental and landscape value are in the absolute desert situated in the central valley starting from Arica and reaching until the northern part of Atacama region. Nevertheless, cities and historical sites should be avoided. The results of this thesis provide new information about ecological environment of PV plants and gives alternatives to multidisciplinary site selection.

Keywords: Arthropods; Atacama Desert; ecological impacts; environmental-social effect; photovoltaic solar power plant; site selection; sustainable energy.

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CONTENTS

ABSTRACT

LIST OF ORIGINAL PUBLICATIONS

1 INTRODUCTION 7
    1.1 Sustainable development 7
        1.1.1 Renewable energy..7
        1.1.2 Solar energy 8
    1.2 Solar energy impacts 9
        1.2.1 Environmental impacts..9
        1.2.2 Social impacts 10
    1.3 Location optimization of PV plants 10

2 OBJECTIVES 12

3 MATERIAL AND METHODS 13
    3.1 Study Sites 13
    3.2 Studied PV plants 14
    3.3 Study methods 15

4 RESULTS AND DISCUSSION 17
    4.1 Microclimate of PV plants 17
    4.2 Ecological environment of PV solar power plants 18
    4.3 Location optimization of PV plants in northern Chile.........................20

5 CONCLUSIONS...21

Acknowledgements...23

YHTEENVETO (RÉSUMÉ IN FINNISH)..25

REFERENCES..28

LIST OF ORIGINAL PUBLICATIONS

The thesis is based on the following original papers, which will be referred to in the text by their Roman numerals I-III.

Anna Suuronen had the original ideas of the studies and Anssi Lensu, Markku Kuitunen and Jussi V.K. Kukkonen helped to plan the field work. Suuronen was the main writer of the manuscripts and did the statistical analyses with the help of Anssi Lensu and Christian Muñoz-Escobar. Muñoz-Escobar participated in writing the manuscripts I and II, and he did part of the statistical analyses of the same manuscripts. Anssi Lensu gave several notes and comments to manuscripts I, II, and III and corrected the language. In addition, Markku Kuitunen gave notes to manuscripts I and II, and gave the idea of survey study in the III manuscript. Marcelo Miranda helped to plan the manuscripts I and III. Anna Suuronen realized the field work and identified the arthropod groups together with Marcos Ferrú, Andrés Taucare-Ríos, Pablo Espinoza Astudillo and Natalia Guajardo Celis. Natalia Guajardo Celis and Rodrigo Andrade-Alvear assisted in the field work. In addition, Andrade-Alvear realized survey questionnaires together with Suuronen. Marcelo Perez gave several notes and comments on manuscript III.

I Suuronen A., Muñoz-Escobar C., Lensu A., Kuitunen M., Guajardo Celis N., Espinoza Astudillo P., Ferrú M., Taucare-Ríos A., Miranda M. & Kukkonen J.V.K. 2017. The influence of solar power plants on microclimatic conditions and the biotic community in Chilean desert environments. *Environmental management* 60(4): 630−642.

II Suuronen A., Muñoz-Escobar C., Lensu A., Andrade-Alvear R., Taucare-Ríos A., Kuitunen M. & Kukkonen J.V.K. Biota responses to solar Power Plant Environment in the Valley of Copiapó, Chile. Submitted manuscript.

III Suuronen A., Lensu A., Andrade-Alvear R., Kuitunen M., Miranda M., Perez M., Ferrú M. & Kukkonen J.V.K. Optimization of photovoltaic solar power plant locations in northern Chile. Submitted manuscript.

1 INTRODUCTION

1.1 Sustainable development

1.1.1 Renewable energy

Sustainable development (Brundtland 1989) is described as development that meets the needs of current demands, but does not compromise the future demand so that also future generation can meet their needs (Brundtland 1989, Omer 2008a). International agreements such as the World Summit on Sustainable Development in Johannesburg (2002) and Paris Agreement (United nations 2015) were ratified to promote the goals of sustainable development (Omer 2008a). There are many factors when considering sustainable development, but energy demand is one of the essential factors. Traditional energy sources have many problems including global warming, air pollution, acid precipitation, forest destruction, and emission of radioactive substances (Dincer 2000).

Climate change is a consequence of human activities where fossil fuels are used and carbon dioxide (CO_2), among many other greenhouse gases, is emitted (Omer 2008a). To mitigate the harmful effects of energy production, requirement is that the energy resources must be fully sustainable (Dincer and Rosen 1998, 2011). Therefore, renewable energy is the most effective and efficient solution to sustainable development because it´s almost emissions free (Dincer 2000, Omer 2008a).

Sustainable development not only considers emission free energy supply, but also energy efficiency (Dincer 2000) and energy saving (Omer 2008b). In fact, all energy production has environmental impacts, but if negative impacts are thought to be small compared to the amount of produced energy, it is sustainable energy. Sustainable energy is described as energy that has minimal negative impact on human health and the healthy functioning of vital ecological systems during the production or consumption phase (Omer 2008b). Sustainable development requires that sustainable energy can be used to all tasks without negative social impacts. Nevertheless, sustainable energy should meet the needs of cost effectiveness (Dincer 2000).

Constant environmental degradation is not sustainable over time and can lead to various health, ecological, and other problems. Utilization of renewable energy sources has much less environmental impacts because the energy resources are not depleted unlike fossil fuel or uranium resources. In addition, renewable energy decentralizes the energy supply and gives more flexibility to energy consumption. Because many renewable energy technologies are based on solar radiation, such as winds or waves, energy sources are available without extraction and consumption (Dincer 2000). Renewable energy forms are constantly supplemented and, therefore, they do not run out (Elliot 2000). Energy supply derives ultimately from the Sun, or in case of geothermal energy, Earth's internal heat supply (Kelly 1993).

1.1.2 Solar energy

Solar energy is considered environmentally most advantageous among renewable energy resources, considering that it is noiseless, CO_2 free during operation, scale flexible, and operation and maintenance are considered straightforward (Wang and Qiu 2009). There are three solar energy forms: Solar-thermal panels, solar photovoltaic (PV) panels, and solar power plants (Afgan *et al.* 1998), which can be either solar-thermal or photovoltaic. Solar-thermal techniques concentrate sun light to heat fluids that drive turbines (De Laquil *et al.* 1993). In contrast, PV converts sun light directly into electricity (Kelly 1993). Since solar energy potential varies between locations, lack of solar radiation data is a critical problem. Equipment that measures solar radiation are expensive and evaluating solar energy potential at remote places is difficult (Omer 2008b). Fortunately, the price of solar energy per kWh has decreased because of improved solar cell efficiency and because prices have gone down due to improvements in manufacturing-technology. Consequently, lower prices have enabled solar electric energy share of markets to grow (Carrasco *et al.* 2006).

The basic unit device in a PV system is a PV cell. Cells can be grouped to form panels, and arrays can be formed from one panel or several panels, which are connected in series or parallel to form large PV systems (Villalva *et al.* 2009). Earth movement changes solar radiation diurnally and seasonally. Fixed mounts are facing the Sun with a locally chosen optimal angle; however, in sun tracker systems the solar panels turn optimizing the orientation to the Sun (Mousazadeh 2009). For example, a "One axis three position sun tracking PV module" has three positions: morning, noon, and afternoon (Huang and Sun 2006). Nevertheless, the tracking system consumes 2–3 % of produced energy and, therefore, is not suitable for small solar power plants (Mousazadeh 2009).

1.2 Solar energy impacts

1.2.1 Environmental impacts

Solar energy technologies (SET) have positive environmental impacts when compared to conventional energy, for instance, reduction of the greenhouse gas emissions (CO_2, N_2O, CH_4, etc.), and prevention of toxic gas emissions (SO_2, particulates). In addition, SETs can reduce transmission lines of electricity grids (Tsoutsos *et al.* 2005). Unfavourable effects are considered usually minor and they can be minimized. These effects are site specific and are depending on SET project type (Tsoutsos *et al.* 2005, Turney and Fthenakis 2011). In addition, an environmental impact of solar power plants depends on distance from sensitive ecosystems (Tsoutsos *et al.* 2005).

PV panel production is energy intensive and causes depletion of some natural resources, because bulk semiconductor material is needed in high quantities (Tsoutsos *et al.* 2005). Some PV cell types contain hazardous materials (such as CdTe modules), although their release to the environment is not common since that would require a fire, for example.

Impacts on wildlife are largest during the construction phase of solar power plants. Despite the fact that PVs themselves are noiseless, the construction phase causes some intensive noise (Tsoutsos *et al.* 2005, Wu *et al.* 2014). In addition, construction increases dust formation (Lovich and Ennen 2011) and vibration (Wu *et al.* 2014). During the construction, soil is removed alongside its flora and fauna. Inherent biological soil crusts are turned over and the soil becomes vulnerable to soil erosion (Wu *et al.* 2014), and water infiltration rate changes (Lovich and Ennen 2011). Recovery of the ecosystem may require many years (Turney and Fthenakis 2011), especially in deserts where recovery is slow (Tsoutsos *et al.* 2005). For the above reasons, it takes time for flora and fauna to return during the operational phase (Wu *et al.* 2014). In addition, solar plants are enclosed by a fence, which limits the movements of some animals. Therefore, solar power plant can also change habitat quality, migration routes, and cause habitat fragmentation (Turney and Fthenakis 2011).

Positive effects for wildlife are also possible (Turney and Fthenakis 2011). Shade of the panels can offer a beneficial microclimate to vegetation (Tsoutsos *et al.* 2005, Wu *et al.* 2014). SETs can increase the albedo of a desert environment, which could change the local temperature and precipitation patterns through wind speed changes and evapotranspiration (Lovich and Ennen 2011). If panels are cleaned with water, impact can be extensive in desert environments where lack of water is normally a problem (Charabi and Gastli 2011). On the other hand, solar power plant environments can be fragile to exotic species invasion (Lovich and Ennen 2011). Despite the fact, that construction phase causes notable disruptions to wildlife and habitat, wildlife and ecosystem impacts are poorly understood (Turney and Fthenakis 2011).

Typical characteristic of invasive species invasions is that they can be better fit to their environment than local endemic species (Lozon and Maclsaac 1997, Vellend *et al.* 2007). Invasive species can compete directly for the same space with the endemic species or they can indirectly affect the resources available to species (Tilman 1982). These changes can affect the whole ecosystems. When anthropogenic effect, for example the construction of solar power plant facility, is introduced to some habitat, it creates a new kind of anthropogenic environment (Vellend *et al.* 2007).

1.2.2 Social impacts

Social impacts are not easy to define and they are often left with less attention than environmental impacts because measurement methods are slow and complicated (Daniel 2001, Sevenant and Antrop 2009). Most important social impacts of solar power plants are public acceptance, job creation, and social benefits (i.e. progress of the region, income, health benefits of improved air quality, etc.) (Wang *et al.* 2009). Other positive socio-economic benefits are that solar energy projects increase regional or national energy independence, increase work opportunities, diversify and secure energy supply, deregulate energy markets, and can promote rural electrification in developing countries (Tsoutsos *et al.* 2005).

Among social impacts, public acceptance of RES is often related to landscape (Olson-Hazboun *et al.* 2016). However, landscape has both cultural and environmental aspects: Diverse landscape can maintain more biodiversity along with aesthetic and cultural value. Therefore, landscape should be integrated as one of the socio-ecological impacts (Azar *et al.* 1996) or be divided into ecological landscape and visual landscape (Daniel 2001).

With the help of the visual landscape planning, cultural heritance and aesthetics can be protected. Visual impacts are dependent on the type of surroundings and landscape where the PV system is installed. As with the environmental impacts, the amount of social impact depends on the location. Near natural beauty and cultural heritage areas, PV installations usually have a strong negative impact (Tsoutsos *et al.* 2005). Naturally, this may lead to public resistance and negative attitudes towards solar energy. Even though renewable energy has become a part of visual landscape in many countries (Antrop 2005), renewable energy can divide public opinions so that some people experience them positively, while others may reject the installations (Yonca Aydin *et al.* 2010).

1.3 Location optimization of PV plants

Physical characteristics of a site and its economic factors define the best locations to the PV plants (Arán Carrion *et al.* 2008, Charabi and Gastli 2011). True deserts are considered as optimal sites for SETs because they have little cloud cover, scarce amount of biomass and low human population. However, desert scrublands have the same kind of biodiversity as grasslands or farmlands (Turney and Fthenakis 2011). Nevertheless, in site selection or location optimization it is essential to mitigate the negative impacts of RES facilities (Tsoutsos *et al.* 2005). Beside solar radiation, physical aspects include: temperature, orientation of the ground, slope, and distances to the roads and substations of grid (Arán Carrion *et al.* 2008). Costs can be diminished if PV plant is built into close proximity to roads and already existing electric grid. In addition, former land use affects the magnitude of PV project's impacts (Arán Carrion *et al.* 2008, Charabi and Gastli 2011).

Diminishing the negative environmental effects, high biodiversity areas should be avoided (Tsoutsos *et al.* 2005). High biodiversity does not mean only the number of species, also rare and endemic species should be included (Ayyad 2003, Rey Benayas and de la Montaña 2003, Mittermeier *et al.* 2003, Kier *et al.* 2009). Number of guilds, variety of life cycles and diversity of biological recourses are other dimensions of biodiversity, which are unique to arid environments (Ayyad 2003). Many desert species are dormant and become active after rainfall (Chesson *et al.* 2004). Nevertheless, in some desert environments rain does not fall every year (Tracol *et al.* 2011). Biodiversity assessments of those environments may be neglected, yet they can possess even endangered species (Ayyad 2003, McNeely 2003). In addition, ecosystems rarity should not be overlooked because conservation of whole ecosystems also protects the species in them (Saunders *et al.* 2002, Roberts *et al.* 2003). Nevertheless, biomass is used to characterise ecosystems, although only few species form the bulk of biomass (Walker *et al.* 1999). Most important ecosystems are usually converted to world heritage sites, Ramsar sites, national parks, private protected areas, etc. (Dubley 2008). Natural places, such as rivers and their biota possess also natural beauty value (Meitner 2004).

Analysing the scenic and environmental landscape, observation points define visibility (O´Sullivan and Turner 2001). Visibility of a target depends on its size and location, and analysis of visibility is often over or under estimated (Ogburn 2006). Therefore, visibility of a PV plant depends of its size and the topography of the surroundings. Visual impact varies also according to the hours of visibility to an observer. Therefore, PV plants close to big cities have more observers and the impact becomes bigger (Fernandez Jimenez 2015).

Despite of positive public acceptance of renewable energy, seeing the installations on the field can cause resistance (Wüsterhagen *et al.* 2007, Yonca Aydin *et al.* 2010). Gaining the public support and stakeholders' acceptance of PV projects is crucial to sustainable development, and with careful site selection future conflicts can be avoided (Wüsterhagen *et al.* 2007).

2 OBJECTIVES

The present thesis aims to promote construction of PV solar power plants in a sustainable manner and understand their effect on Atacama Desert environment. Very little is known about solar power plants' microclimate and it's' effect on the local biota. Especially ecological and social aspects of solar power plants are not yet studied comprehensively (Turney and Fthenakis 2011). Therefore, the present thesis aims to understand ecological events in two different power plants (I, II). Effects were observed through changes in biodiversity, arthropod species composition, and plant allocation, and how much microclimate conditions were responsible for the observed ecological changes (I, II). In addition, habitat selection of web building spiders was observed (II). The objectives of the thesis were to 1) describe the microclimate of two different PV solar power plants, 2) study changes in biodiversity of arthropods, species composition, and interactions in the PV solar power plant environment. It is expected that microclimate is more cool and humid under the panels especially when the panels are fixed. Most likely, microclimatic conditions create favourable conditions to arthropod species in desert environment. Finally, 3) favorable locations for PV solar power plant projects in northern Chile is suggested. To get a comprehensive understanding of various impacts of PV solar energy in Chile, Geographic Information Systems were used (III). Multiple criteria of social (i.e. distance from cities, vegetation and landscape values), environmental (i.e. land use, biomass, vegetation), and physical (i.e. temperature, global irradiation, orography, distance to roads and powerlines) factors were used to select the optimal sites for PV solar power plants. Social impacts of solar energy were analysed with the help of a survey and conflicts of environmental, social, and solar energy potential of RES installations were analysed in geospatial space (III). Finally, the aim was to give recommendations how to promote sustainable construction of PV solar power plants in Chile (I, II, III).

3 MATERIAL AND METHODS

3.1 Study Sites

The studies of this thesis were conducted in four regions of Northern Chile: Arica and Parinacota (region XIV), Tarapacá (region I), Antofagasta (region II), and Atacama (III). In addition, answers to survey questions were collected from whole country. Intertropical Convergence zone (ITCZ) and its circulation systems are responsible for Chilean weather. Tropic of Capricorn is situated in the same latitude as northern Chile (Fig. 1). The tropic of Capricorn and the tropic of Cancer are latitudes where dry winds flow in the upper atmosphere, which makes these areas dry on the ground level, too. Chile is situated along the South American continent beside the Pacific Ocean (Fig. 1). Chile is isolated from its neighbours, Argentina and Bolivia, by the Andes. Beside the long but narrow country flows the Humboldt Current. The current is cold, which reduces evaporation. Therefore, cloud and mist formation are minimal, and steep Chilean coastal range limits the humidity from the sea to the coast. The Atacama Desert is situated in the highlands, which makes it the driest desert in the world (Moreira-Muñoz 2011). Vegetation of the Northern Chile varies from non-vegetated deserts, via shrubs and / or herbaceous lands to ice and snow (Luebert and Pliscoff 2006, Moreira-Muñoz 2011). There are some broadleaf and evergreen forests, but with regional distributions (Luebert and Pliscoff 2006).

Precipitation in the Northern Chile is not regular every year (Luebert and Pliscoff 2006). Variation in the amount of precipitations is related to El Niño Southern Oscillation (ENSO) phenomenon. In addition, there are studies that have found that the amount of coastal mist is related to ENSO unlike the precipitation in the inland (Aceituno and Montecinos 1993, Muñoz-Schick *et al.* 2001, Houston 2006). ENSO is oscillation in the Pacific Ocean. It occurs irregularly and changes weather conditions. During the years called "El Niño" warm waters arrive to the coast of Chile increasing the amount of water vapour in the air (Aceituno and Montecinos 1993, Vargas *et al.* 2000, Houston 2006).

Northern Chile has few big cities, which are mainly on the coast. Inland infrastructure has been built around the mines and agriculture (in the valleys). The inland area contains many little villages, of which some have a high cultural value. Historical and natural monuments are frequent along with archaeological sites. Landscape includes snow-covered Andes, salt lakes with flamingos, hieroglyphs, herbaceous highlands, mineral rich coloured mountains, etc.

FIGURE 1 Chile is situated on the west coast of South America (on the right). Study area includes the northern Chile (on the left). Study area had four regions. Studied solar power plants are presented with black dots: upper dot denotes PAS3 in Tarapacá region and lower dot PSPS in Atacama region.

3.2 Studied PV plants

Two different technologies of PV solar power plants were included in the study: Fixed mount PV plant "Photovoltaic Solar Plant Subsole" (PSPS, hereafter) and PV plant with solar tracking "Pozo Almonte Solar 3" (PAS3, hereafter). PSPS was situated in the Atacama region, and PAS3 in the Tarapacá region (Fig. 1). These two plants were chosen among existing solar power plants, because we could get permission to study them. In addition, these solar power plants where one of the first installed in Chile. More detailed descriptions of the two solar power plants are given and their differences are described in article I.

PSPS was studied every year during September and November from 2013–2015 and PAS3 during January and February 2014. Studies were timed according to possible water availability to get a higher arthropod activity. Raining season is most likely to occur during June to August in the Atacama region (Houston 2006). Central valley of Tarapacá, were PAS3 is located, can have floods from the raining season at the Andes during January to March (Houston 2006).

3.3 Study methods

To be able to suggest sustainable construction of PV plants, many different approaches were needed, including studies related to microclimatic conditions under the panels and analyses of arthropods distribution in the PV plants. In addition, georeferenced data together with survey results were used to cover the four regions in northern Chile.

The PV panels cause some areas of power plants to be shaded, and there are almost windless sunny areas between the arrays. Abiotic (I) and biotic (I, II) aspects of these two areas (i.e. Sun and Shade) were studied and compared to the reference area situated in the northern side of the plants. Microclimate was measured with 16 data loggers (I, II). GLS models and Kendall´s Tau correlation coefficient were used to analyse changes in temperature, relative humidity and dew point (I) between environmental conditions (i.e. Sun, Shade, and Reference), day and night, and study months.

Arthropod species of the solar power plants were studied on the ground level by pitfalls (I) and web building spider species from the mount structure were collected by hand, and their webs were calculated (II). Plant coverage and the number of pods (*Hoffmannseggia prostrata*) were calculated (II). Identification of the plants and arthropods were done according to Snelling and Hunt (1975), Aguilera and Casanueva (2005), Ferrú and Elgueta (2011), Taucare-Ríos and Sielfeld (2013), among others.

Multivariate methods were used to analyse biotic changes in solar power plant conditions. Changes in plant coverage, number of pods (II), arthropod biodiversity, and arthropod species composition changes (I) were studied in different environmental conditions and study periods using permutational multivariate analysis of variance (PERMANOVA). Also, distribution of web building spiders was analysed among the panel arrays and study years with PERMANOVA. Multivariate analyses were made using PRIMER v6.1.12 (Clarke and Gorley 2006) with PERMANOVA+ v1.0.2 add-on software (Anderson *et al.* 2008) (I) and with PRIMER v7.0.13 (Clarke and Gorley 2015)

(II). Finally, the effects of abiotic conditions were compared to biotic patterns with BIO-ENV routine (Clarke *et al.* 2008) (I, II).

Location optimization of PV plants included physical, environmental and social aspects (III). Social data was partly related to a survey performed in connection to this thesis in Chile in 2014 (III). The aspects were divided into factors. Physical factors included spatial data of global irradiation data, temperature, slope, orientation, distance to the roads and power lines. Environmental factors consisted of land use, biomass, and rarity of vegetation type and social factors of distance from cities, landscape and vegetation values. In addition, biomass was considered again with social factors because ecosystems have health benefits (Tzoulas *et al.* 2007) (III). Constraints included social and environmental considerations, such as historical sites, conservation areas, natural parks, etc.

Spatial multi criteria decision making with analytic hierarchy processes (AHP) and ordered weighted averaging (OWA) were applied to optimal site selection (Saaty 1997, Malczewski 2006). Fuzzy sets were used to standardize the factors (III). Standardized factors were first given pair-wise weights inside every aspect (AHP). Afterwards suitability levels were given with OWA-weights allowing all aspects to have some trade-off between the factors with minor risk. Finally, equal weights with weighted linear combination (WLC) were used to calculate the final map that combined all three aspects (III). Pre-treatment, spatial analyses and raster calculations were done using TerrSet® v18.20 (Clark Labs, Worcester, MA) and ArcGIS ® v10.3.1 (ESRI, Redlands, CA) (III).

4 RESULTS AND DISCUSSION

4.1 Microclimate of PV plants

It is known that shading of panels in concentrated solar power (CSP) plants change the energy balance of the soil (Wu *et al.* 2014). Because the sun light is converted to energy, temperature changes significantly and, therefore, effects on the biota are expected (Wu *et al.* 2014). The same way as the CSP power plants, also PV plants change the microclimate underneath the panels (I). Depending on PV technology, shade conditions are different (I). Ground level has lower temperature under the panels than between the panels during the midday time at both fixed and solar tracking technologies. Nevertheless, the difference between shading conditions of fixed and moving mount occurs during the morning and afternoon: The Sun is shining under the panel mounts longer in the studied solar-tracking system than in the studied fixed mount plant (I). In both PV plants, relative humidity rises in Shade conditions although in Sun conditions humidity is lower than outside the solar power plants (I). Like Wu *et al.* (2014) suggested, microclimate described above can have beneficial effects to biota (I).

Ground temperature of the small PV solar power plant raised fast with the increasing number of panel arrays (I). Nevertheless, in large scale solar tracking technology there was no significant correlation between temperature and number of array groups (I). Wu *et al.* (2014) detected that wind speed slows down in CSP plants. Most likely slowdown of wind speed at the first arrays is the reason why temperature rises in the back part of the solar power plant at the studied small-scale PV plant with fixed mounts (I). Studied large-scale PV plant had more space between the panels and solar power plant was divided by corridors. That can be the reason why the temperature did not rise at the large scale solar plant like it did in the small-scale PV plant (I). Therefore, we recommend, leaving space or corridors between the panel mounts. Space lets the air to flow into the solar power plant and decreases the temperature of the panels. The wind can also bring arthropods to inner parts of the facilities. Wind could also balance temperature differences between arrays. Nevertheless, using more space per array causes also the total area of the facility to grow and the plant to have an effect to a larger area. Space between panel mounts can work as an ecological corridor resembling the desert conditions outside the panel area. On the other hand, those corridors are used by maintenance cars, which make the corridors to be more disturbed than the sunny between-panel areas.

4.2 Ecological environment of PV solar power plants

Detected arthropod biodiversity (abundance and species richness) changes were caused by temporal factors and not by the different conditions in the solar power plants (I). In contrary, species composition was affected by the environmental conditions (i.e. Sun, Shade, and Reference) (I). The Shade of fixed mount solar power plant had different species composition than Sun and Reference area, but at the solar tracking facility, species were not different between Sun and Shade, although some changes were detected between Reference and the panel area (I).

In PSPS spider species *Lactrodectus geometricus* and their webs were detected from panel mount legs. Other web building spider *Dictyna sp.* was detected from back surface of the panels, pitfalls, and from the panel mounts legs. Only two species of vegetation were identified from the study plots: *Hoffmannseggia prostrata* and *Malva nicaeensis*.

Of all studied arthropods, only the distribution of spiders was significantly affected by the microclimate conditions (I, II). *Dictyna sp.* reacted to the increased temperature by placing her webs on the ground (II). Because arthropod species distribution was not affected by the microclimate, we suspect that species interactions play a significant role in solar power plant ecosystems. In the future studies, more attention should be paid to species interactions and invasive species ecology.

Distinct solar power plant conditions are suitable for different arthropod groups depending on their habitat requirements. Some groups were found only from sunny conditions like *Solifugae*, whereas coleopterans and dipterans were found to be more frequent in Shade (I). In addition, we detected a higher amount of flying insects at the solar power plant facilities than within the reference area and wind speed changes can accumulate flying insects into the solar power plant (I). Though, on the ground level arthropods could find refuge from the Sun conditions under the fixed mounts (I).

Distributions of different arthropod species were found to have interactions (I). Species interactions were detected among arthropod species (I) and distribution of web building spiders (II) at the fixed mount facility (I). Abundant amount of both spider species was detected on the mount legs and on the back surface of panels of first two arrays. We believe that this might be because of more abundant prey availability, and surely this attracts spiders to build their webs to the mounts of solar power plants. In addition, coleopterans were more abundant in Shade than Sun conditions (I) which makes it a good preying surroundings to *L. geometricus*, which can prey on bigger arthropods than *Dictyna sp*.

Web building spiders build their webs using vegetation as a base of the structure, but in solar power plant environment mounts and panels structure can substitute that function and spiders' distribution can be independent of the vegetation (II). That might mean that pray species used by spiders are also distributed independent of the vegetation, but there most likely are other arthropod groups that are dependent on vegetation. Notable impact of vegetation changes happened on fixed mount solar plant where *H. prostrata* pod production was inclined in Shade, which can lead to severe ecosystem changes (I). Change in resource allocation in plants can be one of the reasons why arthropod species were divided among Shade and Sun at fixed mount solar plant.

Quickly constructed solar-tracking technology seems to have less effect on the environment than fixed mounts (I), but more studies should be conducted to be able to know if exotic species will inhabit the moving table mounts. Moving of the panels would break some of the webs, but would not stop web-building spiders from colonizing solar-tracking mounts, if the environment is favourable. In fact, species migrate mainly from the surrounding desert and if exotic species are not present in the surrounding nature, they may not find their way to the solar power plant. On the other hand, construction and maintenance of the facility can bring species from further off that travel with the personnel. Therefore, wildlife management has been recommended (Lovich and Ennen 2011).

Since soil and local biota is moved during the construction phase of a solar power plant (Wu *et al.* 2014), panel environment can be completely different from the original environments and therefore be unfit to the biota that was moved. Nevertheless, ecological impacts of solar power plant technologies are minor and radical changes between species distribution was not detected. On the other hand, if solar power plants would be constructed into areas with vulnerable species of flora or fauna, construction of solar power plant would cause serious harm. Shading causes plants to change their resource allocation and invasive species can take over, leaving fewer resources to endemic species (II). When performing evaluation of desert environments, seasonality should be taken into account with extra care. For the reasons mentioned before, careful site selection for each solar power plant projects is advised. Biota of the deserts typically is of dormant nature (Ward 2009), which should be considered when planning solar plant facilities.

According to my studies, solar tracking technology changes the original environment less than panels with fixed mounts. Therefore, I recommend solar tracking technology over fixed mounts. On the other hand, studied solar power plants were not comparable, because of the difference in size and location, and the temporal differences of the studies. In fact, these results should be confirmed with the two technologies in the same study sites and times.

4.3 Location optimization of PV plants in northern Chile

Ecological impacts of solar power plant facilities were included in the location optimization process by using constraints (III). Therefore, high biodiversity areas, natural parks, and protected areas were ruled out from the site selection before any other criteria were considered. In addition, high biomass areas were given less value as a suitable site (III).

Highest suitability score was found nearby roads and electrical grids, and the score slowly increased towards the mountainous areas. Elevated temperatures decrease the energy efficiency of the panels (Dubey *et al.* 2013), but the enormous amount of radiation available compensates the productivity decrease in northern Chile (III). Finding was partly in conflict with environmental aspects because high biomass areas, outside the constraint areas, were also found at the Andes. The Andes also possess scenic landscapes that were found to be of high importance to conserve (III). Mountainous areas are less attractive for solar power plant projects because of their distances from cities and extreme conditions (deep slopes, low air pressure, snow storms). On the other hand, several mines are situated in those areas as well. Therefore, solar energy projects can be an attractive option even at the Andes. Nevertheless, site selection is of foremost importance in those areas (III).

I recommend that physical, environmental, and social factors of PV plant location optimization should be considered to guarantee sustainable development (III). AHP and OWA methods have been tested in multiple spatial multi criteria decision making processes (Siddiqui *et al.* 1996, Arán Carrión *et al.* 2008, Boroushaki and Malczewski 2008, Jamali *et al.* 2014). I recommend AHP-OWA method as a good preplanning method of site selection to PV solar power plant projects. The method used in this thesis can be repeated to other regions where similar data as in this study is available. Maintaining environmental and social impacts small, only little trade-off in these factors should be allowed to make sure that we reach a satisfying solution (III).

5 CONCLUSIONS

According to my studies, photovoltaic solar power plants change microclimate of desert environment (I), and the microclimatic conditions do change some biota distribution and behaviour especially at fixed mount solar plant (II). There are species that can benefit from solar power plant conditions, and some biota clearly avoid the shadow conditions. Fixed mount solar power plants can act as refuge to some arthropod groups during the day time heat (I), but for vegetation, that is adapted to direct sun light, Shade conditions can disturb florescence (II).

Arthropod species composition was divided between Shade and Sun conditions at fixed mount power plant (I). Solar power plants create patchy habitats where species composition is different below the panels and between them. Sunny conditions lack web-building spiders and that can be part of the detected interactions. Temperature and dew point seemed to affect habitat selection of local spider species while invasive species could habit the solar power plant mount legs entirely (II). PV solar power plants can act as a good habitat to invasive species if they are not sensitive to extreme temperatures. Nevertheless, regular wildlife observations are advised also in Chile. Considering the facts presented above, I conclude that ecological impacts of photovoltaic solar power plants are minor compared to some other forms of energy production, but precaution should be taken when planning projects in areas with sensitive nature (I). Solar tracking technology will most likely have less effect on the desert arthropods and would let the Sun shine more equally to the ground beneath the mount. Nevertheless, more studies should be conducted in multiple solar power plants to confirm the magnitude of the effects of different technologies (I).

Generalisation of the ecological impacts of the two studies (I and II) cannot be done to cover large areas in northern Chile, but habitats of naturally endemic species with restricted distribution should be avoided. Therefore, it is not possible to rule out the environmental assessment with this study. In contrast, more studies should be conducted to understand the Atacama Desert's local conditions. We should also have information about desertification of the adjacent areas of true deserts. For example, there are only few studies about the biological crust of the Atacama Desert (Drees at al. 2006, Warren-Rhodes *et al.* 2006 Azua-Bustos *et al.* 2012). Therefore, it is not known what biodiversity potential lies in the extreme conditions of northern Chile.

Here I must admit that Northern Chile is an ideal place for solar power plant projects because of its high solar energy potential. Nevertheless, I suggest that the environmental and social aspects of site selection should be considered in more detail using multi criteria decision-making tools and their locations should be optimized. Nevertheless, local site selection planning should be done with more detailed large-scale information than presented here. My thesis provides only initial location optimization over a large area. On the other hand, the accuracy of these maps is more than enough to describe the four regions in northern Chile. Ideal places with low environmental and landscape value are in the absolute desert situated in the central valley starting from Arica and reaching until the northern part of Atacama region (III). Nevertheless, cities and historical sites should be avoided.

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YHTEENVETO (RÉSUMÉ IN FINNISH)

Aurinkosähkövoimaloiden ekologiset vaikutukset ja kestävän kehityksen huomioiva sijoittelu Pohjois-Chilessä.

Aurinkoenergian suosio on kasvanut nopeasti Kioton sopimuksen (1998) jälkeen. Sopimus edisti merkittävästi hiilineutraalin energian käyttöönottoa. Aurinkoenergia on jo suosittua monissa maissa, kuten USA:ssa, Kiinassa ja Saksassa. Myös Chilessä kestävää energiaa tuetaan säädöksellä, jossa on tavoitteena täyttää 20 % koko maan energian tuotosta uusiutuvalla energialla vuoteen 2025 mennessä. Isoja aurinkovoimaloita on jo rakennettu Chileen, mutta monet projektit odottavat vielä hyväksymistä. Aurinkoenergian suosio on kasvamassa etenkin Pohjois-Chilessä, jossa aurinkoenergiapotentiaali on yksi suurimmista koko maailmassa.

Atacaman aavikko sijaitsee Chilen pohjoisosassa. Se on maailman kuivimpia aavikoita ja siellä taivas on lähes aina pilvetön. Äärimmäisten olosuhteiden vuoksi elämä aavikolla on niukkaa. Koska aurinkovoimaloiden ympäristövaikutusten arvioidaan olevan erittäin pienet Chilessä, ajatellaan usein yksioikoisesti, että Atacaman aavikko on ideaalinen paikka isoille aurinkovoimaloille. Pohjois-Chilen alueella on kuitenkin 40 erilaista kasvillisuusvyöhykettä, jotka sisältävät myös monia endeemisiä lajeja. Näiden lajien levinneisyys on hyvin paikallista. Lisäksi monet lajit ovat kehittyneet monofyleettisesti eli yhdestä lajista on eriytynyt monta paikallista lajia.

Vaikka aurinkovoimaloiden ympäristövaikutusten on todettu olevan erittäin pieniä verrattaessa perinteisiin energiantuotantomuotoihin, haitallisia ympäristövaikutuksia aurinkoenergialla on kuitenkin etenkin aurinkovoimaloiden rakennusvaiheessa, jolloin suuria määriä maata joudutaan muokkaamaan paneeli- tai peiliasennuksien tieltä. Alkuperäinen maaperä eliöstöineen poistetaan ja lisäksi rakentamisesta aiheutuu pölyä, melua ja maan tärinää. Paneelialueet suljetaan aidalla, jolloin pienehköjenkin maaeläinten pääsy paneelialueelle estyy. Rakennusvaiheen jälkeen aurinkovoimala-alueella liikutaan säännöllisesti puhdistamassa ja huoltamassa paneeleita ja niiden rakenteita. Tästä aiheutuu kasvien tallaantumista ja isoilla voimaloilla myös autoja käytetään liikkumiseen. Mikäli paneeleita puhdistetaan tislatulla vedellä, tämä ylimääräinen vesi voi myös muuttaa aurinkovoimalan ympäristöolosuhteita. Vaikka aurinkovoimaloiden rakentamisenaikaiset ympäristövaikutukset tiedetään verraten hyvin, ekologisia vaikutuksia on tutkittu varsin vähän.

Atacaman alueella on laajoja alueita ilman kasvillisuutta, ja siksi paneelien tuoma varjo voi muuttaa aavikon mikroilmastoa. Varjo voi tarjota suojaa aavikon kuumuudelta. Lisäksi suhteellinen kosteus on varjossa suurempaa ja on mahdollista, että kasvit voisivat hyötyä aurinkovoimalan olosuhteista. Nämä olosuhteet ovat kuitenkin hyvin erilaisia aavikon alkuperäisiin olosuhteisiin verrattuna, joten myös vieraslajien levittäytyminen voimala-alueille on mahdollista.

Kun aurinkovoimalaprojekteja suunnitellaan, sosiaalisiin vaikutuksiin tulisi myös kiinnittää huomiota. Sosiaalisten vaikutusten arviointi on jäänyt vähemmälle huomiolle, koska tutkimusmenetelmät ovat hitaita ja työläitä. Jotta sosiaaliset vaikutukset eivät kasvaisi liian suuriksi, aurinkovoimalat tulisi sijoittaa riittävän suuren etäisyyden päähän kaupungeista. Mikäli aurinkovoimala on liian lähellä kaupunkia, jo liikkuminen ulos kaupungista tai sisään hankaloituu. Osa kaupungin asukkaista voi kokea aurinkovoimalan positiivisena osana maisemaa, mutta osa ihmisistä vastustaa niitä. Toistuva näkeminen voi kuitenkin aiheuttaa negatiivisen asenteen kehittymisen etenkin, jos aurinkovoimala on sijoitettu esteettistä tai historiallista arvoa omaavalle alueelle. Kun etsitään optimaalista paikkaa aurinkovoimalalle, tulisi optimoinnissa huomioida aurinkoenergiapotentiaalin lisäksi myös ympäristöön ja sosiaalisiin aiheisiin liittyvät seikat. Tätä varten monikriteerisiä päätöstentekotyökaluja on kehitelty tutkijoiden käyttöön. Paikkatietosovellukset ovat tyypillisiä menetelmiä, joiden avulla on mahdollista toteuttaa monikriteeristä päätöksentekoa.

Tietoa siitä, miten aurinkovoimalat vaikuttavat Pohjois-Chilen luontoon, ei ole aikaisemmin julkaistu. On kuitenkin tärkeä tietää, mitä ekologisia vaikutuksia aurinkovoimaloilla on, jotta voidaan ennustaa, miten aurinkovoimalaympäristö muuttaa luontoa. Siksi väitöskirjassani olen tutkinut, minkälaisen ympäristön aurinkovoimalat luovat Pohjois-Chilessä ja miten muuttunut ympäristö vaikuttaa eliöstöön. Lisäksi arvioin väitöskirjassani aineistojen perusteella, mitkä fysikaaliset, ympäristölliset ja sosiaaliset seikat on otettava huomioon, kun valitaan parhaita alueita aurinkovoimaloita sijoitettaessa. Tietoisuutta sosiaalisista vaikutuksista lisättiin kyselyn avulla, jonka tuloksia sovellettiin sen jälkeen lisätietoina muodostettaessa taustamuuttujia monikriteeriseen paikkatietoanalyysiin.

Työtä varten kahta erityyppistä aurinkosähkövoimalaa tutkittiin Pohjois-Chilessä vuosien 2013–2015 aikana. Voimalat erosivat toisistaan paneelien asennustekniikoissa. Kolmen vuoden seuranta suoritettiin Copiapó:n laaksossa sijaitsevassa voimalassa, jossa paneelit ovat kiinteillä, pohjoiseen päin kallistetuilla, pöydillä. Yhden vuoden tutkimus suoritettiin Tarapacá-alueen aurinkovoimalassa, lähellä Pozo Almonten kaupunkia. Siellä paneelit seurasivat aurinkoa kääntyen idästä länteen päivän aikana. Työ toteutettiin tutkimusruutujen avulla, jotka olivat sijoitettu kolmeen erilaiseen ympäristöön: paneelien alle, paneelien väliin ja paneelialueen ulkopuolelle. Ruuduista laskettiin kasvillisuuden peittävyys ja kasveissa olevien hedelmien lukumäärä. Kuoppaloukut asennettiin kasvillisuusruutujen ympärille ja dataloggerit asennettiin mittaamaan lämpötilaa, suhteellista kosteutta ja kastepistettä ruuduilta. Verkkoa kutovat hämähäkit ja/tai niiden verkot laskettiin paneelipöytäkohtaisesti.

Aiemmassa kirjallisuudessa esitetään, että aurinkovoimaloiden ympäristövaikutukset ovat pieniä, mutta osa ekologisista vaikutuksista on kuitenkin syytä ottaa huomioon. Yleinen paikallinen kasvilaji, *Hoffmannseggia prostrata,* kasvoi kiinteäpaneelisen aurinkovoimalan alueella. Kun kasvi kasvoi referenssialueella, se tuotti runsaasti palkoja. Paneelien alla varjossa se ei kuitenkaan pystynyt tuottamaan palkoja. Ilmeisesti suoran auringonvalon puute sai *H. pro-*

strata:n allokoimaan kasvuun kukkimisen sijaan, koska kasvillisuuden muutokset eivät riippuneet abioottisista olosuhteista. Sen sijaan verkkoja kutovien hämähäkkien elinympäristövalintaan abioottiset olosuhteet vaikuttivat. Kun lämpötilat kohosivat, paikallinen hämähäkkilaji, *Dictyna sp.*, ei kiivennyt ylös paneeleihin rakentamaan seittejään, vaan pysytteli maan tasalla. Chilelle vieraslajina tunnettu hämähäkkilaji, ruskea leski (*Lacrodectus geometricus*), ei ollut herkkä abioottisille muutoksille, ja sen verkkoja löytyi kaikkialta aurinkopaneelien jalkarakenteista kiinteäpaneelisessa aurinkovoimalassa. Niveljalkaisten lajisto oli jakautunut eri tavoin kiinteäpöytäisessä voimalassa aurinkoisten alueiden ja varjon välillä. Jotkut niveljalkaisryhmät, kuten arolukit (*Solifugae*), löytyivät enimmäkseen aurinkoisista olosuhteista, kun taas suurempi osa kovakuoriaisista (*Coleoptera*) ja kaksisiipisistä (*Diptera*) oli paneelien alla enemmin kuin niiden välissä auringossa. Voimalassa, jossa paneelit seurasivat aurinkoa, niveljalkaisten lajisto ei ollut jakautunut. Lajistossa kuitenkin havaittiin eroja, kun aurinkovoimala-alueen tuloksia verrattiin referenssialueen tulosten kanssa.

Optimaalisin aurinkovoimaloiden sijoittelualue Pohjois-Chilessä oli Atacaman aavikon keskiosa alkaen Arican alueesta jatkuen Atacaman alueen pohjoisosaan. Tällä alueella kasvillisuus on erittäin niukkaa ja aurinkoenergia on voimakasta, vaikka korkeat lämpötilat heikentävätkin paneelien hyötysuhdetta. Alue oli optimaalinen lukuun ottamatta kaupunkien lähistöjä, historiallisia monumentteja tai luonnonsuojelualueita. Ristiriitaiset alueet löytyivät Andien vuoristosta teiden ja sähköverkon lähettyvillä, jossa alueen sopivuus fysikaalisilta ominaisuuksiltaan (aurinkoenergian potentiaali, lämpötila, maaperän kaltevuus, ym.) oli suurimmillaan, mutta myös biomassan määrä oli suurempaa kuin keskialueella. Vuoristoisuus rajoitti aurinkoenergian tuotantoon kelpaavat alueet lähelle tieverkostoja. Andeilla sijaitsee myös suuri määrä esteettisesti tärkeitä maisemia, joiden suojeluarvon tärkeys tuli esille kyselyssä. Atacaman alueen eteläosa on myös biomassaltaan runsas verrattuna tutkimusalueen ylempiin keskiosiin. Koska tyypillisten maisemien ja vuoristomaisemien osuus Andeilla on suuri, katsottiin alueen olevan heikompi sijoittelun kannalta.

Väitöskirjani lisää tietoisuutta aurinkovoimaloiden ekologisista vaikutuksista ja ottaa kantaa niiden kestävän kehityksen mukaiseen sijoitteluun Pohjois-Chilessä. Tuloksia voi soveltaa Pohjois-Chilen alueellisessa päätöksenteossa, sekä aurinkovoimaloiden sijoittelun optimointia voi soveltaa myös muille alueille, joilta vastaavia aineistoja ja lähtötietoja on saatavilla.

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ORIGINAL PAPERS

I

THE INFLUENCE OF SOLAR POWER PLANTS ON MICROCLIMATIC CONDITIONS AND THE BIOTIC COMMUNITY IN CHILEAN DESERT ENVIRONMENTS

by

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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, *Dipteran*s 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 · The Atacama Desert · Environmental effect · Microclimate · Photovoltaic power plant

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; Hernandez et al. 2014).

Solar radiation intensity in the North of Chile is one of the best worldwide, with an annual average Direct Normal

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Irradiation of 9–10 kWh/(m^2/day) (del Sol and 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 et al. 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 fuels (Tsoutsos et al. 2005) although solar energy installation 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 and 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 and 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 and 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 and 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 and 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 and Elgueta 2011; Hughes and Eastwood 2006; Pennington et al. 2010; Pizarro-Araya et al. 2008; Pizarro-Araya and Jerez 2004; Roig-Juñet and Flores 2001; Taucare-Ríos and 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 and 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; Kaygusuz 2009; Lovich and Ennen 2011; Turney and 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 and 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 microenvironments (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.

Material and Methods

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. The plant was built on former agricultural land beside the river Copiapó and has an elevation of approx. 773 m.

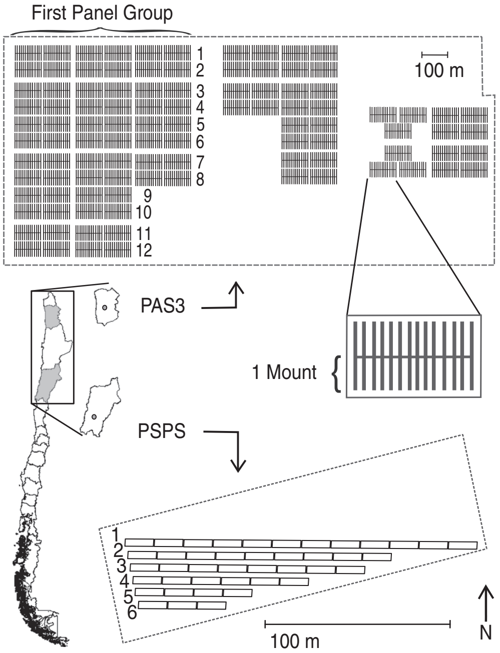


Fig. 1 Location and structure of solar power plants PAS3 (*above*) and PSPS (*below*). PAS3 is divided into three array groups and the first group is numbered according to the arrays, each including 30 mounts. Numbers 1–6 in PSPS indicate arrays. *Dashed lines* around the panel areas indicate perimeter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

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 1030 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.

Measurements of Abiotic Variables

Abiotic variables, temperature, humidity, and dew point were recorded with 16 data loggers (Lascar, EL-USB-1-LCD) during a 6-day period at PSPS and during 1 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 2 days at PSPS and for 30 days at PAS3. Temperature, humidity, and dew point were measured with 1-min intervals at PSPS, and every 5 min 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.

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 m. 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 and Hunt (1975), Aguilera and Casanueva (2005), Ferrú and Elgueta (2011), Taucare-Ríos and Sielfeld (2013), among others were followed.

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.

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 programmed with Python (Ascher et al. 2001) (Online Resources 5–6).

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 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 and 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 and 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 and 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 and Gotelli 2013) as proxy. These analyses (i.e., nestedness and aggregation/segregation) were performed using the programs NODF v2.0 (Almeida-Neto et al. 2008) and TURNOVER v1.1 (Ulrich and Gotelli 2013), respectively.

Results

Abiotic Conditions

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. 2a). In contrast, Sun-back were warmer than other environmental conditions (Fig. 2a). 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. 2b). Shade humidity conditions were higher than Sun or Reference during the day time from 8:00 to 18:15 (Fig. 2c) at PSPS. This was also true at PAS3, however, only between 10:11 and 16:30 (Fig. 2d).

Table 1 Results of LME models for abiotic response variables (temperature, humidity, dew point) in both study sites

	Temperature *F*-value	Humidity *F*-value	Dew Point *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 × 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 × Env. × Day / Night	9.03***	3.34**	4.94**

Env. stands for environmental condition (Sun, Shade, Reference)

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

PSPS Reference dew point was significantly different from Shade or Sun conditions during the day time (Fig. 2e). 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 (Figs. 2a, c) except References' dew point was significantly lower (Fig. 2e). The same was true at PAS3 (Fig. 2f). Nevertheless, diurnal dew point at PAS3 did not show statistical differences between environmental conditions (Fig. 2f). Reference was significantly cooler and more humid during the night compared to panel area while Sun and Shade did not differ (Figs. 2b, 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 (Figs. 2a–f).

Correlations of abiotic variables

Statistically significant Kendall's correlation was observed between the mean temperatures and the array numbers in Sun ($z = 2.07$, $p = 0.039$, $\tau = 0.41$) and Shade ($z = 2.04$, $p = 0.042$, $\tau = 0.42$) (Fig. 3a) sampling units at PSPS in 2013. The mean humidity (Fig. 3b) had a significant negative correlation ($z = -2.27$, $p = 0.023$, $\tau = -0.46$) with the array numbers. Thus, the maximum temperatures strongly correlated with the array numbers ($z = 4.40$, $p < 0.001$, $\tau = 0.84$) (Fig. 3c), 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. 3d).

Biotic Conditions

Diversity and taxonomic composition

1364 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.

The main difference in species richness was among environmental conditions at PSPS, but at PAS3 depended

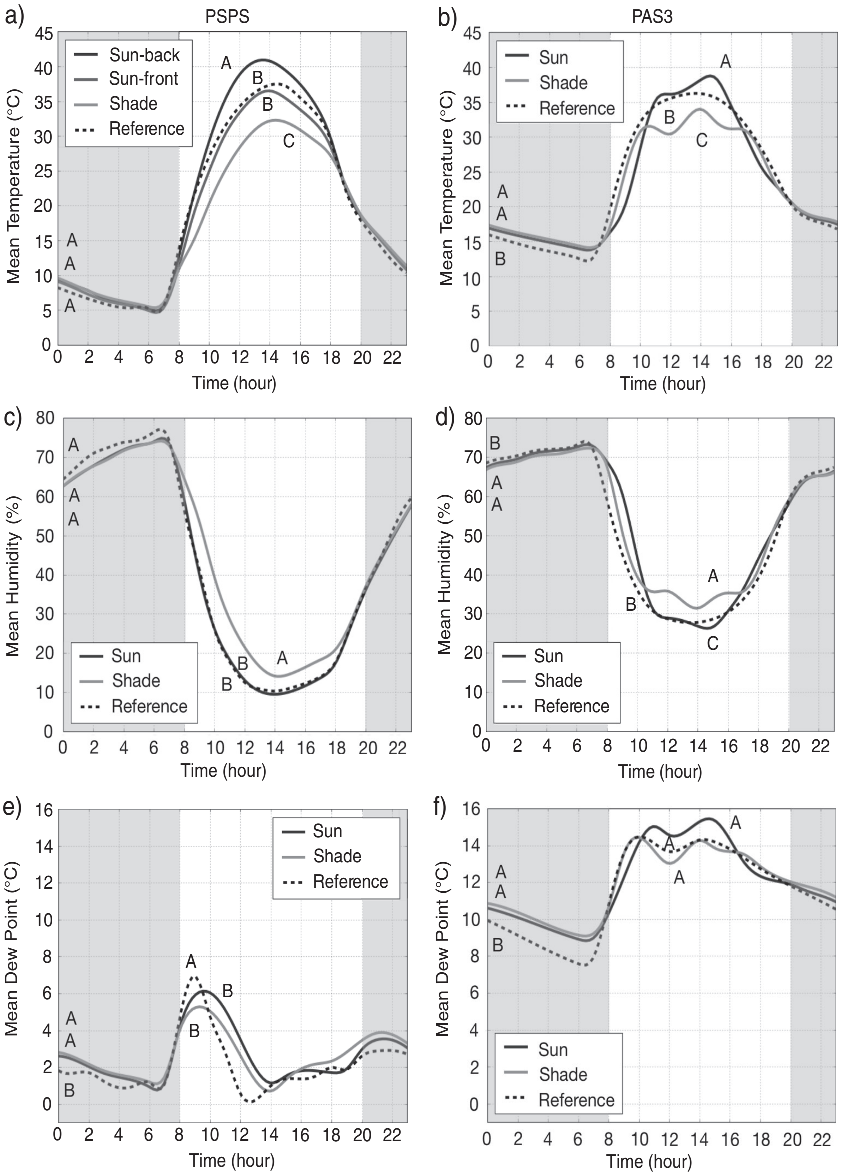


Fig. 2 Plots of **a** and **b** mean temperature, **c** and **d** mean humidity, and **e** and **f** mean dew point at PSPS on the *left* and PAS3 on the *right*. Nights are denoted with a *grey background*. Letters A–C in the figures indicate significant contrast between environmental conditions during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

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 (Figs. 4a and b) and temporal (Fig. 5). For instance, the number of morphospecies (*S*) at PSPS was higher in Shade compared to Sun (Fig. 4a, Table 4). Opposite pattern was observed in the richness (*S*) at PAS3 (Fig. 4b), 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

Fig. 3 Scatterplots of **a** average temperature **b** average RH, and **c** maximum temperature among array numbers at PSPS, and **d** maximum temperature among array groups at PAS3

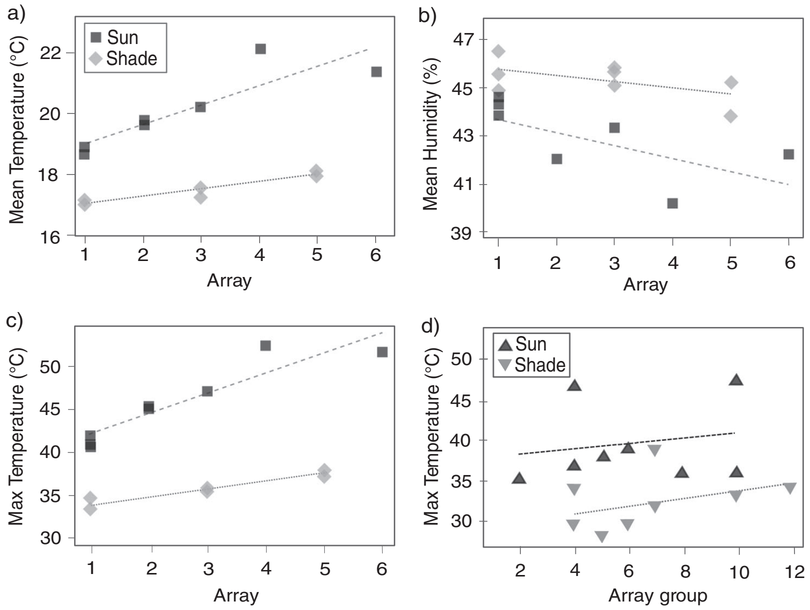


Table 2 Percentages and counts of most abundant taxa

	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

(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).

Linkages among arthropod assemblages and abiotic variables

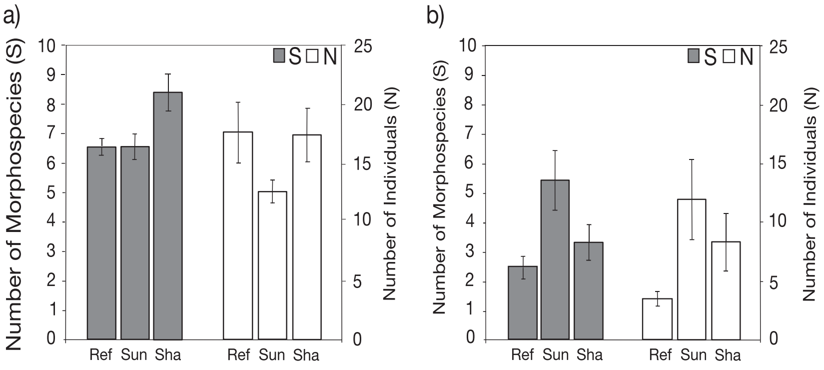
The BIO-ENV test showed a significant link between global arthropod assemblages and statistical descriptor values calculated from a suite of environmental variables at both sites. For instance, five of the studied variables, temperature (minimum and standard deviation), and humidity (standard deviation, range, and mode) best explained the overall species arrangement at PSPS (BEST: Spearman's $\rho = 0.238$, $p < 0.004$). However, variables related to

Table 3 Results of PERMANOVA main test among environmental conditions and sampling times

		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						

Env. stands for environmental condition (Sun, Shade, Reference), and S. time for sampling time

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



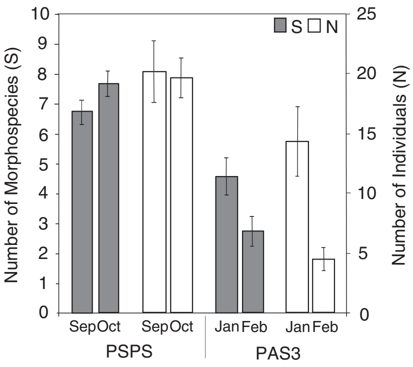


Fig. 5 Temporal averages of richness (*S*), and abundance (*N*). *Vertical lines* show standard error

Table 4 Summary of paired t-tests among environmental conditions

	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	

Results of pairwise comparisons between environmental conditions at PAS3 and at PSPS are above and below the main diagonal, respectively

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

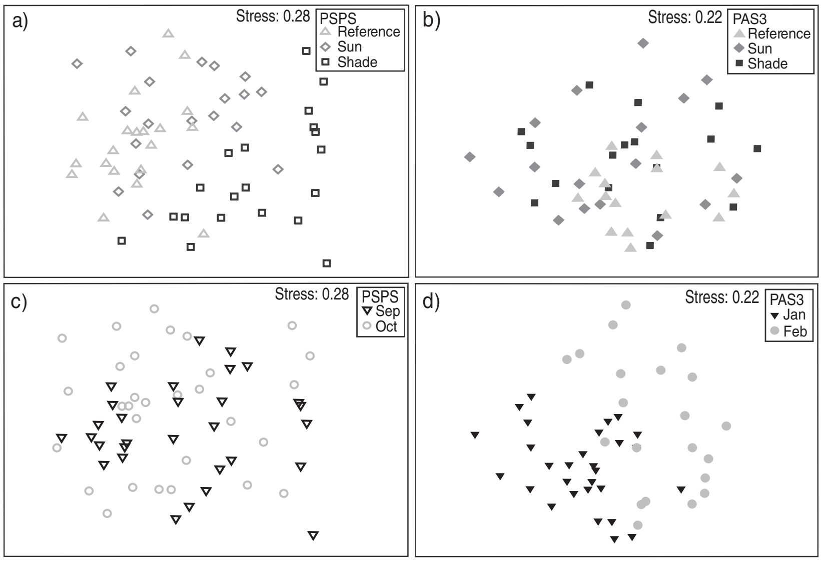


Fig. 6 Ordination of observed arthropod species composition by non-metric multidimensional scaling based on square root transformed Bray-Curtis similarities between environmental conditions **a** at PSPS and **b** at PAS3, and sampling times **c** at PSPS and **d** at PAS3 with 50 restarts

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

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).

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).

Discussion and Conclusions

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.

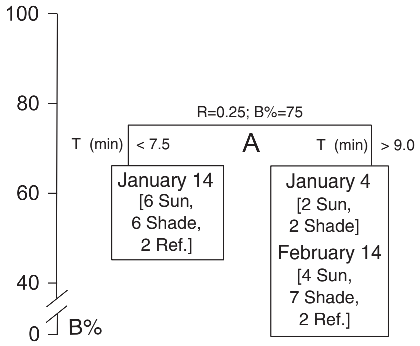


Fig. 7 Linkage tree analysis (LINKTREE) at PAS3 showing clustering of sampling units based on morphospecies composition constrained by abiotic variables. For each split, *R* is the optimal ANOSIM R value (relative subgroup separation). The B% statistic shows the absolute measure of group differentiation, 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

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.

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 and Ennen 2011; Turney and 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

Table 6 Co-occurrence analysis of morphospecies by sampling unit data set of PSPS and PAS3 arthropods

	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)

Term "sites" refers to sampling units in this table 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 and 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.

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 the 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 et 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 the 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 and 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 and 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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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no competing interests.

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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

Online Resource 4

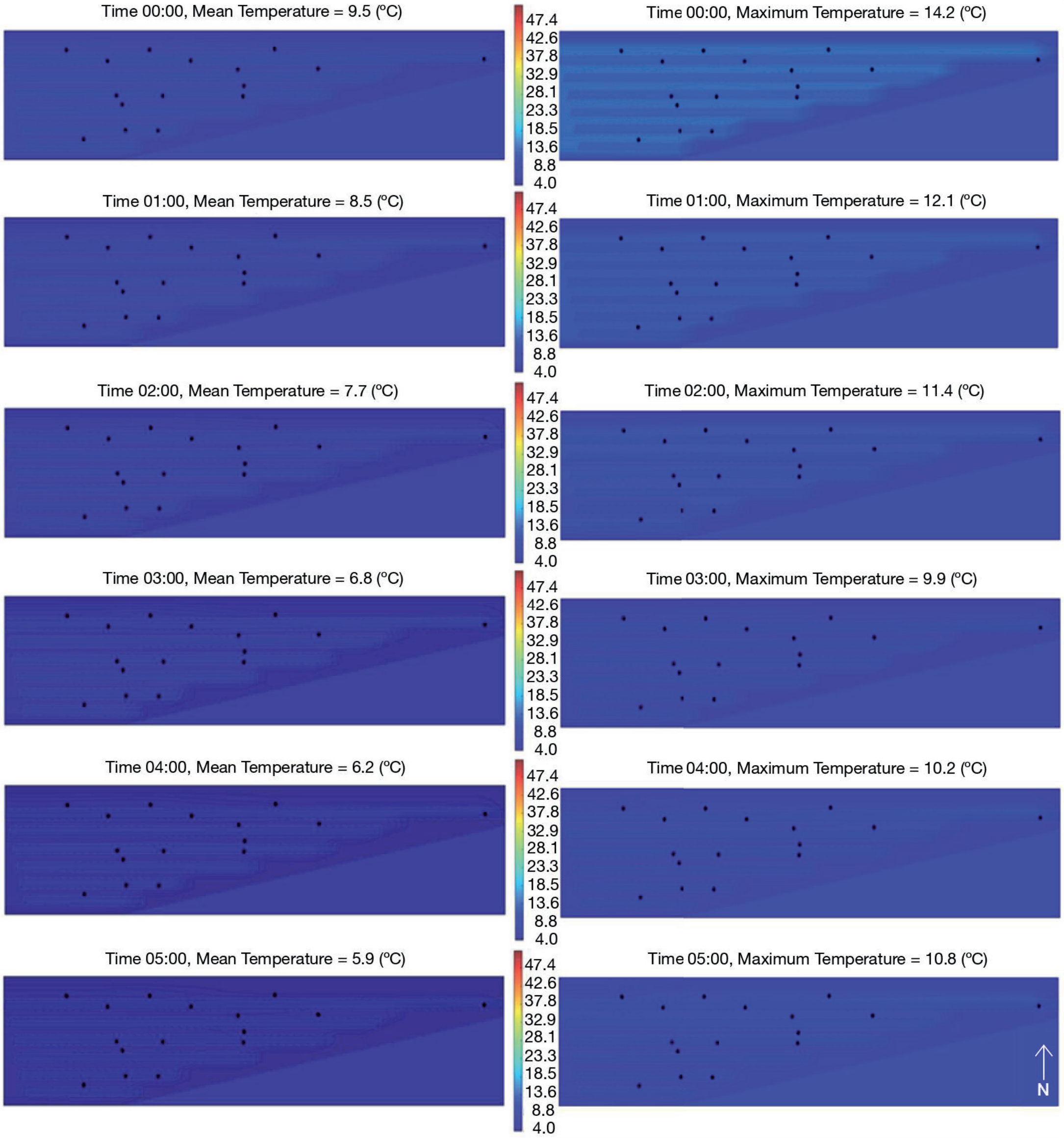
Kendall´s tau correlation test of temperature, humidity, and dew point among rows in PSPS during September and October 2013 and among mount groups in PAS3 during January and February 2015.

	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

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

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 00:00, Mean Temperature = 9.5 (ºC)

Time 00:00, Maximum Temperature = 14.2 (ºC)

Time 01:00, Mean Temperature = 8.5 (ºC)

Time 01:00, Maximum Temperature = 12.1 (ºC)

Time 02:00, Mean Temperature = 7.7 (ºC)

Time 02:00, Maximum Temperature = 11.4 (ºC)

Time 03:00, Mean Temperature = 6.8 (ºC)

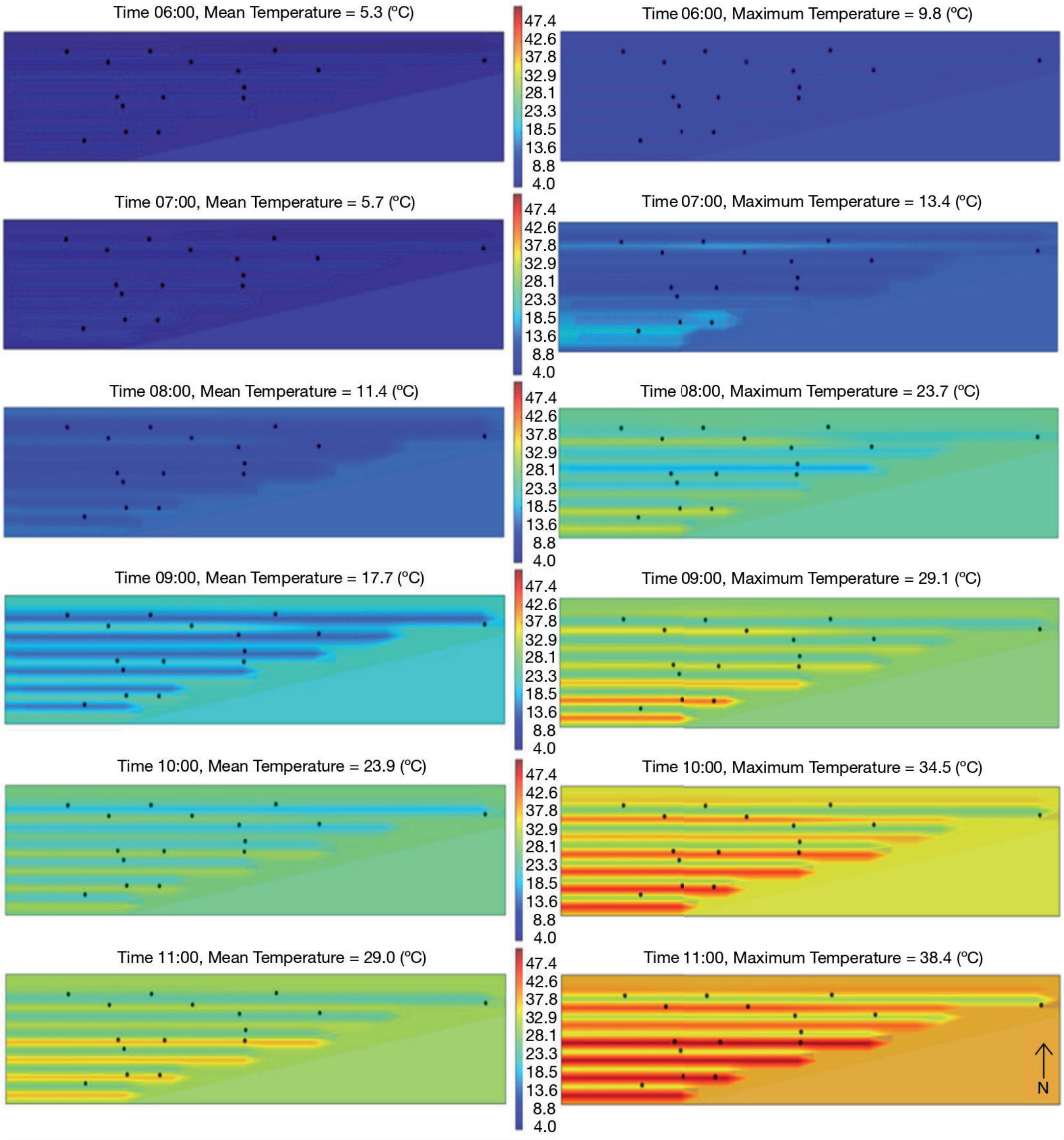
Time 03:00, Maximum Temperature = 9.9 (ºC)

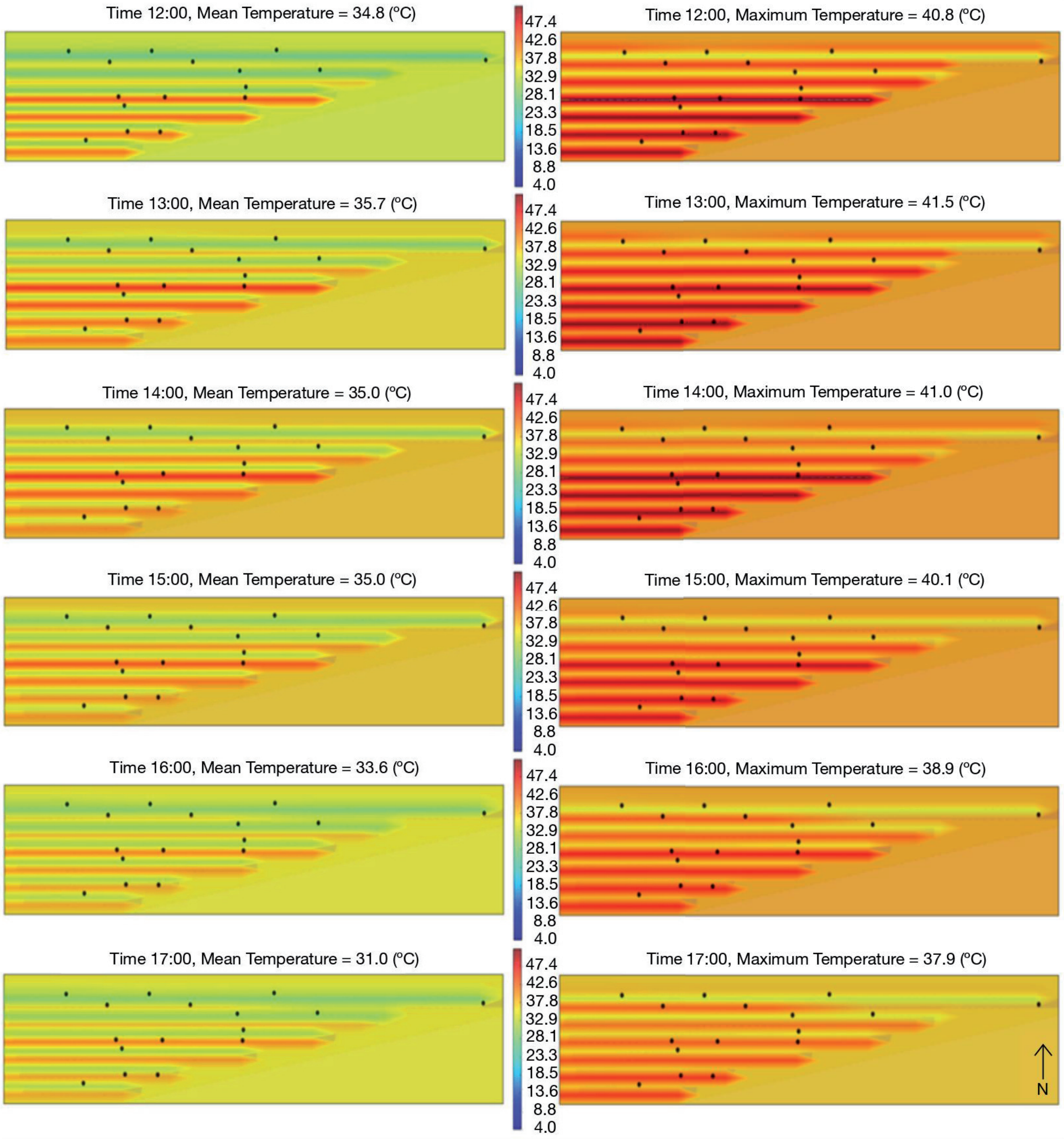
Time 04:00, Mean Temperature = 6.2 (ºC)

Time 04:00, Maximum Temperature = 10.2 (ºC)

Time 05:00, Mean Temperature = 5.9 (ºC)

Time 05:00, Maximum Temperature = 10.8 (ºC)


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)

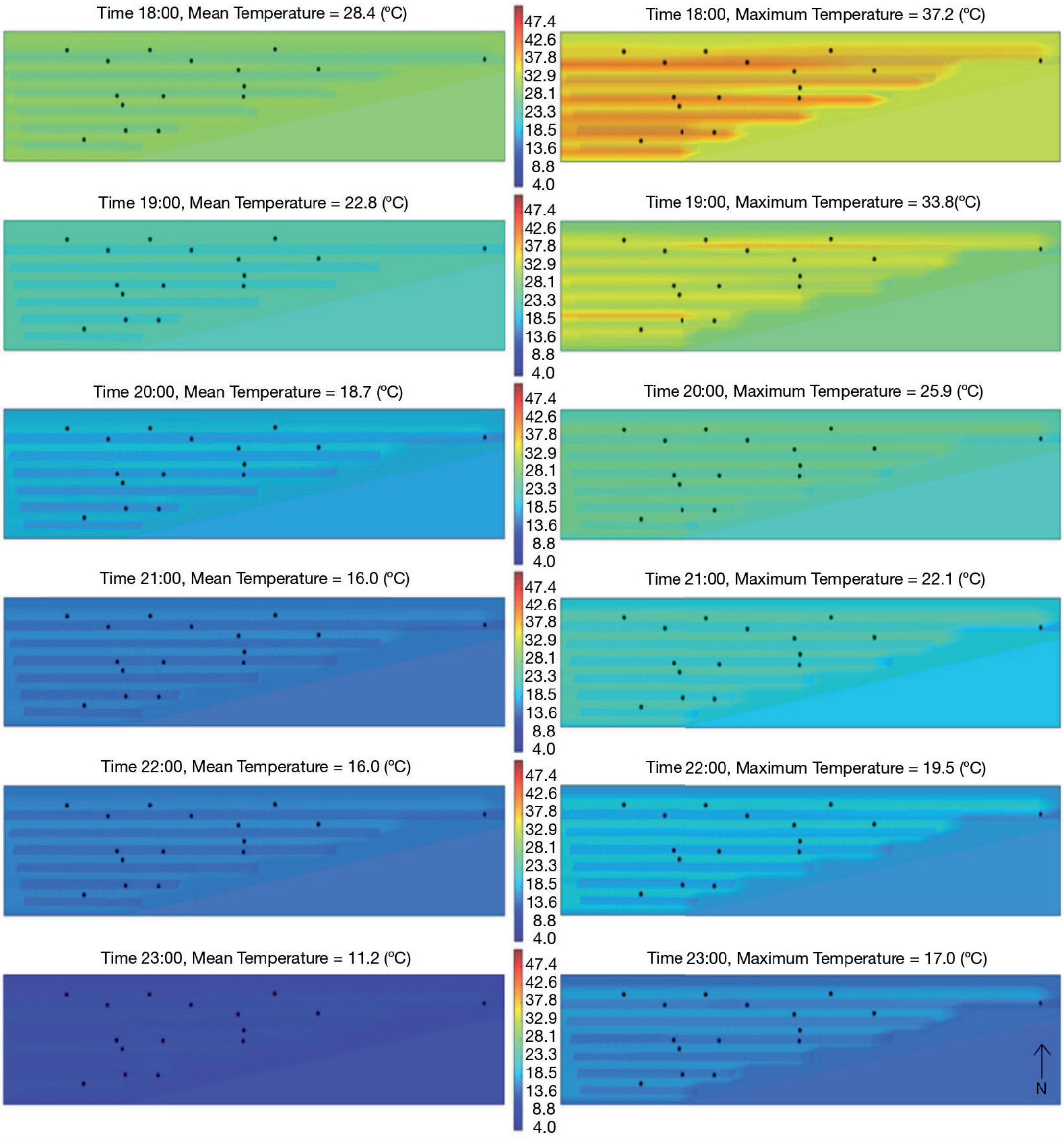
Time 15:00, Maximum Temperature = 40.1 (ºC)

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)



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)

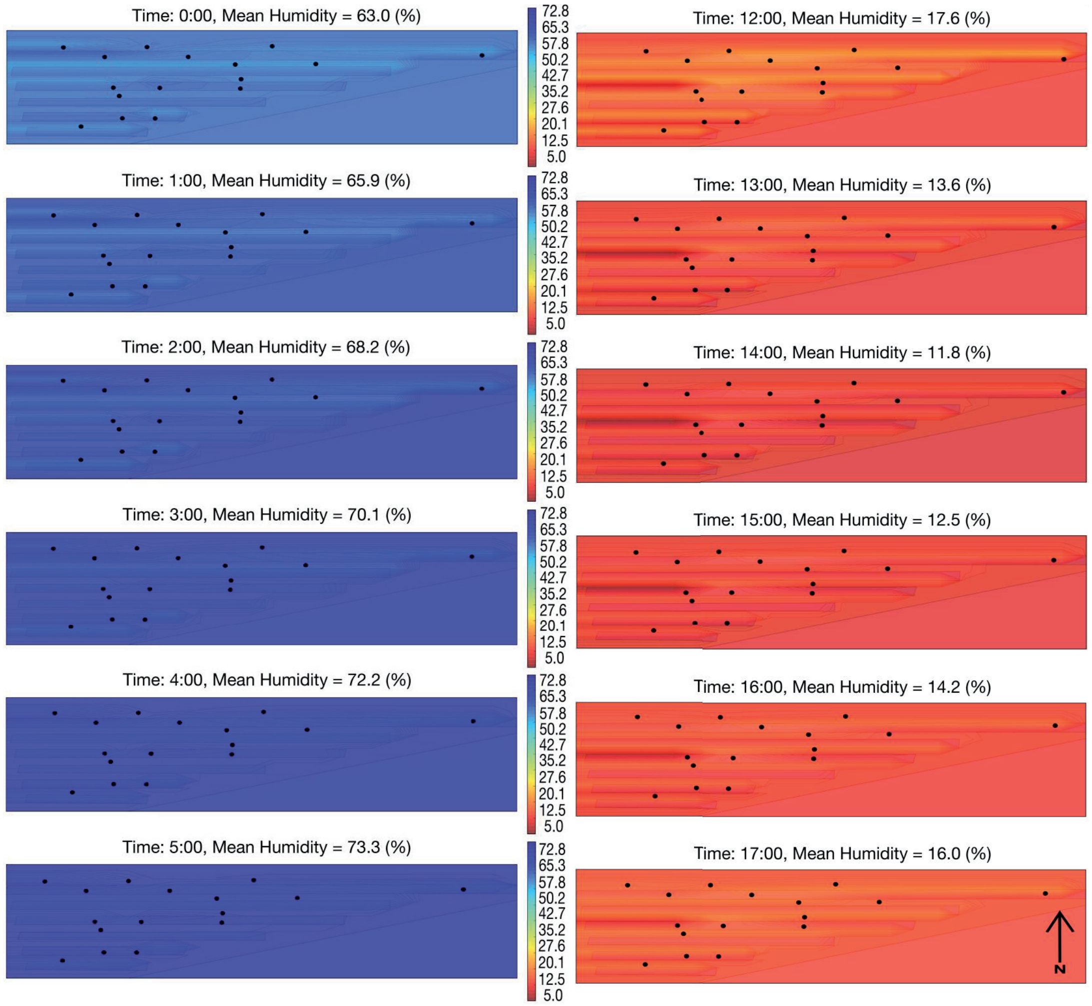
Time 22:00, Maximum Temperature = 19.5 (ºC)

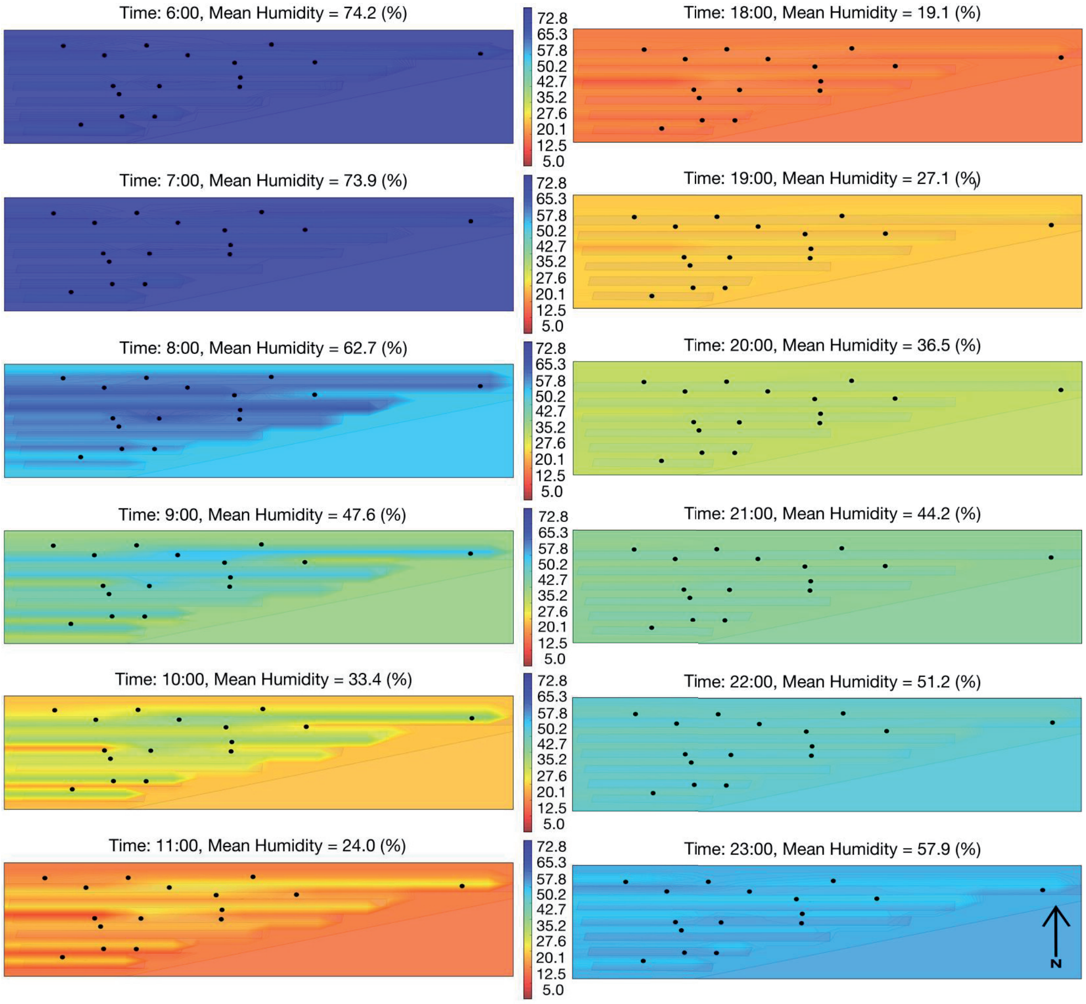
Time 23:00, Mean Temperature = 11.2 (ºC)

Time 23:00, Maximum Temperature = 17.0 (ºC)

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: 18:00, Mean Humidity = 19.1 (%)
Time: 7:00, Mean Humidity = 73.9 (%)
Time: 19:00, Mean Humidity = 27.1 (%)
Time: 8:00, Mean Humidity = 62.7 (%)
Time: 20:00, Mean Humidity = 36.5 (%)
Time: 9:00, Mean Humidity = 47.6 (%)
Time: 21:00, Mean Humidity = 44.2 (%)
Time: 10:00, Mean Humidity = 33.4 (%)
Time: 22:00, Mean Humidity = 51.2 (%)
Time: 11:00, Mean Humidity = 24.0 (%)
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

II

BIOTA RESPONSES TO SOLAR POWER PLANT ENVIRONMENT IN THE VALLEY OF COPIAPÓ, CHILE

by

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Submitted manuscript

III

OPTIMIZATION OF PHOTOVOLTAIC SOLAR POWER PLANT LOCATIONS IN NORTHERN CHILE

by

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Kalevi 2017

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