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Research article

Green roof and photovoltaic panel integration: Effects on plant and arthropod diversity and electricity production

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ABSTRACT

The combination of green roofs with photovoltaic (PV) panels has been proposed to provide synergistic benefits as the panel is cooled by the presence of the vegetation, and thus produces more electricity, while the solar panel enhances growing conditions for vegetation, and increases abiotic heterogeneity, resulting in higher plant diversity. We tested these hypotheses in a non-irrigated green roof in a Mediterranean climate with replicated plots including green roofs only, green roofs with a PV panel, and a conventional roof surface with a PV panel. We found that presence of a panel resulted in higher heterogeneity in substrate moisture, but there was no effect on plant diversity. Plant species showed enhanced growth in plots with PV, including greater growth of *Sedum sediforme* and longer flowering time of annual species. On the other hand, arthropod diversity was lower during part of the year, and abundance of some arthropod taxa was lower in green roof plots with PV. The presence of the green roof also did not improve electricity production by the panels. We conclude that in a Mediterranean climate, it would be appropriate to examine the use of irrigation in green roofs with PV panels, including effects on the plant community and on electricity production.

1. Introduction

Both green roofs and photovoltaic panels (PV) provide environmental benefits, but these two technologies would appear to compete for space on roofs. However, a growing number of studies suggest that integrating PV with green roofs provides reciprocal benefits to both PV electrical production and green roof communities (Schindler et al., 2016). Green roofs appear to improve electricity production by PV (Chemisana and Lamnatou, 2014; Köhler et al., 2007), and the presence of PV, by providing heterogeneity in solar radiation and growing media moisture, may increase the cover and diversity of vegetation on green roofs. This in turn can enhance green roof functions, including its cooling effect and rainwater retention (Cook-Patton and Bauerle, 2012; Lundholm et al., 2010), and potentially enhance arthropod diversity (Siemann, 1998).

1.1. Potential effects of green roof vegetation on PV

PV panels become less efficient as they become warmer, at a rate of 0.025% per degree Celsius at ambient temperatures over 28 °C (Ubertini and Desideri, 2003), so panel efficiency can be improved by cooling the surface of the panel. Since green roofs are cooler than black roofs (Scherba et al., 2011), and heat up more slowly than a white roof, they are expected to keep PV panels cooler and thus operating more efficiently (Scherba et al., 2011). Models and empirical studies comparing solar panels on green roofs and different types of conventional roofs suggest that this is the case, particularly in the summer and in warm climates (Chemisana and Lamnatou, 2014; Hendarti, 2013; Hui and Chan, 2011; Köhler et al., 2007; Nagengast et al., 2013; Ogaili, 2015; Perez et al., 2012; Witmer, 2010). In addition, accumulation of particles on PV panels leads to a decline in panel efficiency, and there is some evidence that green roofs can reduce air pollution (Tan and Sia, 2005) which in turn should reduce particle accumulation on PV panels.

On the other hand, the shade imposed by PV can have an effect on a green roof's plant community. There are very few studies of the effects of PV on green roofs, and these few studies are not designed with true replication, but preliminary results from other researchers suggest that there is higher plant diversity, increased plant height, and lower sedum

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cover under panels, that some species benefit from the presence of PV (Köhler et al., 2007), and that in some cases overwinter survival and vegetation cover were higher under PV (Bousselot et al., 2013). A study of arthropod communities in large photovoltaic panel power plants on the ground also indicated that there were benefits to some arthropod taxa, and higher arthropod species richness in shaded areas, but this study was conducted in the Chilean desert, where climatic conditions are much harsher than in Mediterranean green roofs (Suuronen, 2017).

1.2. PV as a vector to create habitat heterogeneity

An integration of PV and green roofs is likely to result in areas of the roof that are largely or entirely shaded by PV and areas that are not directly under PV, and are thus exposed to different environmental conditions, creating high overall environmental heterogeneity in solar radiation and soil moisture on green roofs. Shade can affect abiotic conditions on green roofs and affect germination, growth rates of the plants, and plant composition. Some of the species most commonly used on green roofs germinate at specific light levels (Benvenuti and Bacci, 2010), and some green roof species produce greater cover in shaded areas, while others produce more cover in non-shaded areas (Getter et al., 2009). Over time, areas with different levels of light and reflectance can achieve different plant compositions (Dewey et al., 2004).

1.3. PV as a nurse object

Research on nurse plants, adult plants that provide shelter to the seedlings of another species (Callaway, 1995), can also provide some insight into the effects that PV may have on green roof plants, since PV may have a similar function as nurse plants under some conditions. However, there are differences in the type of shade provided by nurse plants and objects, and they may have different types of interactions with plants, so studies of green roof integrated PV (GRIPV) have the potential to provide useful information on the effects of abiotic shade on plant communities.

Positive interactions between plant species, such as the nurse plant relationship, are most important in harsh environments (Bertness and Callaway, 1994), where the interactions make the environment less harsh, and areas with high disturbance, where a nurse plant may protect other plants from disturbance (Brooker et al., 2008). Extensive green roofs, non-irrigated roofs with shallow substrate (up to 20 cm), are harsh environments because they have a shallow soil, low availability of water and nutrients, and are often exposed to high wind speeds, so positive interactions between the PV and the plants would be expected to be important in this environment. Moreover, PV would tend to provide more positive than negative effects to the affected species, as the panels do not compete for nutrient resources. Abiotic nurses, such as rocks, can also collect moisture and thus enhance soil moisture (Peters et al., 2008; Turner et al., 1966). Similarly, PV may enhance soil moisture in the surrounding area by collecting dew.

1.4. Utilizing potential interactions between PV panels and vegetation to increase green roof services

We expect two components in the effect of PV on green roofs: providing shade, and creating a heterogeneous environment. Shade in dry environments is often shown to be useful to developing plants, due to increased moisture in shaded areas (Aguiar et al., 1992; Flores and Jurado, 2003; Gómez-Aparicio et al., 2004; Greenlee and Callaway, 1996; Shirley, 1945; Tiedemann et al., 1971) while shade often appears to be unnecessary for seedlings in moist environments (Flores and Jurado, 2003; Gómez-Aparicio et al., 2004; Greenlee and Callaway, 1996; Tiedemann et al., 1971). Since extensive green roofs in Mediterranean climates generally lose moisture quickly following the end of seasonal precipitation, PV would be expected to contribute to higher moisture levels on the green roof, and thus benefit plants.

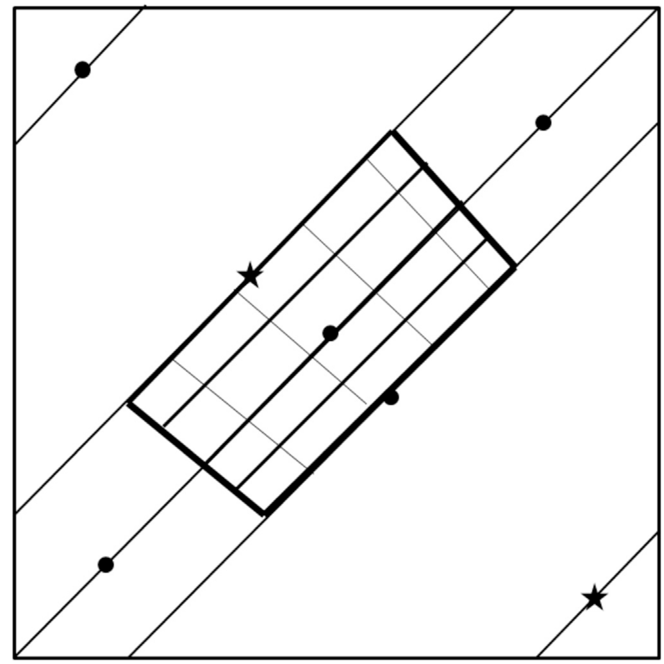

Fig. 1. Locations of measurements in plots, in reference to PV panel. Dot-substrate temperature and moisture. Star-substrate temperature and moisture, air temperature. Five diagonal lines-point intercept transects.

Shade heterogeneity can allow competing species to coexist (Callaway, 1994; Valladares, 2003; Zavala et al., 2000). Several studies that have examined the effects of shade on multiple species found that only some of them responded positively (Blank and Carmel, 2012; Callaway, 1992; Holzapfel and Mahall, 1999; Pérez-de-los-Reyes et al., 2013; van Zonneveld et al., 2012). Since shade and its effects benefit some species, but are detrimental to other species, a green roof with PV, where there is a heterogeneous environment with different levels of shade, would be expected to produce a diverse plant community, relative to a homogeneously sunlit roof.

If there is an effect of PV on the plant community, other trophic levels may also be affected. In general, a more diverse plant community is correlated with a more diverse arthropod community (Moreira et al., 2016), so the heterogeneity produced by the PV could have an indirect positive effect on the arthropod community. In addition, PV could have a direct effect on arthropods, via shade or the habitat produced by the structure itself, which could shape the arthropod community (Nash et al., 2016; Suuronen, 2017). If the area under the PV has a different arthropod community, a green roof with areas covered by PV and exposed areas could have higher overall diversity than a green roof without PV.

The aim of this experiment was to study the benefits of integrating green roofs and PV systems. We examined the effects on green roofs' abiotic conditions and plant diversity and abundance. We hypothesized that: 1) Vegetation abundance and diversity would be higher on green roofs with PV than green roofs without PV, as result of increased microhabitat diversity and higher overall soil moisture; 2) Arthropod diversity would be higher on green roofs with PV due to increased microhabitat diversity; 3) PV panels on green roofs would produce more electricity than on non-greened roofs, as a result of lower temperatures on the roof and reduced dust cover on the panels.

2. Materials and methods

2.1. Experimental design

The study was conducted on a green roof located at ground level at