From butterflies to bighorns: Multi-dimensional species-species and species-process interactions may inform sustainable solar energy development in desert ecosystems

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ABSTRACT — Solar energy development is a contemporary, anthropogenic driver of disturbance in desert ecosystems. Although solar energy may contribute to global deep decarbonization and mitigation of climate change through emissions reductions, net effects of solar energy development on desert ecosystems are largely unknown. Siting, construction, and operation of solar energy infrastructure in natural desert environments may affect interactions between soils, plants, and animals, inducing "bottom-up" and/or "top-down" trophic responses to disturbance and modified environmental conditions. Understanding species-species and species-process interactions may elucidate systematic effects of solar energy development on desert ecosystem function and integrity more comprehensively than addressing effects of solar energy on individual desert biosphere constituents exclusively. Further, ecological effects of disturbance-mediated biological invasions specific to solar energy development in deserts are intrinsically better demonstrated when interactions among native and invasive species and ecological processes are considered. If "umbrella" species are used in studies at the desert ecology-solar energy nexus, we recommend adoption of species representative of species-process interactions at a variety of spatial scales. Consideration of these novel and integrative approaches to solar ecology may help guide future research objectives, thereby leading to better understanding of the complex interface between solar energy and desert conservation.

Introduction

Concerns regarding finite fossil fuel resources, increased energy demand, and climate change, coupled with current socioeconomic drivers, have bolstered global renewable energy development (Shafiee and Topal 2009, IPCC 2011). Solar energy in the form of ground-mounted, utility-scale [i.e., ≥1 megawatt$_{DC}$ (MW)] photovoltaic and concentrating solar power technologies is a burgeoning renewable energy option that has exhibited significant industrial growth over the last decade (Bazilian et al. 2013, Hernandez et al. 2014**a**). Favorable environmental conditions and abundant public lands (e.g., Bureau of Land Management) may make deserts of the southwest United States the ideal recipient environment for solar energy development (BLM 2012, Hernandez et al. 2015). Although solar energy may help advance decarbonization, sensitive desert ecosystems may be imperiled by solar energy development (Lovich and Ennen 2011). For example, construction of solar facilities creates a series of biophysical disturbances, including grading of soils and vegetation removal, which in turn may affect biota via "bottom-up" trophic interactions (e.g., degraded soils → decreased plant growth → reduced food and cover for wildlife; Hernandez et al. 2014**b**). Meanwhile, aridland Southwest ecosystems support exceptional biodiversity and many endemic, threatened and endangered species already stressed by climate change (Lovich and Bainbridge 1999, Mittermeier et al. 2001).

Studies explicitly quantifying potential effects of solar energy development on desert ecosystems are limited (Lovich and Ennen 2011); however, these data and the body of desert-disturbance literature provide a conceptual framework for guiding sustainable solar energy development (Moore-O'Leary et al., *in review*). Few past studies measured effects of solar energy facilities on biodiversity (e.g., birds – McCrary et al. 1986). However, effects of other forms of anthropogenic disturbance on desert ecosystems have been documented, which may

Figure 1. Some potential indirect effects of solar energy development on soils, plants, and animals in desert ecosystems. Photo credit: Steve Grodsky.

inform future ecosystem response to disturbance caused by solar energy development (Hernandez et al. 2014**b**).

Solar energy development may negatively or positively affect desert ecosystems via direct (i.e., proximate) or indirect effects. Proximate effects of solar energy on biodiversity may involve direct mortality of organisms, theoretically ranging from soil microbes to birds of prey. Disturbance from construction of solar facilities and associated infrastructure may lead to mortality of exposed soil biota and burrowing and/or fossorial wildlife, including reptiles and invertebrates (Lovich and Bainbridge 1999). Increased densities of transmission lines stemming from solar facilities may result in increased avian fatalities caused by direct collision with power lines (Smith and Dwyer 2016). Extreme heat radiating from beams of light reflected by heliostats towards central heating towers in concentrating solar plants may incinerate flying wildlife, including birds (McCrary et al.1986, Walston et al. 2016) and butterflies (S. M. Grodsky, *unpublished data*). Anecdotal evidence suggests that some bats, birds, and insects may mistake the surface of photovoltaic solar panels for water (i.e., lake effect), leading to direct mortality via collision with panels (Greif and Siemers 2010). Similarly, light pollution from photovoltaic panels and heliostats may attract insects (Horváth et al. 2009), which in turn may increase the likelihood of collision for insectivorous birds.

Given the extensive web of possible ecological interactions driven by anthropogenic disturbance, indirect effects of solar facilities on desert ecosystems are inherently more numerous than proximate effects. We describe some of the primary, potential indirect effects of solar energy development on desert ecosystems in Fig. 1. Lovich and Ennen (2011) and Hernandez et al. (2014**b**) comprehensively reviewed potential indirect effects of solar energy facilities on desert ecosystems.

Potential effects of solar energy development on desert ecosystems have been covered in several reviews and a conceptual framework for solar energy and the land-energy-ecology nexus is forthcoming (i.e., Moore-O'Leary et al., *in review*). While existing reviews mostly present potential effects of solar energy development on individual species or groups of species, we recognize the opportunity to enhance this framework by exploring integrative approaches to desert ecology based on species-species and species-process interactions. As such, our objectives are to: 1) exemplify how the study of trophic interactions may holistically inform systematic, desert biosphere response to solar energy; 2) demonstrate the inherent connection between disturbance-mediated invasion ecology and native-invasive species interactions and resultant ecosystem effects; and 3) examine how species-process interactions may help inform selection of study species representative of spatially explicit ecosystem processes. Consideration of these novel and integrative approaches to solar ecology may guide future research objectives, thereby leading to better understanding of the complex interface between solar energy and desert conservation.

Trophic interactions: the Milkweed–Monarch Nexus example

When considering effects of solar energy development on entire desert ecosystems, a "bottom-up" approach can be useful for elucidating interconnected rather than isolated impacts on representative desert systems (Hunter and Price 1992). For example, studying how solar energy facilities affect soils, which in turn affect milkweed, which in turn affect monarchs (and vice versa) may reveal mechanisms behind ecological responses to associated disturbance and environmental change (Fig. 2**a**). In contrast, measuring response of one individual element of the milkweed-monarch nexus (i.e., the series of interactions between soil, milkweed, and monarchs and indirectly associated flora and fauna) to solar energy-mediated disturbance may uncover patterns, but is less likely to reveal causation. Pre-construction site preparation at solar facilities may vary in intensity (e.g. blading vs. mowing), which dictates levels of soil disturbance and consequently plant community response (Hernandez et al. 2014**b**). Heliostat presence and configuration may alter microclimate conditions of soils via shading and altered water dynamics, including availability, runoff, and erosion (Tanner et al. 2014). Soil variables may in turn affect milkweed physiology, photosynthetic rate, and overall plant health, potentially leading to variable rates of herbivory and granivory (Moore-O'Leary et al., *in review*). Positive and/or negative feedback loops between individual milkweed plants and monarch caterpillars may result in further "bottom-up" implications, including individual caterpillar survival. We summarize trophic interactions of the milkweed-monarch nexus in Fig. 2**b** (*see also* Fig. 2**a**).

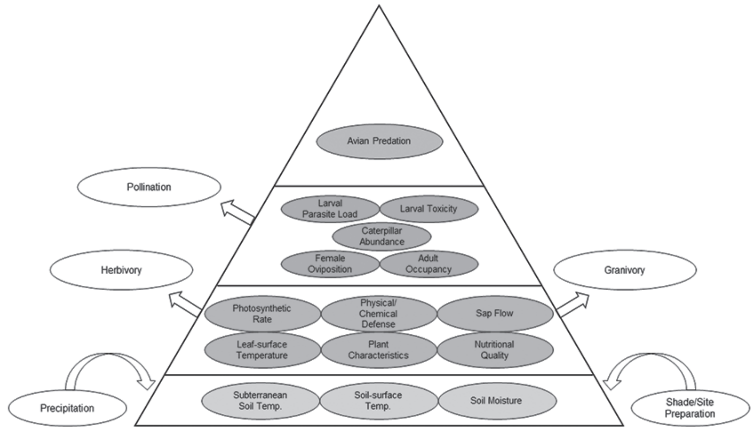

Figure 2**a**. Measurements informing "bottom-up" effects of solar facility site preparation, configuration, and operations on desert monarchs at the Ivanpah Solar Facility. From bottom to top of pyramid: soil (beige), Mojave milkweed (green), monarch butterfly (orange), and monarch predators (blue).

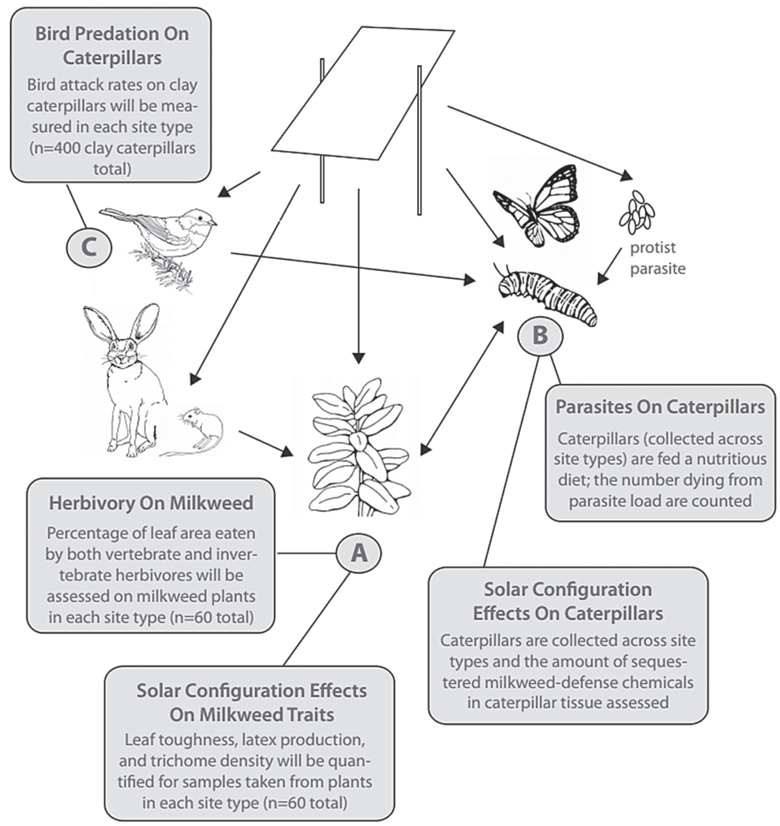

Figure 2**b**. Interconnectedness between Mojave milkweed, monarch, and their associates potentially affected by solar energy infrastructure.

Disturbance-mediated biological invasions interactively affect desert ecosystems

Conceptually, ecological disturbance events often lead to "winners and losers" (Grodsky et al. 2016**a**). For example, clearcutting a forest will benefit wildlife species that thrive in early-successional vegetation communities, but will inherently displace wildlife reliant on mature forest canopy. In desert ecosystems, the "winners" responding to disturbance may mostly consist of invasive species [e.g., Saharan mustard (*Brassica tournefortii*)] because native desert species are often not adapted to frequent or large-scale disturbances. Colonization of invasive species may be further facilitated by the fact that native desert communities often take centuries to naturally restore following disturbance (Lovich and Bainbridge 1999).

Anthropogenic disturbance in the form of solar energy development may alter desert disturbance regimes and facilitate spread of invasive species (e.g. invertebrates, plants), which in turn may reshape species-species and species-process interactions (D'Antonio and Vitousek 1992, Lovich and Ennen 2011, Tanner et al. 2014). In general, disturbance in deserts often facilitates colonization of invasive species (Gelbard and Belnap 2003, Zink et al. 2015). While endemic, desert flora and fauna are adapted to a relatively narrow range of environmental conditions and historically infrequent disturbance, invasive species can occur within a wide range of environmental and habitat conditions (Sakai et al. 2001). Roads associated with solar facilities also may perpetuate spread of invasive plants (Gelbard and Belmap 2003). Once populations of invasive species become established in and around solar facilities, propagules may disperse to adjacent undisturbed desert and potentially outcompete native species for resources (Zink et al. 1995). For example, invasive ants may outcompete native, seed-dispersing ants for nesting substrate and food; ecosystem-wide effects may consequently occur, since many invasive ants are far less efficient seed dispersers than the native ants they displace

(Warren et al. 2015). Disturbance from solar energy development may facilitate the spread of flammable, invasive annual plants [e.g., cheatgrass (*Bromus tectorum*)] in the desert Southwest (Brown and Minnich 1986, Abatzoglou and Kolden 2011). Southwestern deserts and the species that live there are not fire-adapted (Brooks and Esque 2002). As such, increased fire frequency resulting from a combination of abundant, invasive plant fuels and higher likelihood of anthropogenic ignitions could have potentially severe ecosystem effects in deserts, adversely affecting sensitive plant communities and wildlife (Esque et al. 2003, Lovich et al. 2011).

Species representative of systematic interactions in the desert ecosphere

At first glance, the concept of "umbrella" species appears to contradict our proposed conceptual framework aimed at addressing effects of solar energy on system-wide, ecological interactions. However, "umbrella" species have disproportionate conservation value relative to some other species in that their protection often cascades to multiple species. Further, "umbrella" species also promote and help fund desert ecology research. For example, conservation concerns regarding solar energy development in deserts of the southwest United States have largely centered on the Agassiz's desert tortoise (*Gopherus agassizii*), a federally threatened species and important ecosystem engineer (Lovich and Ennen 2011). Indeed, the desert tortoise serves as a useful "umbrella" species in areas currently supporting utility-scale solar energy development, potentially extending protection from some anthropogenic disturbance to entire desert communities (Tracy and Brussard 1994). If "umbrella" species must be used, we suggest including study species that encapsulate species-process interactions at multiple spatial scales to enhance desert conservation in the face of solar energy development. We exemplify use of two such species for desert ecosystems threatened by solar energy development: 1) desert bighorn sheep (*Ovis canadensis nelson*) to address integrated, landscape-level effects on animal movement; and 2) monarch butterfly (*Danaus plexippus*) to explore local-scale, trophic interactions.

Desert bighorn sheep (Fig. 3) are charismatic megafauna emblematic of the ruggedness of the desert Southwest with large home ranges and expansive movements, and thus may serve as a sentinel species indicative of landscape-level effects of solar energy development on animal movement and dispersal. The desert bighorn sheep, a subspecies of bighorn sheep, has been particularly susceptible to anthropogenic changes, including habitat loss, overgrazing by livestock, diseases contracted from domestic livestock, and loss of water resources, throughout its range (Papouchis et al. 2001). Independent desert bighorn populations are generally demographically separated by intervening desert, making connectivity among populations essential for maintaining genetic diversity in the regional metapopulation (Bleich et al. 1990, Bleich et al. 1996). Fragmentation caused by highways has blocked gene flow and significantly reduced genetic diversity in bighorn sheep (Epps et al. 2005). Solar energy development and associated roads and corridors also may increase fragmentation in desert landscapes at large-spatial scales (Lovich and Ennen 2011), which in turn may similarly restrict desert bighorn movement and gene flow. Further, desert bighorns may demonstrate long-term avoidance of solar energy facilities, although they do occupy areas developed long ago for wind energy (Agha et al. 2015). Analogous avoidance behavior exhibited by mule deer (*Odocoileus hemionus*) was observed in areas supporting oil and gas development in the Intermountain West, which lead to disconnection between breeding populations of the species (Sawyer et al. 2009). Recent upgrades in GPS collar-technology enable collection of high fidelity, spatiotemporal data of individual animals; desert bighorn sheep equipped with these collars would provide sufficient data to quantify landscape-level effects of solar energy development on bighorn movement. Concurrent collection of DNA samples from these sheep populations would help researchers better understand how genetic connectivity relates to recorded movement of individuals.

Figure 3. Desert bighorn sheep (*Ovis canadensis nelson*) in the Mojave Desert. Photo credit: Rebecca Hernandez.

Monarch butterflies may be especially useful as an indicator of "bottom-up" effects of solar energy development in novel desert ecospheres. Given their holometabolous live cycle, inextricable ties to milkweed, and contribution to ecosystem services, monarchs are model organisms for addressing trophic interactions. Further, invertebrates are excellent ecological indicators of land use change, including renewable energy development, at micro-sites with highly integrated ecological processes (Grodsky et al. 2015). Variable environmental and microclimate conditions created by solar energy infrastructure may affect soils and thereby milkweed species serving as host plants for monarchs (Moore-O'Leary et al. *in review*). In turn, overall milkweed health and fitness may affect factors contributing to monarch caterpillar survival, including cardenolide sequestration, susceptibility to predation and parasitism, and forage quality.

The western population of the monarch butterfly has precipitously declined in response to severely reduced populations of milkweed host plants, loss and reduced quality of overwintering sites along the California coast, and climate change (Monroe et al. 2017). In fact, nationwide population declines of the monarch butterfly have been so precipitous that the species currently is under consideration for listing under the Endangered Species Act, with a final protection decision scheduled for 2019. A western monarch migration route begins in southern California and passes through much of the desert Southwest, which is inhabited by several species of desert milkweed and thus serves as a spring and summer breeding-ground for the butterflies (Moore and André 2014, Xerces Society 2015).

Conclusions

Research at the nexus of solar energy development and desert ecology will be essential for informing sustainable development of solar energy in the desert Southwest. Among major renewable energy technologies, solar energy has a high propensity for large-scale development in undisturbed, sensitive ecosystems with high biodiversity (Hernandez et al. 2015). In contrast, wind energy facilities may be sited in agricultural areas with typically low biodiversity (McDonald et al. 2009), and woody biomass harvests for forest bioenergy often occur after timber harvest in industrial forests (Fritts et al. 2014, Grodsky et al. 2016**b**). We suggest that desert ecology studies on solar energy development will be enhanced by prioritizing research efforts that address species-species and species-process interactions. Specifically, we recommend that future studies focus on "bottom-up" ecological interactions, ecosystem-wide effects, and landscape-level impacts. We encourage desert researchers to consider connections and intersections of their own work with solar energy development in the desert Southwest.

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