Sustainability of utility-scale solar energy – critical ecological concepts

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Renewable energy development is an arena where ecological, political, and socioeconomic values collide. Advances in renewable energy will incur steep environmental costs to landscapes in which facilities are constructed and operated. Scientists – including those from academia, industry, and government agencies – have only recently begun to quantify trade-offs in this arena, often using ground-mounted, utility-scale solar energy facilities (USSE, ≥1 megawatt) as a model. Here, we discuss five critical ecological concepts applicable to the development of more sustainable USSE with benefits over fossil-fuel-generated energy: (1) more sustainable USSE development requires careful evaluation of trade-offs between land, energy, and ecology; (2) species responses to habitat modification by USSE vary; (3) cumulative and large-scale ecological impacts are complex and challenging to mitigate; (4) USSE development affects different types of ecosystems and requires customized design and management strategies; and (5) long-term ecological consequences associated with USSE sites must be carefully considered. These critical concepts provide a framework for reducing adverse environmental impacts, informing policy to establish and address conservation priorities, and improving energy production sustainability.

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A central challenge of the 21st century is to increase the sustainability of our energy systems while maintaining societal priorities for conserving biodiversity and safeguarding ecosystem services. Humans all over the world are developing renewable energy, and especially utility-scale solar energy (USSE, ≥1 megawatt [MW]), to match demands for clean energy and curb global climate change by replacing fossil fuels. In the US alone, over 14 gigawatts of solar energy capacity were installed in 2016 (Solar Energy Industries Association 2016). The environmental impacts of ground-mounted USSE installations will be extensive over space and time, especially when built on previously undisturbed land or when large-scale grading (leveling) of the landscape is implemented (Macknick *et al.* 2013). Peer-reviewed research by academic, agency, and industry scientists will help to further demonstrate the relative benefits of USSE over fossil-fuel-generated energy by assessing their respective environmental impacts at local and landscape scales. For USSE, these impacts largely originate from the amount of land required by facilities and the sensitivity of arid lands (which are frequently targeted as sites) to anthropogenic disturbances (Lovich and Ennen 2011; Hernandez *et al.* 2014a; Tanner *et al.* 2014). To simultaneously advance solar energy and conservation goals, ecologists are helping to clarify the potential benefits of and trade-offs between energy systems and the environment. By developing research and analytical tools to evaluate energy system and land-use alternatives, inform management strategies, and track local and landscape-wide consequences, ecologists play critical roles in guiding more sustainable development of renewable energy (WebPanel 1).

In a nutshell:

- To help mitigate the impacts of anthropogenic climate change, we argue that the connections between utility-scale solar energy (USSE) development and environmental conservation should be closely examined
- We present five critical ecological concepts to improve sustainable development of solar energy
- Integration of these concepts is needed to facilitate ground-mounted, USSE sustainability and conservation goals

Utility-scale solar energy is being deployed in diverse settings, including the built environment and natural areas of varying conservation value (Stoms *et al.* 2013; Hernandez *et al.* 2015a,b). These settings can in fact be used as experimental systems to test ecological hypotheses (eg responses of organisms, communities, and landscapes to perturbations), thus informing improved design of future facilities to reduce impacts. Industrial solar complexes are associated with novel ecological questions, such as what are the effects of panel shading and

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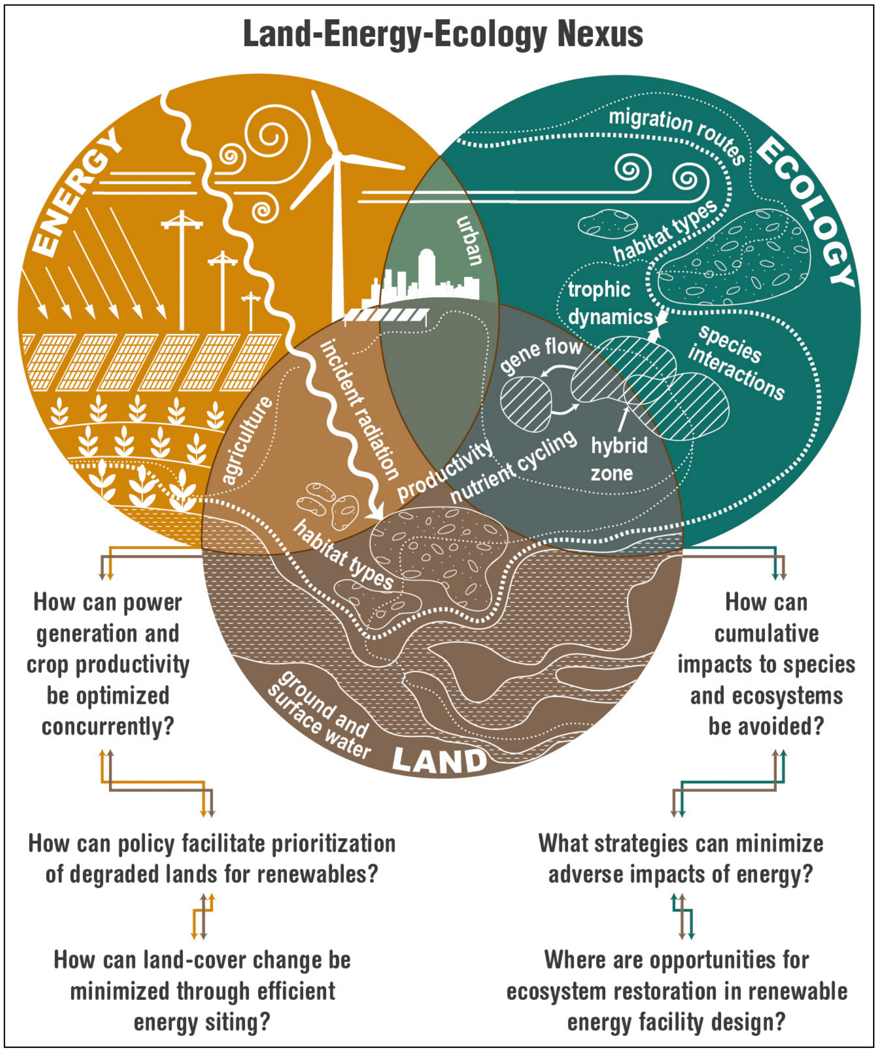

Figure 1. *The land-energy-ecology nexus is the space where energy facilities, the surrounding landscape, and populations of organisms within that landscape interact. Synergistic opportunities that offer benefits for energy and ecology or land and reduce overall costs, rather than in a single focal area, occur in areas of overlap.*

precipitation exclusion on seedling emergence (eg Tanner *et al.* 2014), what are the influences of vegetation beneath panels on energy production (Macknick *et al.* 2013), and what are the effects of mulitple energy systems on local and regional climate (Millstein and Menon 2011)? These and other questions exist in a context that we define below as the "land-energy-ecology nexus", which spans local to regional scales and involves a wide range of political, socioeconomic, commercial, and academic interests. For example, how can USSE land use proceed while maintaining conservation priorities? What are the long-term USSE environmental costs to landscapes and species of conservation concern relative to cleaner energy benefits? Given that USSE development addresses a critical conservation need (ie curbing carbon emissions), how do we maximize benefits in reducing carbon emissions while minimizing negative impacts to landscapes and species?

Here we identify five critical ecological concepts as a framework to underpin policy, siting, restoration, and management of renewable energy development, using USSE as a model. These concepts stimulate novel ecological research questions that can be extended to other energy generation systems. We suggest a course of action to facilitate informed land-use decisions and environmentally conscious management of USSE facilities, promoting conservation alongside energy production. We highlight these ecological concepts for USSE development and issue a call to ecologists, industry representatives, policy-setting organizations, research institutions, and governing bodies to collaborate in advancing the development of solar energy over fossil-fuel use.

■ Concept 1: USSE exists within the land-energy-ecology nexus

For a given energy system (renewable or otherwise), the land-energy-ecology nexus represents the interactions among (1) energy production and development facilities or activities, (2) the physical landscape within which the energy system is sited, and (3) the populations of organisms and their habitats within the energy system and the surrounding environment (Figure 1). Although all energy systems can be conceptualized within this nexus, the energy-generating capacity of USSE is several orders of magnitude greater than that of any other renewable energy system (Tsao *et al.* 2006). USSE therefore provides an excellent model for identifying an optimal balance between conservation goals and energy production goals.

Solar energy has great potential for mitigating greenhouse-gas (GHG) emissions by replacing the burning of fossil fuels (see Ito *et al.* 2016; Fthenakis and Kim 2013; Whitaker *et al.* 2012, to compare life-cycle assessments of global warming potentials). However, as currently deployed, it can result in substantial land-use, environmental, and conservation costs in sensitive natural habitats (Lovich and Ennen 2011; Turney and Fthenakis 2011; Cameron *et al.* 2012). Solar energy technologies fall into two categories: photovoltaic (PV) cells, which convert sunlight into electric current, and concentrating solar power (CSP), which uses reflective surfaces to focus sunlight to heat a working fluid. The global

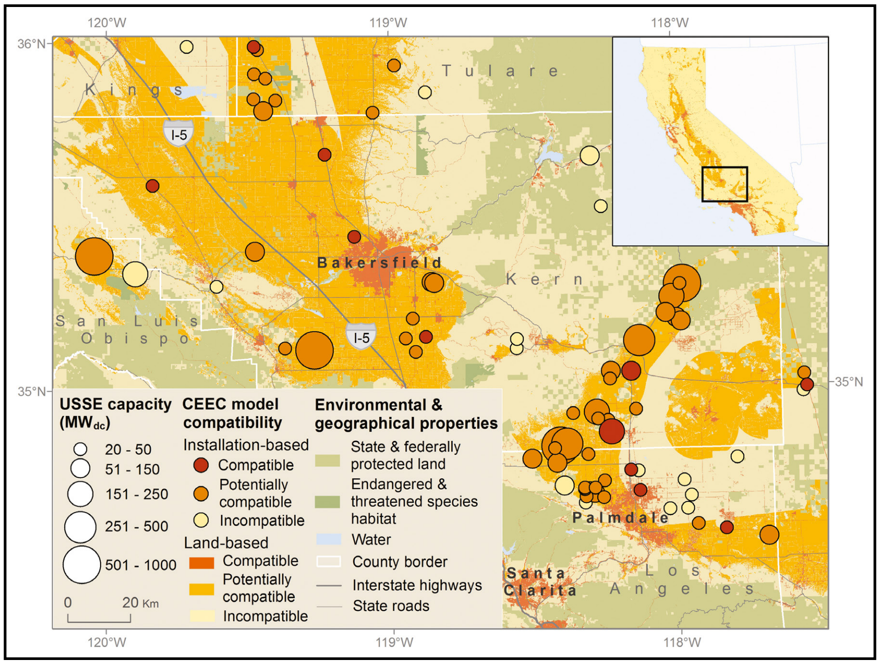

Figure 2. *Map showing three tiers (*compatible, potentially compatible, *and* incompatible*) of environmental and technical compatibility for siting solar energy from the Carnegie Energy and Environmental Compatibility (CEEC) decision-support tool for Kern County, CA. The CEEC Model integrates satellite-based solar radiation models with hydrologic, socioeconomic, topographical, energy infrastructure, and ecological resource opportunities and constraints (Hernandez* et al. *2015a,b).*

geographic potential of solar energy is vast, spanning approximately 200 million square kilometers on six continents (Hernandez and Hoffacker, unpublished data; www.aridlab.org/global-solar-energy-hotspots). Solar energy can be integrated into the built environment (eg residential and commercial rooftop installations), conferring environmental co-benefits such as conserving wildlands, revegetating disturbed lands, reducing the heat island effect at the local scale, and enhancing thermal insulation benefits to buildings. It can also be installed on previously disturbed lands (Hoffacker *et al.* in review; Macknick *et al.* 2013), such as the 250-MW California Valley Solar Ranch project in central coastal California, which was built on failed farmland. To date, USSE facilities are generally ground-mounted and sited outside the built environment, with 1 megawatt direct current (MW_{dc}) of output requiring approximately 3 hectares of land (Hernandez *et al.* 2014b). In California, the majority of USSE installations ≥ 20 MW are sited in natural ecosystems, and are located close to (on average within 7 km of) protected natural areas (Hernandez *et al.* 2015b). Similarly, in Italy, 66% of USSE installations are located where adverse impacts to local ecosystems, including loss of carbon sequestration, are high (De Marco *et al.* 2014). Because USSE siting decisions generally result in complete land-cover change at the chosen locations, effective tools are clearly needed to improve siting efficacy and to reduce negative environmental outcomes such as habitat fragmentation, as well as adverse impacts to sensitive areas or to species of conservation concern (Cameron *et al.* 2012).

As the number of USSE installations multiply, so too do the associated impacts of land-use change. The Carnegie Energy and Environmental Compatibility Model (CEEC) is one of a number of decision-support tools that stakeholders rely on to categorize land by environmental compatibility (Hernandez *et al.* 2015a; eg Figure 2; see also Cameron *et al.* 2012). Such tools can be used not only to identify synergies where conservation goals can be advanced alongside solar energy technologies but also to predict land-use impacts such as habitat loss and fragmentation, disruption of wildlife connectivity and gene flow, alteration of biogeochemical processes, and direct mortality of plants and animals (Lovich and Ennen 2011; Hernandez *et al.* 2014a).

Like many forms of land-use change, the effects of USSE can be detected at various temporal and spatial scales, ranging from short-term, local effects of a specific project, to long-lasting, cumulative influences of multiple facilities across large landscapes. Impacts of USSE facilities are indeed juxtaposed by the pervasive effects of fossil-fuel-based emissions driving global climate change. Uncertainty regarding the ecological outcomes of USSE proliferation increases as the spatiotemporal scale of impacts increases, and is compounded by climate change and other land-use conversion. For example, if USSE siting, conservation planning, and impact mitigation efforts fail to compensate for shifts in species distributions under altered climate regimes, future environmental costs of USSE development in natural environments will be higher than anticipated. Careful spatial planning to optimize the siting of USSE facilities and thereby minimize adverse ecological impacts is an important first step toward reducing such costs (Cameron *et al.* 2012; Stoms *et al.* 2013; Hernandez *et al.* 2015a; Kreitler *et al.* 2015). Development of USSE in the built environment or on degraded and developed lands avoids many of these impacts.

Concept 2: there are "winner" and "loser" species in USSE ecosystems

The environmental impacts of USSE play out across multiple scales, locally affecting ecological communities ranging from soil microbiota to old-growth vegetation

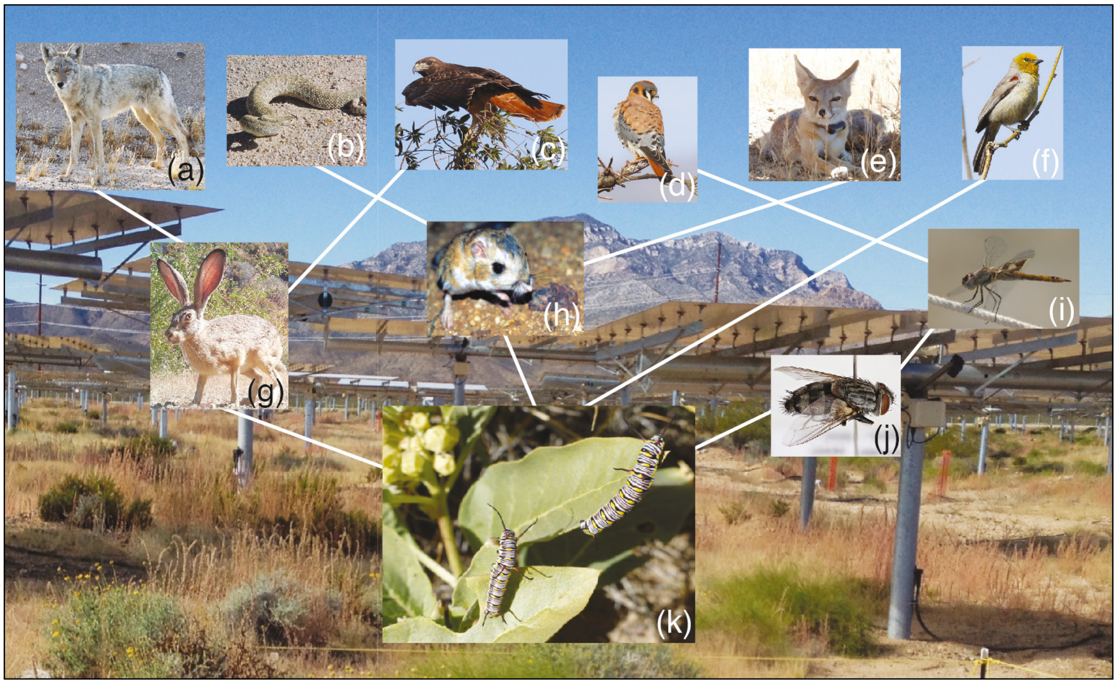

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Figure 3. *Relationships potentially affecting the success of (k) Mojave milkweed (*Asclepias nyctaginifolia*) in the retained understory of Ivanpah Solar Electric Generating System, in California. Lines indicate a subset of potential effects.*

and more broadly affecting migratory wildlife and landscape processes such as soil and water distribution. Paradoxically, by damaging biological soil crusts and affecting deeper soil microbial communities responsible for nutrient cycling, construction of USSE to quell fossil-fuel use may actually release detrimental GHGs, increasing local estimates of relative atmospheric heating capacity, or global warming potential. Vegetation removal also causes changes in C cycling (Wardle *et al.* 1999; Zipperer *et al.* 2012; Beniston *et al.* 2015) including conversion from a CO_2 sink to a source (Schlesinger 1990; Post and Kwon 2000; Huang *et al.* 2015). In semi-arid and arid lands, this could reduce the typical C sequestration rate, which ranges from 10 to 110 g C m^{-2} yr^{-1} (Wohlfahrt *et al.* 2008; Schlesinger *et al.* 2009; Petrie *et al.* 2015). Increased GHG emissions are also affiliated with the transport of materials and use of natural gas during USSE construction and operation.

An estimated 86,000 hectares are already affected by USSE in California alone (Hernandez *et al.* 2014a), and more than 220,000 hectares in the Mojave Desert have pending requests to install USSE on Bureau of Land Management land (Hernandez *et al.* 2014b). The extent of these proposed installations warrants further study to better understand how this prolific USSE development affects the C budget, particularly in arid lands. Elimination of vegetation can also alter local microclimates (eg Armstrong *et al.* 2014) and severely degrade wildlife habitat. Retention of vegetation, which is being implemented in a growing minority of USSE systems, could maintain C sequestration, benefit ecosystem structure, and preserve species of interest, although it may conversely also attract sensitive species into areas that may put them at greater risk (Figure 3).

To date, only a few peer-reviewed publications discuss the effects of USSE on certain animal taxa (Table 1; WebPanel 1). For instance, polarized light reflected from PV solar panels attracts insects that require water for their reproductive cycle into an "ecological trap" (Horváth *et al.* 2010) and at some USSE facilities, panels have similarly been hypothesized to attract certain guilds of birds (Kagan *et al.* 2014). In addition, solar "flux" comprising concentrated solar light energy at CSP facilities can cause birds' feathers to singe, and flying insects such as butterflies and dragonflies can burn (Diehl *et al.* 2016; avian literature reviewed in Walston *et al.* 2015). USSE can also have negative effects on riparian and xero-riparian (typically dry ecosystems that are characterized by intermittent or ephemeral streams and that include habitats such as desert washes) systems in arid regions with concomitant impacts to wildlife that depend upon these fragile habitats for survival (Grippo *et al.* 2015). Walston *et al.* (2016) estimated annual avian mortality caused by ground-mounted USSE facilities to be between 16,200 and 59,400 birds in southern California alone; the authors extrapolated their estimate to between 37,800 and 138,600 birds annually for the entire US based on USSE projects that are either installed or under construction. In comparison, Sovacool (2012) estimated that 4.5 million and 327,000 bird fatalities occur annually in the US due to fossil-fuel plants and nuclear plants, respectively.

Known and suspected impacts to wildlife resulting from facility construction and operation include: habitat

Table 1. Known or expected potential impacts of USSE on a subset of species and groups of organisms

		Habitat fragmentation	*Panels and mirrors*	*Fences**	*Air-cooled condenser (CSP only)*	*High-energy flux field (CSP only)*
Birds	**Passerines and insectivorous birds**	–	–	o	–	–
	Raptors	o	–	o	o	–
	Ravens	+	o	+	o	+
	Waterbirds	o	–	o	o	o
Mammals	**Bats**	o	+	o	–	o
	Bighorn sheep	–	o	–	o	o
	Coyotes	–	o	–	o	o
	Kit foxes	o	+	+/–	o	o
Reptiles	**Desert tortoises**	–	o	–	o	o
Insects	**Flying insects**	–	–	o	–	–
Plants	**Native annuals**	–	o	–	o	o
	Native perennials	–	–	–	o	o
	Invasive plants	o	o	+	o	o
Total type disturbance known effect	**Negative**	**7**	**5**	**5**	**3**	**3**
	Positive	**1**	**2**	**2**	**0**	**1**

Notes: Impacts are listed as positive (+), negative (–), or neutral (o) based on experience and judgment of the authors and citations. We used a rule of preponderance. Ratings were assigned based on the majority of evidence from the literature; expectations were based on knowledge of the ecology, behavior, and life-history traits of an organism or group. Each cell is a testable hypothesis and research opportunity; additional research will likely change some of our predictions. See WebPanel 1 for additional details and citations. *Fences that are designed to be permeable can benefit wildlife survival; fences that are impermeable to movement fragment habitat and have negative impacts.

fragmentation, dust, road mortality, electromagnetic field effects, changes to local and regional climates, pollution, water consumption, and light pollution (reviewed in Lovich and Ennen 2011). All of these can negatively affect wildlife, depending on species-specific sensitivities. Off-site impacts are caused by construction material acquisition and transport, disturbing wildlife far from the facility itself. However, it is important to evaluate these effects in comparison with various types of energy development, as well as with urban growth and other land uses. Research is needed both to determine the relative effects of USSE on wildlife and to increase their advantage over fossil fuels through improved management strategies.

Each species or species group has unique ecological, behavioral, and life-history attributes that collectively determine its demographic response to USSE activities (Table 1; WebPanel 1). For example, subsidized predators (those that benefit from resources associated with anthropogenic activities) like ravens and coyotes do well in human-altered landscapes due to their behavioral flexibility (Boarman 2003; Esque *et al.* 2010). Animals may benefit from disturbances that attract prey or provide carcasses, and small mammals and lizards may be protected within facility fences (eg Brooks 1999). Similarly, plants that specialize in seed production and that establish at disturbed sites may increase in semi-natural habitats around USSE landscapes, as they often do under power transmission lines (eg Lathrop and Archbold 1980). Other species with high site fidelity and small home ranges within energy installations will be more vulnerable, especially those that are sensitive to disturbance and do not prosper when the subject of translocation efforts (Sullivan *et al.* 2015, but see Brand *et al.* 2016).

Concept 3: cumulative and large-scale environmental impacts require careful consideration and planning

Debates regarding the siting of individual facilities or the translocation of species often make news headlines, but the aggregation of multiple USSE installations within a region compounds environmental impacts and is largely understudied. These regional and landscape-scale changes must be considered early in the land-use planning phase. Individual ground-mounted USSE facilities can occupy hundreds of hectares and are often clustered in areas with intense solar radiation. In the US Desert Southwest, 17 "Solar Energy Zones" are prioritized for fast-tracked development (BLM 2012). Similarly, in China, the Gobi Desert offers enormous potential for solar energy installations and is being rapidly developed (Liu *et al.* 2011). In comparisons of the land-use intensity of energy (LUIE) – that is, the land needed for new energy infrastructure – across common electricity sources, ground-mounted USSE power plants (PV and CSP) show higher LUIE than integrated PV (see definition below), nuclear, geothermal, and coal plants (McDonald *et al.* 2009; Lovering *et al.* in review). Lovering *et al.* (in review) found that large LUIE electricity sources could greatly increase the contribution of energy to industrial sprawl as compared to lower LUIE renewable energy portfolios.

Regional habitat fragmentation by USSE yields cumulative impacts including limitation of gene flow for plants and animals (eg Vandergast *et al.* 2013) and modification of landscape structure such as hydrological connectivity (Grippo *et al.* 2015). Serious impacts to aquatic ecosystems are projected, including drying of ephemeral water bodies and habitat reduction due to groundwater withdrawal (Grippo *et al.* 2015). Nichols and Bierman (2001) hypothesized that a graded 1000-ha desert solar facility would disrupt up to 1 million meters of drainage channels. While such an estimate requires empirical confirmation on a per site basis, ephemeral stream channels are a dominant geomorphic feature of arid lands and provide vital ecological functions (Hamdan and Stromberg 2016). Such channels accumulate and transport substantial amounts of nutrients and chemicals (including biological toxins) from uplands and influence landscape patterns in terms of soil texture and chemistry (Levick *et al.* 2008). Shrubs on the edges of ephemeral channels also provide cover for wildlife (Schwinning *et al.* 2011). Leveling and therefore severing the connectivity of drainages, rills, and microwashes can alter these functions and may also cause erosion problems within USSE facilities (Schlesinger *et al.* 1989; Schwinning *et al.* 2011; Grippo *et al.* 2015).

Concept 4: USSE ecological commonalities and idiosyncrasies

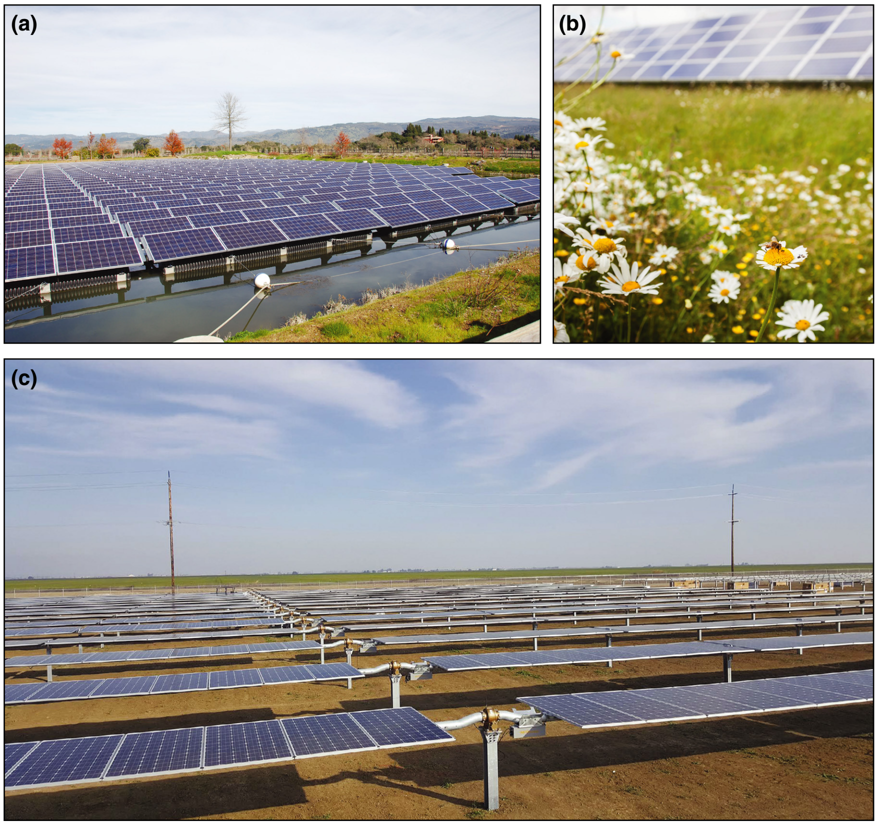
In natural or semi-natural environments, ground-mounted USSE facilities share a few common features, including clean energy benefits, land and infrastructure requirements, and certain ecological impacts. Most facilities will need to control invasive species, manage altered hydrology, and mitigate for the loss of ecological features that cannot be restored, such as desert pavements or old-growth woody plants. These commonalities provide the basis for management policies. However, each installation has site-specific impacts at local and landscape scales that require customized management prescriptions. These impacts represent the greatest challenge in mitigating the effects of USSE, and may require site-specific resource management plans that target each phase of the facility's life cycle.

Typical management actions at the species level include surveys, avoidance through site changes, translocations (for wildlife and rare plants) prior to project construction, control of wildlife movement through selective fencing during operation, mitigation programs, off-site mitigation banking, and restoration after decommissioning. These structural and functional similarities provide the basis for testing the effectiveness of management and restoration methods, and optimizing strategies using commonly occurring wildlife or plant species. The science of measuring neutral, negative, and positive consequences of USSE (eg avian and bat mortality) and evaluating management and mitigation strategies is evolving rapidly.

Because USSE facilities affect entire trophic systems, effective conservation necessitates comprehensive, ecosystem-based (rather than single-species-based) management approaches. For instance, infrastructure may alter fitness or movement of pollinators, reduce predation by birds on insect herbivores, or modify plant nutritional composition as a result of shading by panels. In California, the Ivanpah Solar Electric Generating System (ISEGS) implemented a lower-impact design featuring a retained plant understory throughout most of the 1400-ha facility. Specific habitat remnants within the solar field were also preserved without heliostats (mirrors) to maintain the presence of four rare plant species. This approach has been successful at retaining the focal rare plants and provides benefits to wildlife. However, reduction or exclusion at higher trophic levels, such as mammalian predators or herbivores, may exert cascading influences on organisms beyond anticipated effects of shade and precipitation blocking (Figure 3). For example, herbivory rates on a rare perennial that is a target of mitigation – Mojave milkweed (*Asclepias nyctaginifolia*, Figure 3k) – by black-tailed jackrabbits (*Lepus californicus*, Figure 3g) and monarch butterfly larvae (*Danaus plexippus*, Figure 3k) are frequently elevated within the solar field, reducing the plant's long-term outlook for persistence (Moore and Pavlik 2016; Figure 3).

At ISEGS, disturbance within the solar field reduces the activity of and is a mortality source for many avian species, including the verdin (*Auriparus flaviceps*, Figure 3f; HT Harvey and Associates 2015), which is known to predate on the monarch. Effects of microhabitat variation on invertebrates and microbiota, including monarch parasites (eg tachinid flies, Figure 3j) and parasitoids (eg *Ophryocystis elektroscirrha*), are unknown but could have further cascading effects on the milkweed trophic system. Dragonflies (eg Odonata spp, Figure 3i) and other predatory insects are abundant within the facility, and attract insectivorous birds, possibly exacerbating bird mortality (Walston *et al.* 2016) and influencing monarch population dynamics through predation. Traditional single-species management and policies are inadequate to characterize the complex interplay of site and species interactions in such systems. Management of natural areas both within and adjacent to facilities will increase in effectiveness where networks of interacting species and environmental factors are considered.

Methods of USSE implementation that avoid or reduce impacts and make use of techno-ecological synergies (ie win–win scenarios where solar energy infrastructure confers environmental co-benefits) in the land-energy-ecology nexus are needed to preserve biodiversity and open space. Integrated PV – that is, PV within the built environment on buildings and parking structures, for instance – is by definition unique among energy systems as it does not require additional land use beyond that needed to extract and transport materials for infrastructure (ie its land-use intensity is 0 hectares per terawatt-hour per year; Lovering *et al.* in review). In addition to reducing the footprint of energy sprawl, innovations in technology and deployment (Figure 4) may confer environmental co-benefits beyond their immediate utility as a low carbon energy source. Techno-ecological synergies of PV USSE facilities include the use of the built environment, degraded or contaminated land, the restoration of ecosystem services under panels (eg for pollination services or other beneficial habitat attributes), "agrivoltaic" systems, solar greenhouses, solar-powered drip irrigation, hybrid energy systems, rooftop solar, heat harvesting, "floatovoltaics," and solar rainwater harvesting.



Far Niente Winery

D Butler

Westlands Solar Park LLC

Figure 4. *Examples of environmental co-benefit opportunities of photovoltaic utility-scale solar energy facilities. (a) A floatovoltaic at Far Niente Winery (Oakville, CA) reduces evapotranspiration from the winery's onsite reservoir, sparing land for agricultural production. (b) Westmill Solar (Wiltshire, UK), the UK's first cooperative and community-owned solar farm, planted native annuals and grasses to provide foraging habitat for pollinators. (c) More than 9700 hectares of disturbed land was repurposed for Westlands Solar Park in western Fresno and Kings counties (California).*

Opportunities for synergy also exist through effective management of habitat on and adjacent to USSE sites. While the California Valley Solar Ranch and Topaz Solar Farm sites have been ranked as "incompatible" and "potentially compatible", respectively (Figure 2), habitat management at these projects has provided benefits to two federally endangered species – the San Joaquin kit fox (*Vulpes macrotis mutica*) and giant kangaroo rat (*Dipodomys ingens*) – in an otherwise largely degraded landscape (Phillips and Cypher 2015). However, actions that benefit some species may not translate to others, or to other sites. As the effects of anthropogenic climate change become more severe, creative and prudent use of techno-ecological synergies for all renewables across land, food, energy, and water systems becomes increasingly important.

Concept 5: the long-term ecological consequences of USSE sites are unknown

There is considerable uncertainty in forecasting the operational lifespan of solar development facilities. This stems from differences among solar energy technologies, shifting energy demands, economics, and changing land uses. Solar energy systems have a functional life span constrained by the efficiency of the technology and endurance of their infrastructure relative to the benefits of building new systems. Renewable energy facilities have been decommissioned, dismantled, recycled, or repurposed, and more rarely, restored; however, we are unaware of any peer-reviewed publications investigating the ecological aspects of decommissioned facilities. In the US, renewable energy facilities are often located on leased public land for a time, after which "reclamation" of the land is required to bring it back to a condition deemed similar to its predevelopment state (US GAO 2015). Yet project funders and managers are frequently underprepared for the reclamation phase, which can cost millions of dollars and take years, or decades, to complete (US GAO 2015).

Environmentally sound development plans for USSE must include long-term goals either for retrofitting solar infrastructure as it ages or for deconstruction, recycling, and site repurposing or restoration. Some regions, such as California, provide important mandates for such planning, but many others do not. Restoration potential also varies among sites. Restoration of forests and grasslands is largely feasible and is based on well-tested methodologies. In contrast, restoration in arid regions is challenging due to extreme and variable climates, slow soil formation, and herbivory and granivory (Lovich and Bainbridge 1999;

Abella and Newton 2009). USSE projects that do not include extensive grading or leveling are expected to be far easier to restore than those where topsoil was removed to accommodate infrastructure. Thus far, most arid land restoration and related research has occurred at scales smaller than that of a typical USSE facility. Key uncertainties include whether adjacent natural ecosystems will still exist in the future, providing sources of native propagules, or whether new local land uses could undermine restoration efforts on decommissioned facilities. Furthermore, rising concentrations of atmospheric CO_2 and changing climatic conditions could favor non-native plants over native plants (Knapp *et al.* 2015).

Solar energy sustainability in the land-energy-ecology nexus

Advancing solar energy while maintaining ecological diversity will require coordinated action by industry, researchers, resource managers, and policy makers to identify and take advantage of opportunities for synergetic applications that have low land-use footprints and that prevent land-type conversions of natural areas to industrial complexes. To perform impact-related studies and maintain sites for demonstration purposes, scientists will require unrestricted access to USSE facilities for data collection and should develop standardized experimental designs, all of which will necessitate increased funding through public and private investment. At present, access to USSE facilities for scientific research is limited, even though the majority of facilities are situated on publicly owned lands. Renewable energy research would be greatly advanced by improved access not only to USSE sites but also to the resource management data collected by land and environmental managers contracted by energy companies.

Experiments, modeling exercises, and observational studies are needed to inform effective management of ecosystems within, adjacent to, and regionally affected by USSE projects. Currently, information on USSE effects is available for only a few species, locations, and ecosystem types. Studies on efficacy of management actions within or adjacent to renewable energy facilities, comparison of ecological responses to different types of infrastructure, evaluation of potential synergies, and monitoring of cumulative and large-scale impacts will be pivotal in guiding more-sustainable USSE development.

The development of environmentally conscious USSE is also hindered by lack of information exchange. A standardized repository of information on solar energy installations – including locations, managed species, technology and materials used, project terms, ecological management practices, and reclamation programs – would be beneficial to a wide range of stakeholders for evaluating land-use trade-offs, comparing research designs, and cataloguing management successes and failures. Standardizing ecological data collected for environmental compliance and making it publicly available (barring legitimate proprietary limitations) would facilitate data exchange and collaboration among consultants, agencies, academia, and industry.

By working together, policy makers and resource managers have the opportunity to mitigate the impacts of energy development through strategic planning. At local scales, immediate impacts versus economic gains are weighed in careful siting and impact mitigation planning. At the landscape scale, decision-support tools that evaluate land-use intensity and fragmentation, carbon balance, and GHG emissions need to be developed. Both policy makers and site managers can clarify the role that individual facilities play in reducing environmental impacts or providing co-benefits. For example, a recent US state law established a standard under which solar companies can state whether their facilities provide benefits to birds and pollinators (Minnesota bill HF 3353).

Renewable energy production exists within the land-energy-ecology nexus in an intricate interplay with biodiversity and natural landscapes. Policy makers have the opportunity to integrate multiple factors into the land-energy-ecology nexus (Figure 1) as they oversee regional patterns of land use and act on behalf of diverse stakeholders to optimize the balance between conservation and energy generation. Ecologists, resource managers, policy makers, and concerned citizens can engage in one of the most important environmental challenges of the 21st century: a sustainable transition to renewable energy to meet human demand and the mitigation of global environmental change.

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