Solar energy development impacts on land cover change and protected areas

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Decisions determining the use of land for energy are of exigent concern as land scarcity, the need for ecosystem services, and demands for energy generation have concomitantly increased globally. Utility-scale solar energy (USSE) [i.e., ≥1 megawatt (MW)] development requires large quantities of space and land; however, studies quantifying the effect of USSE on land cover change and protected areas are limited. We assessed siting impacts of >160 USSE installations by technology type [photovoltaic (PV) vs. concentrating solar power (CSP)], area (in square kilometers), and capacity (in MW) within the global solar hot spot of the state of California (United States). Additionally, we used the Carnegie Energy and Environmental Compatibility model, a multiple criteria model, to quantify each installation according to environmental and technical compatibility. Last, we evaluated installations according to their proximity to protected areas, including inventoried roadless areas, endangered and threatened species habitat, and federally protected areas. We found the plurality of USSE (6,995 MW) in California is sited in shrublands and scrublands, comprising 375 km^2 of land cover change. Twenty-eight percent of USSE installations are located in croplands and pastures, comprising 155 km^2 of change. Less than 15% of USSE installations are sited in "Compatible" areas. The majority of "Incompatible" USSE power plants are sited far from existing transmission infrastructure, and all USSE installations average at most 7 and 5 km from protected areas, for PV and CSP, respectively. Where energy, food, and conservation goals intersect, environmental compatibility can be achieved when resource opportunities, constraints, and trade-offs are integrated into siting decisions.

concentrating solar power | conservation | greenhouse gas emissions | land use | photovoltaics

The need to mitigate climate change, safeguard energy security, and increase the sustainability of human activities is prompting the need for a rapid transition from carbon-intensive fuels to renewable energy (1). Among renewable energy systems, solar energy has one of the greatest climate change mitigation potentials with life cycle emissions as low as 14 g CO_2-eq·kW·h^{-1} [compare this to 608 g CO_2-eq·kW·h^{-1} for natural gas (2)]. Solar energy embodies diverse technologies able to capture the sun's thermal energy, such as concentrating solar power (CSP) systems, and photons using photovoltaics (PV). In general, CSP is economically optimal where direct normal irradiance (DNI) is 6 kW·h·m^{-2}·d^{-1} or greater, whereas PV, able to use both diffuse and DNI, is economically optimal where such solar resources are 4 kW·h·m^{-2}·d^{-1} or greater. Solar energy systems are highly modular ranging from small-scale deployments (≤1 MW; e.g., residential rooftop modules, portable battlefield systems, solar water heaters) to centralized, utility-scale solar energy (USSE) installations (≥1 MW) where a large economy of scale can meet greater energy demands. Nonetheless, the diffuse nature of solar energy necessitates that large swaths of space or land be used to collect and concentrate solar energy into forms usable for human consumption, increasing concern over potential adverse impacts on natural ecosystems, their services, and biodiversity therein (2–5).

Given the wide range of siting options for USSE projects, maximizing land use efficiency and minimizing land cover change is a growing environmental challenge (6–8). Land use efficiency describes how much power or energy a system generates by area (e.g., watts per square meter, watt-hours per square meter, respectively). For example, USSE installations have an average land use efficiency of 35 W·m^{-2} based on nameplate capacity under ideal conditions (9). The ratio of the realized generation of an installation to maximum generation under ideal conditions over a period is the capacity factor. Using these two terms, we can quantify land requirements for USSE at larger spatial scales. If up to 500 GW of USSE may be required to meet United States-wide reduction of 80% of 1990 greenhouse gas emissions by 2050, 71,428 km^2 of land may be required (roughly the land area of the state of South Carolina) assuming a capacity factor of 0.20 (an average capacity factor for PV; Table S1). This underscores the possible vast area requirements for meeting energy needs in the United States and elsewhere. Increasing the land use efficiency of each installation—e.g., decreasing space between rows of PV modules or CSP mirrors—and prudent siting decisions that incorporate the weighting of environmental trade-offs and synergies can reduce land cover change impacts broadly (10).

Land cover change owing to solar energy has received increasing attention over concerns related to conflicts with biodiversity goals (2–4) and greenhouse gas emissions, which are released when

Significance

Decisions humans make about how much land to use, where, and for what end use, can inform innovation and policies directing sustainable pathways of land use for energy. Using the state of California (United States) as a model system, our study shows that the majority of utility-scale solar energy (USSE) installations are sited in natural environments, namely shrublands and scrublands, and agricultural land cover types, and near (<10 km) protected areas. "Compatible" (≤15%) USSE installations are sited in developed areas, whereas "Incompatible" installations (19%) are classified as such owing to, predominantly, lengthier distances to existing transmission. Our results suggest a dynamic landscape where land for energy, food, and conservation goals overlap and where environmental cobenefit opportunities should be explored.

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biomass, including soil, is disturbed or removed during the lifetime of a power plant (11, 12). Siting USSE installations in places already impacted by humans (e.g., parking lots, rooftops) reduces the likelihood that adverse environmental impacts will occur and can exceed generation demands for renewable energy goals in places with moderate- to high-quality solar resources (8, 10, 13), including California. When sites within the built environment are inaccessible, siting that minimizes land use and land cover change within areas acting as carbon sinks, avoids extirpation of biodiversity, and does not obstruct the flow of ecosystem services to residents, firms, and communities, can serve to mitigate adverse environmental impacts (2, 3, 9, 10, 14, 15). Siting within the built environment also reduces the need for complex decision making dictating the use of land for food or energy (16).

Recent studies have underscored the role that proximity of threats to protected areas plays in meeting conservation goals (16–20). Protected areas may preclude habitat loss within boundaries; however, a prevailing cause of degradation within protected areas is land use and land cover change in surrounding areas. Specifically, protected areas are effective when land use nearby does not obstruct corridor use, dispersion capabilities, nor facilitate invasions of nonnative species through habitat loss, fragmentation, and isolation—including those caused by renewable energy development. Quantifying both internal and external threats is necessary for assessing vulnerability of individual protected areas to conversion and landscape sustainability overall. Siting decisions can be optimized with decision support tools (10, 14) that differentiate areas where direct (e.g., land cover change) and proximate effects (e.g., habitat fragmentation) are lowest on the landscape.

Several studies have made predictions regarding which specific land cover types may be impacted by solar energy development (7, 21); however, few studies have evaluated actual siting decisions and their potential or realized impact on land cover change (9, 11). In this study, our objectives were to (*i*) evaluate potential land cover change owing to development of utility-scale PV and CSP within the state of California (United States) and describe relationships among land cover type and the number of installations, capacity, and technology type of USSE; (*ii*) use the decision support tool, the Carnegie Energy and Environmental Compatibility (CEEC) model (10), to develop a three-tiered spatial environmental and technical compatibility index (hereafter called Compatibility Index; "Compatible," "Potentially Compatible," and "Incompatible") for California that identifies environmentally low-conflict areas using resource constraints and opportunities; and (*iii*) compare utility-scale PV and CSP installation locations with the Compatibility Index and their proximity to protected areas to quantify solar energy development decisions and their impact on land cover change (see *Supporting Information* for details).

We selected the state of California as a model system owing to its relatively early, rapid, and ambitious deployment of solar energy systems, 400,000 km^2 of land area (greater than Germany and 188 other countries), large human population and energy demands, diverse ecosystems comprising 90% of the California Floristic Province biodiversity hot spot, and its long-standing use in elucidating the interrelationship between land and energy (9, 10, 22, 23).

Results

We identified 161 planned, under construction, and operating USSE installations throughout 10 land cover types (Figs. 1 and 2) among 16 total in the state of California (Table S2). Broadly, PV installations are concentrated particularly in the Central Valley and the interior of southern California, whereas CSP power plants are sited exclusively in inland southern California (Figs. 1 and 2). For all technology types, the plurality of capacity (6,995 MW) is found in shrubland and scrubland land cover type, necessitating 375 km^2 of land (Table 1). This area is approximately two times greater than USSE development occurring within cultivated croplands, representing 4,103 MW of capacity within 118 km^2. Over 2,000 MW of existing or proposed USSE capacity is sited within the built environment, particularly within relatively lower density areas.

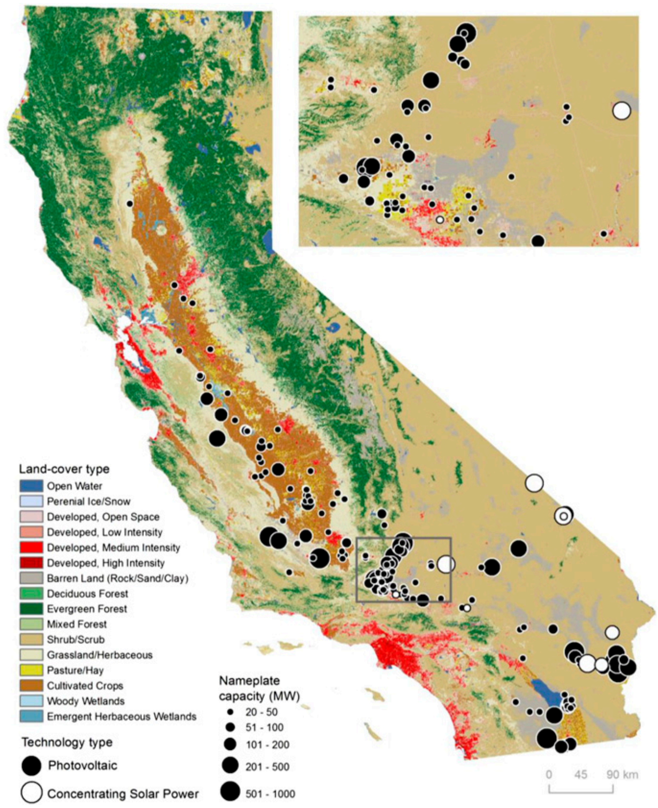

Fig. 1. Map showing land cover types across California and the size and location of USSE installations.

PV power plants are found in 10 land cover types; the plurality of capacity is sited within shrubland/scrublands (6,251 MW; Table 1), representing 26.0% of all PV installations (Fig. 2). Capacity for utility-scale PV installations is also represented within cultivated croplands (3,823 MW), barren land (2,102 MW), developed (2,039 MW), and grassland/herbaceous (1,483 MW) land cover types. Within the developed land cover types, open space is most used (1,205 MW) for utility-scale PV capacity. For CSP, 1,000 MW are located within 34 km^2 of barren land land cover types, and conjointly within shrubland/scrublands (744 MW, 32 km^2).

Using the decision support tool, CEEC (Fig. 3), we identified 22,028 and 77,761 km^2 of Compatible and Potentially Compatible area, respectively, in California for developing PV (Fig. S1). Generation-based potential within Compatible areas—comprising 5.4% of California's area—is 8,565 TW·h·y^{-1} for fixed-tilt modules and up to 11,744 TW·h·y^{-1} for dual-axis modules. For CSP technologies, we found 6,274 and 33,489 km^2 of Compatible and Potentially Compatible area. Generation-based potential for CSP within Compatible areas—comprising 1.5% of California's area—is 5,947 TW·h·y^{-1}.

USSE installations vary in the environmental compatibility of their actual or proposed site (Fig. 4 *A* and *B*). The majority (71.7%) of PV USSE installations are in Potentially Compatible areas, whereas 11.2% are located in Compatible areas. PV installations classified as Incompatible are due to distances from existing transmission infrastructure exceeding 10 km (45.9%), slope exceeding the recommended threshold (41.9%), and to a

Table 1. USSE installations and land cover type

Land cover type	Nameplate capacity, MWdc PV	%	CSP	%	Area, km^2 PV	%	CSP	%
Barren land (rock/sand/clay)	2,102	12	**1,000**	**48**	77	11	**34**	**45**
Cultivated crops	3,823	22	280	14	110	15	8	11
Developed (all)	2,039	12	50	2	70	10	1	1
Developed, high intensity	50	0	0	0	1	0	0	0
Developed, medium intensity	624	4	0	0	17	2	0	0
Developed, low intensity	160	1	0	0	9	1	0	0
Developed, open space	1,205	7	50	2	43	6	1	1
Emergent herbaceous wetlands	60	0	0	0	1	0	0	0
Grass/herbaceous	1,483	9	0	0	72	10	0	0
Pasture/hay	1,397	8	0	0	37	5	0	0
Shrubland/scrubland	**6,251**	**36**	744	36	**343**	**48**	32	43

The nameplate capacity [in megawatts (MWdc)], footprint (in square kilometers), and number of photovoltaic (PV) and concentrating solar power (CSP) USSE installations (>20 MW) in California (in planning, under construction, operating) by land cover type. Bold data represent the greatest value among all land cover types.

lesser degree, owing to development on endangered and threatened species habitat (9.7%) and federally preserved land (3.2%; Fig. 4 *A* and *B*). For CSP installations, 55.5% are located in either Compatible or Potentially Compatible areas. Siting incompatibilities for CSP were either due to slope (25.0%) or distance from transmission lines (75.0%). PV and CSP installations on Compatible areas range in capacity between 20 and 200 MW, and are located within the Central Valley and inland southern California regions, excepting one PV facility in Yolo County (Fig. 4*A*). PV facilities on Incompatible land are found throughout all of California and, excepting one facility (250 MW; San Luis Obispo County), are 200 MW in capacity or less.

PV and CSP USSE installations average 7.2 ± 0.9 and 5.3 ± 2.3 km, respectively, from the closest protected area (Fig. 5). Federally protected areas are the nearest protected area type (7.8 ± 1.0) to land use and land cover change for PV development, whereas both endangered and threatened species habitat (5.7 ± 2.4) and federally protected areas (5.3 ± 2.3) are nearest for CSP development. Of PV installations, 73.7% were less than 10 km and 47.4% were less than 5 km away from the nearest protected area. Of CSP installations, 90.0% were less than 10 km away and 60.0% were less than 5 km away from the nearest protected area.

Discussion

Evaluation of siting decisions for USSE is increasingly relevant in a world of mounting land scarcity and in which siting decisions are as diverse as their deployment worldwide. For example, China has emphasized utility-scale, ground-mounted PV and residential, small-scale solar water heating installations (24), whereas Germany is notable for achieving up to 90% development within the built environment (25). In California, a large portion of USSE installations is sited far from existing transmission infrastructure. New transmission extensions are expensive, difficult to site due to social and environmental concerns, and require many years of planning and construction. Such transmission-related siting incompatibilities not only necessitate additional land cover change but also stand in the way of cost-efficient and rapid renewable energy deployment.

Environmental regulations and laws, which vary drastically from one administrative area to the next, may also cause incongruities in siting decisions. Inherent ambiguities of such policies allows for further inconsistencies. A study in southern Italy (11) found that two-thirds of authorizations for USSE were within environmentally "unsuitable" areas as defined by municipal and international criteria (e.g., United Nations Educational, Scientific and Cultural Organization sites), with adverse implications for land cover change-related CO_2 emissions. Studies (7, 21) including our own reveal that regulations and policies to date have deemphasized USSE development in California, the United States, and North America, respectively, within the built environment and near population centers in favor of development within shrublands and scrublands. California's shrublands and scrublands comprise, in part, the California Floristic Province, a biodiversity hot spot known for high levels of species richness and endemism and where 70% or more of the original extent of vegetation has been lost due to global environmental change-type threats, including land cover change (26, 27). In biologically rich areas like this, land cover change has the potential to greatly impact ecological value and function. Globally, the extent of shrubland and scrubland is vast; therefore, in areas where biodiversity is low, goods and services of shrublands may include diverse recreational opportunities, culturally and historically significant landscapes, movement corridors for wildlife, groundwater as a drinking source, and carbon (sequestration), which may also be adversely impacted by land cover conversion (28).

Proximity impacts result from the fragmentation and degradation of land near and between protected areas, reducing ecological flows of energy, organisms, and goods (16–20). In a study of 57

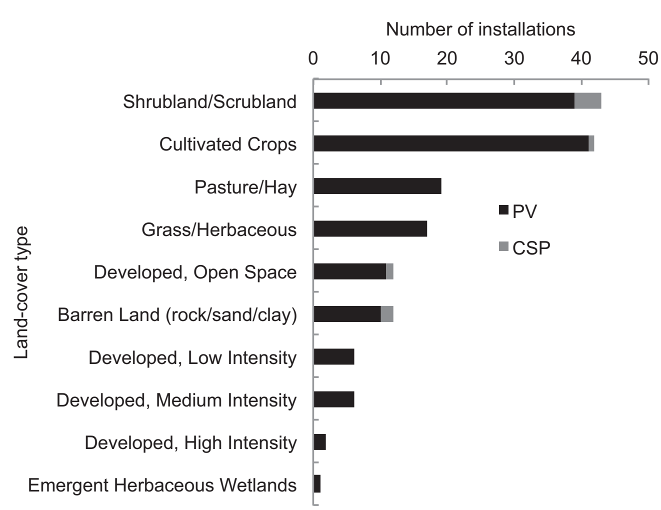

Fig. 2. Number of photovoltaic (PV) and concentrating solar power (CSP) installations (planned, under construction, operating) by land cover type in California; represented in order of most installations to least for both technologies.

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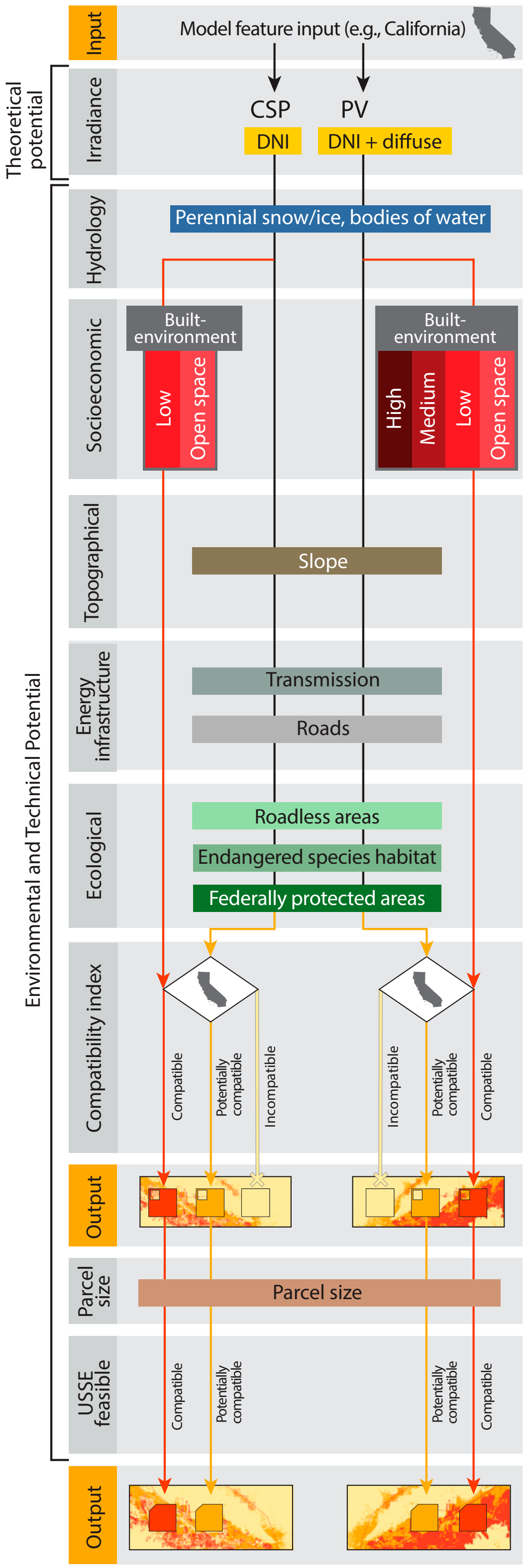

Fig. 3. Workflow of the Carnegie Energy and Environmental Compatibility (CEEC) model, a decision support tool, showing model inputs (resource opportunities and constraints), Environmental and Technical Compatibility Index, and model outputs.

US protected areas, Hansen et al. (16) found such zones extended an average of 18 times (in area) beyond the park area (e.g., Mojave National Preserve, three times protected area, i.e., ~30 km radially beyond preserve boundary). Additionally, Hamilton et al. (17) used distances of 5, 25, and 75 km from all US protected area boundaries to represent three spatial scales (i.e., buffers) of proximity impacts owing to US land cover and land use change. Last, the US Fish and Wildlife Service's Partners for Fish and Wildlife Program, seeks to reduce adverse proximity impacts by augmenting protected areas with private land restoration, targeting land within a maximum distance of 75 km from existing protected areas. Thus, our results confirm USSE development in California engenders important proximity impacts, for example, encompassing all three spatial scales from Hamilton et al. (17) and decreasing land available for US Fish and Wildlife Service partner restoration programs.

Industrial sectors—including energy and agriculture—are increasingly responsible for decisions affecting biodiversity. Concomitantly, target-driven conservation planning metrics (e.g., percentage of remaining extant habitat does not fall below 40%), geospatial products (e.g., decision support tools), and the monetization of carbon and ecosystem services are increasing and may be effective in compensating for the lack of target-driven regulation observed in policy (29).

Last, development decisions may overlook environmental resources unprotected by policies but valued by interest groups [e.g., important bird areas, essential connectivity areas, vulnerability of caliche (i.e., mineralized carbon) in desert soils, biodiversity hot spots, percent habitat loss]. Several elements of the environment providing ecosystem services that humans depend upon remain widely unprotected by laws and regulations and vastly understudied. By integrating land conservation value earlier in the electricity procurement and planning process, preemptive transmission upgrades or expansions to low-impact regions could improve the incentive to develop in designated zones, avoiding future incompatible development. However, zones themselves must also be carefully designated. The landscape-scale Desert Renewable Energy Conservation Plan initially provided a siting framework—including incidental take authorizations of endangered and threatened species—for streamlining solar energy development within the 91,000 km^2 of mostly desert habitat in public and private lands and designated as the Development Focus Area (DFA). After accounting for unprotected environmental attributes like biodiversity, Cameron et al. (14) identified ~7,400 km^2 of relatively low-value conservation land within the Mojave Desert Ecoregion (United States) that can meet California's 33% renewable portfolio standard for electricity sales seven times over. Since this publication, the Desert Renewable Energy Conservation Plan's DFA has now been restricted to only public lands, which some argue to be more intact, and to the ire of certain local interest groups and government agencies. Hernandez et al. (10) developed a satellite-based decision support tool, the CEEC model, that showed that generation-based technical potential of PV and CSP within the built environment could meet California's total energy demand 4.8 and 2.7 times over, respectively. Development decisions may also overlook synergistic environmental cobenefit opportunities. Environmental cobenefit opportunities include the utilization of degraded or contaminated lands, colocation of solar and agriculture, hybrid power systems, and building-integrated PV (2).

This study found that nearly 30% of all USSE installations are sited in croplands and pastures; signifying perhaps an increasing affinity for using agricultural lands for renewable energy, specifically within the Central Valley of California, renowned for agricultural productivity globally. The growing demand for food, affordable housing, water, and electricity puts considerable pressure on available land resources, making recent land use decisions in this region a noteworthy case study for understanding the food–energy–water nexus that should be explored. Opportunities to minimize land use change include colocating renewable energy systems with food production and converting degraded and salt-contaminated lands, unsuitable for agriculture, to sites for

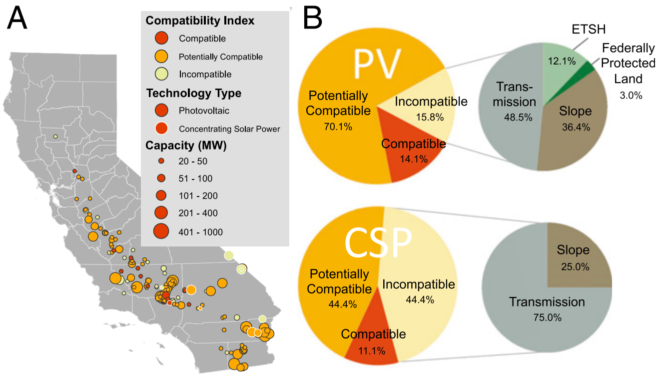

Fig. 4. (*A*) Map of California showing utility-scale solar energy (USSE) (planned, under construction, operating) installations' compatibility by technology [i.e., photovoltaic (PV), concentrating solar power (CSP)], site, and capacity (in megawatts). (*B*) Percentage of USSE installations sited in Compatible, Potentially Compatible, and Incompatible areas. For USSE installations in incompatible sites, we provide the percentage of each incompatibility type.

renewable energy production. Using unoccupied spaces such as adjacent to and on top of barns, parking lots, and distribution centers in agricultural areas is another win–win scenario. In sub-Saharan Africa, integrating solar energy into a drip irrigation system has enhanced food security by conserving water, enhancing reliability of power, and conserving land and space (30). As the development of renewable energy and the production of food are expected to grow, so will the need to understand and evaluate their interactions with the land supporting this expansion in other landscapes.

Conclusion

A growing body of studies underscores the vast potential of solar energy development in places that minimize adverse environmental impacts and confer environmental cobenefits (2, 10, 14, 15, 21). Our study of California reveals that USSE development is a source of land cover change and, based on its proximity to protected areas, may exacerbate habitat fragmentation resulting in direct and indirect ecological consequences. These impacts may include increased isolation and nonnative species invasions, and compromised movement potential of species tracking habitat shifts in response to environmental disturbances, such as climate change. Furthermore, we have shown that USSE development within California comprises siting decisions that lead to the alteration of natural ecosystems within and close to protected areas in lieu of land already impacted by humans (7, 21). Land use policies and electricity planning that emphasizes the use of human-impacted places, complies with existing environmental regulations at the federal, state, and municipal level, and considers environmental concerns over local resource constraints and opportunities, including those of communities, firms, and residents, may prove an effective approach for avoiding deleterious land cover change. Empirical analyses using decision support tools, like CEEC, can help guide development practices toward greater environmental compatibility through improved understanding of the impacts of policy and regulatory processes to date.

Methods

To achieve our objectives, we (*i*) created a multiinstitution dataset of 161 USSE installations in the state of California and compared these data to land cover data; (*ii*) developed a spatial Compatibility Index (i.e., Compatible, Potentially Compatible, and Incompatible) for California using the CEEC model that identifies environmentally low-conflict areas for development, integrating environmental and technical resource constraints and opportunities; (*iii*) compared USSE installation locations with the Compatibility Index to enumerate the number of installations sited within each area type; and (*iv*) compared USSE installation locations with their proximity to protected areas, including Inventoried Roadless Areas, Endangered and Threatened Species Habitat, and Federally Protected Areas (*Supporting Information*). All analyses were conducted using ArcGIS (10.x) and R (R: A Language and Environment for Statistical Computing).

To evaluate land cover change owing to USSE development, we collected data on PV and CSP USSE installations in California that vary in development stage (i.e., planned, under construction, operating) and range in nameplate capacity, selecting a subset of all USSE that range from 20 to 873 MW, 20 MW being a legislative capacity threshold for transmission connection affecting development action. Data for each installation included nameplate capacity under standard test conditions (in megawatts), land footprint (in square kilometers), technology type, and point location (latitude, longitude). Data were collected exclusively from official government documents and records (see *Supporting Information* for details). We define the land footprint as the area directly affected during the construction, operation, and decommissioning phases of the entire power plant facility, excluding existing transmission corridors, land needed for raw material acquisition, and land for generation of energy required for manufacturing. Installations that did not meet data quality criteria (e.g., lacking exact location) were excluded, resulting in a total of 161 USSE installations (see *Supporting Information* for details). Data were collected beginning in 2010 and updated until May 2014. Installations in our dataset vary in their development stage and therefore include installations that may change in attribute or may never reach full operation. Given that we are interested in decisions regarding siting, we included siting data for planned installations, despite their potential uncertainty, as these reflect the most current siting practices that may not be fully represented in decisions for installations that are already under construction or operating.

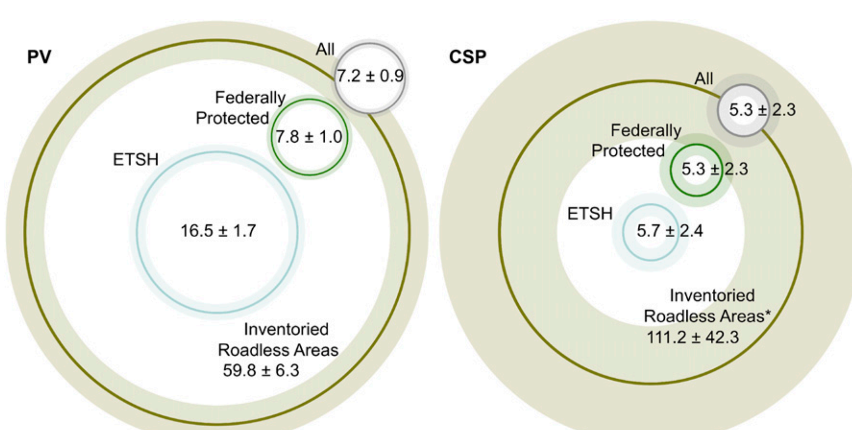

Fig. 5. Proximity of PV and CSP USSE installations to Endangered and Threatened Species Habitat, Federally Protected Areas, Inventoried Roadless Areas, and the closest for all protected area types. Circles are to scale, relatively (with the exception of Inventoried Roadless Areas for CSP), showing 95% confidence intervals (shaded area).

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To evaluate land cover change by USSE development, we compared the point location of each USSE power plant from our dataset (by their latitude and longitude) to the land cover type according to the National Land Cover Dataset (NLCD) (30-m resolution) and allocated the reported total footprint of the installation as land cover change within this land cover type. All 16 land cover types, as described by the NLCD, are represented in California, including developed areas within the built environment (Table S3). Developed areas are further classified according to imperviousness of surfaces: open-space developed (<20% disturbed surface cover; e.g., large-lot single-family housing units, golf courses, parks), low-intensity developed (20–49% disturbed cover), medium-intensity developed (50–79% disturbed cover), and high-intensity developed (80–100% disturbed cover; e.g., apartment complexes, row houses, commercial and industrial facilities).

The CEEC model (10) is a decision support tool used to calculate the technical potential of solar electricity generation and characterize site suitability by incorporating user-specified resource opportunities and constraints (Fig. 3 and Tables S2–S5). The CEEC model uses the National Renewable Energy Laboratory's satellite-based diffuse/direct normal radiation and direct normal radiation models, which estimate average daily insolation (in kilowatt-hours per square meter per day) over 0.1° surface cells (~10 km in size), to identify areas with annual average solar resources adequate for PV ($\geq$4 $kW \cdot h \cdot m^{-2} \cdot d^{-1}$) and CSP ($\geq$6 $kW \cdot h \cdot m^{-2} \cdot d^{-1}$) technologies, respectively (Table S1).

Among these areas, bodies of open water and perennial ice and snow were excluded as potential sites. We indexed the resulting area for solar energy infrastructure—independently for PV and CSP—as follows: Compatible, Potentially Compatible, and Incompatible (*Supporting Information*). Because solar energy potential within California's developed areas can meet the state's current energy consumptive demand 2.7 times over, decrease or eliminate land cover change, and reduce environmental impacts (10), we defined all four developed land cover classes as Compatible, excepting CSP in high and medium intensity as, to date, CSP technologies have not been deployed there owing to the relatively lower modularity of CSP.

Potentially Compatible areas augment site selections beyond Compatible areas. As slopes of 3% and 5% or less are most suitable for CSP and PV installations, respectively—owing to reduced costs and impact associated with surface grading—we used the National Elevation Dataset (varies from 3- to 30-m resolution; US Geological Survey) to exclude areas without these criteria. To minimize costs and impacts linked to new construction activities and materials, Potentially Compatible areas were also restricted to areas within 10 and 5 km of transmission lines (California Energy Commission) and roads (TIGER), respectively (*Supporting Information*, Fig. 3, and Table S4). We excluded areas where road construction is prohibited ("Federal Roadless Areas"; US Department of Forest and Agriculture), critical habitat of threatened and endangered species (US Fish and Wildlife Service), and federally protected areas (i.e., GAP Statuses 1 and 2, Protected Areas Database of the United States, US Geological Survey; Table S1). We reported generation-based potential for PV and CSP at the utility-scale, i.e., within areas identified as Compatible and Potentially Compatible and within areas meeting a minimum parcel size as needed for a 1-MW installation. Incompatible areas are not classified as Compatible and Potentially Compatible areas. To quantify impacts of solar energy development decisions, we spatially characterized the number, capacity, technology type, and footprint of USSE power plants dataset within the Compatibility Index and analyzed the reasons for incompatibility.

To quantify impact of proximity to protected areas from USSE development, we calculated the distance between each USSE facility data point (by technology type) to the nearest protected area by type (i.e., inventoried roadless areas, critical habitat of threatened and endangered species, and federally protected areas) using the "Near (Analysis)" in ArcGIS, and subsequently calculated the average of all distances (by protected area type) and 95% confidence intervals. For "all" protected area types, we used the shortest distance between each USSE facility data point and the three protected area types, and subsequently calculated the average of these shortest distances and 95% confidence intervals.

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