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Solar Energy Development and Endangered Species in the San Joaquin Valley, California: Identification of Conflict Zones

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***Abstract*.—A number of animal and plant species in the San Joaquin Valley (SJV) of California are rare due to profound habitat loss and degradation. A significant portion of the remaining habitat for these species also has high potential for solar energy generation. We conducted a spatially explicit GIS analysis of lands in the SJV to identify areas of potential conflict between rare species and solar energy development and also to identify areas where such conflict would be minimized. We modeled solar energy generation potential and also modeled habitat suitability for five federally listed animal species whose ranges encompass those of additional rare species. We then layered the model results to identify areas of greater or lesser conflict. Approximately 4,145 km^2 have moderate to high potential for solar energy development and also have moderate to high quality habitat for listed species. The potential for environmental conflicts is high on these lands. Approximately 8,436 km^2 have moderate to high potential for solar energy development but no or low-quality habitat for rare species. These lands are the optimal sites for solar energy generation projects. Furthermore, siting projects on lands with no or marginal habitat value could enhance the value of these lands for rare species and create linkages between occupied areas. Our approach can be applied in other locations to identify general areas and even specific locations where siting solar facilities would result in minimal or no impacts to sensitive resources and possibly even enhance regional conservation efforts.**

Key Words.—Ammospermophilus nelsoni; forbs; grasses; San Joaquin Desert; shrubs

Introduction

Solar power is a rapidly growing renewable energy source world-wide, and concomitant with this has been an accelerated rate of construction of utility-scale solar energy generation facilities. The marked increase in such facilities has been particularly acute in California (Solar Energy Industries Association 2016) where optimal conditions (e.g., flat terrain, high insolation rates) are abundant, and where the state legislature passed a bill in 2015 requiring all power-supplying utilities to obtain at least 50% of their electricity from renewable energy sources by 2030 (de León 2015). This bill was followed by another in 2018 (de León 2018) that mandated that the 50% target be reached by 2026, that 60% be achieved by 2030, and that renewable and zero-carbon sources supply 100% of retail sales of electricity by 2045. This could further accelerate the construction of solar facilities in California.

Although the rapid proliferation of solar facilities is positive with regards to helping ameliorate climate change impacts, a significant concern is adverse effects to sensitive biological resources resulting from these facilities (Lovich and Ennen 2011; Turney and Fthenakis 2011, Hernandez et al. 2015), particularly when the facilities are constructed on lands that provide habitat for species at risk (Leitner 2009; Lovich and Ennen 2011; Stoms et al. 2013; Moore-O'Leary et al. 2017). Some of the rare species affected by recent solar projects in California include the San Joaquin Kit Fox (*Vulpes macrotis mutica*), federally listed Endangered (FE) and California-listed Threatened (CT), Giant Kangaroo Rat (*Dipodomys ingens*), FE and California-listed Endangered (CE), Desert Tortoise (*Gopherus agassizii*), Federally listed Threatened (FT) and CT, and Mohave Ground Squirrel (*Xerospermophilus mojavensis*), CT (Leitner 2009; Moore-O'Leary et al. 2017).

Numerous utility-scale solar facilities have been constructed or proposed for the San Joaquin Valley (SJV) region of California. In addition to high insolation rates and an abundance of flat terrain, relatively low land prices and proximity to transmission corridors enhance the attractiveness of this region for such facilities (Pearce et al. 2016); however, a large number of rare species also occurs in this region due to geographic isolation and high levels of endemism coupled with profound habitat loss (U.S. Fish and Wildlife Service [USFWS] 1998). By 2004, approximately 70% of the over 3.9 million ha of historical habitat in the SJV had been replaced by irrigated agriculture and urban development (Kelly et al. 2005). Thus, developments in the remaining natural lands further enhance the risk of extinction for multiple animal and plant species.

We conducted a spatially explicit analysis using a GIS-based model to assess location-specific potential for conflicts between listed species and solar energy development in the SJV. Our objectives were to identify areas more conducive to solar energy facilities due to high solar energy potential and low impacts to rare species, and identify areas where solar projects should be avoided based on the presence of high-value habitat and the potential for the occurrence of multiple rare species.

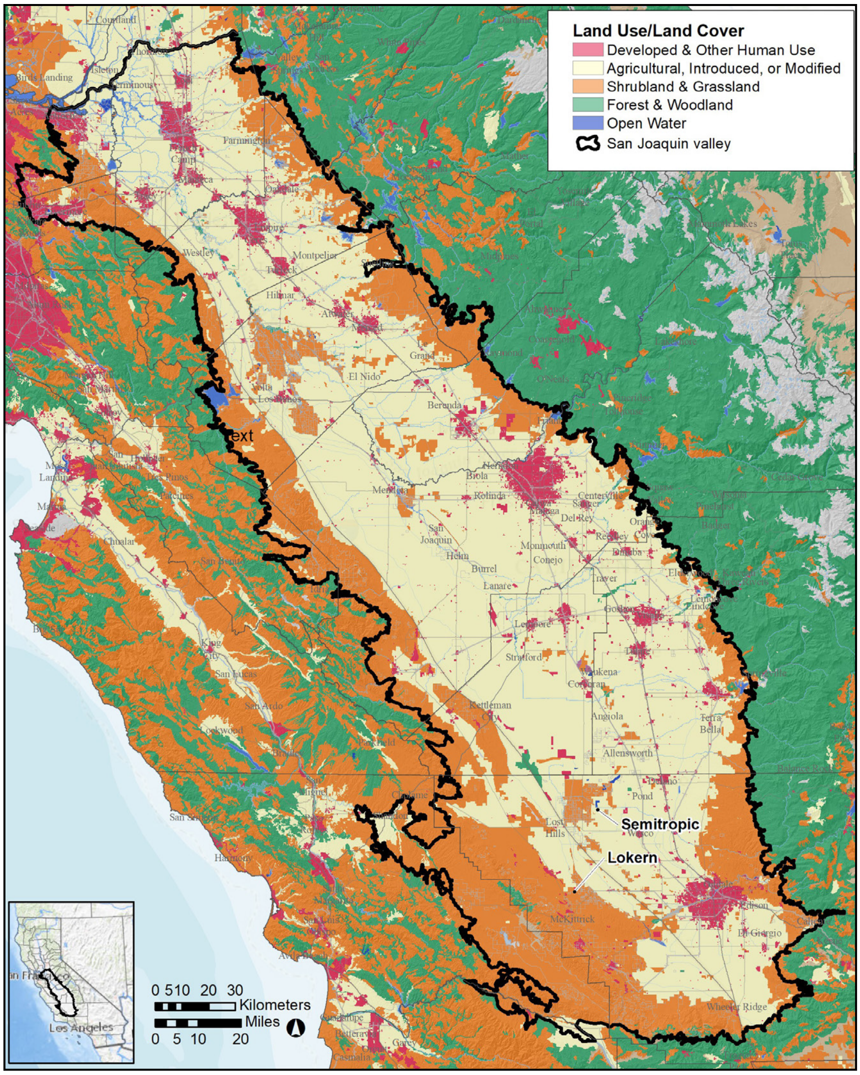

Figure 1. The San Joaquin Valley region in California. Land use/land cover classes are from a state-wide vegetation layer (University of California-Santa Barbara Biogeography Lab 1998) combined with a more recent layer of farmland and urban areas in California (California Department of Conservation 2015).

This approach can be applied in other regions as well where the potential for conflict between rare species and solar energy development is high.

Methods

Study area.—The SJV in central California (Fig. 1) extends about 415 km from north to south, and encompasses approximately 3.44 million hectares below the 152-m (500-ft) contour (USFWS 1998). The SJV is bounded on the east by the Sierra Nevada, on the west by the Coast Ranges, on the south by the Transverse Ranges and on the north by the extensive delta of the Sacramento and San Joaquin Rivers. The SJV is an arid region characterized by hot, dry summers and cool, rainy winters. Historical habitat types included arid grasslands, arid shrublands, woodland savannahs, and lakes and marshes on the valley floor connected by rivers and sloughs (USFWS 1998, Germano et al. 2011). The savannahs, lakes, and wetlands have been all but eliminated by agricultural and urban development, and the grasslands and shrublands have been significantly reduced to a fraction of their former acreage (USFWS 1998; Kelly et al. 2005). Urban regions in the SJV are growing rapidly and major population centers include Stockton, Modesto, Merced, Fresno, Visalia, and Bakersfield. Most constructed and planned solar energy plants are located in the more arid western and southern SJV described by Germano et al. (2011) as the San Joaquin Desert.

To examine conflicts between listed species and energy development in the SJV, we developed a GIS-based model (see Appendix A for model schematic) to determine how those areas best-suited for solar development compare with the suitability of remaining habitat for five federally or state listed animal species typically associated with the San Joaquin Desert. The five species were the Blunt-Nosed Leopard Lizard (*Gambelia sila*), FE and CE, San Joaquin Kit Fox, FE and CT, San Joaquin Antelope Squirrel (*Ammospermophilus nelson*), Federal Species of Concern and CT, Giant Kangaroo Rat, FE and CE, and San Joaquin Kangaroo Rat (*Dipodomys nitratoides*),

Table 1. Criteria used to evaluate suitability for large-scale solar development in the San Joaquin Valley, California. Slope was averaged over a 128-ha (320-ac) neighborhood.

	Potential for Solar Development		
Criteria	None to low	Moderate	Highest
Land use	Developed (urban areas, industrial, extractive), permanent crops (orchards or vineyards), open water, forests, or wetlands.	Irrigated farmland excluding permanent crops (e.g., row crops)	Rangeland, fallow/idle farmland, or dryland-farmed areas (e.g., winter wheat)
Slope	> 15°	< 15°	< 15°
Protected lands	Protected lands (public lands, private conservation lands, or conservation easements)	Other private land	Other private land
Insolation	N/A	5.68 - 6 kWh/m^2/day (or row crops with > 6 kWh/m^2/day)	6.00–6.42 kWh/m^2/day

which consists of three subspecies: Tipton Kangaroo Rat (*D. n. nitratoides)*, FE and CE, Fresno Kangaroo Rat (*D. n. exilis*), FE and CE, and Short-nosed Kangaroo Rat (*D. n. brevinasus*), Federal Species of Concern and California Species of Special Concern. We selected these species because of their relatively wide distributions, which encompass those of most other rare species occurring in the San Joaquin Desert. GIS models have been used elsewhere to identify areas of conflict between solar energy development and conservation goals (Cameron et al. 2012; Stoms et al. 2013). Our analysis did not explicitly include other regionally important components of conservation concern, in particular wetland habitats and associated species, and listed or rare plants.

Suitability for solar development.—We evaluated suitability for solar development using methods similar to those used by Butterfield et al. (2013) to evaluate site-suitability for large-scale (e.g., photovoltaic sites > 20 MW) solar facilities. Our criteria included land use, terrain, protected land status, and insolation rates (Table 1). These criteria are not comprehensive and other factors, such as proximity to transmission corridors and land values, also can affect site selection for solar farms; however, as noted by Pearce et al. (2016), these other factors can change rapidly and so we did not consider them in this analysis. We assumed that utility-scale solar facilities sites would need to be larger than 80 ha (200 acres) in area based on a high estimate (75th percentile) of acres/MW for photovoltaic solar sites larger than 20 MW estimated by the National Renewable Energy Laboratory (NREL 2013), and screened out areas smaller than that minimum size. Because we did not include all possible factors, some areas identified as suitable may be impractical to develop because of other limiting factors.

We developed a GIS layer of current land use classes based on a combination of the National Agricultural Statistics Service (NASS) 2014 cropland data layer (U.S. Department of Agriculture NASS 2015) and the California Department of Conservation (CDOC) Farmland Mapping and Monitoring Program (FMMP) 2012 important farmland layer (CDOC 2015). We combined land use classes from both layers to create a simplified classification (Table 2) that we used to evaluate both solar site potential and habitat availability. The two source layers (FMMP, NASS) are created using different methods and for different purposes and so differ in thematic accuracy (correct classification) and thematic resolution (number of mapped land use classes). The FMMP layer is created using direct interpretation from aerial photography and field observations (CDOC 2004), whereas NASS uses semi-automatic classification of satellite imagery. Based on a comparison of NASS classifications to observed classifications in reconnaissance surveys (Endangered Species Recovery Program, unpubl. data), we found that semi-automatic classification techniques are less reliable for land uses that have similar vegetation and ground cover such as rangeland and idle farmland (two important categories for our analysis). We also found that the FMMP included a more accurate depiction of the extent of rangeland but lacked the thematic resolution (detailed land use categories) of NASS (e.g., orchards, vineyards, wetlands, and forest). Because it takes less time to produce, NASS is updated on a yearly cycle, and is usually more current than what is available from FMMP at any given time. To

Table 2. Land use classification used to evaluate solar and habitat potential in the San Joaquin Valley, California. The acronym FMMP = Farmland Mapping and Monitoring Program 2012 important farmland layer from the California Department of Conservation and NASS = National Agricultural Statistics Service 2014 cropland data layer. For primary source, NASS[1] has no equivalent category in FMMP.

Land use class	Primary source	Secondary source
Urban/Industrial/Other developed	FMMP	NASS
Permanent crops	NASS[1]	-
Row crops	NASS[1]	-
Fallow or dryland-farmed	NASS[1]	-
Rangeland	FMMP	NASS
Barren	NASS[1]	-
Forests or wetlands	NASS[1]	-
Water	FMMP	NASS

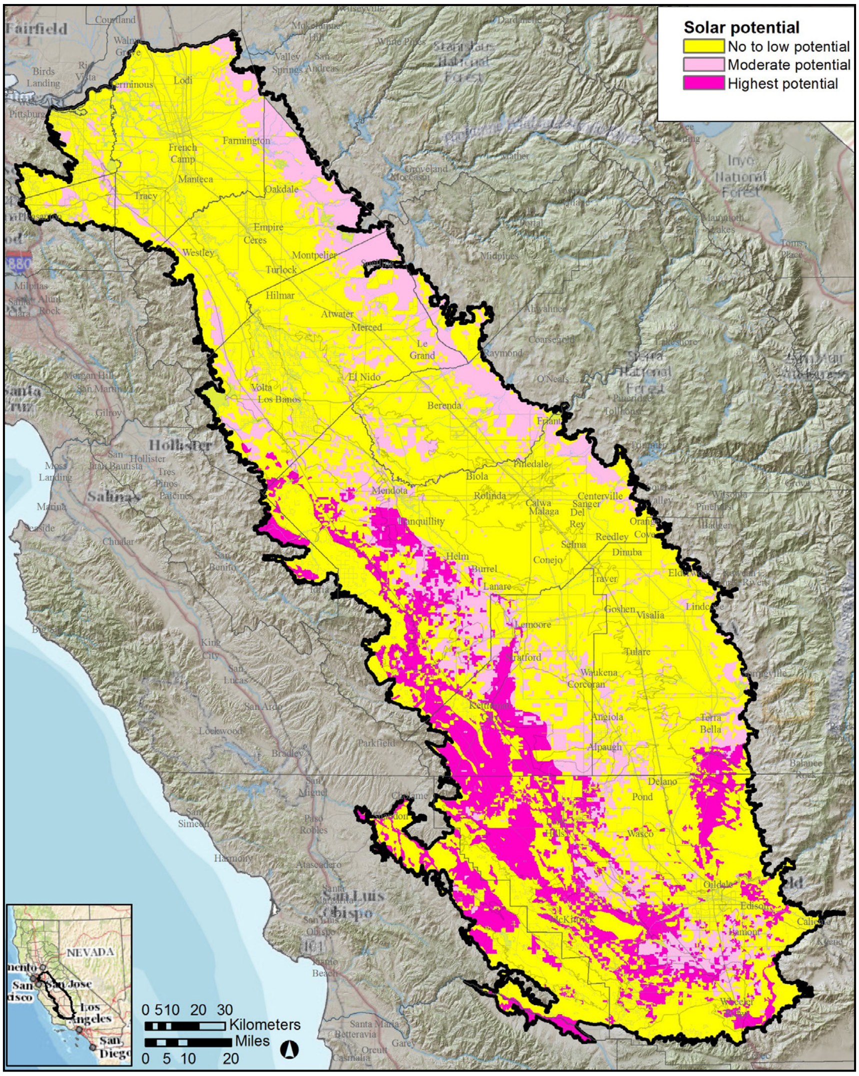

Figure 2. Estimated solar potential based on land use, protected land status, slope, and insolation in the San Joaquin Valley, California.

take advantage of both the thematic accuracy of FMMP and thematic resolution of NASS, we used a GIS overlay analysis to combine information data from both sources using the following classification rules: Where FMMP land use was classified as agricultural land or unknown, we used the more-detailed categories from the NASS. Otherwise, we used the FMMP land use categories that we found to be more-thematically accurate for non-agricultural areas, urban areas, and water. For the non-agricultural area (e.g., rangeland), we added supplemental information where the more-detailed NASS data had identified areas of forest or wetlands (classes included in the NASS but not included in the FMMP).

We calculated slope (in degrees) from digital elevation models available from the U.S. Geological Survey (USGS) National Elevation Program (USGS 2014). To screen out small patches of flat slope in otherwise steep terrain, we used a spatial averaging function (Focal Statistics in ArcGIS). Specifically, we calculated each cell as the mean value of cells within a 640-m-radius circular area (approximately 320 ac or 128 ha).

We screened out areas identified as protected fee or easement lands (GreenInfo Network 2015). While fee and easement lands have varying levels of protection from development such as large-scale utility solar facilities, we considered them all as having generally higher protection against solar development and focused our analysis on private lands. We also estimated insolation using solar resource data available from the National Renewable Energy Laboratory (NREL 2012). Solar resource data were derived from NREL estimates for photovoltaic energy (tilt = latitude collector) available as 10-km grids. To match the resolution of our other data sources, we converted the grids to a higher-resolution surface using a spatial interpolation function using an Inverse Distance Weighting function in ArcGIS (Power = 2; Search Radius = 12 neighboring cells). We combined map layers for the four criteria using a series of GIS Map Algebra steps statements (Appendix A) to create a composite map of potential suitability for solar development consisting of three categories: Low, Moderate, and High (Fig. 2).

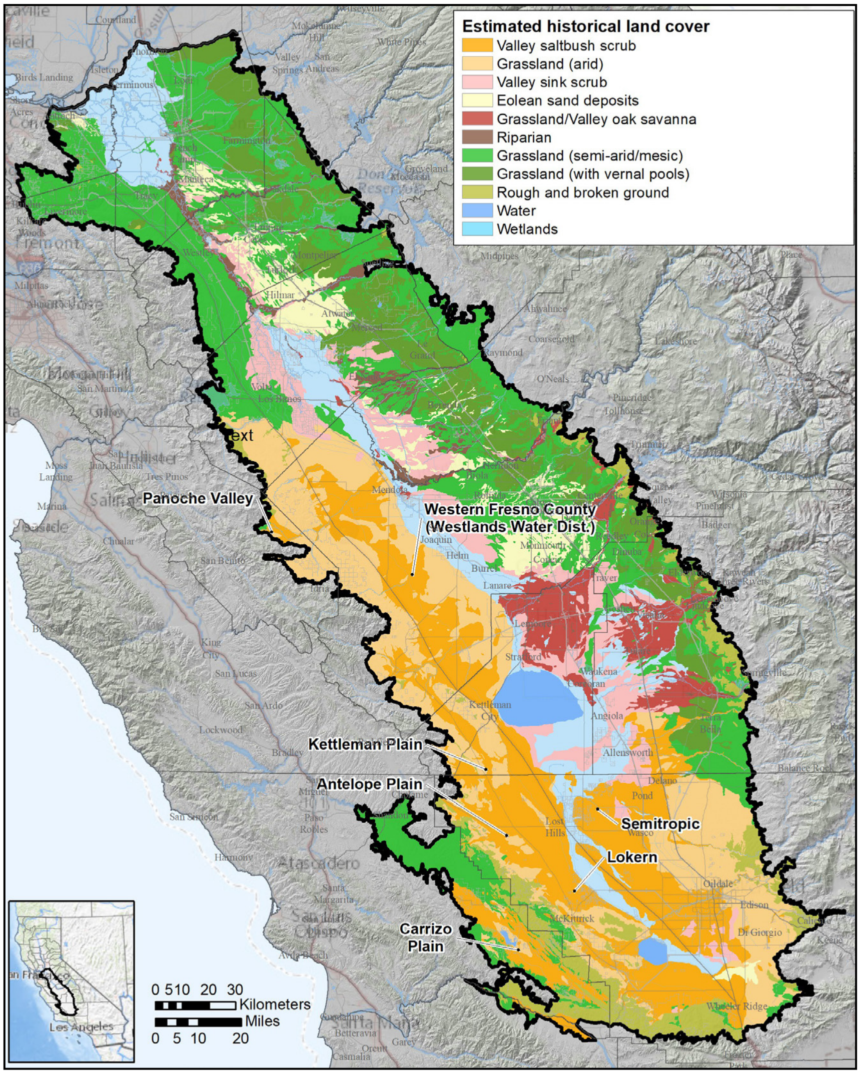

Figure 3. Estimated historical land cover in the San Joaquin Valley, California.

Suitability for listed species.—We evaluated habitat quality for the listed species using an approach similar to Germano et al. (2011) who used the distribution of multiple species along with ancillary information to identify a general region (i.e., San Joaquin Desert) important to multiple arid-adapted species of the SJV. Our approach was to develop a relatively detailed (approximately 1:125,000) GIS layer of historical land cover. To do this (Fig. 3), we digitized map units from a set of soil surveys of the San Joaquin Valley that pre-date most of the conversion of rangelands to irrigated agriculture (Holmes et al. 1919; Nelson et al. 1918; Nelson et al. 1921). To fill some data gaps near the edges of our study area, we also used information from contemporary soil surveys (U.S. Department of Agriculture, Natural Resources Conservation Service 2014, 2015). We assigned vegetation classes to map units primarily using descriptions (and example photographs) of soil series map units (Appendix B). For example, series descriptions may include descriptions of grazing conditions, presence of brush, or information on terrain and drainage.

While we assigned classes mostly by the description of the soil type, we also reviewed historical map sources (Hall, W.H. 1890. Topographic and irrigation maps of San Joaquin Valley, Sheets 1-4. Water Resources Archives, University of California, Berkeley, California; Piemeisel and Lawson 1937; Kuchler 1977; Werschull et al. 1984), historical photographs (MVZ 2015), and climate data (PRISM Group at Oregon State University 2014) and in some cases updated our classification based on climate or another secondary source (Appendix B). We used a subset of species occurrence records from the Natural Diversity Database (CDFW 2014) and the recovery plan for upland species of the San Joaquin Valley of California (USFWS 1998) along with habitat descriptions from literature sources (Grinnell 1918, 1922, 1932) to assign historical presence of each of our target species to our historical land cover map units. We used the occurrence records and habitat descriptions to estimate the historical geographic distribution of each species and then used the historical vegetation classes to refine the distribution. For

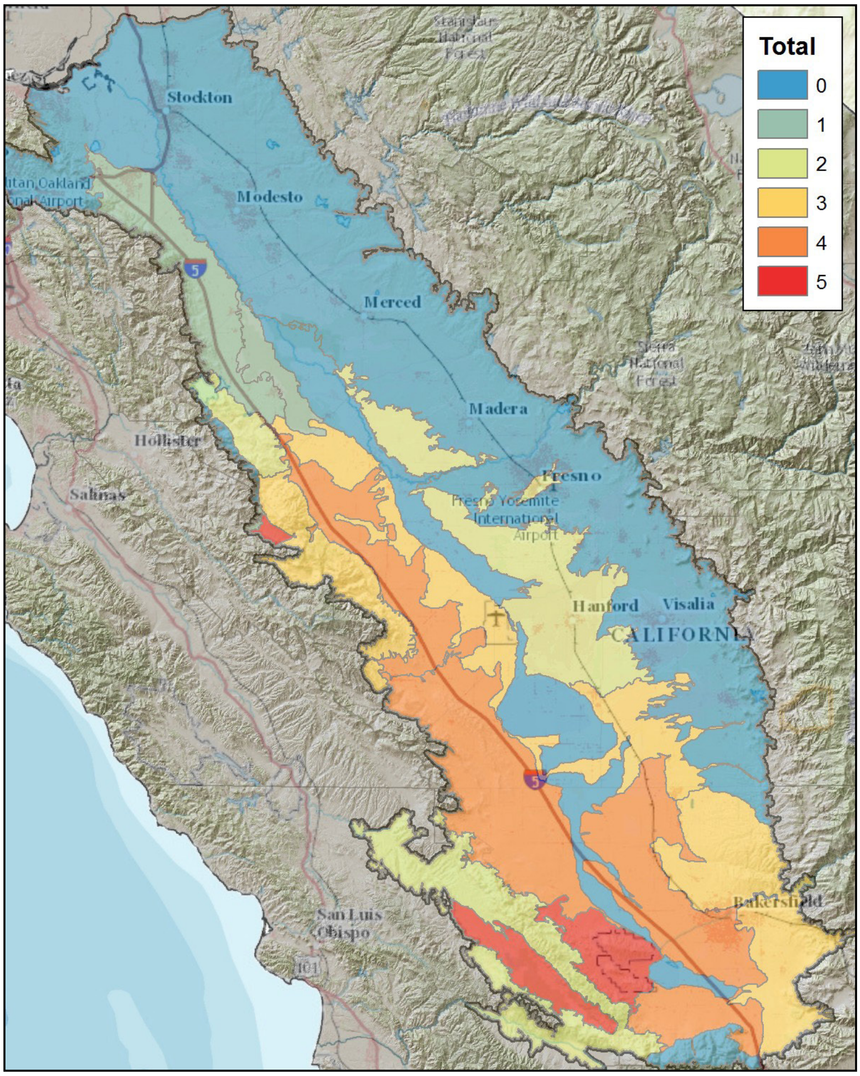

Figure 4. Total number of range overlaps for Giant Kangaroo Rats (*Dipodomys ingens*), Short-nosed Kangaroo Rats (*D. nitratoides brevinasus*), Fresno Kangaroo Rats (*D. n. exilis*), Tipton Kangaroo Rats (*D. n. nitratoides*), San Joaquin Antelope Squirrels (*Ammospermophilus nelsoni*), Blunt-nosed Leopard Lizards (*Gambelia sila*), and San Joaquin Kit Foxes (*Vulpes macrotis mutica*) based on historical ranges in the San Joaquin Valley, California.

example, we used historical records of Fresno Kangaroo Rats to identify map units where they were present, but also included contiguous or nearby map units with similar conditions. For map units with few occurrence records, we reviewed the descriptions and sources of the record to screen out those with high spatial uncertainty or those where the species identification was questionable (e.g., San Joaquin Kit Fox records based only on presence of sign but no captures).

We estimated historical habitat value by adding up the number of co-occurring species (Fig. 4). Using the slope layer, we identified and removed steep and rugged lands (> 30º slope) and grouped the remaining lands into four habitat quality categories: No to low, Low to moderate, Moderate to high, and Highest (Fig. 5). We combined the estimated composite historical habitat layer (Fig. 5-A) with a layer of contemporary land use (Fig. 5-B). Contemporary rangelands (e.g., grasslands, saltbush scrub) were assigned their estimated historical value and non-rangelands (e.g., irrigated farmland, developed areas) were assigned a value of No to Low habitat value (Table 3, Fig. 6).

Table 3. Criteria used to evaluate habitat quality for potential solar projects in the San Joaquin Valley, California. Slope was averaged over a 128-ha (320-ac) neighborhood.

	Habitat value			
Criteria	None to low	Low to moderate	Moderately high	Highest
Estimated historical species ranges	-	0–1 overlapping range	2–4 overlapping ranges	Greater than 4 overlapping ranges
Land use	Not rangeland	Rangeland	Rangeland	Rangeland
Slope	> 30°	< 30°	< 35°	< 30°

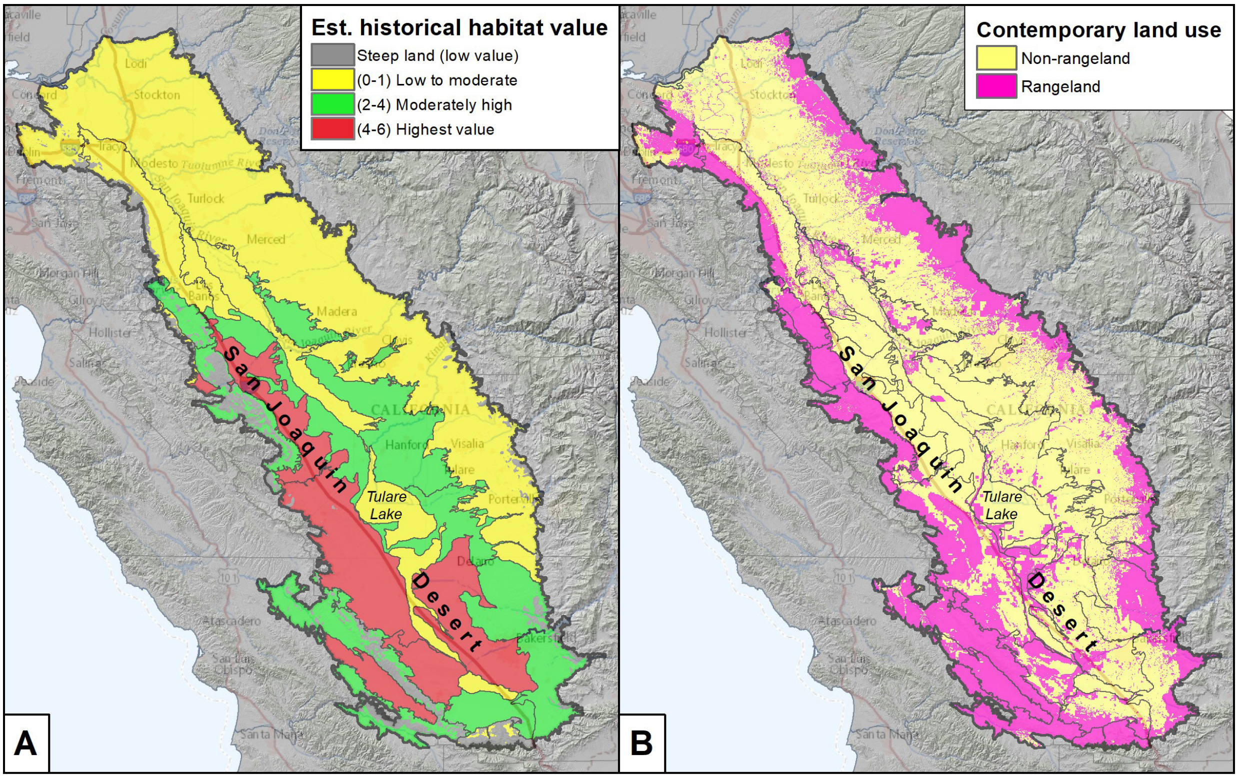

Figure 5. Estimated historical habitat value (A) and contemporary land use showing current rangeland or non-rangeland (B) in the San Joaquin Valley, California.

Results

We determined the habitat value for listed species and the potential for solar development for 42,707 km² in the SJV (Table 4). In particular, arid shrublands and grasslands tended to have attributes favorable for solar energy development. Thus, of the species we evaluated, Blunt-nosed Leopard Lizards, San Joaquin Antelope Squirrels, Giant Kangaroo Rats, Short-nosed Kangaroo Rats, and San Joaquin Kit Foxes would be most affected. Tipton and Fresno kangaroo rats primarily occur in alkali sink habitat, which was less suitable for solar development and so would be less affected.

Nearly 40% of areas with the highest potential for solar development were in areas with the highest habitat value. Thus, these areas can be considered conflict zones. This overlap increased to 64% when both the highest and moderate to high habitat value categories were considered (Table 4; Fig. 7). These conflict areas were concentrated in the southwestern portion of the SJV. Nearly a third (31%) of areas with the highest potential for solar development were in areas of less conflict (e.g., No to Low quality habitat consisting of marginal or idle farmland). Likewise, two thirds (67%) of the areas of highest habitat value were in the areas with the highest potential for solar development (Table 4; Fig. 7).

Table 4. Cross-tabulation of area for zones of suitability for solar development and habitat quality zones in the San Joaquin Valley, California.

	Solar Potential			
Habitat Value	Low	Moderate	High	Total
None to low value	24,821 km² (9,584 mi²)	3,002 km² (1,159 mi²)	1,789 km² (691 mi²)	29,612 km² (11,433 mi²)
Low to moderate value	1,931 km² (746 mi²)	3,337 km² (1,288 mi²)	308 km² (119 mi²)	5,576 km² (2,153 mi²)
Moderate to high value	2,349 km² (907 mi²)	440 km² (170 mi²)	1,375 km² (531 mi²)	4,164 km² (1,608 mi²)
Highest value	1,025 km² (396 mi²)	85 km² (33 mi²)	2,245 km² (867 mi²)	3,355 km² (1,295 mi²)
Total	30,126 km² (11,632 mi²)	6,864 km² (2,650 mi²)	5,717 km² (2,207 mi²)	42,707 km² (16,489 mi²)

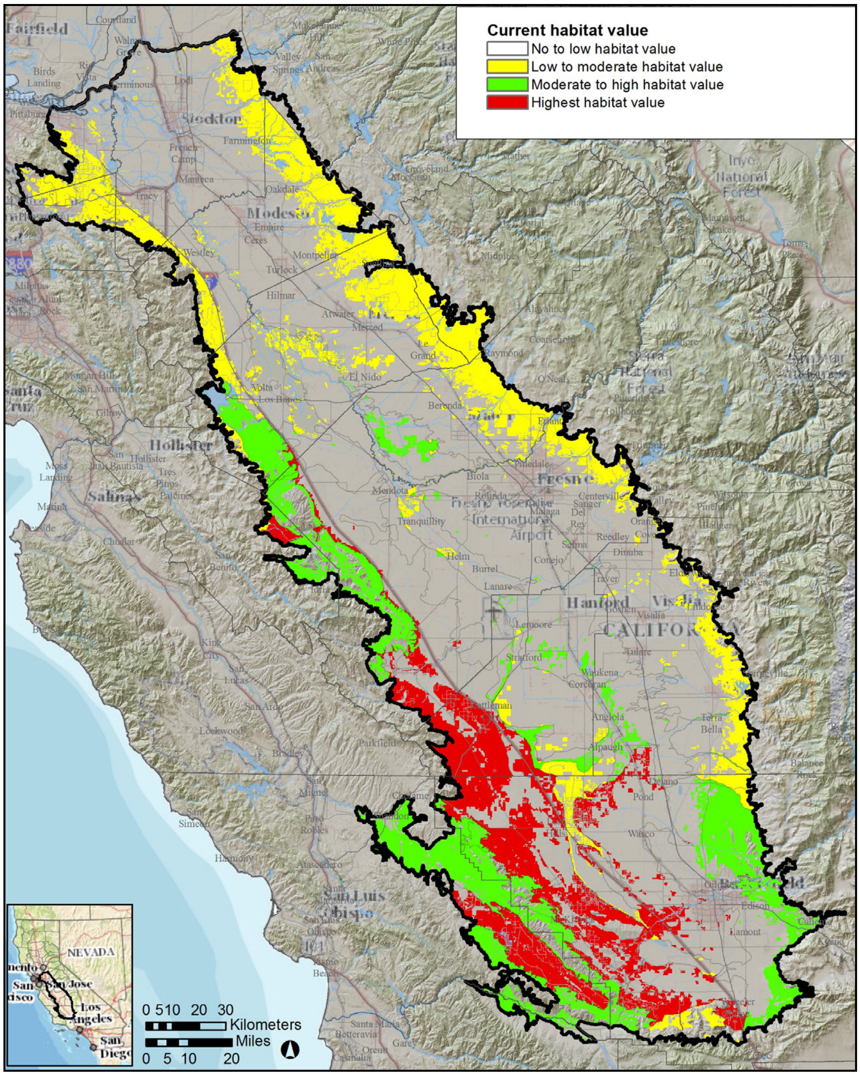

Figure 6. Estimated habitat value based on historical species ranges, land use, and slope in the San Joaquin Valley, California.

Discussion

Our analysis indicated that there is considerable overlap between site qualities needed for solar energy generation and those that constitute suitable habitat for listed species in the SJV. Consequently, a large proportion of the remaining high-quality habitat for these species also is optimal for solar energy development. This overlap results in the potential for significant conflict between development of new energy sources and conservation of at-risk species. Most historical habitat for these species has been converted to other land uses (e.g., agriculture) and habitat loss continues to be the greatest threat to listed arid-adapted species (USFWS 1998). Additional conversion of habitat for any reason, including solar energy development, could further imperil these species. Furthermore, although our analysis was based on select species, a number of other rare species share similar habitat requirements with the featured species (USFWS 1998), and therefore the results of our analyses are applicable to a large suite of species of conservation concern in the SJV.

Based on our analyses, there are approximately 4,145 km^2 (1,601 mi^2) with moderate to high potential for solar energy development and that also constitute moderate to high quality habitat for listed species. These lands comprise the highest potential for conflict. Securing permits to develop these lands, particularly from agencies such as USFWS and California Department of Fish and Wildlife that are charged with protecting listed species, is difficult and also costly due to the complex impact analyses and substantial mitigation measures typically required. Furthermore, environmental groups commonly have filed lawsuits against project proponents proposing solar energy projects in good quality habitat and this further increases the cost of constructing solar facilities. For three large solar farms recently constructed in high quality habitat for listed species in the SJV (Topaz Solar Farms, California Valley Solar Ranch, Panoche Valley Solar Farm), impact analyses and permitting required several years to complete and mitigation costs were in the 10s of millions of dollars (David Hacker, pers. comm.). Environmental groups initiated legal challenges to all three projects resulting in many more millions of dollars

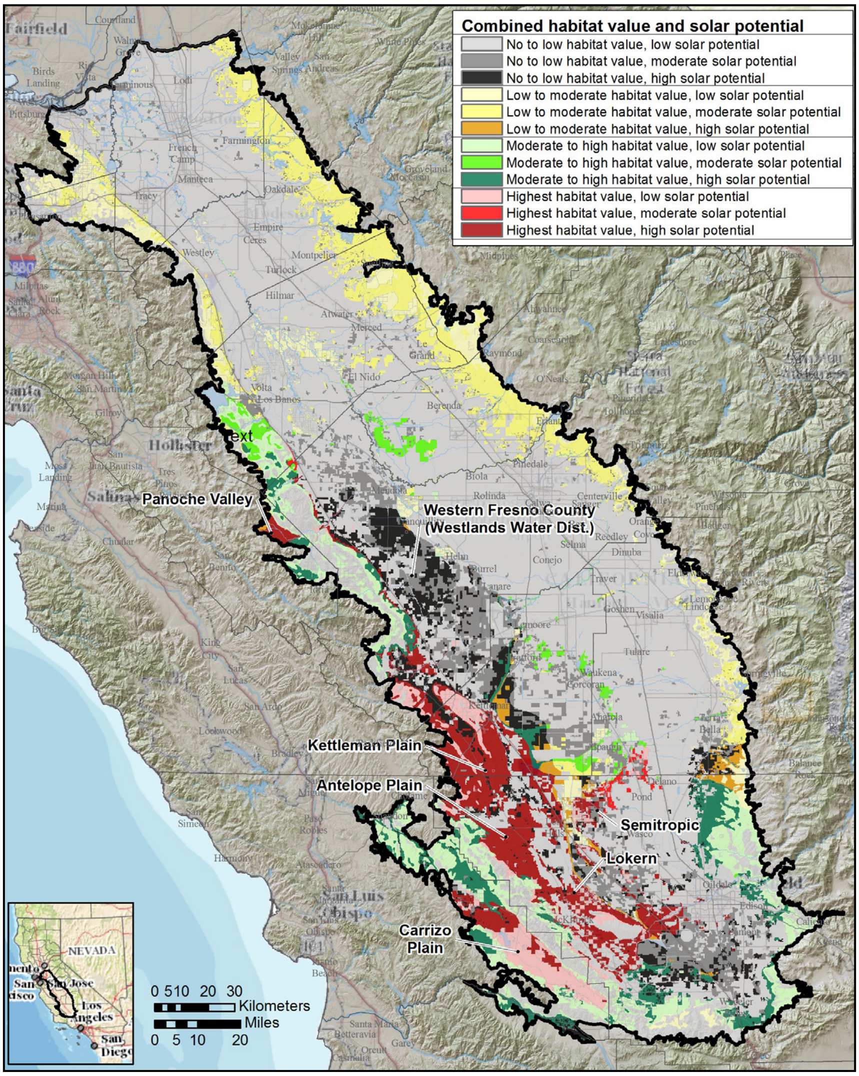

Figure 7. Combined suitability for solar development with contemporary habitat conditions for five listed animal species in the San Joaquin Valley, California.

in additional mitigation costs.

Potential conflict areas with moderate to high habitat value and moderate to high potential for solar energy development are particularly concentrated in the southwestern portion of the SJV from Kern County up into southwestern Fresno County. Other areas include private lands in the northern and eastern Carrizo Plain, valley floor lands in northern Kern and southern Tulare counties, and the Panoche Valley region in eastern San Benito County. These areas all are recognized as being important for the conservation and recovery of the listed species considered in this report and other rare species as well (USFWS 1998).

Conversely, approximately 8,436 km^2 (3,257 mi^2) have moderate to high potential for solar energy development but no to moderate value quality habitat for listed species. These lands constitute more optimal sites for solar energy generation projects. Conflicts with listed species would be minimal or non-existent on these lands. Permit acquisition would be easier and mitigation requirements would be lower. With the ample availability of lands that have high potential for solar development but low habitat value for listed species, there appears to be abundant opportunity to site new solar projects in areas where at-risk species will be minimally affected, and could reduce the additional costs (e.g., mitigation requirements) associated with higher-quality habitats.

Lands with low habitat value but high potential for solar energy development are scattered throughout the southern SJV with particular concentrations in western Fresno County, southern Kings County, and southern Kern County. There also is a small concentration of such lands on the east side of the valley on the Kern-Tulare County boundary. Many of the lands in western Fresno County are in the Westlands Water District (https://wwd.ca.gov/) where considerable agricultural land already has been taken out of production (retired) or otherwise retired due to salt concentrations and drainage issues (Brian Cypher et al., unpubl. report). Solar energy generation would constitute an excellent alternate use of these lands.

GIS-based approaches have been used previously to identify areas of conflict with solar energy development. Cameron et al. (2012) used GIS modeling to identify areas of least conflict between biodiversity values and solar energy development in the Mojave Desert of California and Nevada. Stoms et al. (2013) conducted a similar effort for the Mojave and Colorado Desert regions in California. Three previous analyses have been conducted for the SJV, although the objectives, methods, and conclusions differed from ours. Butterfield et al. (2013) identified 1,592 km^2 (615 mi^2) of lands where suitability for solar farms was high but conservation value was low. Similarly, Jane Cowan et al. (unpubl. report) and Pearce et al. (2016) identified 4,047 km^2 (1,563 mi^2) and 1,902 km^2 (734 mi^2) respectively, of lands where conflict between solar development and conservation would be limited. These studies and ours differed in two significant ways. A much broader collection of lands (e.g., fallow agricultural lands, wetlands), were used to assess conservation values, but in many instances these lands do not support listed species. We focused on lands considered important for arid-adapted listed species (USFWS 1998). Each of these other analyses also included conservation of agricultural lands as an objective, and this likely is the reason that the least conflict lands totaled considerably less than the 8,436 km^2 (3,257 mi^2) that we identified. Agricultural lands in the SJV generally are flat and therefore are optimal for solar farms, but agricultural lands have little or no value for the listed species we considered (Warrick et al. 2007; Cypher et al. 2013).

A notable point of agreement among our study and the three others conducted in the SJV is the identification of a sizeable concentration of lands in western Fresno County where conflicts between solar energy development and conservation values would be minimal. As described previously, many of these lands lie within the Westlands Water District. Due to soil salinity and other issues, many acres within the District have been taken out of agricultural production. Thus, this region potentially could serve as a focal area for solar energy production.

Siting projects in areas with no or marginal habitat value actually might increase the value of these lands for listed species. Preliminary data from recently constructed solar generating facilities indicated continued, and in some cases increased, use by listed species (Cypher et al. 2019). The Topaz Solar Farms in northeastern San Luis Obispo County was largely constructed on active and fallowed dry-land farmed fields. San Joaquin Kit Foxes were present in low abundance on the site prior to construction, and they continue to occupy the site now that construction has been completed and the facility is fully operational (Meade, Althouse and Meade, Inc., pers. comm.). The results of surveys involving genetic analyses of fecal samples indicate that kit fox numbers have increased on the site (Jesus Maldonado and Tammy Wilbert, unpubl. report). Similarly, kit foxes continue to use another nearby solar facility, the California Valley Solar Ranch (Robyn Powers, pers. comm.). This facility was constructed on lands that were previously farmed or intensively grazed. Both solar sites appear to be used by kit foxes to fulfill all life-history requirements (e.g., foraging, denning, resting). Reproduction by kit foxes also has been documented on both sites. Furthermore, Giant Kangaroo Rats were present in low numbers on the California Valley Solar Ranch lands prior to construction and continue to be present and have even increased in some areas now that construction has been completed (Robyn Powers, pers. comm.). Conservation measures that have facilitated use of these solar facilities by listed species include permeable fencing, movement corridors, vegetation management, enhancements such as artificial dens, and prohibition of rodenticide use.

The examples above indicate that if designed and managed appropriately, solar generating facilities can provide habitat value for listed species. Given the overlap in habitat requirements (USFWS 1998) among the listed species used in our analyses, we predict that San Joaquin Kangaroo Rats, San Joaquin Antelope Squirrels, and Blunt-Nosed Leopard Lizards also potentially would use solar facilities, similar to that observed for San Joaquin Kit Foxes and Giant Kangaroo Rats. Thus, solar facilities constructed in low value habitat adjacent to lands occupied by any of these species might actually increase the amount and patch size of useable habitat. Such construction of solar facilities could be particularly valuable if sited in such a manner as to create a corridor across marginal habitat to link areas of higher quality habitat. With the extensive fragmentation of habitat that currently exists in the SJV ecoregion (e.g., USFWS 1998; Kelly et al. 2005; Cypher et al. 2013), the potential for improving conditions for listed species by connecting habitat patches is immense. The recovery plan for upland species in the SJV (USFWS 1998) specifically calls for establishing corridors and improving connectivity in the region in western Fresno County that includes the Westlands Water District. As described previously, species habitat values are generally low and solar energy development potential is relatively high in this region, and solar projects potentially could contribute to conservation strategies as well-managed solar facilities could provide greater habitat value than the existing agriculture.

Per our previous caution, our analysis did not consider all possible factors that could influence the selection of a proposed site for a solar facility in the SJV (for example, listed species associate with wetlands). Our analysis, however, constitutes a useful decision support tool for identifying general areas and even specific locations in this region where siting such facilities would result in minimal or no impacts to listed species. Of the remaining 7,519 km^2 of moderate and high-quality habitat in the SJV, almost half (48.2%) is also highly suitable for solar energy generation. Consequently, the potential for conflict between these two competing land uses is high; however, there are 29,612 km^2 of low-quality habitat that also is highly suitable for solar energy generation. Thus, there is abundant opportunity to site solar energy plants on lands that will not adversely affect listed species.

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Literature Cited

Cameron, D.R., B.S. Cohen, and S.A. Morrison. 2012. An approach to enhance the conservation-compatibility of solar energy development. PLoS ONE 7(6):e38437. doi:10.1371/journal.pone.0038437

Cypher, B.L., S.E. Phillips, and P.A. Kelly. 2013. Quantity and distribution of suitable habitat for endangered San Joaquin kit foxes: conservation implications. Canid Biology and Conservation 16:25–31.

Cypher, B. L., T. L. Westall, K. A. Spencer, D. E. Meade, E. C. Kelly, J. Dart, and C. L. Van Horn Job. 2019. Response of San Joaquin Kit Foxes to Topaz Solar Farms: implications for conservation of kit foxes. California State University-Stanislaus, Endangered Species Recovery Program, Turlock, California. 80 p.

Germano, D.J., G.B. Rathburn, L.R. Saslaw, B.L. Cypher, E.A. Cypher, and L.M. Vredenburgh. 2011. The San Joaquin Desert of California: ecologically misunderstood and overlooked. Natural Areas Journal 31:138–147.

Grinnell, J. 1918. Natural History of the Ground Squirrels of California. University of California Press, Berkeley, California.

Grinnell, J. 1922. A Geographical Study of the Kangaroo Rats of California. University of California Press, Berkeley, California.

Grinnell, J. 1932. Habitat relations of the Giant Kangaroo Rat. Journal of Mammalogy 13:305–320.

Hernandez, R.R., M.K. Hoffacker, M.L. Murphy-Mariscal, G.C. Wu, and M.F. Allen. 2015. Solar energy development impacts on land cover change and protected areas. Proceedings of the National Academy of Science 112:13579–13584.

Holmes, L.C., E.C. Eckmann, J.W. Nelson, and J.E. Guernsey. 1919. Reconnaissance soil survey of the middle San Joaquin Valley, California. United States Agriculture Department, Soils Bureau, Washington, D.C. 119 p.

Kelly, P.A., S.E. Phillips, and D.F. Williams. 2005. Documenting ecological change in time and space: the San Joaquin Valley of California. Pp. 57–78 *in* Mammalian Diversification: From Chromosomes to Phylogeography. Lacey, E.A., and P. Myers (Ed.). Publications in Zoology Series. University of California Press, Berkeley, California.

Kuchler, A.W. 1977. The map of the natural vegetation of California. Pp. 909–938 + supplement *In* Terrestrial Vegetation of California. Barbour, M.G., and J. Major (Ed.). John Wiley & Sons, New York, New York.

Leitner, P. 2009. The promise and peril of solar power. Wildlife Professional 3:48–53.

Lovich, J.E., and J.R. Ennen. 2011. Wildlife conservation and solar energy development in the Desert Southwest, United States. BioScience 61:982–992.

Moore-O'Leary, K.A., R.R. Hernandez, D.S. Johnston, S.R. Abella, K.E. Tanner, A.C. Swanson, J. Kreitler, and J.E. Lovich. 2017. Sustainability of utility-scale solar energy - critical ecological concepts. Frontiers in Ecology and the Environment 15:385–394.

National Energy Renewal Laboratory (NREL). 2013. Land-use requirements for solar power plants in the United States. Technical Report NREL/TP-6A20–56290. National Energy Renewal Laboratory, Golden, Colorado.

Nelson, J.W., J.E. Guernsey, L.C. Holmes, and E.C. Eckmann. 1918. Reconnaissance soil survey of the Lower San Joaquin Valley, California. U.S. Agriculture Department, Soils Bureau, Washington, D.C. 106 p.

Nelson, J.W., W.C. Dean, and E.C. Eckmann. 1921. Reconnaissance soil survey of the Upper San Joaquin Valley, California. U.S. Agriculture Department, Soils Bureau, Washington, D.C. 112 p.

Piemeisel, R.L., and F.R. Lawson. 1937. Types of vegetation in the San Joaquin Valley of California and their relation to Beet Leafhopper. Technical Bulletin No. 557, U.S. Department of Agriculture, Washington, D.C.

Stoms, D.M., S.L. Dashiell, and F.W. Davis. 2013. Siting solar energy development to minimize biological impacts. Renewable Energy 57:289–298.

Turney, D., and V. Fthenakis. 2011. Environmental impacts from the installation and operation of large-scale solar power plants. Renewable and Sustainable Energy Reviews 15:3261–3270.

U.S. Fish and Wildlife Service (USFWS). 1998. Recovery plan for upland species of the San Joaquin Valley, California. United States Fish and Wildlife Service, Portland, Oregon. 319 p.

Warrick, G.D., H.O. Clark, Jr., P.A. Kelly, and D.F. Williams, and B.L. Cypher. 2007. Use of agricultural lands by San Joaquin Kit Foxes. Western North American Naturalist 67:270–277.

Werschull, G.D., F.T. Griggs, and J.M. Zaninovich. 1984. Tulare Basin Protection Plan. The California Nature Conservancy, San Francisco, California.

On-line Works

Butterfield, H.S., D. Cameron, E. Brand, M. Webb, E. Forsburg, M. Kramer, E. O'Donoghue, and L. Crane. 2013. Western San Joaquin Valley least conflict solar assessment. The Nature Conservancy, San Francisco, California. https://www.scienceforconservation.org/assets/downloads/WSJV_SolarAssessment_2013.pdf.

California Department of Conservation (CDOC). 2004. CDOC, Division of Land Resource Protection, A Guide to the Farmland Mapping and Monitoring Program, 2004 Edition. https://www.conservation.ca.gov/dlrp/fmmp/Documents/fmmp_guide_2004.pdf

California Department of Conservation (CDOC). 2015. CDOC, Division of Land Resource Protection, Farmland Mapping and Monitoring, Important Farmland (multiple counties), Geospatial data. http://conservation.ca.gov/dlrp/FMMP/

California Department of Fish and Wildlife (CDFW). 2014. California Natural Diversity Database. Geospatial data. http://www.dfg.ca.gov/biogeodata/cnddb/

de León, K. 2015. Senate Bill 350: Clean Energy and Pollution Reduction Act, Chapter 547, Statutes of 2015. https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB350

de León, K. 2018. Senate Bill 100: California Renewables Portfolio Standard Program: Emissions of Greenhouse Gases, Chapter 312, Statutes of 2018. https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB100

GreenInfo Network. 2015. California Protected Areas Database (CPAD) and the California Conservation Easement Database (CCED). Geospatial data. http://calands.org/

Museum of Vertebrate Zoology at Berkeley (MVZ). 2015. MVZ Field Note, Photograph, and Annotated Map Collections. Online resource (digital photographs). http://mvz.berkeley.edu/FieldnotePhotoMap_Collection.html

National Energy Renewal Laboratory (NREL). 2012. Lower 48 and Hawaii PV 10km Resolution 1998 to 2009 (us9809_latilt_updated). Geospatial data. http://www.nrel.gov/gis/data_solar.html

Pearce, D., J. Strittholt, T. Watt, and E.N. Elkind. 2016. A path forward: identifying least-conflict solar PV development in California's San Joaquin Valley. Conservation Biology Institute, Corvallis, Oregon. https://consbio.org/products/reports/path-forward-identifying-least-conflict-solar-pv-development-californias-san-joaquin-valley.

PRISM Group at Oregon State University. 2014. United States 30-Year Normals, 1981 – 2010. The PRISM Group at Oregon State University, Corvallis, Oregon. Geospatial data. http://prism.oregonstate.edu/normals/

Solar Energy Industries Association. 2016. www.seia.org/research-resources/solar-industry-data

University of California Santa Barbara Biogeography Lab (CGAP). 1998. California Gap Analysis Vegetation Layer (Statewide). 1:100,000-1:250,000. University of California, Santa Barbara, CA. Geospatial data. http://www.biogeog.ucsb.edu/projects/gap/gap_home.html

U.S. Department of Agriculture (USDA), National Agricultural Statistics Service (NASS). 2015. USDA, NASS, Research and Development Division, Geospatial Information Branch, Spatial Analysis Research Section 2014 California Cropland Data Layer, Geospatial data. http://www.nass.usda.gov/research/Cropland/Release/

U.S. Department of Agriculture, Natural Resources Conservation Service (USDA NRCS). 2014. General Soil Map (STATSGO2). Geospatial Data. https://gdg.sc.egov.usda.gov/

U.S. Department of Agriculture, Natural Resources Conservation Service (USDA NRCS). 2015. Gridded Soil Survey Geographic (gSSURGO). Geospatial Data. https://gdg.sc.egov.usda.gov/

U.S. Geological Survey. 2014. National Elevation Dataset (1/3 arc-second). Geospatial data. http://ned.usgs.gov/

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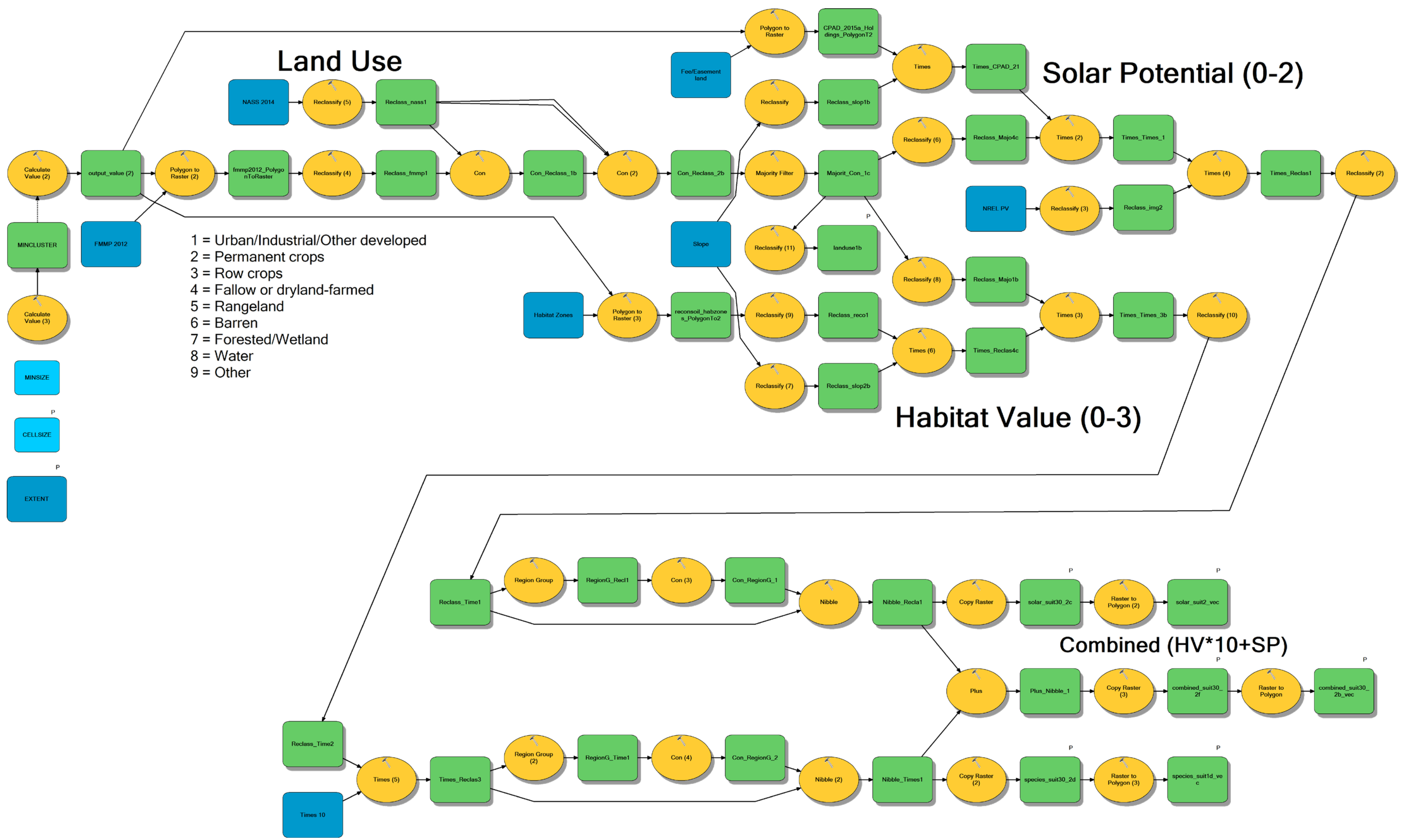
Appendix A. Geographic Information System (GIS) model for assessing overlap between solar energy potential and habitat suitability for five at-risk animal species in the San Joaquin Valley, California.



Appendix B. Soil series and vegetation classifications for historical land cover.

Soil series	Vegetation class	Primary classification source	N map units
Aiken loam	Grassland	Soil description	11
Aiken stony loam	Grassland	Soil description	25
Alamo clay adobe	Grassland	Soil description	45
Altamont adobe soils	Grassland	Soil description	33
Altamont and Diablo loam and clay loam, undifferentiated	Grassland	Soil description	2
Altamont loam and clay loam	Grassland	Soil/climate	165
	Arid grassland	Soil/climate	3
Altamont sandy loam	Grassland	Soil/climate	42
	Arid grassland	Soil/climate	2
Antioch loam and clay loam	Arid grassland	Soil/climate	17
	Grassland	Soil/climate	4
Arnold sandy loam	Arid grassland	Soil/climate	3
Capay and Merced clay, undifferentiated	Alkali sink	Soil description	2
Chino and Foster loam, undifferentiated	Wetland	Secondary sources	43
	Alkali sink	Secondary sources	1
	Desert scrub	Secondary sources	1
Corning and Pleasanton loam, undifferentiated	Grassland	Soil/climate	5
	Arid grassland	Soil/climate	1
Cuyama sandy loam and loam	Grassland	Soil/climate	7
	Arid grassland	Soil/climate	2
Delano loam	Arid grassland	Soil/climate	14
	Grassland	Soil/climate	1
Delano sand and sandy loam	Arid grassland	Soil/climate	21
	Grassland	Soil/climate	6
Diablo adobe soils	Vernal pool grassland	Soil description	30
Dublin adobe soils	Grassland	Soil description	20
Dublin and Yolo loam and clay loam, undifferentiated	Grassland	Soil description	1
Ducor loam	Grassland	Soil description	1
Foster sandy loam	Valley oak	Secondary sources	29
	Alkali sink	Secondary sources	4
Fresno and Merced loam, undifferentiated	Alkali sink	Soil description	8
Fresno clay loam	Alkali sink	Soil description	1
Fresno clay loam, dark phase	Alkali sink	Soil description	4
Fresno clay loam, light phase	Alkali sink	Soil description	14
Fresno fine sandy loam, dark phase	Grassland	Soil description	72
Fresno fine sandy loam, light phase	Alkali sink	Soil description	61
Fresno loam, dark phase	Grassland	Secondary sources	48
	Alkali sink	Secondary sources	1
Fresno loam, light phase	Alkali sink	Soil description	5
Fresno sandy loam, heavy phase	Grassland	Soil description	132
Fresno sandy loam, light phase	Alkali sink	Soil description	40
Hanford and Foster sandy loam, undifferentiated	Desert scrub	Soil description	1
Hanford fine sandy loam	Riparian	Secondary sources	68
	Valley oak	Secondary sources	45

Appendix B (continued). Soil series and vegetation classifications for historical land cover.

Soil series	Vegetation class	Primary classification source	N map units
	Grassland	Secondary sources	1
Hanford loam	Alkali sink	Secondary sources	15
	Riparian	Secondary sources	10
Hanford sand	Riparian	Soil description	67
	Desert scrub	Secondary sources	7
	Arid grassland	Secondary sources	3
Hanford sandy loam	Valley oak	Secondary sources	88
	Grassland	Secondary sources	32
	Desert scrub	Secondary sources	11
	Arid grassland	Secondary sources	4
	Alkali sink	Secondary sources	1
Holland loam	Grassland	Soil description	24
Holland sandy loam	Valley oak	Soil description	34
	Grassland	Secondary sources/climate	6
	Arid grassland	Secondary sources/climate	1
Holland sandy loam, dark phase	Vernal pool grassland	Soil description	1
Honcut loam	Valley oak	Secondary sources	2
	Grassland	Secondary sources	1
Kettleman loam and clay loam	Arid grassland	Soil description	55
Kettleman sandy loam	Arid grassland	Soil description	35
Laguna loam and sandy loam	Arid grassland	Soil description	1
Madera and San Joaquin sandy loam, undifferentiated	Vernal pool grassland	Soil description	22
Madera clay loam and clay	Vernal pool grassland	Soil description	30
Madera loam	Vernal pool grassland	Soil description	78
Madera sandy loam	Grassland	Soil/climate	110
	Arid grassland	Soil/climate	3
Mariposa sandy loam and silt loam	Grassland	Soil description	8
Merced clay loam	Wetland	Soil description	11
Merced loam	Wetland	Soil description	15
Mohave sandy loam	Arid grassland	Soil description	3
Montezuma clay adobe	Grassland	Soil description	23
Muck and Peat	Wetland	Soil description	3
Oakdale sandy loam	Grassland	Soil description	39
Oakley and Fresno sand, undifferentiated	Sand dune	Soil description	121
Oakley and Madera sand, undifferentiated	Sand dune	Soil description	66
Oakley sand	Sand dune	Soil description	27
Olympic adobe soils	Grassland	Soil description	19
Olympic loam	Grassland	Soil description	14
Panoche adobe soils	Arid grassland	Soil description	2
Panoche clay loam	Arid grassland	Soil description	32
Panoche loam	Desert scrub	Secondary sources	52
	Arid grassland	Secondary sources	1
	Grassland	Secondary sources	1
Panoche loam and clay loam	Arid grassland	Soil description	33

Appendix B (continued). Soil series and vegetation classifications for historical land cover.

Soil series	Vegetation class	Primary classification source	N map units
Panoche sandy loam	Desert scrub	Soil description	80
Placentia loam and sandy loam	Grassland	Soil description	3
Pleasanton and Antioch loam and clay loam, undifferentiated	Grassland	Soil/climate	9
	Arid grassland	Soil/climate	3
Pleasanton loam and sandy loam	Arid grassland	Soil description	16
Pond clay loam	Desert scrub	Soil description	8
Pond loam	Desert scrub	Soil description	15
Pond sandy loam	Desert scrub	Soil description	7
Porterville adobe soils	Grassland	Soil description	35
Redding gravelly loam	Vernal pool grassland	Soil description	47
Riverwash and Tailings	Riparian	Soil description	4
Rough broken land	Rock	Soil description	64
Rough stony land	Rock	Soil description	113
Sacramento clay	Water	Secondary sources	3
	Wetland	Secondary sources	1
Sacramento clay loam	Wetland	Soil description	9
San Joaquin and Altamont sandy loam, undifferentiated	Vernal pool grassland	Soil description	6
San Joaquin and Madera sandy loam, undifferentiated	Vernal pool grassland	Soil description	1
San Joaquin clay loam and clay	Vernal pool grassland	Soil description	21
San Joaquin loam	Vernal pool grassland	Soil description	105
San Joaquin sandy loam	Vernal pool grassland	Soil description	105
	Arid grassland	Secondary sources	1
Sierra sandy loam	Grassland	Soil description	6
Stockton adobe soils	Grassland	Soil description	9
Stockton and Fresno soils, undifferentiated	Wetland	Soil description	1
Stockton and Madera soils, undifferentiated	Grassland	Soil description	5
Tulare clay	Water	Secondary sources	1
	Wetland	Secondary sources	1
Tulare clay loam	Wetland	Soil description	3
Tulare loam	Wetland	Soil description	3
Tulare sandy loam and sand	Wetland	Soil description	3
	Alkali sink	Secondary sources	1
Water	Water	Soil description	5
Yolo adobe soils	Grassland	Soil description	17
Yolo clay loam	Grassland	Soil description	26
Yolo loam	Grassland	Soil description	26