Supplementary online information for:

Climatic niche contraction, habitat restoration opportunities, and conservation biogeography in California's San Joaquin Desert

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Appendix 1. *Habitat conservation priorities*

A prudent strategy as a hedge against uncertainty is to maintain a diverse portfolio of endangered species genetic lineages occupying a range of geographically and climatically differentiated habitats (Lawler, 2009). Recent analysis of *G. sila* genomic and mitochondrial datasets (Richmond et al., 2017) identify six regional groups that generally align with U.S. Fish and Wildlife Service designated recovery areas (USFWS, 2010). The northernmost of these groups, which includes populations on the northern San Joaquin Valley floor at Madera Ranch and on the northwestern side of the Valley stretching from the Kettleman Hills to the Panoche Hills, have less habitat protection than groups occurring in the southern part of the species' range. The *G. sila* habitat in and around Madera Ranch has the distinction of being the largest patch of intact habitat in the northern portion of the SJD floor, yet much of the habitat is not protected and little is known about the current status of *G. sila* populations at these sites (but see Kelly et al., 2009). The underrepresentation of habitat protection and monitoring in these northern areas suggests that greater focus on these habitats would be prudent, especially in light of potential vulnerability of southern San Joaquin Valley floor populations to 21^st^-century climate change (Westphal et al., 2016).

One site of ongoing solar development on intact habitat for *G. sila* and other endangered species, the Panoche Valley, is part of one of the two northern clades of *G. sila* genetic diversity. Developers propose to mitigate approximately 10 km^2 of solar infrastructure by protecting 98 km^2 of surrounding land, some of which is appropriate habitat for endangered species (Cypher, 2015). Habitat suitability model output for *G. sila* suggests that the proposed infrastructure may obstruct the only suitable habitat corridor between populations in Silver Creek Ranch, a site with considerably higher genetic diversity than surrounding areas, and Little Panoche Valley. Genomic data confirm historical gene exchanges between the Little Panoche Valley and Silver Creek Ranch populations (Richmond et al., 2017). This connection, almost certainly made through the Panoche Valley, suggests that the corridor may have been important historically for maintaining genetic variation in these populations (Sgrò et al., 2011). Loss of connectivity may be especially problematic for the small, peripheral population in Little Panoche Valley, as migrants essentially have no other way to enter the population except from the south via Panoche Valley.

Appendix 2. *Impacts of climate change*

Much uncertainty remains in how *G. sila*, and other SJD endangered species, will respond to climate change. On the cool-wet margin of species distributions, historical and modern distributional limits appear to be governed by herbaceous vegetation productivity. Our models indicate that drought conditions during the 21st-century could result in decreased vegetation productivity and expansion of suitable habitat back into more mesic areas where introduction of exotic grasses and forbs resulted in historical extirpations. These same drought conditions could also result in a bridge of suitable habitat connecting the range of *G. sila* in the SJD with the range of *G. wislizenii* in the Mojave Desert. While not all global circulation models predict a decline in regional precipitation, even scenarios of increased precipitation result in worsening drought conditions due to the effect of warmer temperatures on evaporative demand (Cook et al., 2015). Anticipated shifts in the seasonal distribution of precipitation toward winter and away from spring and fall are also likely to affect vegetation productivity (Pierce et al., 2013).

The hot-dry limit on the distribution of *G. sila* and other SJD endangered species may be masked by topographic barriers to dispersal separating the SJD from the Mojave Desert. As a result, we excluded the Mojave Desert (i.e. included in the range of *G. wislizenii*) from model parameterization, and our resulting model does not detect a hot-dry limit. Drought conditions, such as water-year precipitation below 94 mm, have been documented to result in temporary cessation of reproduction and demographic decline in *G. sila* (Germano & Williams, 2005; Westphal et al., 2016), but it is unclear if drought conditions to date have contributed to any population-level extirpations.

Demographic modeling approaches may be more well suited to understanding temperature and hydrological thresholds that could lead to *G. sila* extirpation and range contraction (Boyce et al., 2006). Previous studies have documented demographic decline of *G. sila* in response to both above and below average precipitation (Germano & Williams, 2005). This negative response to both above and below average water-year precipitation is concerning in light of historical and projected future increases in interannual precipitation variability in our study area (Abatzoglou et al., 2009; Berg & Hall, 2015). Given anticipated hot and dry conditions during the 21st-century, vulnerability to climate change would appear to be most pronounced in the hottest and driest portions of the species range—such as areas that experienced cessation of reproduction in response to 2014 drought conditions (Westphal et al., 2016). However, increase in interannual precipitation variability or increase in the proportion of very wet years could also plausibly result in further range contraction from the cool-wet margins of the species distribution.

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Table S1. Threatened and endangered species of the San Joaquin Desert. List includes 34 species with California Natural Diversity Database occurrence records that fall within the boundary of the San Joaquin Desert (*sensu* Germano et al., 2011). Candidate upland umbrella species are upland species with a majority of occurrence records within the San Joaquin Desert and at least 10 unique occurrence records on undeveloped habitat.

Species	Fed. Status	CA Status	Candidate Umbrella
Ambystoma californiense	Threatened	Threatened	no
Ammospermophilus nelsoni	None	Threatened	yes
Atriplex tularensis	None	Endangered	no
Branchinecta conservatio	Endangered	None	no
Branchinecta longiantenna	Endangered	None	no
Branchinecta lynchi	Threatened	None	no
Buteo swainsoni	None	Threatened	no
Camissonia benitensis	Threatened	None	no
Caulanthus californicus	Endangered	Endangered	yes
Charadrius alexandrinus nivosus	Threatened	None	no
Chloropyron palmatum	Endangered	Endangered	no
Coccyzus americanus occidentalis	Threatened	Endangered	no
Desmocerus californicus dimorphus	Threatened	None	no
Dipodomys ingens	Endangered	Endangered	yes
Dipodomys nitratoides exilis	Endangered	Endangered	no
Dipodomys nitratoides nitratoides	Endangered	Endangered	yes
Eremalche kernensis	Endangered	None	yes
Eryngium racemosum	None	Endangered	no
Euphorbia hooveri	Threatened	None	no
Euproserpinus euterpe	Threatened	None	no
Gambelia sila	Endangered	Endangered	yes
Gymnogyps californianus	Endangered	Endangered	no
Haliaeetus leucocephalus	None	Endangered	no

Lepidurus packardi	Endangered	None	no
Monolopia congdonii	Endangered	None	yes
Neostapfia colusana	Threatened	Endangered	no
Opuntia basilaris var. treleasei	Endangered	Endangered	yes
Pseudobahia peirsonii	Threatened	Endangered	no
Rana draytonii	Threatened	None	no
Riparia riparia	None	Threatened	no
Sorex ornatus relictus	Endangered	None	no
Thamnophis gigas	Threatened	Threatened	no
Vireo bellii pusillus	Endangered	Endangered	no
Vulpes macrotis mutica	Endangered	Threatened	yes

Table S2. Biases and critiques of previous species distribution models for San Joaquin Desert species.

	Pearce et al. 2015	**Bean et al. 2014**	**Cypher et al. 2013**
Sampling bias; conflated land use and environmental determinant of habitat suitability	**X**	**X**	
Erroneous procedure used for merging multiple model runs based on data subsets	**X**		
Low number of occurrence points associated with a multitude of dummy variables associated with land use and hydrological categorical variables; low predictive power within these categories	**X**		
Expert assessment based SDM; not statistically linked to empirical occurrence data			**X**

Table S3. Information on 13 candidate predictor variables evaluated for their strength in determining habitat quality and distribution. Eleven variables used in the more specialized model for *G. sila* are indicated with [G]. Nine variables used for developing generic models and evaluating umbrella species performance (Table S1) are indicated with [U].

Variable	**Abbrev.**	**Definition and explanation**
Climate, Hyrdoclimate, Ecophysiology, and Vegetation		
Hours of Restriction	H_r	Average number of hours per day during the breeding season (AMJJ) that operative environmental temperatures are too hot for *G. sila* to be active above ground (Sinervo et al., 2010). Derived at 270-m resolution for the period 1981–2010. [G]
Hours of Activity	H_a	Average number of hours per day during the active season (AMJJASO) that operative environmental temperatures are hot enough for *G. sila* to be active above ground (Sinervo et al., 2010). Derived at 270-m resolution for the period 1981–2010. [G]

Precipitation	MAP	Mean annual precipitation. Derived at 270-m resolution for the period 1981–2010 (Flint & Flint, 2012). [G, U]
Actual Evapotranspiration	AET	Actual evapotranspiration is a strong correlate of vegetation productivity. Derived at 270-m resolution from the basin characterization model for the period 1981–2010 (Flint & Flint, 2012). [G, U]
Vegetation Index	NDVI	Normalized difference vegetation index is a satellite measurement of vegetation productivity. Values are the mean NDVI for the period 2001–2010 as derived from 250m resolution MODIS satellite data. [G]
Climate Water Deficit	CWD	Climate water deficit is an index of drought stress and is defined as the difference between actual evapotranspiration and potential evapotranspiration. Derived at 270-m resolution from the basin characterization model for the period 1981–2010 (Flint & Flint, 2012). [G, U]
Mean Summer Temperature	MST	Mean temperature during the summer season (JJA). Derived at 270-m resolution from the basin characterization model for the period 1981–2010 (Flint & Flint 2012). [U]
Mean Winter Temperature	MWT	Mean temperature during the winter season (DJF). Derived at 270-m resolution from the basin characterization model for the period 1981–2010 (Flint & Flint 2012). [U]
Topography		
Slope	slope	Slope in degrees as derived from 30-m grid cells. [G, U]
Soil		
Percent Clay	clay	Percent soil clay in the surface horizon as derived from SSURGO and with missing values filled with estimates from Hengl *et al* (2014). [G, U]
Soil pH	pH	pH of the surface horizon as derived from SSURGO and with missing values filled with estimates from Hengl *et al* (2014). [G, U]
Electrical Conductivity	EC	Electrical conductivity of soil in the surface horizon as derived from SSURGO and with missing values filled with estimates from Hengl *et al* (2014). [G, U]
Interspecific Interaction		
Dipodomys suitability	dipo	Modeled habitat suitability for *Dipodomys spp*. Kangaroo rats (*Dipodomys spp*) are in important keystone species in the San Joaquin

		Desert and other arid ecosystems. They improve habitat for *G. sila* by creating burrows, maintaining networks of paths through herbaceous vegetation, and regulating herbaceous vegetation density. The model is fit to the nine variables used for evaluating umbrella species performance. [G]

Table S4. Summary of resurvey effort for two apparently extirpated historical record locations at or near *Gameblia sila's* historical northern range margin.

Latitude, Longitude	Resurvey Period and Effort	Historical Record Information
37.63779, -121.4937	Annually 1989–1994, 1997, 2000; ca. 200 person-hrs resurvey effort per year.	Corral Hollow Road, 1958 Laurie Vitt observations.
37.47642, -121.2342	Annually 1989–1994, 2001, 2008; ca. 200 person-hrs resurvey effort per year.	Del Puerto Canyon, 1958 Laurie Vitt observations.

Table S5. Locations of some recent *Gambelia sila* habitat destruction. This list is by no means comprehensive. It is a partial list of locations where the authors and collaborators have observed habitat loss in the course of other work duties. Examining historical aerial imagery in the vicinity of many of these disturbances reveals additional instances of habitat loss that are not included in this table. Year and acreage of disturbances may represent multi-year habitat erosion processes.

Year	County	Adjacent to Protected Habitat	Distance to Documented *G. sila* Occupancy	Corridor Connecting Habitat Patches	Approx. Acreage	Latitude, Longitude
2015	Kern	No	On Site	N	160	35.409198, -119.399173
2007	Kern	Yes	< 700 m	Y	220	35.479899, -119.425824
2008	Kern	Yes	< 300 m	N	200	35.127131, -119.354716
2015	Kern	Yes	< 150 m	N	180	35.213365, -119.416336
2015	Tulare	Yes	On Site	Y	320	35.796286, -119.388074
2011	Tulare	Yes	< 200 m	N	160	35.772953, -119.411945
2012	Tulare	Yes	< 2.5 km	Y	640	35.782770, -119.517220
2003	Tulare	Yes	On Site	Y	160	35.796215, -119.394069
2007	Kings	No	On Site	Y	10000	35.843955, -119.803449
2011	Kern	Yes	< 500 m	N	85	35.370365, -119.498551
2012	Kern	No	< 250 m	N	200	35.264218, -119.259748
2016	Madera	Yes	On Site	N	160	36.884134, -120.309301
2013	Madera	Yes	On Site	N	80	36.877427, -120.315046
2009	Tulare	Yes	On Site	Y	2500	35.836928, -119.368604
2012	Tulare	Yes	< 1km	N	150	35.832188, -119.330774
2013	Kern	No	< 2km	N	5	35.614723, -119.650583
2013	Tulare	Yes	< 200m	N	100	35.866522, -119.326672
2014	Kings	No	< 300m	N	1840	36.203196, -119.726509
2015	Kern	Yes	< 2km	Y	757	35.622921, -119.628334
2015	Kings	Yes	On Site	Y	1500	35.803193, -119.562347
2016	Kern	No	< 3 km	N	151	35.621325, -119.639746

2016	Kern	No	< 12 km	N	80	35.447827, -119.274736
2016	Kern	Yes	On Site	Y	20	35.463298, -119.387983

Table S6. Locations of *G. sila* occurrence observed on retired agricultural lands. Scars from former ploughing are clearly visible on aerial imagery of these sites.

Latitude, Longitude	Year of *G. sila* Observation
35.088084, -119.679246	2012
35.088777, -119.679645	2012
35.089945, -119.677698	2012
35.268610, -119.860016	2012
35.270076, -119.858573	2012
35.271588, -119.859976	2012
36.626220, -120.863500	2009

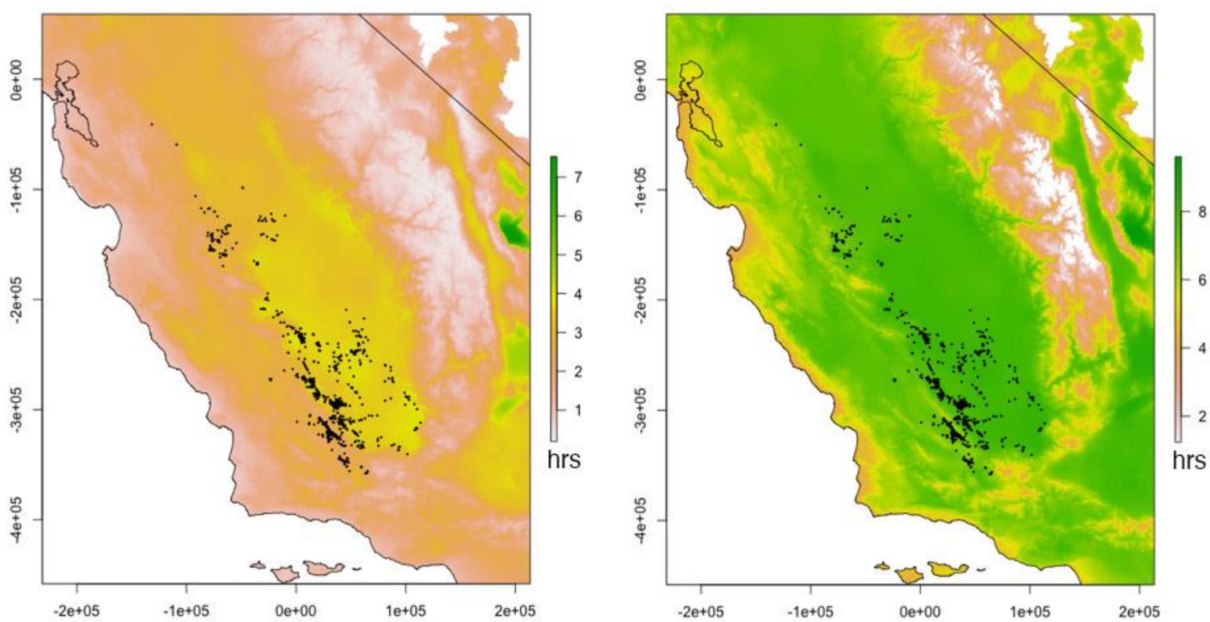

Fig. S1. Hours of restriction during the breeding season (left) and hours of activity during the active season (right). Hours of restriction are average number of hours per day during the breeding season (AMJJ) that operative environmental temperatures are too hot for *G. sila* to be active above ground. Hours of activity are number of hours per day during the active season (AMJJASO) that operative environmental temperatures are hot enough for *G. sila* to be active (Sinervo et al., 2010). *G. sila* occurrence locations are shown in black. Values are derived from temperatures from 1981–2010.

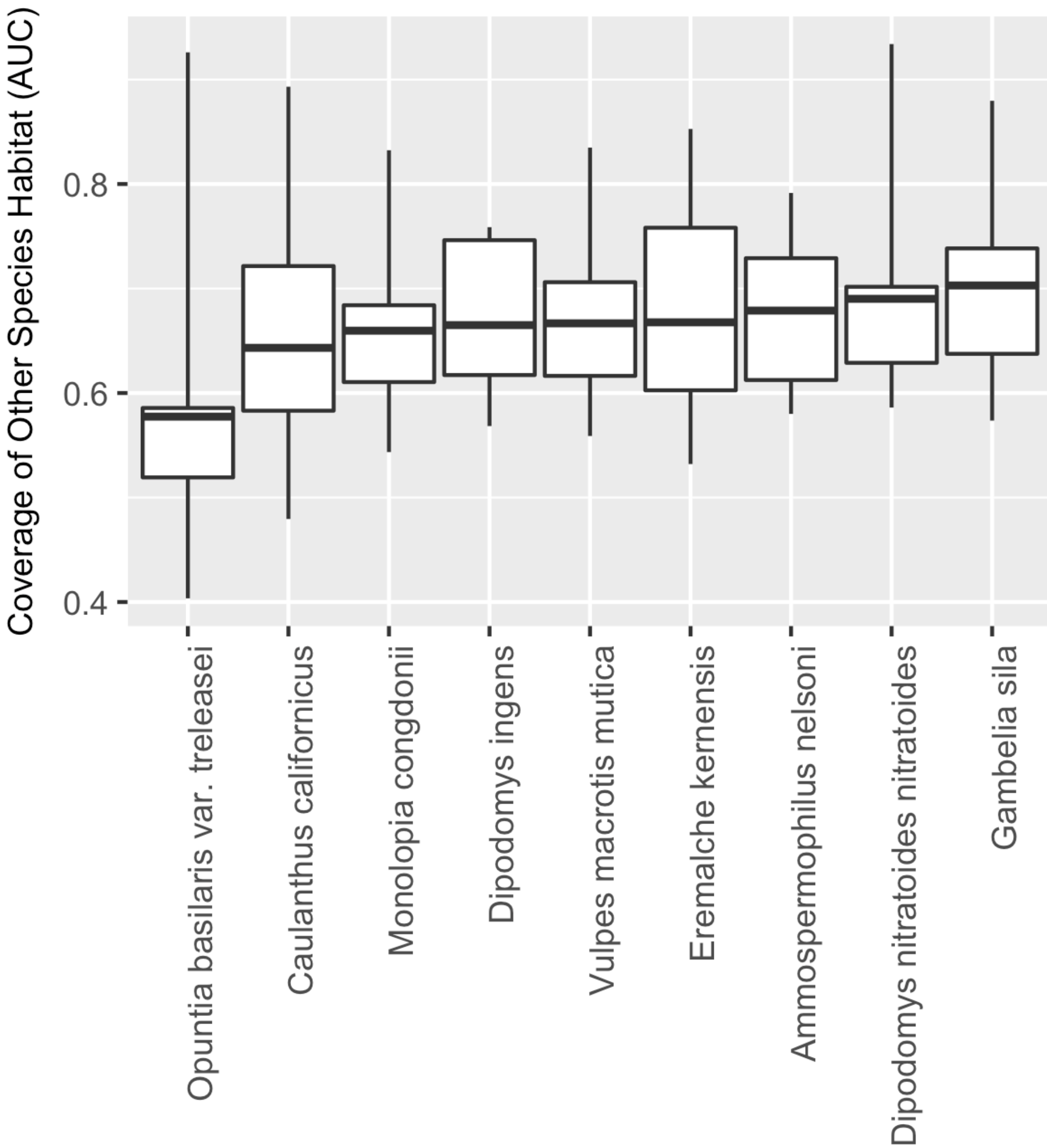

Fig. S2. Performance of nine candidate umbrella species in delineating the distribution of the other species. Jittered black dots show AUC scores for habitat suitability models, fit to the labeled species, in predicting occurrence record locations for each of the nine species. Boxes and whiskers depict the mean, interquartile range, and range.

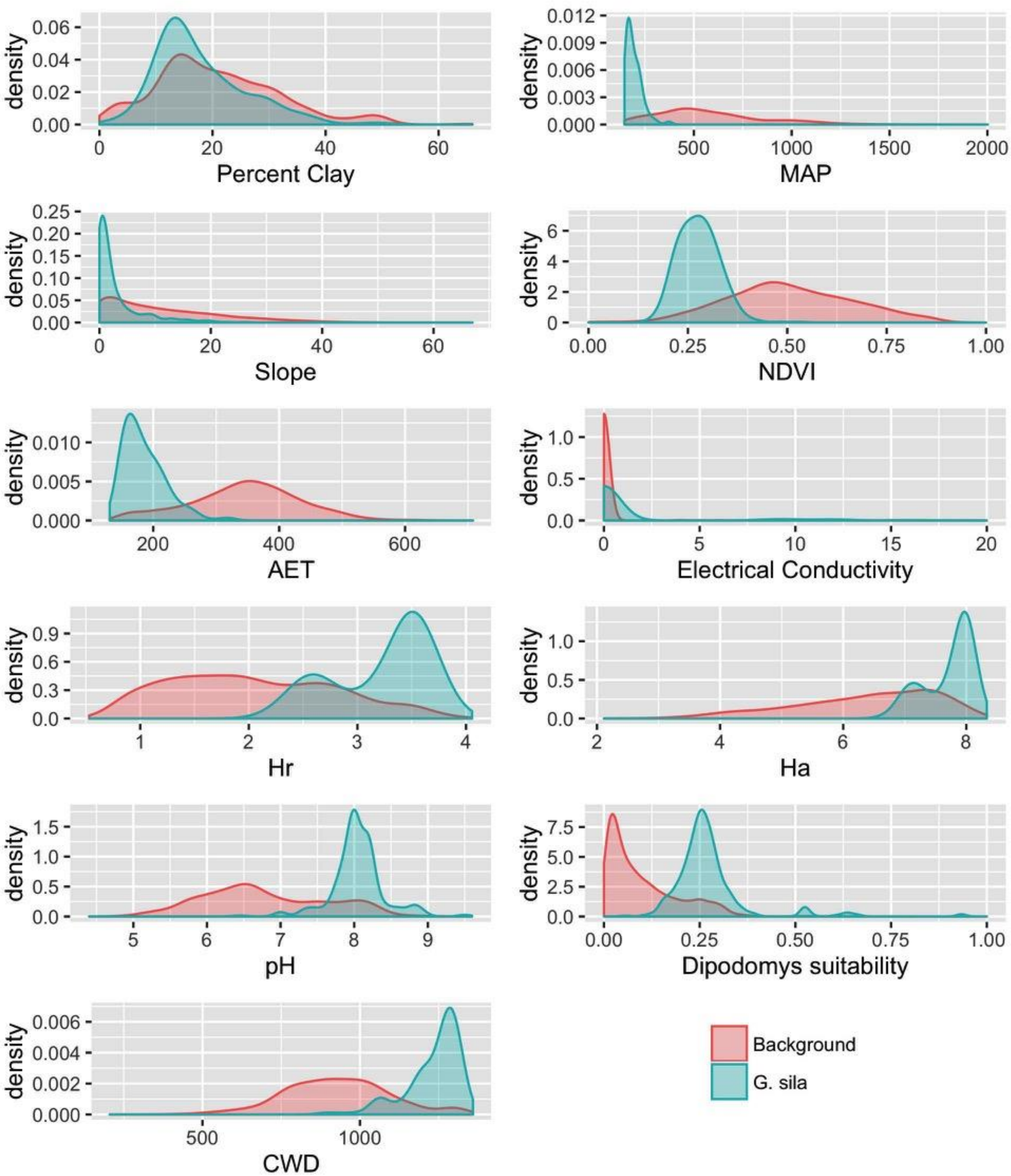

Fig. S3. Density plots for 11 candidate predictor variables. Shown are *G. sila* occurrence locations and background sampling locations.

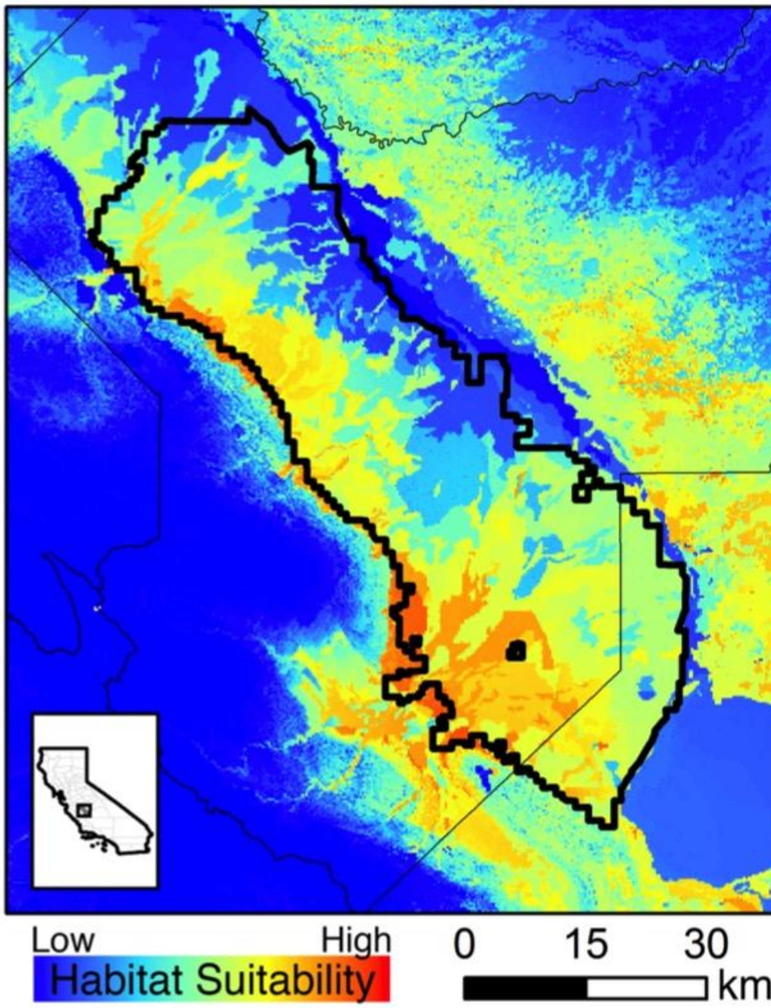

Fig. S4. Habitat suitability in Westlands Water District peaks on alkaline soils located in the western portions of the district. Under a settlement negotiated with the federal government at least 405 km^2 of ag lands in Westlands Water District will be permanently retired, including 70–210 km^2 of suitable habitat for *G. sila*. Thick border is Westlands Water District boundary. Thin borders are county boundaries.

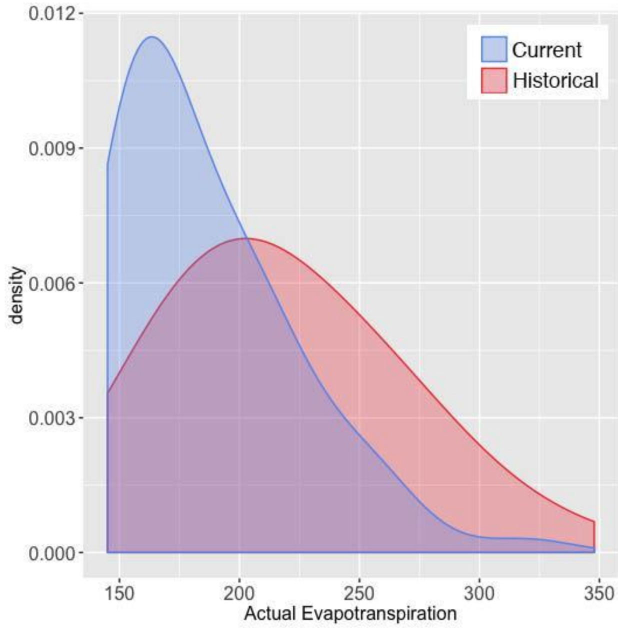

Fig. S5. Change in climatic niche of blunt-nosed leopard lizards (*G. sila*) over time with respect to actual evapotranspiration (AET). The distribution of all distinct *G. sila* record locations on intact habitat has shifted toward sites with lower AET from the historical (pre-1960) to modern (1995 or after) periods.