Supplementary online information for:

Habitat restoration opportunities, climatic niche contraction, and conservation biogeography in California's San Joaquin Desert

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Appendix S1. Discussion of potential impact of climate change.

Much uncertainty remains in how blunt-nosed leopard lizards (*Gambelia sila*) will respond to climate change. Given uncertainty in the impacts of climate change, the ideal conservation strategy may be functionally equivalent to the ideal conservation strategy in the absence of climate change: managers should maintain a diverse portfolio of genetic lineages on environmentally diverse habitats (Lawler, 2009).

On the mesic margin of the species' distribution, historical and modern distributional limits appear to be governed by herbaceous vegetation productivity (i.e. AET, Figure S2). This limit to the species' climatic niche is supported by multiple lines of evidence: demographic decline in response to high precipitation years with high herbaceous biomass (Germano & Williams, 2005), observations of *G. sila* having difficulty moving through dense thatch, the apparent invasive-species-mediated climatic niche contraction we document in this paper (Section 3.3) , and geographic patterns in occurrence data. Accordingly, our distribution models are sensitive to changes in precipitation and evapotranspiration, with scenarios of decreased future precipitation resulting in projections of peripheral range expansion and scenarios of increased future precipitation resulting in projections of peripheral range contraction (Figure S4).

While the current distribution of *G. sila* is limited by excess water availability, it does not appear that its distribution is currently controlled by hot or dry limits to its climatic niche. The species currently occupies the hottest and driest portions of its geographic range in the San Joaquin Desert (Figure S2). Though authors of this paper documented temporary cessation of reproduction in response to extreme drought conditions and water year precipitation below 92 mm (Germano et al., 1994; Westphal et al., 2016), no instances of extirpation or range limitation appear to be associated with hot or dry conditions. Population viability analyses may be necessary to assess whether potential drought scenarios could pose a risk for *G. sila*. Further, other members of the genus *Gambelia* occur in hotter and drier environments than are occupied by *G. sila* (Figure S6), suggesting that G. sila could possess capacity to tolerate similar conditions.

We urge caution in interpreting our projections of changes in habitat suitability under potential climate change scenarios (Figure 2C, Figure S4). The projections we present were selected to represent approximate bounds of the range of projected change in precipitation represented in CMIP5 for California. Most future climate scenarios project less change in mean annual precipitation in California than the scenarios presented, with end-century ensemble means approximating no change in mean annual precipitation (Thorne et al., 2016). Additionally, the model does not account for projected increases in interannual precipitation variability (Swain et al., 2018), which could negatively impact *G. sila* throughout its range (Germano & Williams, 2005; Westphal et al., 2016). Developing models that account for the response of *G. sila* to these components of climate change may be possible with sufficient demographic data. Populations residing on habitat that features edaphic and topographic diversity may be more robust to forecasted increases in interannual precipitation variability.

Table S1. Threatened, endangered, extinct, and extirpated species of the San Joaquin Desert. List includes 42 species with occurrence records that fall within the boundary of the San Joaquin Desert (*sensu* Germano et al., 2011). SSC indicates a California species of special concern.

Threatened and Endangered Species	**Fed. Status**	**CA Status**	**Persistence**
Sacramento perch, *Archoplites interruptus*	None	SSC	Extirpated
Gray wolf, *Canis lupus*	Endangered	Endangered	Extirpated
Western yellow-billed cuckoo, *Coccyzus americanus occidentalis*	Threatened	Endangered	Extirpated
Southwestern willow flycatcher, *Empidonax traillii extimus*	Endangered	Endangered	Extirpated
California condor, *Gymnogyps californianus*	Endangered	Endangered	Extirpated
Thicktail chub, *Siphatales crassicauda*	None	None	Extinct
California grizzly bear, *Ursus arctos californicus*	None	None	Extinct
California tiger salamander, *Ambystoma californiense*	Threatened	Threatened	Extant
Nelson’s antelope squirrel, *Ammospermophilus nelsoni*	None	Threatened	Extant
Bakersfield saltbush, *Atriplex tularensis*	None	Endangered	Extant
Conservancy fairy shrimp, *Branchinecta conservatio*	Endangered	None	Extant
Longhorn fairy Shrimp, *Branchinecta longiantenna*	Endangered	None	Extant
Vernal pool fairy shrim, *Branchinecta lynchi*	Threatened	None	Extant
Swainson's hawk, *Buteo swainsoni*	None	Threatened	Extant
San Benito evening primrose, *Camissonia benitensis*	Threatened	None	Extant
California jewelflower, *Caulanthus californicus*	Endangered	Endangered	Extant
Western Snowy Plover, *Charadrius alexandrinus nivosus*	Threatened	None	Extant
Palmate Salty Bird's-Beak, *Chloropyron palmatum*	Endangered	Endangered	Extant
Valley elderberry longhorn beetle, *Desmocerus californicus dimorphus*	Threatened	None	Extant
Giant kangaroo rat, *Dipodomys ingens*	Endangered	Endangered	Extant
Fresno kangaroo rat, *Dipodomys nitratoides exilis*	Endangered	Endangered	Unknown
Tipton kangaroo rat, *Dipodomys nitratoides nitratoides*	Endangered	Endangered	Extant
Kern mallow, *Eremalche kernensis*	Endangered	None	Extant
Delta button celery, *Eryngium racemosum*	None	Endangered	Extant
Hoover’s spurge, *Euphorbia hooveri*	Threatened	None	Extant
Kern primrose sphinx moth, *Euproserpinus euterpe*	Threatened	None	Extant
Blunt-nosed leopard lizard, *Gambelia sila*	Endangered	Endangered	Extant
Greater sandhill crane, *Grus canadensis tabida*	None	Threatened	Extant
Bald eagle, *Haliaeetus leucocephalus*	None	Endangered	Extant
Vernal pool tadpole shrimp, *Lepidurus packardi*	Endangered	None	Extant
San Joaquin woollythreads, *Monolopia congdonii*	Endangered	None	Extant
Colusa grass, *Neostapfia colusana*	Threatened	Endangered	Extant
San Joaquin Valley woodrat, *Neotoma fuscipes riparia*	Endangered	SSC	Extant
Bakersfield cactus, *Opuntia basilaris var. treleasei*	Endangered	Endangered	Extant
San Joaquin adobe sunburst, *Pseudobahia peirsonii*	Threatened	Endangered	Extant
California red-legged frog, *Rana draytonii*	Threatened	SSC	Extant
Bank swallow, *Riparia riparia*	None	Threatened	Extant
Buena Vista Lake ornate shrew, *Sorex ornatus relictus*	Endangered	SSC	Extant
Riparian brush rabbit, *Sylvilagus bachmani riparius*	Endangered	Endangered	Extant

Giant garter snake, *Thamnophis gigas*	Threatened	Threatened	Extant
Least Bell's vireo, *Vireo bellii pusillus*	Endangered	Endangered	Extant
San Joaquin kit fox, *Vulpes macrotis mutica*	Endangered	Threatened	Extant

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 11 candidate predictor variables evaluated for their strength in determining habitat quality and distribution.

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.
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.
Precipitation	MAP	Mean annual precipitation. Derived at 270-m resolution for the period 1981–2010 (Flint & Flint, 2012).
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).
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.

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).
Topography		
Slope	slope	Slope in degrees as derived from 30-m grid cells.
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).
Soil pH	pH	pH of the surface horizon as derived from SSURGO and with missing values filled with estimates from Hengl *et al* (2014).
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).
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 Maxent model was fit to statewide species occurrence data and the following variables: MAP, AET, CWD, slope, clay, pH, EC, Mean Summer Temperature, and Mean Winter Temperature

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

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

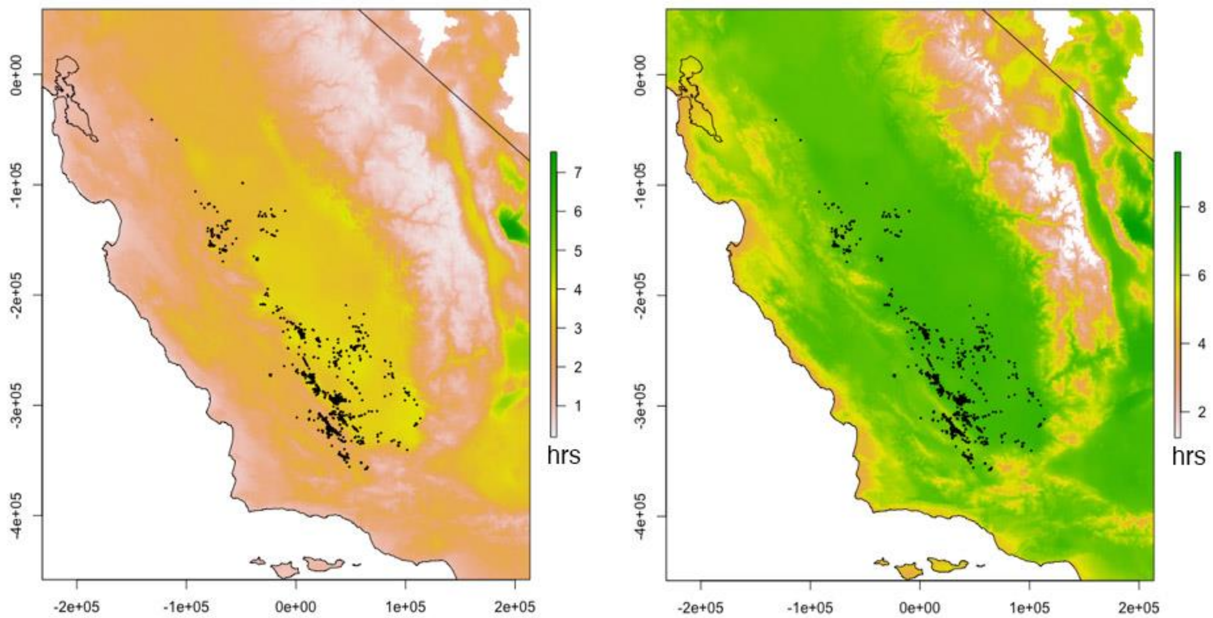

Figure S1. Hours of restriction during the breeding season (left) and hours of activity during the active season (right). Hours of restriction are average number of hours per day during the breeding season (AMJJ) that operative environmental temperatures are too hot for *Gambelia sila* to be active above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

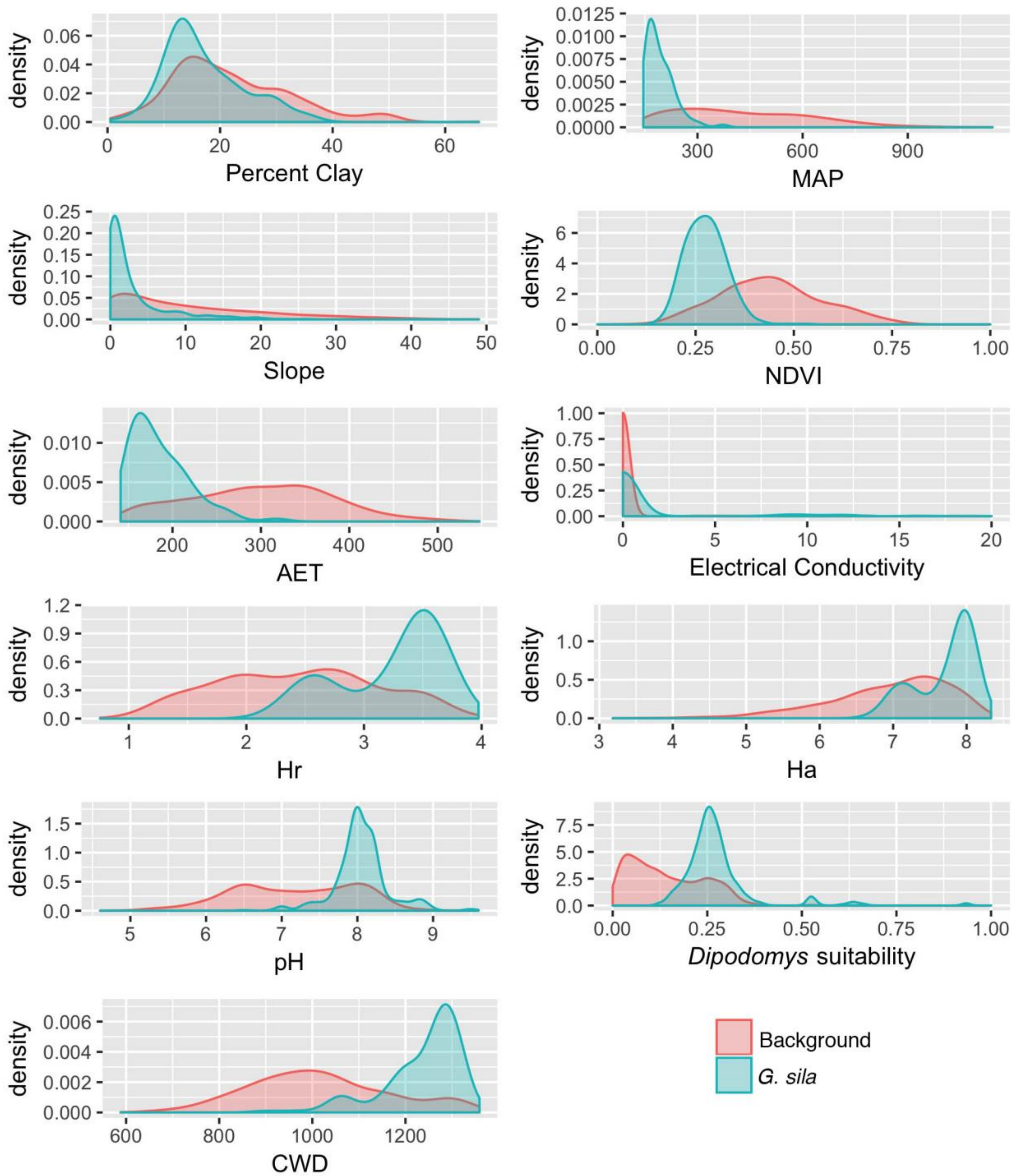

Figure S2. Density plots for 11 candidate predictor variables. Shown are *Gambelia sila* occurrence locations and background sampling locations used for parameterizing our models. Occurrence data was thinned to one record per 1-km grid cell. Old locations on developed habitat were not included.

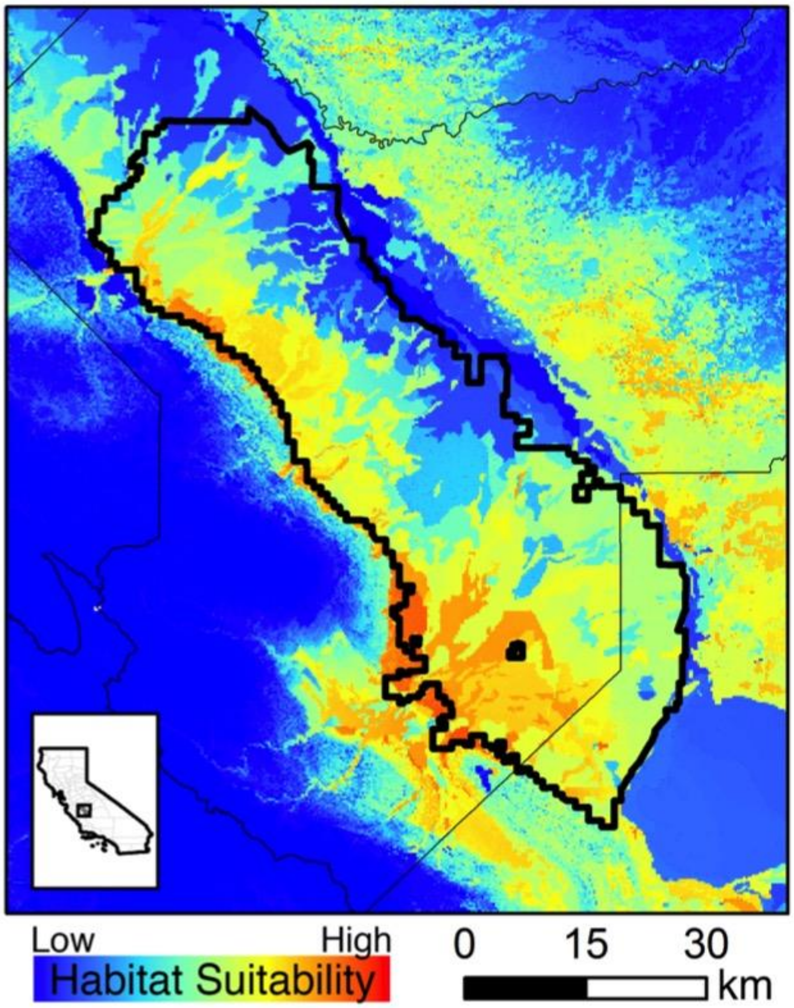

Figure S3. Habitat suitability in the Westlands Water District peaks on alkaline soils located in the western portions of the district. Under a settlement negotiated with the federal government at least 405 km^2 of farmland in Westlands Water District will be permanently retired, including 70–210 km^2 of formerly suitable habitat for *Gambelia sila*. The thick border is Westlands Water District boundary. Thin borders are county boundaries. For information on the settlement between the federal government and Westlands Water District see https://wwd.ca.gov/resource-management/drainage-settlement-documents/.

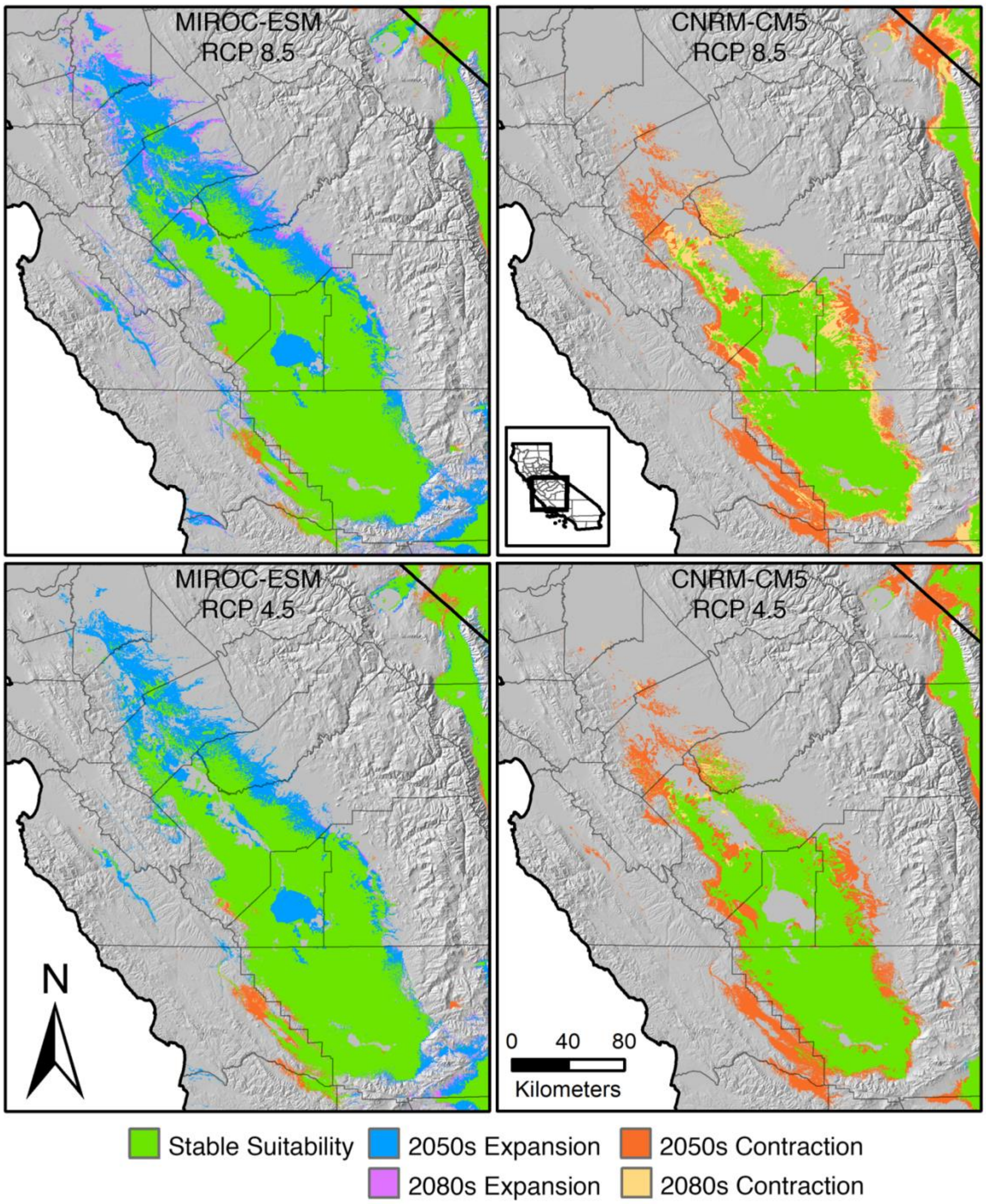

Figure S4. Modeled change in habitat suitability over time for four future climate scenarios. Climate scenarios were selected to represent a range of potential future conditions, combining two global circulation models with two emission scenarios. The global circulation models predict either a relatively hot and dry future (MIROC-ESM) or a relatively warm and wet future (CNRM-CM5). The emission scenarios represent either relatively high (RCP 8.5) or relatively low (RCP 4.5) emission trajectories. Decreased precipitation leads to a predominant trend of northward expansion in the MIROC-ESM scenarios. Conversely, increased precipitation leads to peripheral contraction in the CNRM-CM5 scenarios.

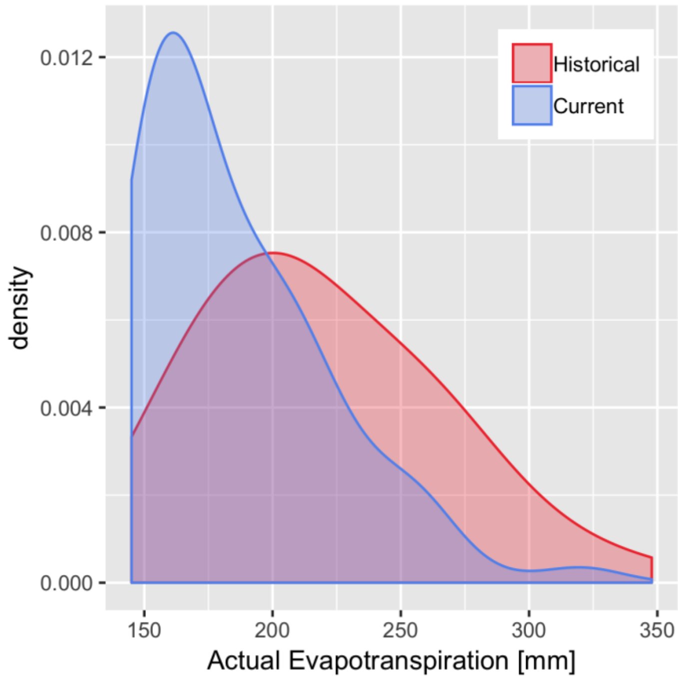

Figure S5. Change in climatic niche of *Gambelia sila* from the historical era to modern era with respect to actual evapotranspiration (AET). The distribution of all distinct *G. sila* record locations on intact habitat has shifted toward sites with lower AET from the historical (pre-1960) to modern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

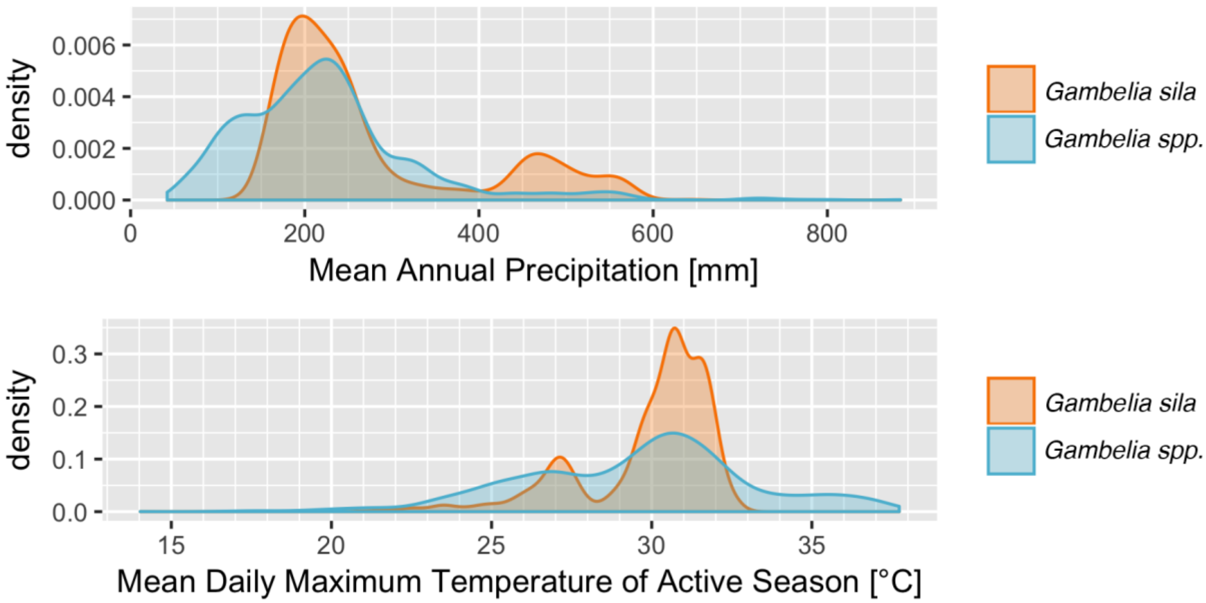

Figure S6. Comparison of realized climatic niches for *Gambelia sila* and congeners in the genus *Gambelia*. Other members of the genus occupy hotter and drier environments than are available to *G. sila* in the San Joaquin Desert (see also Fig S2). Occurrence data were thinned to one record per 30-arcsecond climate grid cell. Climate data were extracted from 30-arcsecond resolution WorldClim surfaces for the period 1960–1990 (Hijmans et al., 2005) instead of from the Basin Characterization Model (used in all other analyses; see text) because occurrence data extends beyond the domain of the later.

References for supplementary online material:

Flint L.E, & Flint A.L. (2012) Downscaling future climate scenarios to fine scales for hydrologic and ecological modeling and analysis: *Ecological Processes*, **1**:2, https://doi.org/10.1186/2192-1709-1-2.

Germano D.J., Williams D.F., & Tordoff W. (1994) Effect of drought on blunt-nosed leopard lizards (*Gambelia sila*). *Northwestern Naturalist*, **75**, 11–19.

Germano D.J. & Williams D.F. (2005) Population ecology of blunt-nosed leopard lizards in high elevation foothill habitat. *Journal of Herpetology*, **39**, 1–18.

Hengl T., Jesus J.M. De, Macmillan R.A., Batjes N.H., Heuvelink G.B.M., Ribeiro E., Samuel-Rosa A., Kempen B., Leenaars J.G.B., Walsh M.G., & Gonzalez M.R. (2014) SoilGrids1km — global soil information based on automated mapping. *PloS one*, **9**, e105992.

Hijmans R.J., Cameron S.E., Parra J.L., Jones P.G., & Jarvis A. (2005) Very high resolution interpolated climate surfaces for lobal land areas. *International Journal of Climatology*, **25**, 1965–1978.

Lawler J.J. (2009) Climate change adaptation strategies for resource management and conservation planning. *Annals of the New York Academy of Sciences*, **1162**, 79–98.

Sinervo B., Méndez-de-la-Cruz F., Miles D.B., Heulin B., Bastiaans E., Villagrán-Santa Cruz M., Lara-Resendiz R., Martínez-Méndez N., Calderón-Espinosa M.L., Meza-Lázaro R.N., Gadsden H., Avila L.J., Morando M., De la Riva I.J., Victoriano Sepulveda P., Rocha C.F.D., Ibargüengoytía N., Aguilar Puntriano C., Massot M., Lepetz V., Oksanen T.A., Chapple D.G., Bauer A.M., Branch

W.R., Clobert J., & Sites J.W. (2010) Erosion of lizard diversity by climate change and altered thermal niches. *Science*, **328**, 894–9.

Swain D.L., Langenbrunner B., Neelin J.D., & Hall A. (2018) Increasing precipitation volatility in twenty-first-century California. *Nature Climate Change*, **8**, 427–433.

Thorne J.H., Boynton R.M., Holguin A.J., Stewart J.A.E., & Bjorkman J. (2016) A climate change vulnerability assessment of California's terrestrial vegetation. California Department of Fish and Wildlife (CDFW), Sacramento, CA.

Westphal M.F., Stewart J.A.E., Tennant E.N., Butterfield H.S., & Sinervo B. (2016) Contemporary drought and future effects of climate change on the endangered blunt-nosed leopard lizard, *Gambelia sila*. *PLOS ONE*, **11**, e0154838.