CLIMATE RESILIENT CONNECTIVITY FOR THE SOUTH COAST ECOREGION OF CALIFORNIA

Final Report

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LIST OF ACRONYMS AND ABBREVIATIONS

ACE III – Areas of Conservation Emphasis

BAU – Business as usual

BIOS – Biogeographic Information and Observation System

BISON – Biodiversity Information Serving our Nation

BLM – Bureau of Land Management

CA-BCM – California Basic Characterization Model

C45 – CNRM-CM5 climate model under RCP 4.5 emissions scenario

C85 – CNRM-CM5 climate model under RCP 8.5 emissions scenario

CDFW – California Department of Fish and Wildlife

CEHC – California Essential Habitats Connectivity

CNDDB – California Natural Diversity Database

CPAD – California Protected Areas Database

EEMS – Environmental Evaluation and Management System

EHL – Endangered Habitats League

FRID – Fire return-interval departure

GBIF – Global Biodiversity Information Facility

GCM – Global Climate Model

HCP – Habitat Conservation Plan

IEMM – Institute for Ecological Monitoring and Management

LOCA – Locally Constructed Analogs

M45 – MIROC5 climate model under RCP 4.5 emissions scenario

M85 – MIROC5 climate model under RCP 8.5 emissions scenario

NAVFAC – Naval Facilities and Engineering Command

NCCP – Natural Community Conservation Planning

NLCD – National Land Cover Database

NPS – National Park Service

OCTA – Orange County Transportation Authority

PRISM – Parameter-elevation Regressions on Independent Slopes Model

RCA – Regional Conservation Assessment

RCIS – Regional Conservation Investment Strategy

RCP – Representative Concentration Pathway

SAMO – Santa Monica Mountains

SANDAG – San Diego Association of Governments

SCAG – Southern California Association of Governments

SCML – South Coast Missing Linkages

SDM – Species Distribution Model

SDNHM – San Diego Natural History Museum

SDSU – San Diego State University

SGCN – Species of Greatest Conservation Need

SWAP – State Wildlife Action Plan

TNC – The Nature Conservancy

USFS – United States Forest Service

USFWS – United States Fish and Wildlife Service

USGS – United States Geological Survey

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EXECUTIVE SUMMARY

Through a comprehensive, multispecies connectivity analysis using robust analytical approaches, we created a connectivity plan, implementation guidance through a decision support tool for climate resilient connectivity across the south coast ecoregion of California. With this data-driven approach, we:

- Worked collaboratively and iteratively with stakeholders and species experts to gather information, feedback, and key input to generate a connectivity plan and conservation tool that can be readily implemented by the diverse range of land management and planning entities in the region.
- Developed species distribution models for five target focal species under historic and four future climate scenarios to assess a range of potential changes in habitat availability and location over time
- Used a foundation of historic conditions to develop a linkage strategy using empirical data while considering potential future conditions using scenarios and a consensus-based approach
- Linked dynamic metapopulation models to the connectivity network to assess the biological importance of corridors in the network
- Combined a suite of connectivity modeling methods with a robust prioritization approach to support decision making under the uncertainty of climate change
- Assembled a regional multispecies linkage network for connectivity under climate change using a suite of focal species complemented by a landscape-focused geodiversity land facet analysis
- Developed two prioritization strategies for identification of key acquisitions within the linkage network and management targets for enhancing connectivity using an approach that can be updated based on stakeholder feedback or implemented by stakeholders themselves to meet management and decision needs over time

INTRODUCTION

Background

Maintaining regional biodiversity and ecological function in the face of the direct and indirect impacts of climate change is one of the central and burgeoning issues facing land managers. Across southern California, increasing temperatures and aridity are predicted over the next century (Westerling *et al.* 2003), with more frequent drought events (Hannah *et al.* 2002), both of which can affect habitat suitability and species persistence. Changes in climate can also have indirect effects, such as extending fire seasons and increasing fire frequency (Swetnam and Betancourt 1998, Brown *et al.* 2004). These fire events have the potential to cause direct wildlife mortality, or can affect wildlife indirectly through shifts in vegetation types and habitat suitability. Locally, temperature shifts are likely to drive migration upslope to cooler climates (Parmesan 2006) or westward to areas with greater marine influence and lower temperatures. However, species' capacity to move to future suitable habitat is challenged by habitat fragmentation and loss, as well as land use changes that result in barriers to dispersal (IPCC 2014). Rapid land use development has been observed and is expected in southern California, where high population density and growth is correlated with increasing numbers of rare and threatened California plants and animals (Underwood *et al.* 2009) and increased fire frequency (Syphard *et al.* 2007). Without strategic, science-based mitigation and management, climate and land use change are expected to cause unprecedented species extinctions at the local and global-scales (IPCC 2014).

Habitat connectivity is the most frequently recommended strategy to support adaptation to climate change (Heller and Zavaleta 2009), habitat fragmentation (Beier and Gregory 2012), and post-disturbance recolonization (Noss 1991, Hilty 2006). In southern California, the California Natural Community Conservation Planning (NCCP) program and Habitat Conservation Plans (HCPs) have resulted in protected area networks to address widespread habitat fragmentation across the region (Riverside County 2003, Ogden 1996). These plans are designed to protect biodiversity by establishing networks of core habitats. Connectivity is essential if these networks are to support the long-term goals of protecting biodiversity, particularly as species' ranges are likely to shift in response to climate change. Landscape connectivity allows for movement among patches of suitable habitat, reduces the chance of extinction for small populations (Brown and Kodric-Brown 1977), and maintains gene flow in patchy landscapes (Simberloff *et al.* 1992). Over longer time scales, and in the face of changing environmental conditions, connectivity will prove critical for facilitating range shifts in response to landscape changes caused by changing climate and altered disturbance regimes (Hannah *et al.* 2002, Heller and Zavaleta 2009).

Efforts to develop proactive, adaptive planning for linked and connected landscapes under climate and land-use change have been increasingly employed in other regions of the western U.S. (Nuñez *et al.* 2013, Penrod *et al.* 2012). However, they have yet to be applied to coastal southern California (Figure 1), despite the region's long history of actions to preserve biodiversity. In this project, we aimed to support the collaborative development of decision-making strategies to establish and enhance landscape connectivity in coastal southern California. To accomplish this task, we built on this history of conservation planning and reserve design to identify a spatially-explicit linkage network that addresses landscape dynamics for regional connectivity planning. This linkage network was designed to allow for local movements among individual preserves while supporting landscape-scale regional connectivity. Using robust, innovative, data-driven models, we developed a methodological approach that serves as a framework upon which land managers and conservation planners in the region can prioritize actions to preserve landscape connectivity and biodiversity under future climate and land use scenarios.

Approach

The modeling approach for this project combined the correlative power of traditional habitat niche modeling, recent advances in connectivity modeling to incorporate landscape resistance through networks of patches, and spatially-explicit demographic dynamics for populations under climate change. Our approach is a critical step forward in connectivity assessment and planning as it relied on data-driven models rather than expert opinion, which has been widely used in the past. Further, by using an ensemble of complementary methods and taking a scenario-based approach to assessing future climatic conditions, we are providing support for decision making under uncertainty (Carroll *et al.* 2018, Krosby *et al.* 2015). By relying on the weight of evidence from our complement of approaches and consensus from climate scenarios, proactive conservation and management decisions can be made to plan for future conditions while accounting for uncertainty.

Managing for landscape connectivity under climate and land use change requires robust, innovative methods that address demographic constraints to species persistence. Although corridors or linkages are recognized as important to population dynamics and persistence, the role of connectivity in population dynamics is not often assessed. Spatially connected populations, called metapopulations, are formed as populations reorganize when there are large fluctuations in birth and death across the landscape. Reorganization can also follow when populations: 1) recolonize an area following disturbances (*e.g.* fire, drought, disease) that reduce populations in good habitat, 2) fragment when contiguous habitat is split, or 3) consolidate when new habitat forms, all of which are likely to occur more frequently in the face of climatic and land-use shifts. Because of these processes, population dynamics are integrally linked to connectivity. To first map and then evaluate functional connectivity based on this biological importance of linkages, we employed a species-focused analysis using a suite of representative species – big-eared woodrat (*Neotoma macrotis*), bobcat (*Lynx rufus*), California spotted owl (*Strix occidentalis occidentalis*), western toad (*Anaxyrus boreas*), and wrentit (*Chamaea fasciata*) – to determine which were most likely to increase long-term population persistence, based on demographic models. The species employed in this analyses were chosen via a collaborative process of stakeholder engagement based on specific criteria, namely demographic and distribution data availability and whether the species was a fairly widely distributed, relatively common species. Our focus on common species is in contrast to the majority of connectivity analyses which focus on species of conservation concern or listed/protected species, which are typically habitat specialists. Efforts focused on protected species have been essential for these specialist species, but may not capture the landscape dynamics necessary for preserving the majority of species or natural communities.

We evaluated and prioritized the key habitats and linkages identified in our modeling that were most likely to provide adaptive capacity for wildlife populations threatened by climate and land-use change to develop strategies for conserving functional connectivity for the South Coast's ecosystems. The linked metapopulation models were combined with other key landscape dynamics and features (*e.g.*, conservation planning status, implementation feasibility) to develop a conceptual framework for identifying and ranking actions to preserve or enhance connectivity. These efforts have, for the first time in this region, applied empirical data to assess and plan for likely future landscape dynamics that will affect habitat suitability and species' persistence.

Purpose and Goal

The purpose of this project was to establish management approaches that maintain landscape connectivity and support biodiversity conservation at the regional level. Our goal was to develop a regional landscape connectivity plan that identified landscape linkages while accounting for species distribution shifts under climate change. The deliverables from the project were designed to:

- provide information and context for decision-making under uncertainty
- complement existing fine-scale preserve designs for rare/protected/listed natural communities, not serve as a substitute
- maintain targets for preservation of biodiversity beyond rare/protected/listed species (*i.e.*, **keep common species common**).
- serve as a complement to work done on rare, habitat specialists
- contribute a needed application to the expanding conservation planning toolbox

In designing a landscape scale approach to connectivity assessment and planning, a multispecies approach was essential. By adopting this multispecies approach and selecting a suite of species that move across the landscape differently, associate with a variety of habitats, and have varying levels of sensitivity to habitat fragmentation and climate, we were striving to provide functional connectivity for many species. At the larger landscape scale, the benefits from this project will support the establishment of feasible and adaptive management approaches and land acquisition strategies to retain landscape connectivity and resiliency, supporting biodiversity within preserve networks and across the region.

METHODS

Study Area

This study was focused on the south coast ecoregion of southern California. This included lands from the Transverse and Peninsular mountains ranging from Santa Barbara County to the U.S. border with Mexico in San Diego County. To ensure we were capturing a range of climatic conditions and avoiding artifacts of edge effects in our connectivity modeling, we expanded our analysis extent north to central coast and southern Sierra Nevada and incorporating desert regions to the east. The analysis area encompassed lands within Monterey, Kings, Tulare, San Luis Obispo, Kern, San Bernardino, Santa Barbara, Venture, Los Angeles, Orange, Riverside, San Diego, and Imperial Counties (Figure 1). Elevation in this area ranges from below sea level in the eastern deserts to 11,503 feet at the high point of San Gorgonio Mountain in San Bernardino County. The Mediterranean climate of the study region is characterized by hot, dry summers and mild, wet winters with annual precipitation often less than 12 inches, virtually all coming during the winter months. Both precipitation and temperature vary across the study area, and are dependent on distance from the coast, elevation, and local topographic features. Temperatures ranges from averages of 58.6–89.4° F in summer to averages of 31.7–57.5° F in winter.

Figure 1. Map depicting the primary study area within the South Coast Ecoregion of California and the expanded analytical extent.

The extent and intensity of development is varied over the study area, which includes the greater Los Angeles metropolitan area, the second-most populous in the United States. Anthropogenic development is most intense along the coast with densely populated urban areas located between the coast and the foothills. Lower housing densities in exurban development are located in the foothills and valleys farther from the coast and the mountains and deserts of the eastern portions of the study area, are dominated by rural communities interspersed with protected lands. Areas characterized by both exurban and rural development included farms, orchards, and ranches with livestock grazing, with a range of small- to large-scale operations.

Vegetation in the region is predominantly shrubland types that vary in composition with elevation and distance from the coast as those are the two primary factors influencing weather patterns and vegetation communities in the region. Closest to the coast and at lowest elevations are coastal scrub dominated by California sagebrush (*Artemisia californica*) and sage species (*Salvia apiana, Salvia mellifera, Salvia clevelandii*). Chaparral is found from the inland valleys and foothills to the mountains in the east and is dominated by chamise (*Adenostoma fasciculatum*), manzanita (*Arctostaphylus* spp.), redshank (*Adenostoma sparsifolium*), scrub oak (*Quercus berberidifolia*), or lilac (*Ceanothus* spp.). Grasslands often composed of non-native annual grasses, and oak woodlands dominated by coast live oak (*Quercus agrifolia*) also occurred at these intermediate elevations in the foothills. Riparian zones in the study area frequently had an oak (*Quercus agrifolia*), sycamore (*Platanus racemosa*), and cottonwood (*Populus fremontii*) overstory with herbaceous understory. Vegetation at the highest elevations within the study area are black oak (*Quercus kelloggii*) and coniferous forests dominated by Jeffrey pine (*Pinus jeffreyi*), Coulter pine (*Pinus coulteri*), incense cedar (*Calocedrus decurrens*), and white fir (*Abies concolor*).

Analytical Overview

To facilitate decision making under uncertainty, we developed a scenario-based focal species approach to model, assess, and prioritize landscape linkages. For this assessment, we used a novel complement of ensemble species distribution models (SDMs) and connectivity models linked with dynamic metapopulation models to advance connectivity planning accounting for climate change, land-use shifts, and uncertainty (Figure 2). We applied these methods to each species for four climate scenarios and prioritized landscape linkages across the region to assemble a single, multispecies linkage network. Below, we summarize the modeling we performed. Additional details on the modeling process can be found in Appendix D.

Focal Species

The five selected focal species were chosen because they are associated with common habitat types within southern California, span a variety of life histories and dispersal abilities, allowing broad comparisons to other species and locations, and have the capacity to represent connectivity for other species in the ecoregion. To ensure important landscape elements were not being excluded as a result of our focal species selection, we complemented this approach with a species-agnostic geodiversity analysis to identify important linkage zones association with topographic features.

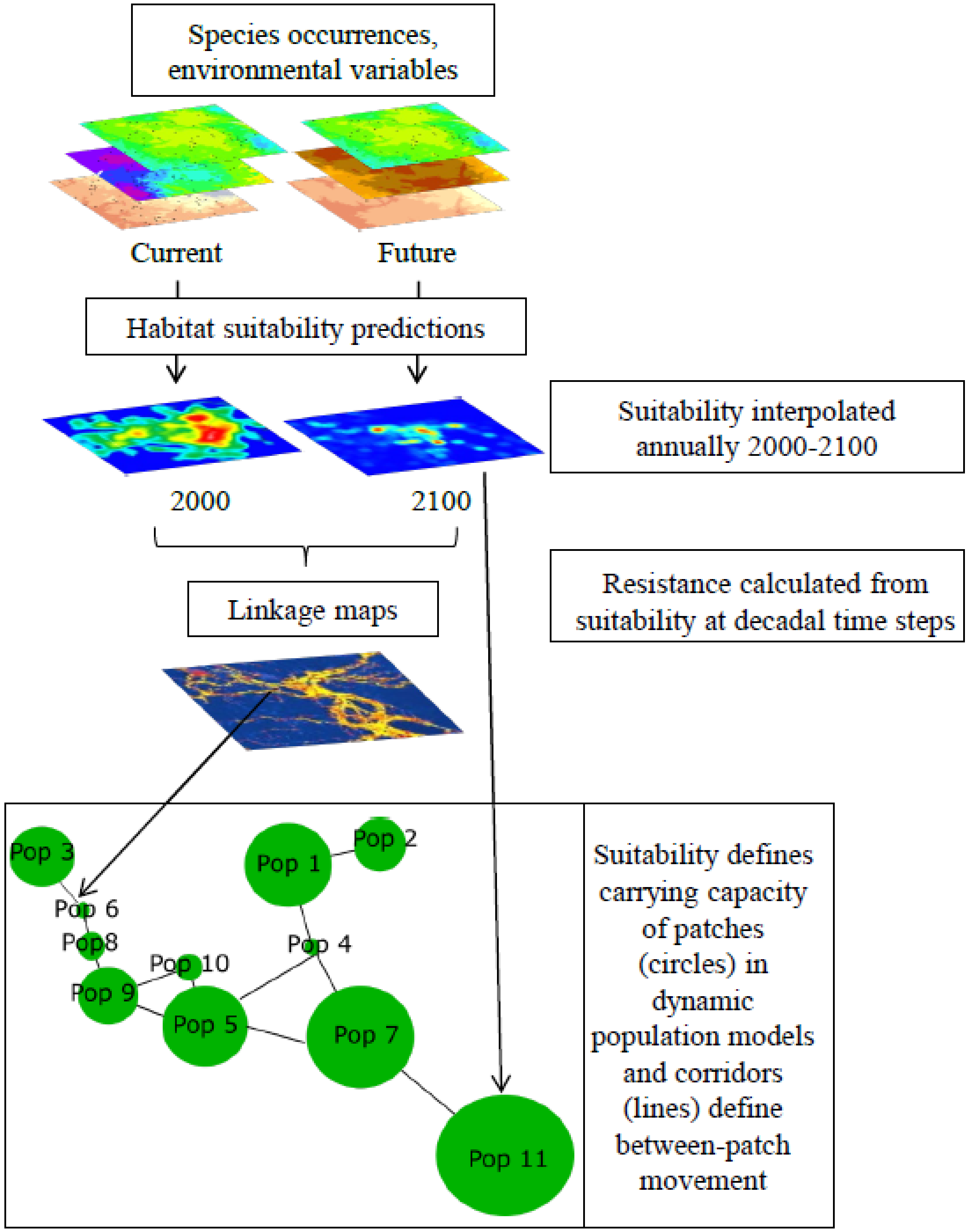

Figure 2. Diagram of analytical process for climate resilient connectivity project. Analysis starts with occurrence points for focal species and their association with climatic and environmental variables. From those points, suitability maps are generated under historic and future conditions. Suitability is converted to resistance, which is used in linkage modeling. Both the habitat suitability and the linkages inform dynamic population models.

At initial stakeholder meetings, we discussed potential focal species for this project. Our goal was to select species that would be representative of connectivity for a broader range of species and were representative of a range of habitat types and movement behaviors/patterns. Because population models were an integral component of this project, we also needed to select species for which adequate demographic data were available to parameterize those models. Our initial selection included the following: bobcat (*Lynx rufus*), wrentit (*Chamaea fasciata*), California spotted owl (*Strix occidentalis occidentalis*), big-eared woodrat (*Neotoma macrotis*), western toad (*Anaxyrus boreas*), and western meadowlark (*Sturnella neglecta*). We developed SDMs for each of these species and initial models were reviewed and then refined based on input from species experts.

Of the six focal species, we found that habitat suitability models for one, the western meadowlark, were not accurate. In consultation with an ornithologist at the San Diego Natural History Museum, Phil Unitt, we determined this was most likely a result of the species ability to utilize typically drier, desert habitats in wet years. As such, we investigated a range of potential other grassland-associated bird species and determined that we would attempt to model habitat suitability the grasshopper sparrow (*Ammodramus savannarum*). We worked to develop and then improve this model based on discussions with Phil Unitt. However, there were limitations in our ability to clearly distinguish between high quality grassland habitats required by the species and degraded grasslands or coastal sage scrub vegetation. After input from our stakeholder review in July 2018, we made several final attempts to improve this model unsuccessfully and removed the species from our focal species list at that time. Instead, we worked to ensure grassland habitats were represented by our geodiversity linkages that were used to fill gaps in our linkage network after we generated the multispecies network. After input from our stakeholder group, we refined models for several other species, requested final expert opinion review and once received, we proceeded with population modeling. For additional details on the stakeholder engagement process, see Appendix G.

More information on each species, as well as a table of species of greatest conservation need identified in California's State Wildlife Action Plan (SWAP) that are likely to directly benefit from the identification and conservation of a resilient linkage network, are in Appendix C.

Climate Scenarios and Environmental Variables

To characterize habitat suitability for each species, we used 90-m resolution environmental layers representing climate, impervious surfaces (land use), stream density, and topography (Table 1). Historic climate variables were derived from 1971-2000 averaged Parameter-Elevation Regressions on Independent Slopes Model data (PRISM, Daly *et al.* 2006) and spatially downscaled to a Digital Elevation Model (U.S. Geological Survey 2009). Projections of future climate originated from global climate model (GCM) projections that were first downscaled to the statewide-level using Localized Constructed Analogs (LOCA) downscaling (Pierce *et al.* 2014) to 1 km followed by further localized downscaling for southern California to 90-m resolution using the California Basin Characterization Model (CA-BCM; Flint and Flint 2012, Flint *et al.* 2013).

To project the distribution of future suitable habitat, future climate variables were substituted into habitat suitability predictor functions estimated from current climate data. To evaluate future climatic shifts on the suitable habitat and connectivity for our focal species, we selected two GCMs that spanned extremes of warmer-wetter (CNRM-CM5) and hotter, drier (MIROC5)

Table 1. Environmental and climatic variables used in species distribution and population models. Bolded scenarios were used in population modeling.

	Name	Description and source	Time variant
Climate	Source: Downscaled (to 90m) **PRISM**, MIROC5 RCP4.5, **MIROC5 RCP8.5**, CNRM CM5 RCP4.5, **CNRM CM5 RCP8.5**		
	Bioclim 1	Mean temperature averaged over all months and the 30-year period preceding 2000 and 2100.	Yes
	Bioclim 2	Mean diurnal range (mean of monthly (max temperature-minimum temperature)) averaged over the 30-year period preceding 2000 and 2100.	Yes
	Bioclim 4	Temperature Seasonality (Monthly standard deviation *100) averaged over the 30-year period preceding 2000 and 2100.	Yes
	Bioclim 6	Minimum temperature of the coldest month averaged over the 30-year period preceding 2000 and 2100.	Yes
	Bioclim 12	Mean precipitation averaged over all months and the 30-year period preceding 2000 and 2100	Yes
	Bioclim 14	Precipitation of the driest month averaged over the 30-year period preceding 2000 and 2100.	Yes
	Bioclim 15	Precipitation seasonality (coefficient of variation across months) averaged over the 30-year period preceding 2000 and 2100.	Yes
Land use	Source: National Land Cover Database 2011 (Jin *et al.* 2013)		
	Impervious surfaces	Used as a proxy for urban land cover	No
Water Resources	Source: Zimmerman *et al.* 2018		
	Distance to seasonal streams	Derived from Zimmerman *et al.* 2018; calculated as Euclidean distance to streams with low probability of year-round flow	No
	Distance to perennial streams	Derived from Zimmerman *et al.* 2018; calculated as Euclidean distance to streams with high probability of year-round flow	No
	Density of all streams within a 5km moving window	Density of all streams within a 5km moving window	No
Topography	Source: National Elevation Dataset (U.S. Geological Survey 2009)		
	Roughness Index	Total curvature derived from National Elevation Dataset with DEM Surface Tools (Jenness 2013)	No
	Percent Slope	Derived from National Elevation Dataset	No

conditions for southern California under two future greenhouse gas emissions simulations: one with substantially mitigated emissions, (Representative Concentration Pathways [RCP] 4.5) and the other with emissions produced under business as usual (RCP 8.5). We modeled habitat suitability and connectivity for all species under these four future climate scenarios: CNRM-CM5 RCP4.5, CNRM-CM5 RCP8.5, MIROC5 RCP4.5, and MIROC5 RCP8.5. For population modeling, we compared only the business as usual emissions scenario for the two climate models (CNRM-CM5 RCP8.5 and MIROC5 RCP8.5) as well as a model with no projected change in conditions in the future.

Recognizing that not all species will respond directly to changes in temperature and precipitation variables, we also evaluated whether incorporating vegetation change or vulnerability would allow us to assess future distribution of our focal species more accurately. We accomplished this by creating an ensemble of vegetation resilience from the vegetation vulnerability conducted by Thorne and colleagues (2016) that we applied to the historic habitat suitability maps for each species. Ultimately, this scenario was only sufficiently divergent from the other scenarios for the California spotted owl. As such, we only included this scenario in population modeling comparisons for that species.

Species Distribution Models

We used SDMs to predict the distribution of suitable habitat for our five focal species representing different habitat associations: mountain-conifer dependent spotted owl, shrub-dependent wrentit, chaparral-dependent big-eared woodrat, riparian-dependent western toad, and the long-distance dispersing generalist bobcat. Because different SDMs can lead to vastly different predictions about habitat suitability (Elith *et al.* 2006), our final suitability surfaces were derived from an ensemble of five different modeling approaches.

For all focal species, we mined public databases (*e.g.*, eBird, iNaturalist, BIOS) and all unpublished literature for each species (Table 2). To avoid including older data points in areas that have since been developed (thus artificially suggesting urban areas may be suitable based on these locations), we implemented a temporal cutoff, only using data from 1980 to present. The data and models for each species were reviewed and discussed with experts, and all models were quantitatively evaluated using cross-validation based on prediction of presence versus absence for withheld testing data. This was repeated with different subsamples of the data in each run for the most robust approach.

Using the SDM suitability in the historic and future (2100) time periods as end points, we interpolated suitability at annual time steps in the intervening years. We then used these suitability surfaces to generate resistance for the decadal connectivity modeling, define habitat patches for linkage and metapopulation modeling, and estimate carrying capacities of metapopulation patches.

Table 2. List of focal species selected for modeling with data sources identified. The number of occurrence points available and the number and type points (background or true absence) used in species distribution modeling for each species. [1]eBird 2016; [2]California Department of Fish and Wildlife 2017; [3]GBIF 2018a; [4]GBIF 2018b; [5]GBIF 2018c; [6]BISON 2017; [7]U.S. Forest Service 2017; [8]U.S. Geological Survey (R.N. Fisher, *unpublished data*); [9]NA HERP 2018; [10]HerpMapper 2018 [11]Arctos 2016; [12]National Park Service (S.P.D. Riley, *unpublished data*); [13]San Diego Natural History Museum (Tremor *et al.* 2017); [14]San Diego State University (M.K. Jennings, *unpublished data*); [15]VertNet 2018.

Focal species *(Scientific name)*	**Habitat association**	**Data sources**	**# presence points**	**Absence or background points**	**# absence/ background points**
California spotted owl *(Strix occidentalis occidentalis)*	Coniferous and hardwood forest	eBird[1], CNDDB[2]	1,865	Absence	5,595
Wrentit *(Chamaea fasciata)*	Shrubland	eBird[1]	5,894	Absence	17,682
Western toad *(Anaxyrus boreas)*	Riparian, wetland, and upland scrub	GBIF[3], BISON[6], USFS[7], USGS[8], NAHerp[9], HerpMapper[10]	1,029	Background	3,087
Bobcat *(Lynx rufus)*	Generalist	GBIF[4], BISON[6], Arctos[11], NPS-SAMO[12], SDNHM[13], USFS7, SDSU[14]	507	Background	1,521
Big-eared woodrat *(Neotoma macrotis)*	Chaparral	GBIF[5], BISON[6], SDNHM[13], VertNet[15]	473	Background	1,419

Linkage Modeling

We took three complementary approaches to linkage modeling for this analysis: least cost corridor analysis and Circuitscape current flow for each of our focal species, and a species-agnostic geodiversity or land facet analysis. Our primary analysis employed a least cost corridor or least cost path analysis implemented in Linkage Mapper (McRae and Kavanagh 2011). This method allowed us to identify discrete linkages between core areas based on the lowest cost of moving through the landscape, represented by our resistance surface. The core and linkage framework for this approach also served as the inputs for the spatially-explicit metapopulation models. We ran least cost corridor analyses for each species under historic conditions (2000) and at ten decadal intervals (2010-2100) under the four climate scenarios. To compare a different approach to modeling connectivity for each species we generated a wall-to-wall surface that did not require designation of discrete habitat patches, we performed electrical circuit theory-based analyses using the program Circuitscape (McRae *et al.* 2008, 2013; www.circuitscape.org) under historic conditions for each species.

Finally, in addition to the focal species linkages, we also generated corridors using a species-agnostic landscape approach focused on geodiversity (Comer *et al.* 2015, Theobald *et al.* 2015), or land facets (Beier and Brost 2010, Brost and Beier 2012), designed to identify linkages that retain a range of features defined by slope angle, solar insolation, topography, and elevation. This method was specifically developed as an approach to connectivity assessments under climate change that would be robust to the uncertainty in climate data and issues with scale. To execute the land facet modeling, we used ecologically-relevant landform data (Theobald *et al.* 2015) as the source for the individual facets. Of the 15 landforms in the original dataset, we selected three representing cool landforms (cool lower slopes, cool upper slopes, and cool peaks and ridges) and two to represent grasslands (valley and narrow valley), which we were not able to incorporate with our focal species. To generate land facet linkages, we used the Land Facet Corridor Designer (Jenness *et al.* 2010) and Linkage Mapper (McRae and Kavanagh 2011).

We transformed habitat suitability surfaces described above to resistance using a non-linear conversion (as described in Keeley *et al.* 2016) related to the species ability to traverse unsuitable habitats. The resistance and habitat patch layers were used as the primary inputs for least cost corridor linkage modeling we performed for decadal time steps under each scenario. We did not apply species-specific dispersal limitations at this stage so as to allow for corridors to be developed that would accommodate species with similar habitat associations but not necessarily the same dispersal limitations. Instead, species-specific dispersal was integrated into the population models to assess functional connectivity and biological importance of each linkage.

Our final linkage plan was reviewed using both the Circuitscape and geodiversity outputs to ensure no critical linkage zones were omitted from this final multispecies linkage network.

Population Models

Once corridors were identified for each species, they were integrated into metapopulation models implemented in RAMAS GIS 5.0 (Akçakaya and Root 2005). These models assumed that individuals were well-mixed within a patch and that distances between patches evolved with climate change. We considered the importance of existing corridors only and the amount of dispersal through linkages was dependent on species' ability, abundance of the giving patch, and carrying capacity of the final patch. We tested the importance of each linkage by comparing the final abundance of the metapopulation with each corridor activated individually and compared that to models where no corridors were active. We used the change in final abundance to calculate the percent increase in the metapopulation when the corridor was added. To focus on biologically important changes in landscape connectivity, we determined a minimum threshold above which we did not expect changes in final population size were due to chance alone. For corridors above this threshold, we calculated a relative importance on a scale from 0 to 1 where 1 was the maximum value observed across all scenarios. This threshold was especially important given the sources of variability in the model.

For spotted owl, wrentit, western toad, and bobcat we began with vital rates identified in COMADRE (Salguero-Gómez *et al.* 2016) and adjusted them to account for errors (spotted owl) and local conditions (wrentit, western toad, and bobcat) using local data sources provided by species experts we consulted. For woodrat we used a model developed by Stephen Rice that calculated survival and fecundity rates using survival and matrilineal data from Kelly (1990), Linsdale and Tevis (1951), and Matocq (2004). In a given year, each individual of a species either lives or dies with or without replacement.

For wrentit and owl, we added local (within population, not across population) catastrophic drought that decreased vital rates in a given time step. Droughts were assumed to occur every 4-5 years, which is less than California's historic drought frequency, but consistent with species response frequency. We imposed periodic drought because the impact of drought on vital rates has been documented in the literature (Preston and Rotenberry 2006; LaHaye *et al.* 2004). No drought catastrophe was included in the metapopulation modeling for bobcat or woodrat as we did not have empirical data to determine if or how drought might negatively impact the vital rates of these species. For the western toad, although we would expect this species to be negatively impacted by drought, incorporating this catastrophe into the metapopulation modeling led to high instability in abundance, making the identification of priority corridors impossible. We therefore omitted drought catastrophes in the population modeling for this species as well.

Multispecies Linkage Assembly and Prioritization

To create a single regional multispecies linkage network, we prioritized the individual species cores and linkages developed with the least cost corridor modeling and then filled gaps in the network using our Circuitscape and geodiversity linkages (Figure 3). For each species, linkages and core areas under historic conditions were assembled into a single polygon layer. From there, a suite of attributes were assigned to each core and linkage segment for prioritization using the Environmental Evaluation Management System (EEMS 2.02; Sheehan and Gough 2016) implemented in ArcGIS. EEMS is a hierarchical fuzzy-logic based prioritization tool that can be used for decision support. Our within-species prioritization was based on four main elements: connectivity and landscape value, climate consensus value, linkage implementation feasibility, and metapopulation persistence value (Figure 4).

Linkage feasibility filtering accounted for factors that would affect how easy or difficult it would be to actually conserve linkages within the network, including percent of area already conserved, number of parcels, and average parcel size/unit area.

Connectivity and landscape value encompassed measures of betweenness (*i.e.*, importance of an individual linkage as a hub within a network), habitat quality metrics including the ratio of patch edge to overall area, impervious cover, and resistance, as well as consideration for whether a linkage overlaps with areas previously identified as important under the South Coast Missing Linkages (SCML; South Coast Wildlands 2008) or California Essential Habitats Connectivity (CEHC; Spencer *et al.* 2010) projects.

Climatic resilience consensus value accounted the value of linkages under climatic changes in the future based on the premise that the more evidence we have that certain linkages are important, the more confident we can be that it will provide climatic resilience value in the future. We calculated consensus two ways: 1) based on connectivity to climate analogs, and 2) accounting for how many time steps in our decadal modeling a linkage persists within each of the four climate scenarios. Our assessment of climate analogs evaluated climatic water deficit (Flint *et al.* 2013) that accounts for temperature and precipitation under two climate scenarios (warmer-wetter and warmer drier, both under business as usual emissions). We assessed linkage connections based on the climatic envelopes of historic and future conditions using the Linkage Priority Mapper tool (Gallo and Greene 2018). The importance of each linkage for connecting climate analogs was combined with closeness, permeability, and core area value to assign a final value. We assigned the climate envelope difference twice the weight of the other factors considered. For our accounting of the value of linkages over time and across scenarios, we evaluated consensus assuming the greater number of times a linkage was present, the more likely it is important for connecting present and future habitat patches.

Finally, **metapopulation persistence** was based on a prioritization determined through the Linkage Priority Mapper (Gallo and Greene 2018) using the relative importance value described above. As with the climate analog prioritization, relative importance of each linkage was determined by combining the relative importance value with closeness, permeability, and core area value. We assigned the relative biological importance twice the weight of the other factors considered. This priority value was calculated under the no change scenario, as well as two climate models (warmer-wetter and warmer-drier) under business as usual emissions. For spotted owl, we also included the more optimistic vegetation vulnerability model.

The climatic consensus metrics allowed us to assign greater value to areas where there was agreement about important linkages over time and across scenarios, providing greater support for decision-making under uncertainty. By combining currently known landscape conditions such as impervious surface cover and percent land conserved with those that are less certain from our climatic modeling, our prioritization approach was grounded in empirical data while providing a robust framework for considering the value of linkages in the future for resilience in the face of climate change.

Once linkages were prioritized for each species, those with highest values were selected for inclusion in the multispecies network. To assemble this network, we took a union of the cores and linkages from the historic framework. We then combined the maximum and average within-species prioritization score across all species and determined which areas of our union served three or more species, assigning a new score based on these three elements ranging from -1 to 1. We then set a threshold of 0.35 and selected all segments from the multispecies union that were above this threshold to form the basis of the multispecies network (Figure 5a). Additional details on this prioritization process can be found in Appendix E.

Once we established this basis using the highest priority segments from the least cost corridor models, we reviewed the output from our individual species Circuitscape models under historic conditions. We created both a multispecies average using the top 20% of flow and a maximum, selecting the top 30% of flow, after normalizing the outputs for all species (Figure 5b). We combined these thresholded flow surfaces and found there were some missing elements in the central part of our network in the eastern Los Angeles Basin and the San Gabriel Mountains, so expanded linkages in these areas accordingly. Finally, we reviewed our species-agnostic geodiversity land facet linkages and found that the facets providing connectivity along cool lower slopes, upper slopes, and peaks and ridges were well-represented by our focal species linkages. However, given the absence of a grassland-associate from our suite of focal species, only a portion of the valley and narrow valley linkages were covered by our species-based linkages. As such, we added these complementary linkage segments to the regional network (Figure 5c).

Upon review of the linkage network with the stakeholder group at the May 24, 2019 meeting, we received feedback that the models appeared to identify several areas of relatively intense development in the greater Los Angeles area as important connectivity areas. As the models we employed were not quite sensitive enough to detect this intermix area adjacent to open spaces, particularly in areas of recent development, we determined that modification of the final linkage network was necessary in these areas. We refined the final linkage network by examining and comparing the geography of existing conservation planning efforts in the region such as the Rim of the Valley plan for the Santa Monica Mountains, the Emerald Necklace Vision Plan that targets the Los Angeles, San Gabriel, and Rio Hondo Rivers for conservation, as well as conservation planning efforts for the upper and lower segments of the Santa Ana River watershed. We refined the final linkage network to match up with these areas and also modified the linkage network through the Chino and Puente Hills to remove areas of recent development that would preclude functional landscape connectivity for most wildlife species.

Linkage Prioritization for Decision Support

To facilitate decision making using the linkage network we generated, we created two different prioritization strategies for the final linkage network focused on identifying acquisition targets and management targets for end users. We accomplished this by segmenting the linkage network into subregions based where major highways or freeways intersected the network to attribute each linkage type within these subregions.

For the acquisition model (Figure 6), we first removed all large, conserved segments of the network. As these areas are already conserved, they did not need to be included in a prioritization for acquisition. The remaining linkage segment types were attributed based on four themes: status from our focal species linkage modeling, more general biodiversity and connectivity values, conserved lands status, and potential for future conversion to urban land uses. The description of these values and their sources are included in Table 3. Using this information, we identified locations that are currently undeveloped and prioritized them if they were important for multiple focal species, had high biodiversity, were either near to or included a large proportion of conserved lands, and were likely to be converted to urban land-uses under either of the future development scenarios considered.

For the management target model, we included the entire linkage network so actions to establish or enhance connectivity on conserved lands could be prioritized based on risks to functioning (Figure 7). The strategy included the same biological/biodiversity values as the acquisition models, but in contrast, focused on areas where management action could potentially mitigate the most pressing threats to connectivity in the region (Table 4). These included either the amount of impervious surface or average distance to nearest urban edge, road density, and average fire return-interval departure (FRID), which could help identify areas that may be at risk of vegetation-type conversion. Whereas our acquisition model selected for maximum or minimum values of most variables, the management prioritization targeted areas with middling values of risk for action. For example, where there is a very high degree or close proximity to urbanization, there is often little that can be done to substantially improve connectivity. On the opposite end of the spectrum are areas that have little existing development or are far from urban areas, which are less likely to need management intervention to improve connectivity. Our prioritization targeted areas where some mitigation of risks is needed and where action is likely to have a measurable impact on connectivity.

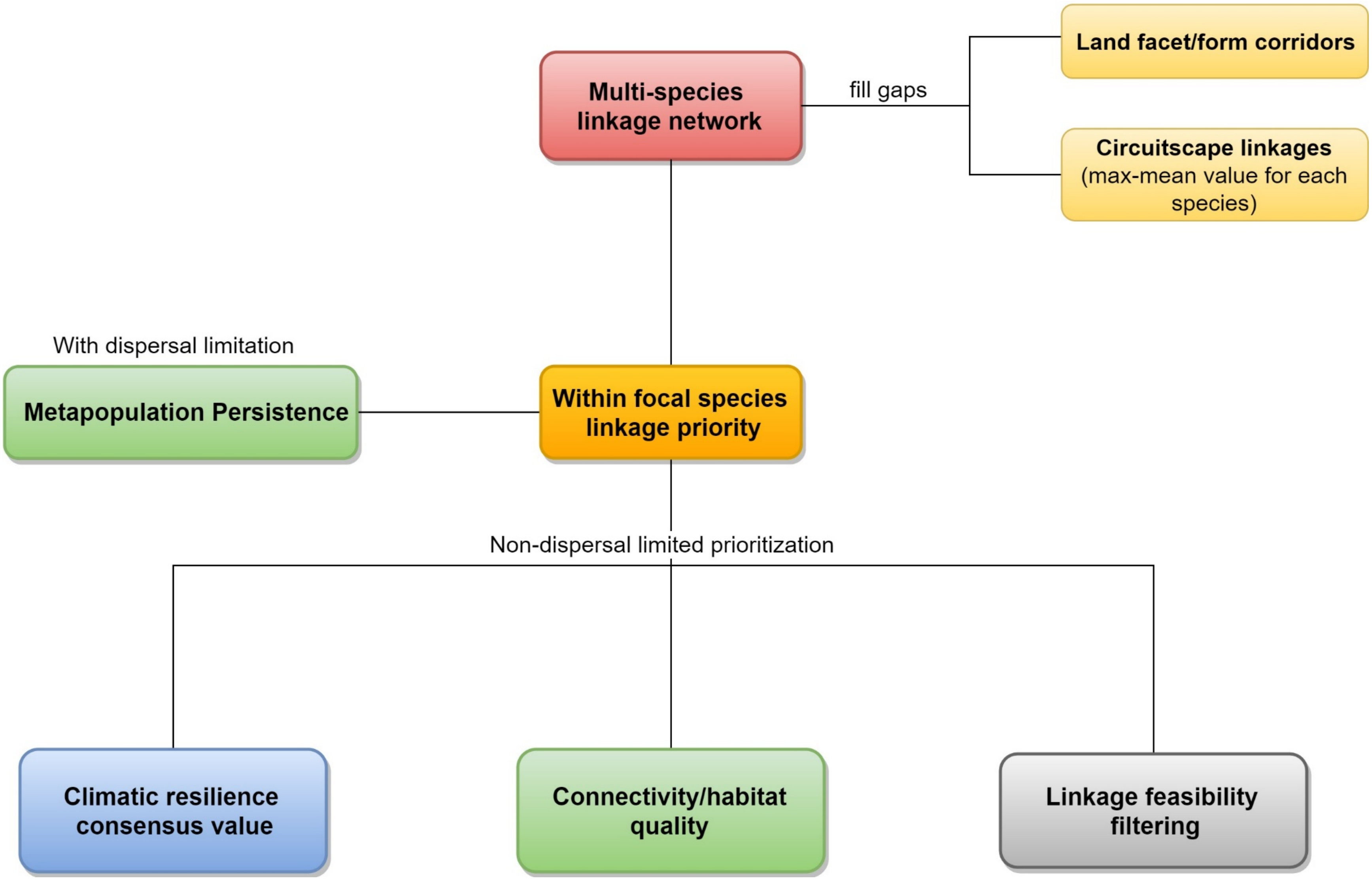

Figure 3. Conceptual model of how individual focal species linkages are assembled into a single multispecies network.

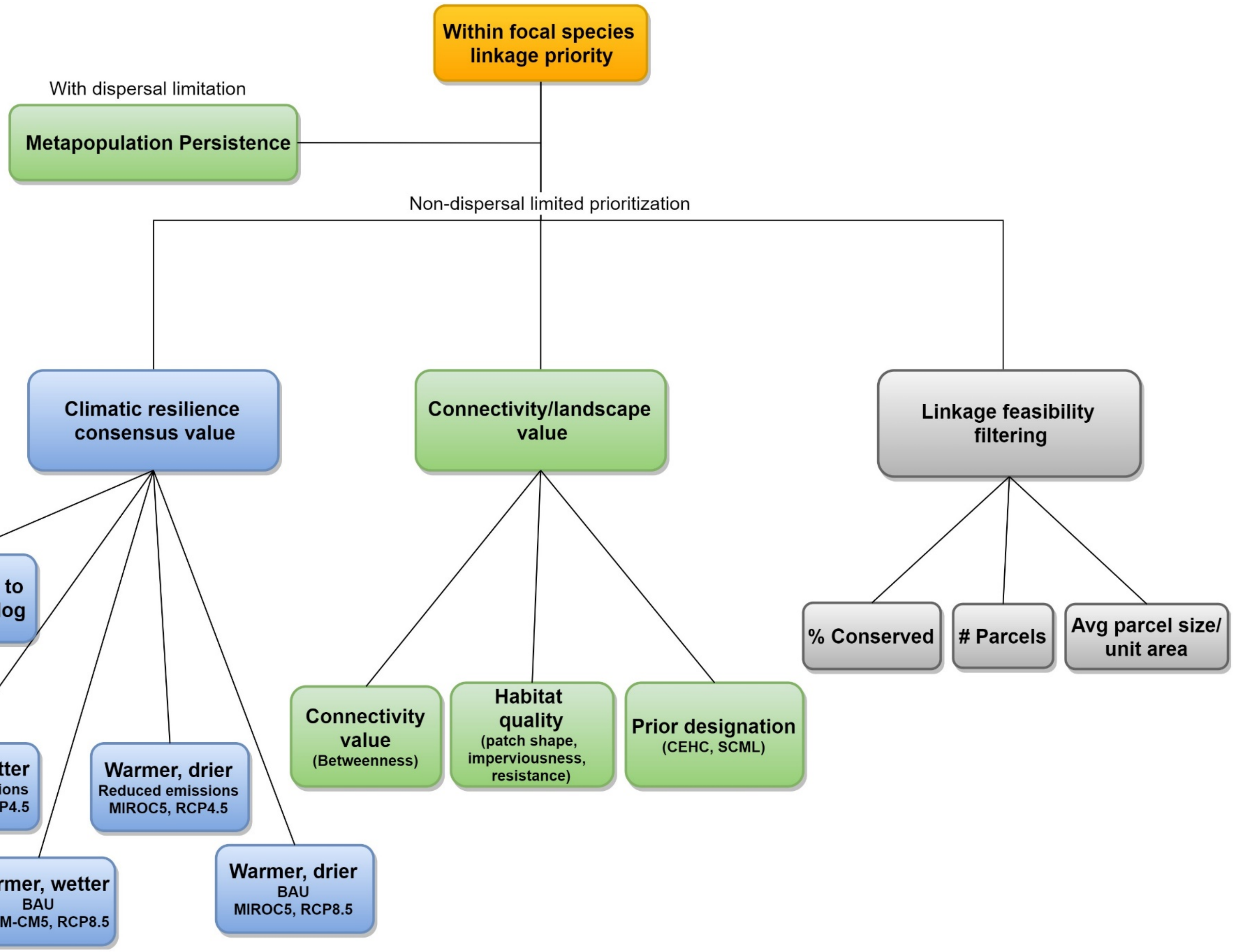

Figure 4. Further detailed conceptual model of linkage prioritization process for each focal species.

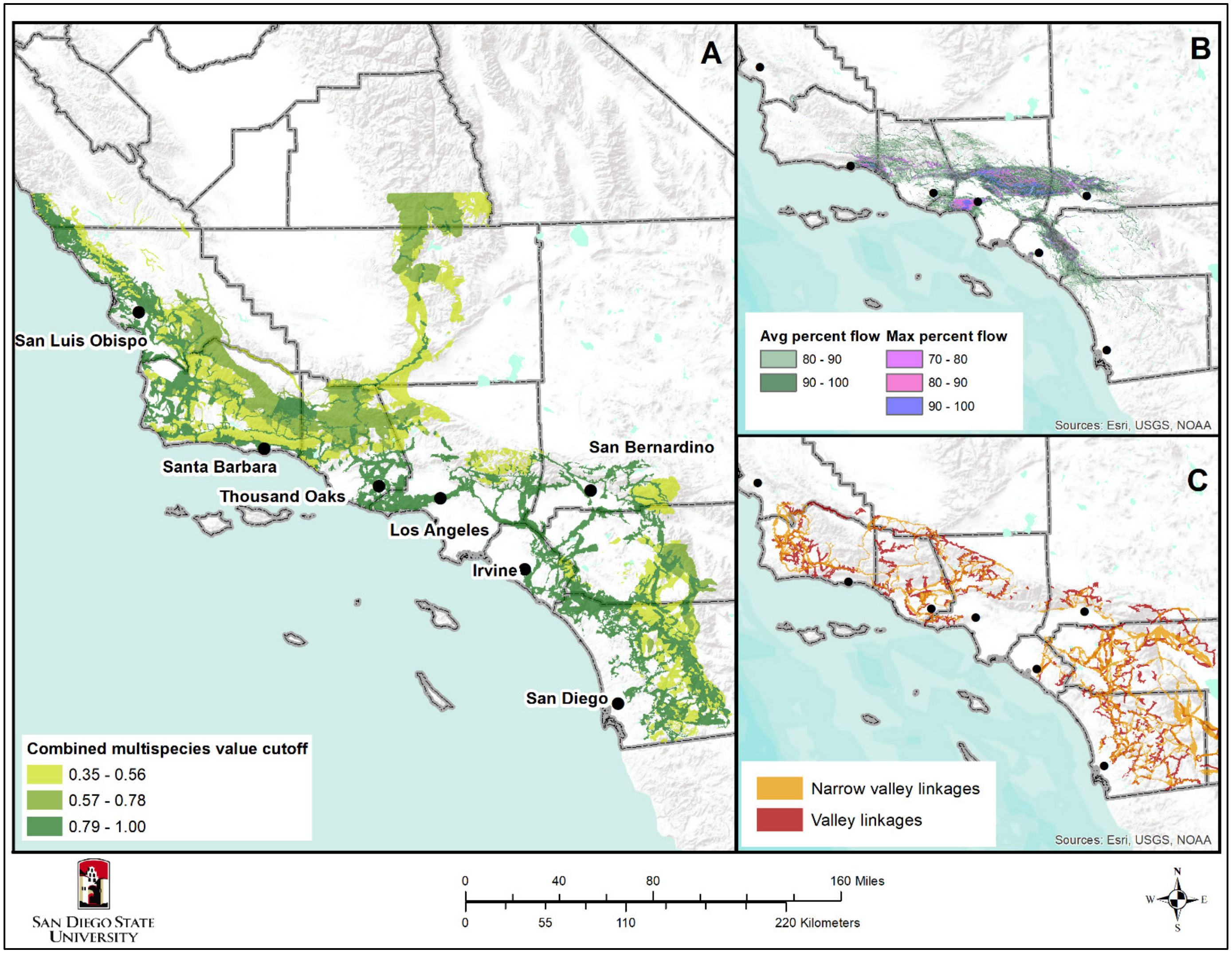

Figure 5. Maps depicting the outputs of the three linkage modeling approaches used to assemble the final linkage network. Panel A shows the selected threshold for the prioritized least cost corridor models; Panel B shows Circuitscape outputs reflecting the combined top 20% of the average normalized percent flow and top 30% of the maximum percent flow for all species; Panel C shows the selected geodiversity land facet linkages through valleys and narrow valleys.

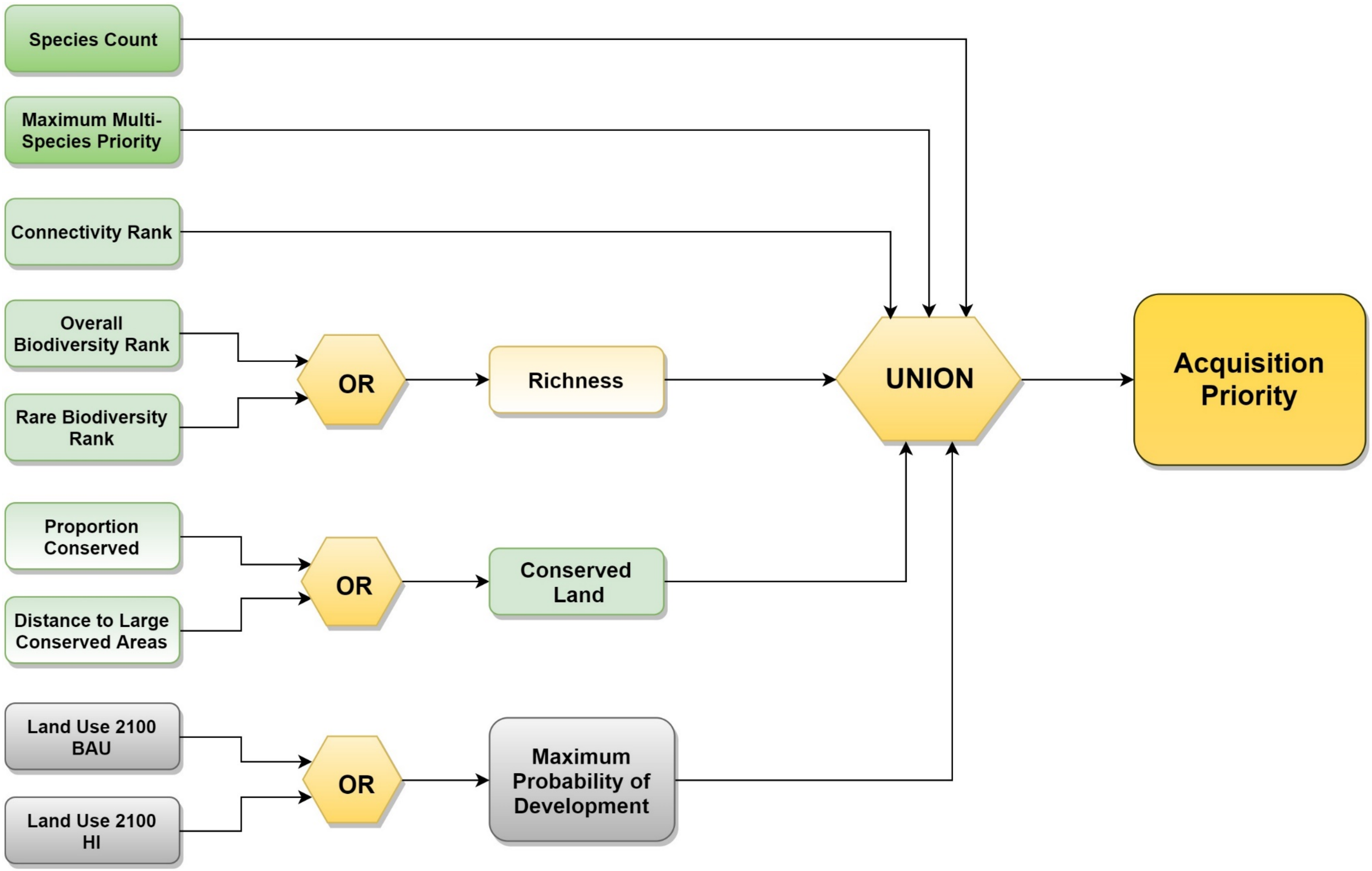

Figure 6. Prioritization scheme for acquisition decision making. All variables were evenly weighted in the final union.

Table 3. Description of variables and sources used in the acquisition prioritization model depicted in Figure 6.

Attribute	Description	Source
Species Count	Count of individual species linkages that overlap linkage segment (up to 5 species)	Climate Resilient Connectivity focal species modeling
Maximum Multi-Species Priority	Averaged maximum priority value of within-species prioritization for any given species across each linkage segment	Climate Resilient Connectivity focal species modeling
Connectivity Rank	Averaged ecoregional connectivity ranking based on compiled connectivity data, including California Essential Habitats Connectivity and South Coast Missing Linkages (ranks range from 1-5 with 5 being the highest)	California Department of Fish and Wildlife, Areas of Conservation Emphasis III (ACE III) database
Overall Biodiversity Rank	Averaged ecoregional biodiversity ranking; ranks range from 1-5 with 5 being the highest.	California Department of Fish and Wildlife, Areas of Conservation Emphasis III (ACE III) database
Rare Biodiversity Rank	Averaged ecoregional rarity ranking; ranks range from 1-5 with 5 being the highest.	
Proportion Conserved	Proportion of each linkage segment in conservation status	Combined data from the SANDAG and the California Protected Areas Database (GreenInfo Network 2018)
Distance to Large Conserved Areas	Calculated as the distance from the centroid of each linkage segment to the nearest edge of any block of conserved land >1,000 acres in size	
Land Use in 2100 Business As Usual	Proportion of each linkage segment projected to have converted to urban land use by 2100 under a business as usual growth scenario.	USGS California land-change projections (Sleeter *et al.* 2017)
Land Use in 2100 High Rate of Development	Proportion of each linkage segment projected to have converted to urban land use by 2100 under a business as usual scenario with a simulated high population growth trajectory.	

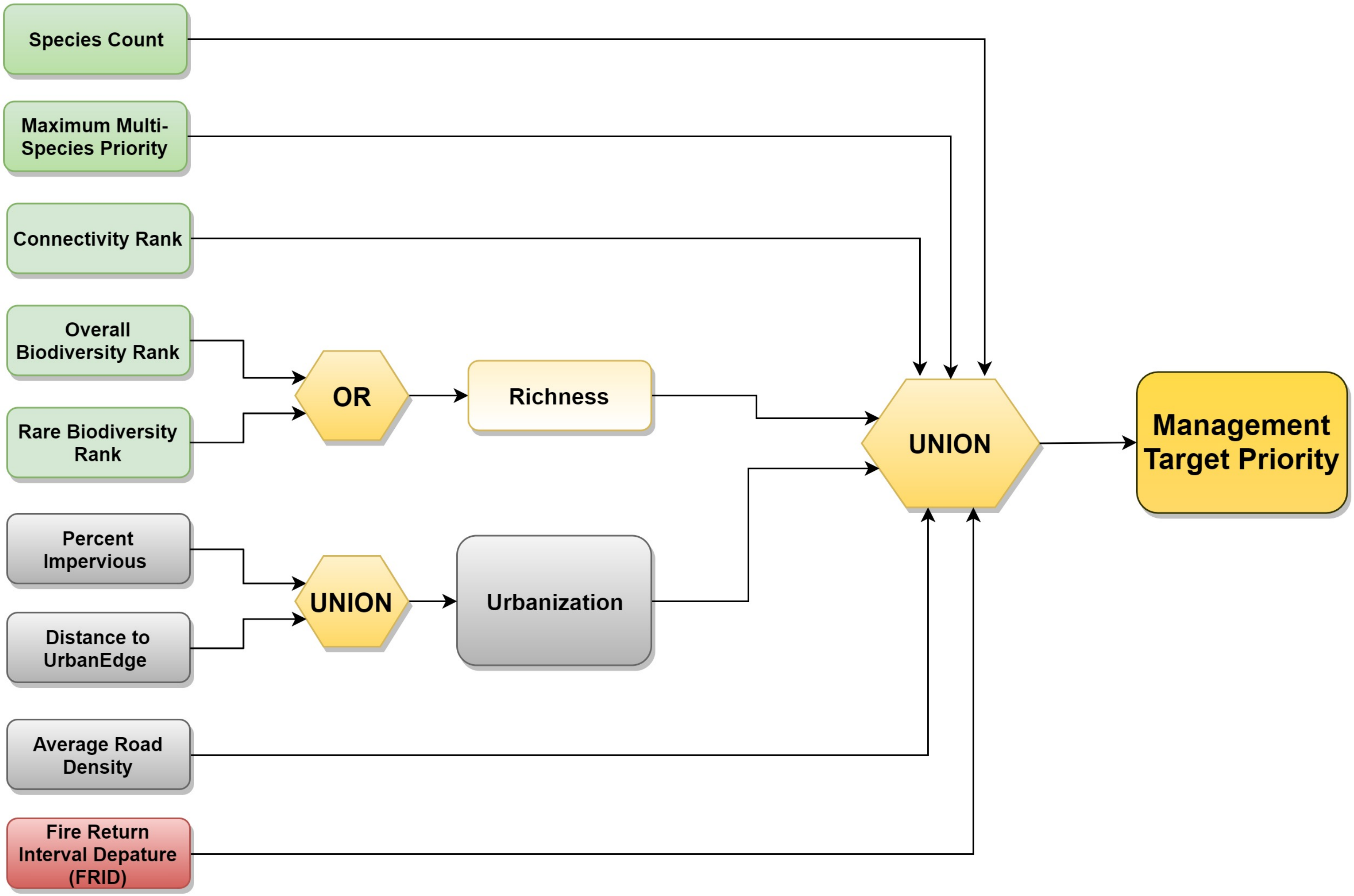

Figure 7. Prioritization scheme for setting management targets to enhance connectivity.

Table 4. Description of variables used in the acquisition prioritization model depicted in Figure 7.

Attribute	Description	Source
Species Count	Count of individual species linkages that overlap linkage segment (up to 5 species)	Climate Resilient Connectivity focal species modeling
Maximum Multi-Species Priority	Averaged maximum priority value of within-species prioritization for any given species across each linkage segment	Climate Resilient Connectivity focal species modeling
Connectivity Rank	Averaged ecoregional connectivity ranking based on compiled connectivity data, including California Essential Habitats Connectivity and South Coast Missing Linkages (ranks range from 1-5 with 5 being the highest)	California Department of Fish and Wildlife, Areas of Conservation Emphasis III (ACE III) database
Overall Biodiversity Rank	Averaged ecoregional biodiversity ranking; ranks range from 1-5 with 5 being the highest.	California Department of Fish and Wildlife, Areas of Conservation Emphasis III (ACE III) database
Rare Biodiversity Rank	Averaged ecoregional rarity ranking; ranks range from 1-5 with 5 being the highest.	
Percent Impervious	Average percent impervious surface cover (used as a proxy for the degree of urbanization) within each network segment	National Land Cover Database (Jin *et al.* 2013)
Distance to Urban Edge (m)	Calculated as the distance from the centroid of each network segment to the nearest edge of urban lands	Urban lands from the California Farmland Mapping and Monitoring Project data (2016)
Average Road Density (km/km^2)	Density of paved roads calculated as km per km^2	Open Street Map (2014)
Mean percent fire return interval departure	Percent departure from assumed historic fire return intervals. Positive values indicate lengthening return intervals with longer periods between fires, and negative values indicate increasing frequency in fires, which can result in vegetation type conversion in shrublands	Fire Return Interval Database (Safford and van de Water 2014)

Results

Species Distribution Models

Based on our assessments of performance using cross-validation, the models for all five focal species performed relatively well at predicting suitability of occupied habitat. The bootstrapped accuracy averaged across models and ten subsamples of data was 0.95 for owls, 0.80 for wrentit, 0.85 for woodrat, 0.83 for western toad, and 0.80 for bobcat, all based on a scale of 0 to 1. Species distribution models can be accessed here.

The model for spotted owl had very high accuracy at predicting suitability in the historic period. The future scenarios all appeared dire for this species with up to 90-96% core habitat area lost by 2100 under future climate scenarios. However, these climate-based models could be inaccurate if forest habitats are able persist for longer than model shows providing opportunities for spotted owl to hold out. Under our vegetation resilience scenario, there was only a 63% projected loss in core habitat area by 2100. The model of historic suitability for the wrentit also appeared to perform reasonably well. Future suitability increased substantially along the central coast, most likely because what is currently too wet and cool for the species will become more suitable by the end of the century as conditions become warmer and drier. This compensated for projected habitat loss for the species in the southern portion of our study area with an estimated habitat losses ranging from 10-26% under future scenarios in 2100. Suitability estimates for the western toad performed reasonably well for identifying riparian areas and identifying instream habitat after additional data were gathered to improve the projections of historic suitability for this species. Projections of future habitat for the toad diverged substantially under the different scenarios with the warmer-wetter scenarios resulting in a more substantial loss of core habitat area (76%) compared to the warmer-drier scenario (29%). Although the model for bobcat was able to distinguish between areas that were more and less suitable under historic condition, the overall suitability values were lower than are likely realistic. In particular, the model appears to underpredict suitability at high elevations likely due to a lack of sampling or observation bias in the occurrence data. We gathered all available data we could obtain for the species and also implemented spatial subsampling to improve model performance in areas where a lack of observations were biasing the model toward reduced suitability. Although the suitability maps were limited by the distribution of existing data, we were able to compensate for the reduced suitability by using a resistance conversion that allowed for a greater degree of movement or lower cost through areas of moderate or low suitability. Under the future scenarios of climatic conditions, bobcats were projected to lose between 36% and 56% of core habitat area. The models for big-eared woodrat, accurately predicted their affinity for high elevation forests as well as dense shrublands and drainages. The future predictions project minimal core habitat area loss for this species with estimated reductions ranging from 5% to 14%.

Linkage Models

After generation of historic least cost corridor surfaces for each species, we truncated results on a species-specific basis to establish linkages that were wide enough to accommodate movement, but restricted to an implementable area. Across the region, the combined core and restricted linkage network under historic conditions resulted in identification of: 8,583 mi^2 for big-eared woodrat, 6,502 mi^2 for bobcat, 5,592 mi^2 for California spotted owl, 4,457 mi^2 for western toad, and 6,397 mi^2 for wrentit. The union of each of these segments comprised 16,115 mi^2 across the region. Maps of the within-species prioritizations used to assemble the final linkage network can be found in Appendix F.

The combination of Circuitscape outputs from the top 30% of the maximum flow value and top 20% of the average flow value resulted in identification 1,804mi^2 of linkage area. A portion of this overlapped with the least cost corridor network and some segments identified flow through areas with very high levels of impervious surface, representing urban density. From the geodiversity land facet linkages, we evaluated an additional 2,572 mi^2 of linkages in valleys and 2,664 mi^2 in narrow valleys.

Metapopulation Models

Under warmer-wetter and warmer-drier conditions for wrentit and big-eared woodrat, we found that dispersal-limitation for both species restricted the number and length of corridors that were important to the metapopulation. Furthermore, we observed that considerable habitat consolidation in the north limited the benefit of connectivity. Connectivity appeared to be most important in the future where habitat fragmentation was projected in the southern portion of our study area. Under warmer-wetter and warmer-drier conditions for bobcat and western toad, we found that fragmentation for both species in the future reduced the overall risk to the population because patches become separated and as such, were less likely to simultaneously experience events that would affect subpopulations (*e.g.,* patch-scale fires). For these two species, corridors connecting patches of habitat that were projected to fragment under climate change were particularly beneficial. As a long-distance disperser, bobcats relied on long corridors, and overall, benefitted more from connectivity than the other focal species. The results for spotted owls were very different under all scenarios and demonstrated the most substantial climate change impacts. With most of their habitat at high elevations, spotted owls are projected to lose too much habitat with 'shrinking mountaintops' and under any of the scenarios, there was not enough habitat remaining to support sustainable populations to the end of the century. This means there was little benefit of corridors in the future, even considering the "optimistic" vegetation resilience scenario. A package of side-by-side maps can be downloaded that compare linkages under a no change scenario at the end of the century to results from two climate change models: warmer-wetter (CNRM-CM5) and warmer-drier (MIROC5).

Multispecies Linkage Assembly

After applying the threshold cutoff to the prioritized multispecies union and adding in components of the Circuitscape and geodiversity land facet linkages, the final linkage network totaled 11,603 mi^2. The final network (Figure 8) identified linkage segments and their source (species and land facet models or prior identification in urban conservation planning) as well as priority areas that were already conserved in large blocks (>5,000 acres). We split the network into subregional management zones using major freeways for strategic planning and implementation (Figure 9; Appendix A). Over 55% of this final multispecies linkage network is already either fully conserved (GreenInfo Network 2018a, SANDAG) or protected under conservation easements (GreenInfo Network 2018b; Table 5). After accounting for military-owned and tribal lands, which may confer some protection from development, just under 40% or 4,687 mi^2 of the linkage network remained on private, unconserved lands that should be considered for acquisition for linkage implementation (Figure 10).

Of the lands across the region we identified as important for climate connectivity, the majority were dominated by chaparral vegetation types. Hardwood forests (including oak woodlands and riparian areas), grasslands, coastal sage scrub, and coniferous forest vegetation types were all well-represented across the network, generally in proportion to their distribution in the region (CALFIRE FRAP 2015, Table 6). Although we implemented linkage cleaning and filtering, approximately 5% of the linkage network overlapped with areas classified as urban. In our review and modification of the final modeled linkage network, we did incorporate several linkages (*e.g.*, in the Rim of the Valley and Emerald Necklace Vision Plans) that traverse the most developed portions of our region in the Los Angeles basin, including small stretches of developed areas along narrow segments. As the only options for connecting islands of habitat in the urban matrix, we retained these segments where establishing connectivity will be more challenging, ensuring they aligned with existing conservation planning efforts in the region so as not to generate confusion regarding conservation priorities in the dense urban matrix. Wherever possible, particularly in areas where wider linkages overlap with areas of development, natural habitats should be prioritized for conservation and management.

Linkage Prioritization for Decision Support

Our initial linkage prioritization identified nearly 2,170 mi^2 of area of high or very high priority for acquisition (Figure 11). These areas of highest priority were located in the foothills of San Diego, Riverside, and San Bernardino Counties, and along the northern coastal portion of our study area. Far more area was ranked highly for management actions (Figure 12) to establish or enhance connectivity, with nearly 10,000 mi^2 rated as a high or very high priority. Within subareas or across the study area however, the prioritization could be reconfigured to identify areas within a county or NCCP plan area for example, to further refine planning for management activities.

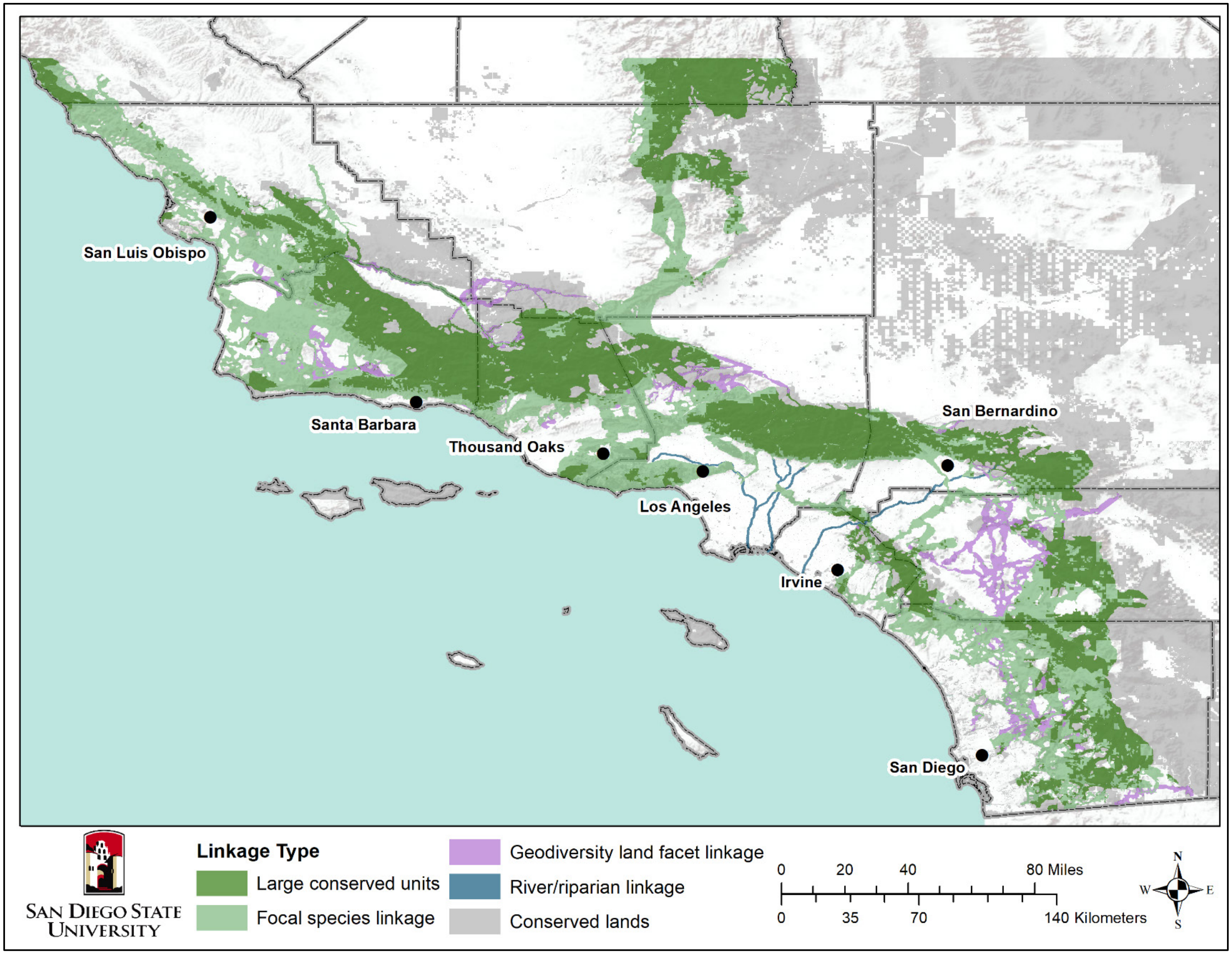

Figure 8. Final multispecies linkage map with different linkage types identified by the source for each type. Map depicts the full linkage network including conserved lands important for climate connectivity and linkage segments yet to be conserved.

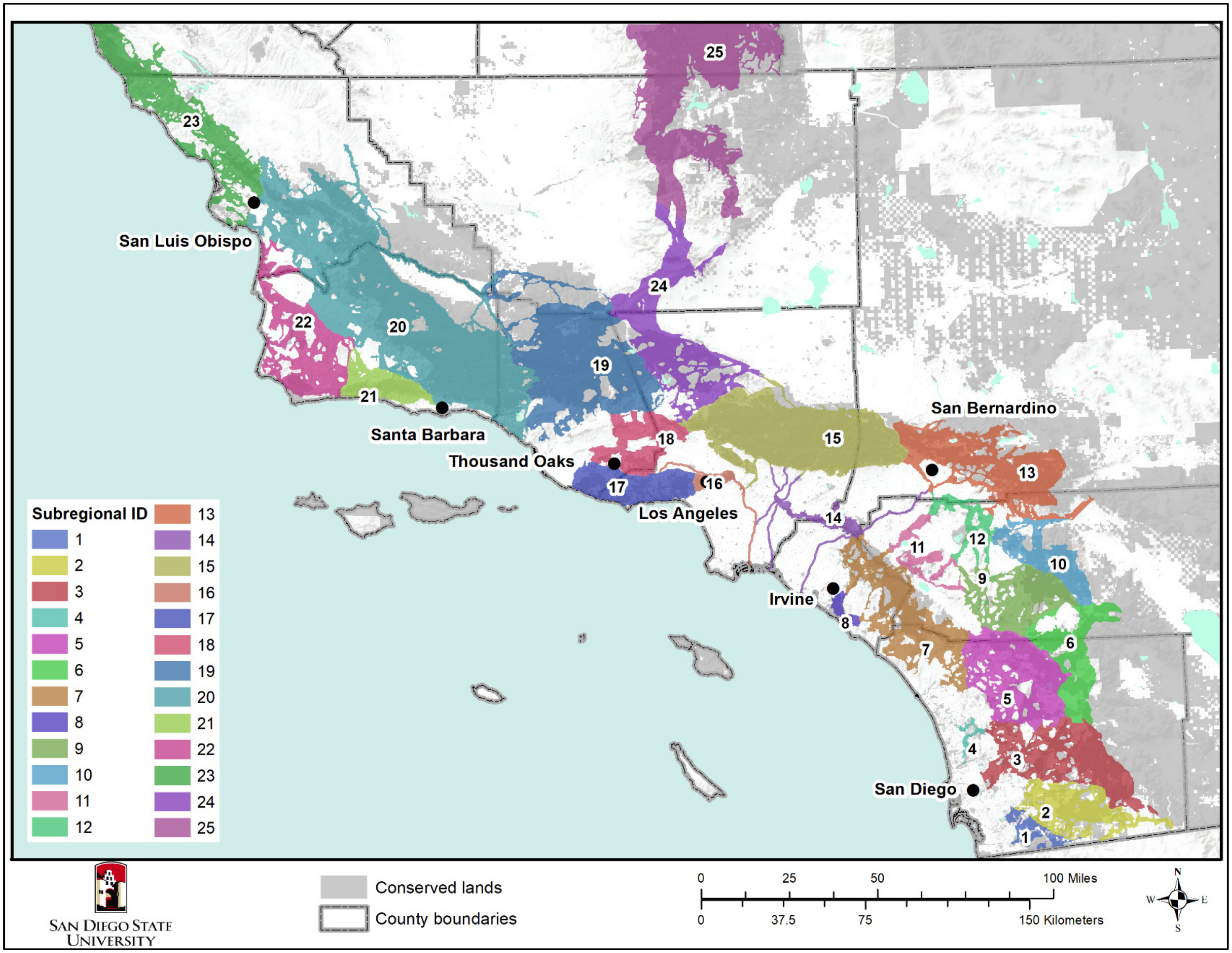

Figure 9. Final multispecies linkage map segmented into subregional zones based on major freeway boundaries. Map depicts the full linkage network including conserved lands important for climate connectivity and linkage segments yet to be conserved.

Table 5. Land ownership status of final linkage network including: lands in conservation status (GreenInfo Network 2018a), those under conservation easements (GreenInfo Network 2018b), Department of Defense owned-property, tribal reservations, and the remaining lands in private ownership with no conservation status.

Subregional ID	Conserved *Acres (Pct)*	Easement *Acres (Pct)*	Dept. of Defense *Acres (Pct)*	Tribal *Acres (Pct)*	Private-Unconserved *Acres (Pct)*
1	34,880 (75.4%)	2,467 (5.3%)	-	6 (0.01%)	8,877 (19.2%)
2	113,436 (55.3%)	3,559 (1.7%)	-	7,333 (3.6%)	80,937 (39.4%)
3	195,093 (56.3%)	7,721 (2.2%)	11,244 (3.2%)	38,149 (11.0%)	94,442 (27.2%)
4	6,669 (43.0%)	2,360 (15.2%)	-	-	6,467 (41.7%)
5	131,615 (38.6%)	7,328 (2.1%)	-	42,248 (12.4%)	159,847 (46.9%)
6	131,612 (63.1%)	262 (0.1%)	-	37,335 (17.9%)	39,438 (18.9%)
7	146,775 (44.4%)	12,314 (3.7%)	59,618 (18.1%)	-	111,560 (33.8%)
8	12,548 (58.1%)	252 (1.2%)	-	-	8,790 (40.7%)
9	67,771 (30.1%)	893 (0.4%)	-	2,010 (0.9%)	154,530 (68.6%)
10	101,537 (63.1%)	296 (0.2%)	-	19,311 (12.0%)	39,709 (24.7%)
11	11,233 (15.5%)	290 (0.4%)	-	16 (0.02%)	61,102 (84.1%)
12	13,024 (16.3%)	455 (0.6%)	-	-	66,279 (83.1%)
13	280,018 (67.4%)	462 (0.1%)	-	17,520 (4.2%)	117,473 (28.3%)
14	33,028 (34.0%)	499 (0.5%)	-	-	63,576 (65.5%)
15	535,464 (83.3%)	280 (0.05%)	-	-	106,733 (16.6%)
16	9,262 (20.5%)	48 (0.1%)	-	-	35,958 (79.4%)
17	82,446 (44.7%)	887 (0.5%)	2 (0.001%)	-	101,053 (54.8%)
18	46,081 (27.5%)	401 (0.2%)	-	-	120,995 (72.2%)
19	467,576 (72.6%)	207 (0.03%)	-	-	176,511 (27.4%)
20	780,468 (56.6%)	12,037 (0.9%)	-	-	585,879 (42.5%)
21	44,112 (36.6%)	2,665 (2.2%)	-	-	73,869 (61.2%)
22	33,369 (11.2%)	6,008 (2.0%)	52,936 (17.8%)	-	205,023 (69.0%)
23	79,866 (21.2%)	73,400 (19.5%)	36,331 (9.6%)	-	187,706 (49.7%)
24	147,139 (35.8%)	36,998 (9.0%)	-	-	226,916 (55.2%)
25	518,352 (73.8%)	7,164 (1.0%)	-	11,157 (1.6%)	166,061 (23.6%)
Sum	**4,023,374 (53.4%)**	**179,253 (2.4%)**	**160,131 (2.1%)**	**175,085 (2.3%)**	**2,999,731 (39.8%)**

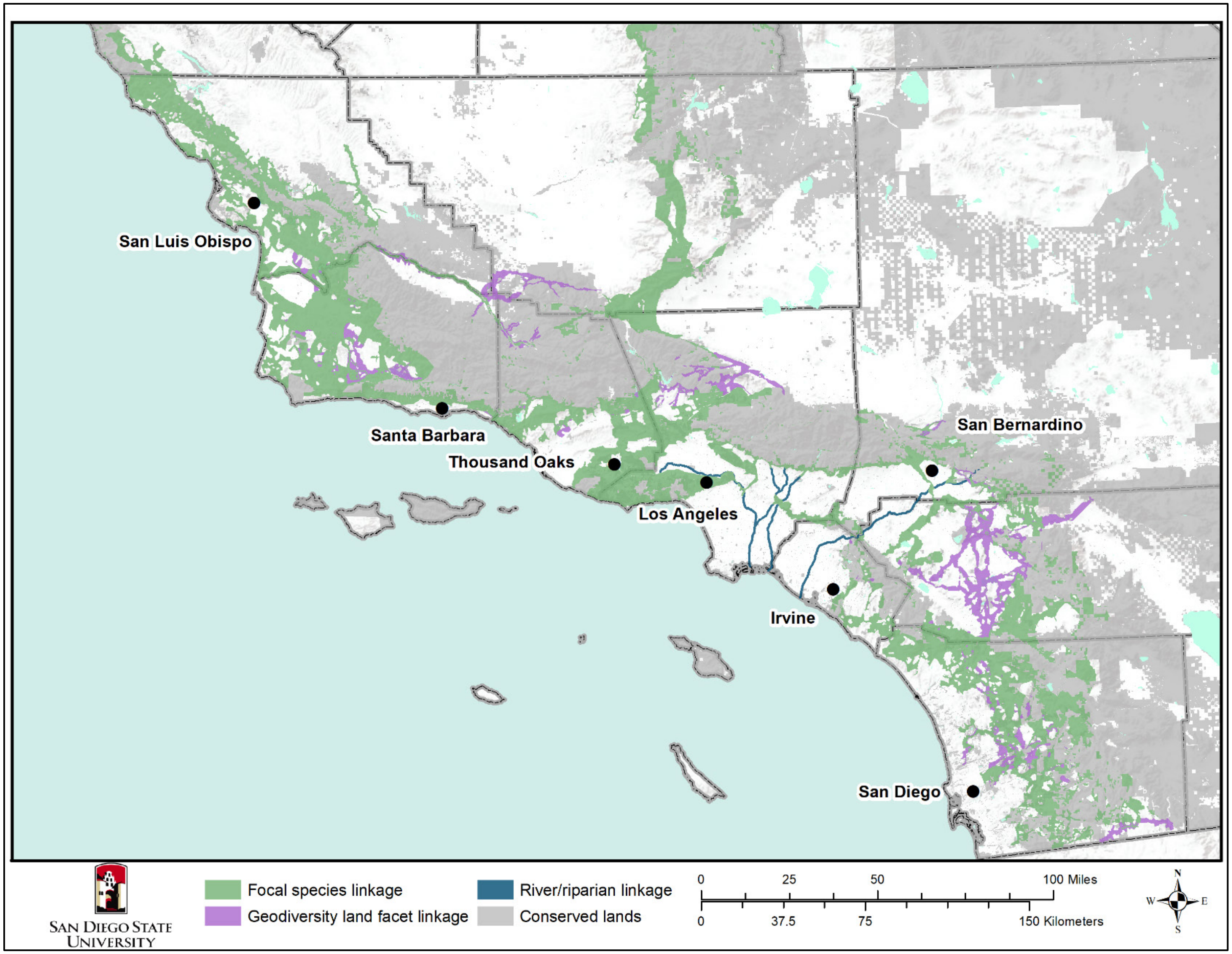

Figure 10. Map of the linkage network excluding large blocks of conserved lands (>5,000 acres). Linkages are identified based on their origin as either focal species linkages (green), geodiversity land facet linkages (purple), or riparian linkages (blue).

Table 6. Vegetation composition of the final linkage network based on 30-m statewide vegetation data (CALFIRE FRAP 2015).

Sub-regional ID	Chaparral *Acres (Pct)*	Coastal Sage Scrub *Acres (Pct)*	Conifers *Acres (Pct)*	Desert Scrub *Acres (Pct)*	Grassland *Acres (Pct)*	Hardwood *Acres (Pct)*	Water/ Wetland *Acres (Pct)*	Agriculture *Acres (Pct)*	Barren *Acres (Pct)*	Urban *Acres (Pct)*
1	15,099 (32.7%)	20,090 (43.5%)	1,191 (2.6%)	-	6,311 (13.7%)	1,360 (2.9%)	1,111 (2.4%)	183 (0.4%)	10 (0.02%)	879 (1.9%)
2	131,678 (64.2%)	34,046 (16.6%)	305 (0.1%)	1,493 (0.7%)	11,271 (5.5%)	11,029 (5.4%)	2,095 (1.0%)	2,633 (1.3%)	900 (0.4%)	9,793 (4.8%)
3	198,360 (57.2%)	46,012 (13.3%)	12,524 (3.6%)	428 (0.1%)	25,099 (7.2%)	34,078 (9.8%)	3,739 (1.1%)	6,972 (2.0%)	878 (0.3%)	18,516 (5.3%)
4	3,159 (20.4%)	3,337 (21.5%)	-	-	2,782 (18.0%)	935 (6.0%)	896 (5.8%)	302 (1.9%)	449 (2.9%)	3,627 (23.4%)
5	148,655 (43.6%)	31,596 (9.3%)	9,677 (2.8%)	362 (0.1%)	39,016 (11.4%)	53,026 (15.5%)	5,490 (1.6%)	36,590 (10.7%)	1,420 (0.4%)	15,190 (4.5%)
6	144,902 (69.4%)	8,494 (4.1%)	8,644 (4.1%)	3,921 (1.9%)	15,337 (7.4%)	22,082 (10.6%)	981 (0.5%)	1,873 (0.9%)	168 (0.1%)	2,075 (1.0%)
7	143,854 (43.6%)	65,115 (19.7%)	3,075 (0.9%)	857 (0.3%)	38,588 (11.7%)	30,599 (9.3%)	741 (0.2%)	27,524 (8.3%)	2,600 (0.8%)	17,253 (5.2%)
8	1,362 (6.3%)	9,894 (45.8%)	-	20 (0.1%)	3,760 (17.4%)	517 (2.4%)	56 (0.3%)	95 (0.4%)	339 (1.6%)	5,550 (25.7%)
9	97,638 (43.4%)	42,244 (18.8%)	5,666 (2.5%)	35 (0.02%)	12,342 (5.5%)	7,899 (3.5%)	6,690 (3.0%)	29,299 (13.0%)	93 (0.04%)	23,263 (10.3%)
10	77,248 (48.0%)	20,474 (12.7%)	32,462 (20.2%)	6,671 (4.1%)	7,702 (4.8%)	6,836 (4.3%)	708 (0.4%)	2,246 (1.4%)	1,656 (1.0%)	4,830 (3.0%)
11	2,436 (3.4%)	27,343 (37.6%)	624 (0.9%)	-	5,751 (7.9%)	3,325 (4.6%)	457 (0.6%)	8,802 (12.1%)	-	23,887 (32.9%)
12	9,243 (11.6%)	21,220 (26.6%)	-	119 (0.1%)	14,646 (18.4%)	1,935 (2.4%)	2,868 (3.6%)	22,798 (28.6%)	372 (0.5%)	6,534 (8.2%)
13	170,530 (41.0%)	10,363 (2.5%)	107,559 (25.9%)	25,419 (6.1%)	11,151 (2.7%)	54,214 (13.0%)	3,984 (1.0%)	3,419 (0.8%)	7,507 (1.8%)	21,283 (5.1%)
14	6,830 (7.0%)	5,867 (6.0%)	-	683 (0.7%)	24,383 (25.1%)	13,063 (13.5%)	2,425 (2.5%)	896 (0.9%)	1,753 (1.8%)	40,907 (42.1%)
15	377,504 (58.8%)	33,977 (5.3%)	102,987 (16.0%)	12,784 (2.0%)	5,893 (0.9%)	67,108 (10.4%)	2,931 (0.5%)	158 (0.02%)	12,215 (1.9%)	26,597 (4.1%)
16	3,077 (6.8%)	3,820 (8.4%)	-	-	545 (1.2%)	3,064 (6.8%)	832 (1.8%)	50 (0.1%)	490 (1.1%)	33,382 (73.7%)
17	71,363 (38.7%)	46,031 (25.0%)	-	-	7,214 (3.9%)	14,302 (7.8%)	814 (0.4%)	4,882 (2.6%)	1,793 (1.0%)	37,949 (20.6%)
18	33,948 (20.3%)	53,117 (31.7%)	743 (0.4%)	45 (0.03%)	28,240 (16.9%)	15,326 (9.2%)	640 (0.4%)	6,863 (4.1%)	4,724 (2.8%)	23,822 (14.2%)
19	294,084 (45.6%)	69,362 (10.8%)	133,103 (20.7%)	1,237 (0.2%)	58,530 (9.1%)	47,059 (7.3%)	2,265 (0.4%)	13,173 (2.0%)	16,908 (2.6%)	8,361 (1.3%)
20	664,923 (48.2%)	157,499 (11.4%)	20,969 (1.5%)	2,664 (0.2%)	180,037 (13.1%)	283,516 (20.6%)	7,343 (0.5%)	41,930 (3.0%)	10,979 (0.8%)	8,443 (0.6%)
21	51,211 (42.4%)	9,840 (8.2%)	-	-	17,099 (14.2%)	29,080 (24.1%)	255 (0.2%)	9,433 (7.8%)	1,125 (0.9%)	2,596 (2.2%)
22	11,213 (3.8%)	87,868 (29.6%)	1,697 (0.6%)	-	107,232 (36.1%)	57,632 (19.4%)	791 (0.3%)	16,599 (5.6%)	10,005 (3.4%)	4,292 (1.4%)
23	95,457 (25.3%)	36,773 (9.7%)	13,392 (3.5%)	-	101,332 (26.9%)	122,476 (32.5%)	1,090 (0.3%)	5,037 (1.3%)	868 (0.2%)	817 (0.2%)
24	185,787 (45.2%)	24,280 (5.9%)	21,383 (5.2%)	7,236 (1.8%)	77,763 (18.9%)	67,799 (16.5%)	3,270 (0.8%)	1,301 (0.3%)	4,402 (1.1%)	17,670 (4.3%)
25	185,620 (26.4%)	-	245,534 (34.9%)	4,312 (0.6%)	76,075 (10.8%)	175,572 (25.0%)	2,497 (0.4%)	294 (0.04%)	12,443 (1.8%)	310 (0.04%)
Sum	**3,125,180 (41.5%)**	**868,662 (11.5%)**	**721,535 (9.6%)**	**68,288 (0.9%)**	**878,101 (11.6%)**	**1,123,833 (14.9%)**	**54,966 (0.7%)**	**243,354 (3.2%)**	**94,098 (1.2%)**	**357,827 (4.7%)**

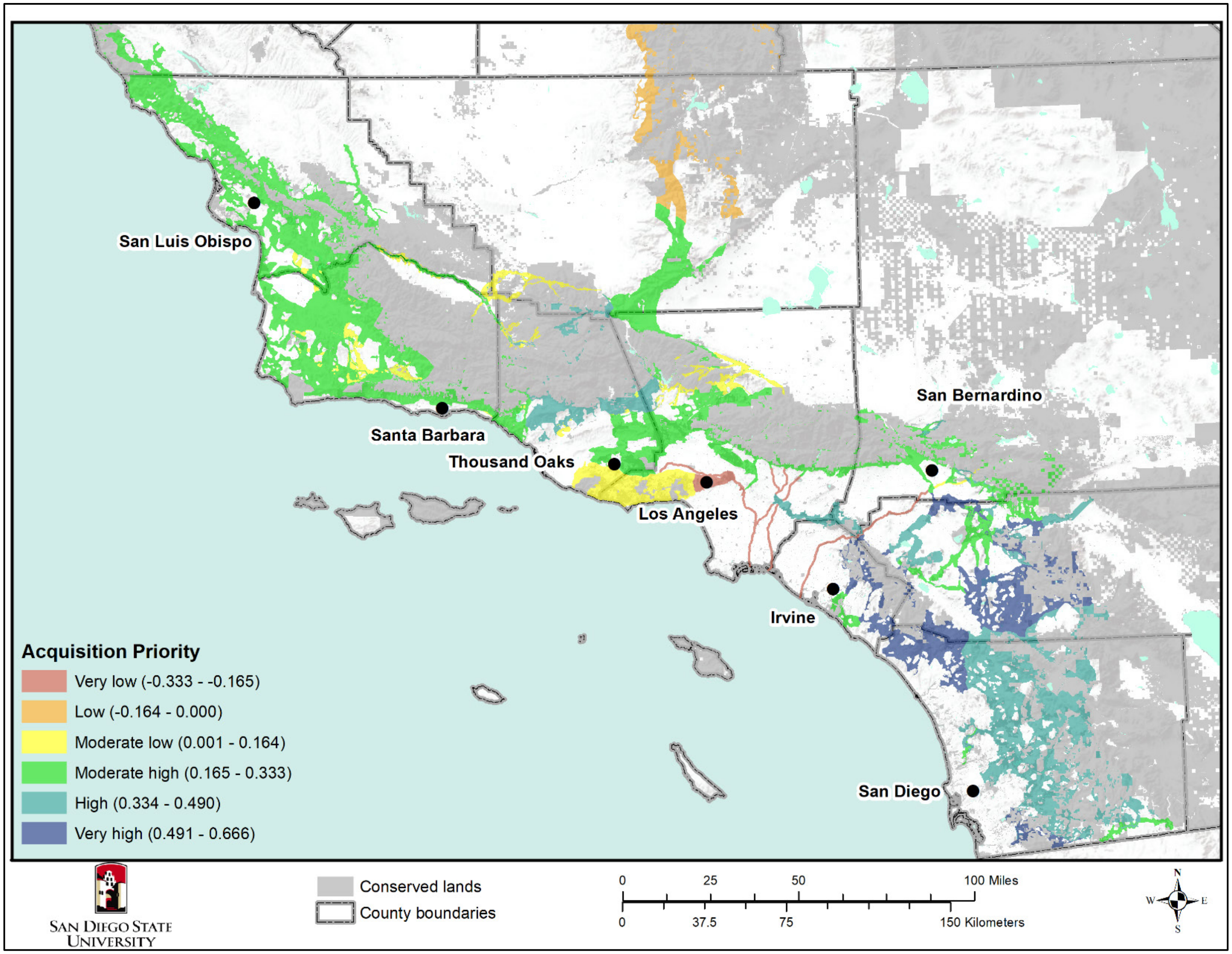

Figure 11. Map of the prioritized linkage network targeting acquisitions. Prioritization was focused only on lands outside large conserved superunits. Priority ranges from very low (brown) to very high (blue).

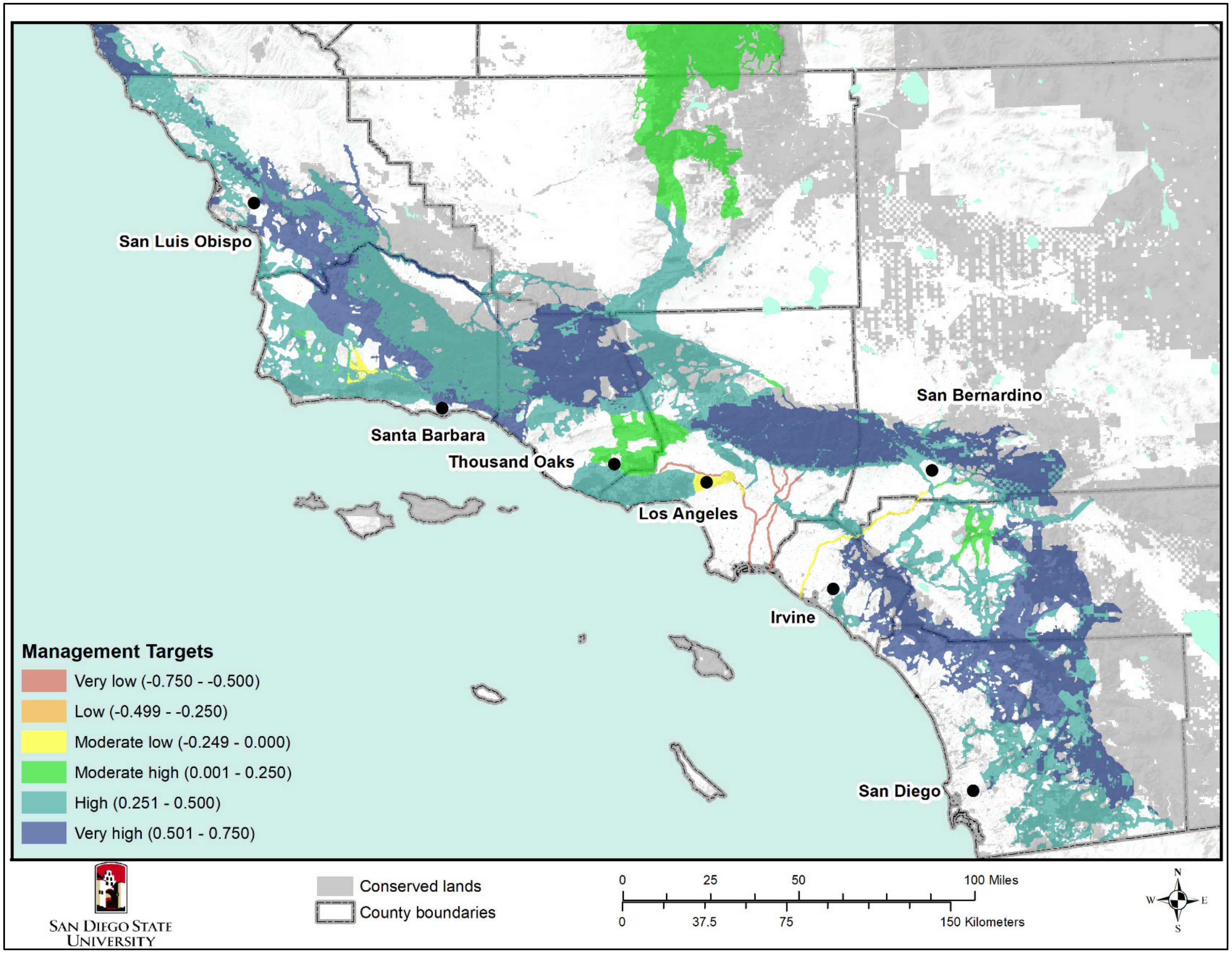

Figure 12. Map of prioritized linkage network identifying management targets where action could be taken to enhance or establish connectivity. Prioritization was focused on all lands. Priority ranges from very low (brown) to very high (blue).

DISCUSSION

Summary Findings

Through a comprehensive, multispecies connectivity analysis using robust analytical approaches, we created a connectivity plan that can be used guide implementation with a decision support tool for climate resilient connectivity across the south coast ecoregion of California. With this data-driven approach, we:

- Worked collaboratively and iteratively with stakeholders and species experts to gather information, feedback, and key input to generate a connectivity plan and conservation tool that can be readily implemented by the diverse range of land management and planning entities in the region.
- Developed species distribution models for five target focal species under historic and four future climate scenarios to assess a range of potential changes in habitat availability and location over time
- Used a foundation of historic conditions to develop a linkage strategy using empirical data while considering potential future conditions using scenarios and a consensus-based approach
- Linked dynamic metapopulation models to the connectivity network to assess the biological importance of corridors in the network
- Combined a suite of connectivity modeling methods with a robust prioritization approach to support decision making under the uncertainty of climate change
- Assembled a regional multispecies linkage network for connectivity under climate change using a suite of focal species complemented by a landscape-focused geodiversity land facet analysis
- Developed prioritization strategies for identification of acquisition and management targets using an approach that can be updated based on stakeholder feedback or implemented by stakeholders themselves to meet management and decision needs over time

Application of the Connectivity Plan

The data products we developed during this project were intended to be used in planning to conserve and enhance regional connectivity across the region. This information can be applied to connectivity planning and implementation decision-making, particularly when considering connectivity as a key component of reserve design. The focal species approach as well as the species we selected were intended to identify linkages that would support connectivity for the most species, thereby preserving biodiversity. By linking additional quantitative metrics to our corridors and prioritizing areas for conservation based on that information, we strived to facilitate decision-making. These prioritized linkage maps can be used for acquisition decision-making, identification of restoration targets to improve connectivity, and to aid end-users in the evaluation of the potential impacts of development projects on wildlife connectivity in the region with an eye towards future changes in climatic conditions and land-use shifts.

This linkage network was developed to support planning for climate resilience for biodiversity. Although our focal species approach provides specific information about connectivity for the five species we used throughout our modeling process, the data we present here is not appropriate for use in single-species conservation planning or decision-making, particularly those species that are narrow habitat specialists. While the network can help guide decisions about identifying and prioritizing conservation actions, no single modeling output or scientific study can completely guide this planning. Instead, we recommend the combination of our model outputs and geospatial data with existing monitoring data and research. Furthermore, connectivity is a complex concept that must be addressed at different time scales and spatial extents. As such, further analyses may be necessary for different planning and management goals. For example, when planning for wildlife crossing structures on roads, additional modeling and analyses that address fine scale movement data and crossing needs, such as described in Jennings and Zeller (2017), will be necessary as a complementary planning tool. We describe how alternative strategies could be applied to prioritize the linkage plan for different goals and detail additional data sources that should be considered when planning or making conservation decisions in Appendix B.

Decision Support and Implementation

The linkage network we have designed can serve as a framework for future conservation decision making that can be adapted and re-prioritized based on agency and end user needs. By splitting the network into subregional areas, we hoped to facilitate localized planning given the context of needs and the existing landscape in each of these subregions. We used the delineation of the network into conserved lands and linkage segments to support identification of land management targets and activities to promote connectivity through conserved lands versus planning for acquisition to preserve connectivity on currently unprotected lands.

Now that we have fully developed and completed this comprehensive analysis resulting in the linkage network, this framework can be readily adapted and the prioritization replicated with decision support tools tailored to different end-users across the region. The implementation of our prioritization using the EEMS tool will allow GIS specialists at our end users' agencies and organizations to modify these outputs to meet institutional needs.

Next Steps

In the near-term, we plan to support training on the use of these tools and provide user-friendly mapping products (*e.g.*, a Story Map) to support broad use of the outputs from this project. To facilitate integration of these data into a conservation planning toolbox, we also plan to gather feedback from stakeholders on the other types of data that would be valuable to view in combination with our linkage network to ensure complementary datasets are available on the same platforms and can be easily assembled for review in connectivity-related decisions.

There are several key aspects we plan to build on to further develop the framework we have established with this project. With continued support through the "Connecting Wildlands and Communities" project funded by California's Strategic Growth Council through the California Climate Investments program, we will expand this project in the following ways:

- Conduct validation of the network with additional species

- By generating population models for two secondary focal species, puma (*Puma concolor*) and mule deer (*Odocoileus hemionus*), to assess the biological importance of our linkage network for two longer-distance dispersing species
- By assessing linkage value to other species of interest, such as federally listed species, based on existing data and modeling (*e.g.* genetic analyses or connectivity modeling)
- Assess the overall biodiversity value of linkages
- Determine the role of our linkage network in providing connectivity to climatic refugia under increasing temperatures and drought conditions
- Consider the fire risk both to and from the linkage network, including an evaluation of vegetation type conversion risk to the connectivity value of linkages
- Perform an analysis to support identification of priority areas for conservation targets versus multiple uses (*e.g.*, recreation)

Future Applications

The products we have created for California's south coast ecoregion illustrate how spatially-explicit corridors can be linked to the organizational and regional conservation and management plans so they are an integral element of management actions and decision-making rather than a separate management task to be executed. Through this project, we have developed a model for utilizing available biological data to design and implement a comprehensive multispecies connectivity plan that is robust in its foundation of historic information, but also considers how our ecosystems, habitats, and species may need to adapt to conditions in the future. The analysis and prioritization approach we have assembled here can readily be adapted to different regions, scenarios, species, and habitats to facilitate planning at many levels and should be applied more broadly to advance proactive, data-informed planning and management that fosters the climatic resilience of our region's native species and habitats.

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