

TECHNICAL ADVANCE

Supporting Tribal resilience in Southern California through plant vulnerability assessment

Connor Magee^{1,2}  | M. Brooke Rose³  | Janet Franklin³  | Gregory A. Backus⁴ ¹Graduate Group in Ecology, University of California at Davis, Davis, California, USA²Citizen of Pala Band of Mission Indians (Payómkawichum/Cahuilla), Pala, California, USA³Center for Open Geographical Sciences, Department of Geography, San Diego State University, San Diego, California, USA⁴Department of Ecological, Evolutionary and Organismal Biology, University of California, Riverside, California, USA

Correspondence

Connor Magee, Graduate Group in Ecology, University of California at Davis, Davis, CA, USA.

Email: cpmagee@ucdavis.edu

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Abstract

In Southern California, Tribal communities codeveloped research supporting Tribal stewardship and climate adaptation planning by conducting a broad assessment of 50 plant species' exposure to future climate change and land use change. The research objective was to understand shifts in biodiversity that may occur in the near future under global change scenarios. We paired species distribution modeling to measure climate exposure with sensitivity and adaptive capacity ranking based on the life-history and fire-response characteristics of each plant species. Our findings revealed a major impact of high-emission scenarios on species' threat categories. We projected average habitat loss of 26% under high emissions and 17% under moderate emissions. Nearly half of the species would shift into higher threat categories based on projected habitat loss under high-emission scenarios. The vulnerability assessment varied across plant communities. The piñon-juniper community may experience significant declines, while conifer forest species would show higher resilience and adaptive capacity. Oak (*Quercus* spp.) and riparian species generally showed resilience, while desert species were more sensitive. California juniper (*Juniperus californica*) and Joshua trees (*Yucca brevifolia*) were highly exposed and vulnerable to environmental stress. Deer grass (*Muhlenbergia rigens*) and California ephedra (*Ephedra californica*) showed higher resilience despite projected habitat losses. The assessments also predict that several desert species, including the teddy-bear cholla (*Cylindropuntia bigelovii*), buckhorn cholla (*Cylindropuntia acanthocarpa*), and palo verde (*Parkinsonia florida*), have low exposure to habitat loss but have high sensitivity and low adaptive capacity, based on their traits. Our vulnerability assessment provides information on the relative magnitude of global change versus other threats. This

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assessment supports the development of strategies to steward ecosystems, address vulnerable plant populations, and advance Tribally led climate adaptation planning.

KEYWORDS

climate adaptation planning, co-development, habitat loss, plant communities, Tribal stewardship, vulnerability assessment

POSITIONALITY STATEMENT

As one of the four coauthors on this paper, I, Connor Magee, recognize my responsibility to clearly articulate my relationship to the research. I am writing from a position of both academic training and lived experience as a member of the Southern California Tribal community. Throughout our research process, I have worked closely with Tribal stewards, knowledge holders, and community members, prioritizing protocols grounded in trust, respect, and reciprocity. I have chosen to write portions of this paper in a style that reflects the community's own ways of speaking. In this paper, the term *Tribal* is used to reference the Indigenous communities participating in this work. The term Tribal is how we most commonly refer to each other and our Intertribal work. In this paper, we work to seamlessly refer to ourselves in the collective terminology: Tribes, Tribal, Intertribal. In doing so, we are referring to the Indigenous Tribes of Southern California. In academic literature we are normally referred to as Indigenous, American Indian or Native American, or by our respective community titles. In this paper, the term Indigenous is used when referencing other academic work or official titles.

INTRODUCTION

Environmental change is profoundly reshaping habitats for plant populations globally, resulting in significant declines in species richness and alarming losses in biodiversity (Habibullah et al., 2022). Many Indigenous communities share kincentric ecological worldviews and maintain a deep cultural connection to biodiversity, understanding the intricate relationships between humans and the nonhuman environment (Martinez et al., 2023). Environmental change is accelerating rapidly and disproportionately impacting Indigenous peoples (Hill et al., 2020). In response, Indigenous peoples are at the forefront of culturally guided climate adaptation planning (Whyte et al., 2023).

Acts of Indigenous self-determination, understood here as the authority of Indigenous communities to

define their own priorities and direct research agendas, increasingly entail communities envisioning, designing, and implementing research that serves their needs (Whyte et al., 2023). This process often involves partnering with research institutions to coproduce knowledge and develop innovative technological tools that support ecosystem stewardship amid changing environmental conditions (Miner et al., 2023). This design process generates outputs and outcomes that inform actionable decision-making for Tribal stewardship. Tribal stewardship of technological tools such as species distribution modeling (statistical models of the correlation of species distributions with environmental drivers, including climate) is vital in promoting data-informed stewardship strategies (Thoreson et al., 2024).

Such initiatives have been undertaken in Northern California. One example, Taylor et al. (2023) describe a collaboration between the Amah Mutsun Tribal Band and the University of California, Berkeley to identify potential gathering areas through spatial modeling of predicted habitat distributions for 10 plant species. The resulting analyses directly inform the Tribe's ecological stewardship programs by helping prioritize management areas. In another collaboration with the University of California, Berkeley, the Karuk-UC Berkeley Collaborative is integrating cultural practitioner knowledge with ecological field data to develop models that identify culturally significant black oak traits and support adaptive stewardship of Karuk forest landscapes (Thoreson et al., 2024). The Karuk Tribe is also using modeling to advance stewardship by combining species distribution models with qualitative cultural knowledge to understand how climate and environmental stressors affect the availability, quality, and cultural use of key plant species, allowing them to proactively guide restoration, harvesting practices, and long-term ecosystem resilience (Mucioki et al., 2022).

Our Tribally led research embarks on understanding the shifts in biodiversity that may occur in the near future under global change scenarios. Here, we present a broad assessment of species vulnerability to both future climate change and land use change for 50 plant species to inform Tribal stewardship in the Southern California region. We used species distribution (or habitat

suitability) modeling and projected the redistribution of habitat under future climate and land use scenarios (e.g., Rose et al., 2023). We not only assessed exposure risk to environmental change based on habitat modeling, but also sensitivity and adaptive capacity based on life-history and fire-response characteristics of each plant species. While individual species are often the focus of conservation biology, ecologists focus on communities (species found in the same area that may interact). We evaluated different groups of species assessed in this study that occur together in ecological communities based on their relative vulnerability. Our goal is to inform actions that enhance Tribal climate adaptation planning with a focus on stewarding the southern California ecosystems. This Tribally driven project was intentionally designed to foster the co-production of knowledge. We use the term co-production of knowledge, following Yua et al. (2022), to refer to a process that brings together Indigenous Peoples' knowledge systems and Western science to generate new insights and understandings that would not likely emerge from either knowledge system alone. Accordingly, we begin by outlining the relationships and collaborative processes that form the foundation of our study and serve as the initial step in our methodology.

METHODS

Collaboration process

This analysis contributes to the broader Resilient Restoration Project, an initiative developed to enhance understanding of how climate change is affecting a suite of plant species that form the ecological foundation of Southern California's biodiversity and are vital to Tribal cultures, health, and well-being. The project concept emerged from the Climate Science Alliance (CSA) TWG, an Intertribal collaborative established in 2017 that includes more than 20 Tribal Nations and Indigenous organizations across Southern California. To articulate a shared vision for the project, the TWG convened monthly meetings facilitated by CSA staff, with ongoing participation from researchers who collaborated with Tribal partners to implement the research aligned with TWG priorities. These discussions focused on identifying opportunities for partnership, learning, and coordination to support the application of stewardship practices.

The overarching goal of the project was to integrate established scientific research approaches with Tribal guidance to inform stewardship and restoration strategies under shifting climatic conditions. The project also supported Tribal resilience by funding pilot projects

designed to test restoration methods and expand capacity within and across Tribal communities. This collaborative framework guided the development of the project's four major components: Ecological Modeling, Genetic Analyses, Adaptation Actions, and Education & Outreach (Jennings et al., 2025). This paper focuses on the ecological modeling component of the project. Our models are used in a web-based GIS-based Data Portal developed for Tribal partners to explore these complex habitat and population models for stewardship and restoration activities.

Research updates were provided regularly at TWG meetings, and four dedicated workshops were held to present data products and coproduce the project's Data Portal. Together, collaborators identified stewardship strategies informed by our modeling outputs, which were synthesized into an interactive adaptation menu to support the selection of on-the-ground restoration and resilience actions.

Ecological modelers attended monthly TWG meetings to build relationships, incorporate Tribal feedback into model inputs and outputs, and refine the models to ensure alignment with Tribal priorities. Accordingly, while our models relied on publicly available datasets, certain plant species information shared by the TWG remains confidential and is stored only in the access-restricted Data Portal. To safeguard the confidentiality of individuals and the knowledge shared throughout this project, all sensitive information was omitted from the research process and reporting. A defining feature of this work is that it prioritizes confidentiality. While Tribal partners may use project outputs to support ecocultural stewardship, the associated cultural practices and beliefs remain confidential and are not described in this paper. The purpose of this technical paper is to detail the vulnerability assessment methods and to illustrate how Tribal stewards and planners coproduced the assessment while protecting culturally sensitive knowledge.

Trust-based relationships were established among all partners, grounded in a shared understanding of the importance of protecting Tribal data. No sensitive information related to the participating Tribes is presented here, nor does this paper infringe upon the TWG's Knowledge Sovereignty Policy, which follows the CARE Principles (Collective Benefit, Authority to Control, Responsibility, Ethics) for Indigenous data governance (Carroll et al., 2021). These principles were embedded and formalized at the outset of the project through the proposal, grant agreement, and collaboration agreements with Tribal partners.

In this collaboration, we opted to use common (English) plant names due to their broader familiarity within an Intertribal context involving participants from diverse linguistic backgrounds. Scientific nomenclature

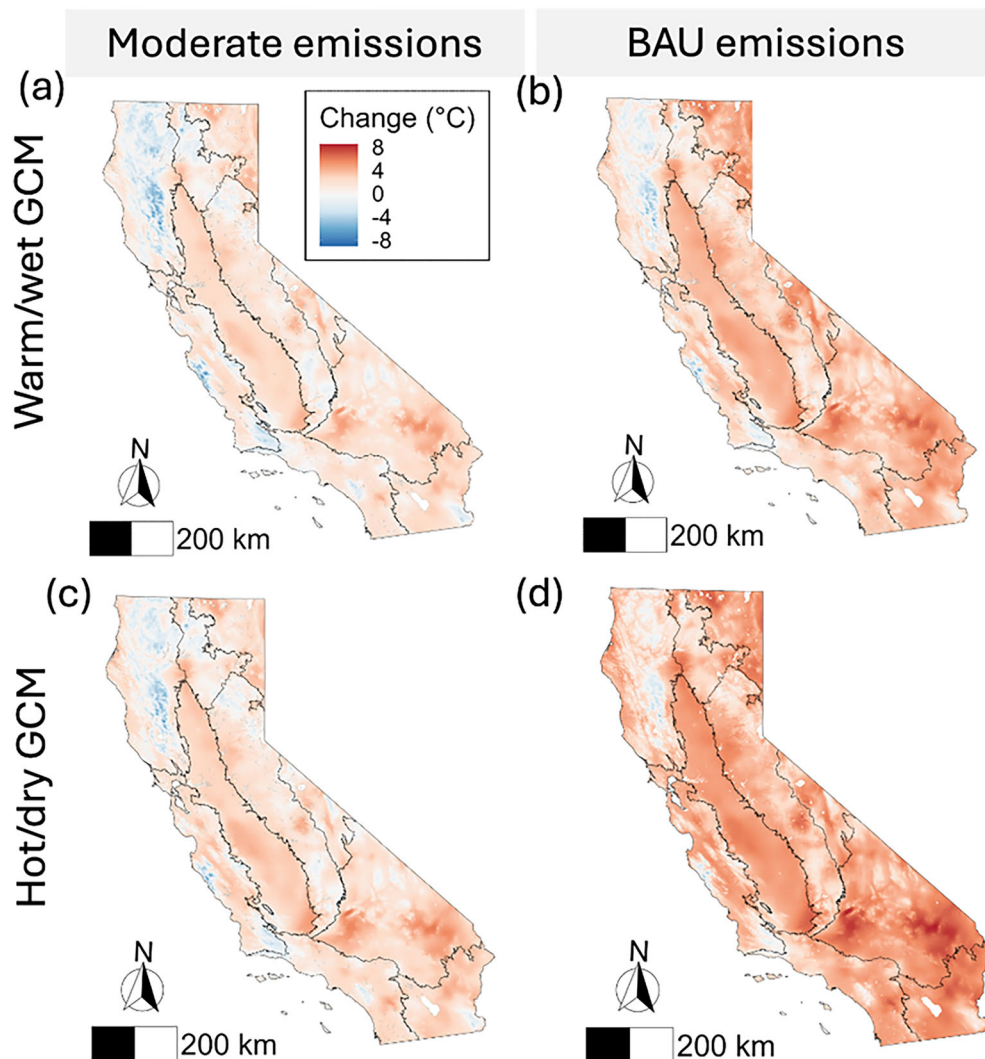


FIGURE 1 Predicted changes from current average minimum temperature of the coldest month (in degrees Celsius) for California under the two general circulation models (GCMs): (a, b) CNRM-CM5 (warm/wet); and (c, d) HadGEM2-ES (hot/dry); and two emissions pathways: (a, c) RCP 4.5 (moderate emissions); and (b, d) RCP 8.5 (a ‘business-as-usual’ emissions scenario), by the late 21st century (2070–2099). Data from the Basin Characterization Model (BCM) version 8 (Flint et al., 2021).

(included parenthetically in this paper when species are mentioned, and provided in Dataset S1), while precise, is generally less familiar to the individuals engaged in this project and is also subject to frequent taxonomic revisions. At the level of individual Tribes, Tribal plant names are typically preferred. However, given the involvement of multiple Tribal languages in this project, the use of common names served as a practical and culturally respectful middle ground.

Geographical setting

California supports over 6900 taxonomic varieties of plants, more than 40% of which are only found in (endemic to) California, with much of that richness and

endemism concentrated in southwestern California (Baldwin et al., 2017). Strong topo-climatic gradients in the physical landscape of Southern California set in a Mediterranean-type climate yield rich patterns of biological diversity (Franklin et al., 2021). Traveling west to east, one can traverse several life zones or biomes—maritime-influenced coastal strand and shrublands, foothill oak woodlands and sclerophyllous evergreen chaparral, montane conifer forest, and desert scrub lee of the north-south trending mountains that form a rain shadow (Jennings et al., 2018; Mooney & Zavaleta, 2016).

Projections of climate change in the region include warming by 2–4°C on average and variable changes in precipitation by the end of the century (Jennings et al., 2018). These projections suggest the region will experience significantly warmer temperatures (Figure 1),

more variable precipitation resulting in occasional high-intensity flooding and more frequent and prolonged droughts, and more fires due to drought and increased ignitions and dry fuel availability (Jennings et al., 2018). These changes already threaten Tribal food security, health, and conservation of culturally and ecologically significant biological resources (Whyte et al., 2023).

The plant species included in this assessment (Table S1) were selected from a longer list of candidate species identified by the TWG. This subset does not reflect a prioritized selection of those with particular cultural significance to the TWG. Instead, they were selected based on the availability of sufficient publicly available and published data to create robust models. As part of our collaborative process, we intentionally considered what information to include in this paper in order to honor both the knowledge shared and the relationships built. Accordingly, we explicitly clarify that the species discussed in this study are not prioritized by importance or value.

Modeling species exposure and sensitivity using distribution modeling and plant traits

We relied on existing data and modeling frameworks to measure two dimensions of plant species vulnerability to climate change. Exposure was measured as the difference between present and future habitat suitability under climate change scenarios based on species distribution modeling (as in Rose et al., 2023). Sensitivity versus adaptive capacity was measured using criteria and a scoring system developed for California plants by Thorne et al. (2016).

Species distribution models (SDM) are widely used to provide distribution maps or forecasts of exposure to climate change, although application to culturally important species is nascent (e.g., Hamilton et al., 2024; Kunwar et al., 2023; Taylor et al., 2023). We used models developed by Rose et al. (2023) available for 29 of the species of interest, and we applied the identical methodology to derive SDMs, climate change projections, and calculate the exposure metric, for 21 additional species not previously modeled. Rose et al. (2023) provide detailed methods including in an ODMAP table (Zurell et al., 2020); therefore, we describe them very briefly here, only for clarity.

Geolocated species true presence-absence records in California from vegetation surveys collected between 1980 and 2020 were compiled for the plant species included in this study (Dataset S1), supplemented with presence-only data from open biodiversity databases. Predictors included climatic, hydrologic, terrain, and soil variables. Climatic predictors included climatic water deficit, actual evapotranspiration, minimum monthly

temperature, and wet- and dry-season precipitation averaged from annual values for the years 1981–2010 at 270-m spatial resolution from the Basin Characterization Model BCM (Flint et al., 2013, 2021). Soil variables, including pH, available water-holding capacity, soil depth, and percent clay, were obtained from the gNATSGO (Soil Survey Staff, 2020). Landform categories were from Theobald et al. (2015). Two Global Circulation Models (GCMs) were used to assess species' future climate change exposure, representing warm and wet (CNRM-CM5) and hot and dry (HadGEM2-ES) climate futures (Pierce et al., 2018). Two greenhouse gas emissions Representative Concentration Pathways (RCP), RCP 4.5 ('Moderate') and 8.5 ('Business-as-Usual' or BAU) were used (IPCC, 2013). All future climate data were available from the BCM at a 270-m spatial resolution (e.g., Figure 1). Land use impacts were evaluated using the Integrated Climate Land Use Scenarios (ICLUS) projections for HadGEM2-ES RCP 4.5 and 8.5 (Bierwagen et al., 2010; Theobald, 2005). These land use change scenarios predict increases in urban and exurban development, and decreases in agricultural and forest lands, in California (Figure 2a,b). We assumed that natural land use had no effect on suitability, exurban reduced suitability by 50%, and developed land rendered habitat unsuitable.

An ensemble of algorithms was used to build SDMs. Continuous suitability values above the threshold that maximized the sum of sensitivity and specificity were retained and values below were set to zero, removing low-suitability areas while preserving within-habitat variation (Muscatello et al., 2021). The thresholded outputs of the ensemble were used to produce a 'mean above threshold' consensus SDM (Araújo & New, 2007). Modeling was conducted in R (R Core Team, 2024) using the *flexsdm* package (Velazco et al., 2022) and documented using the ODMAP (Overview, Data, Model, Assessment, and Prediction) protocol (Zurell et al., 2020) (Table S1; and Rose et al., 2023 tab. S2.4).

We calculated species exposure to global change based on in situ change in habitat suitability (*no dispersal*), which limits the analysis to changes within each species' current distribution (Urban, 2024). While SDMs, and even consensus methods (Rose et al., 2024), can vary in their exposure estimates, this variability is reduced substantially under the no-dispersal assumption. A *full dispersal* projection included potential range expansion across California and, while not analyzed in this paper, was shared with TWG members to support decision-making. TWG members reviewed the model outputs during workshops and recommended summarizing SDM projections from the warm/wet (CNRM-CM5) and hot/dry (HadGEM2-ES) climate models to improve interpretability. We synthesized results to identify areas of (1) *consensus stable* habitat

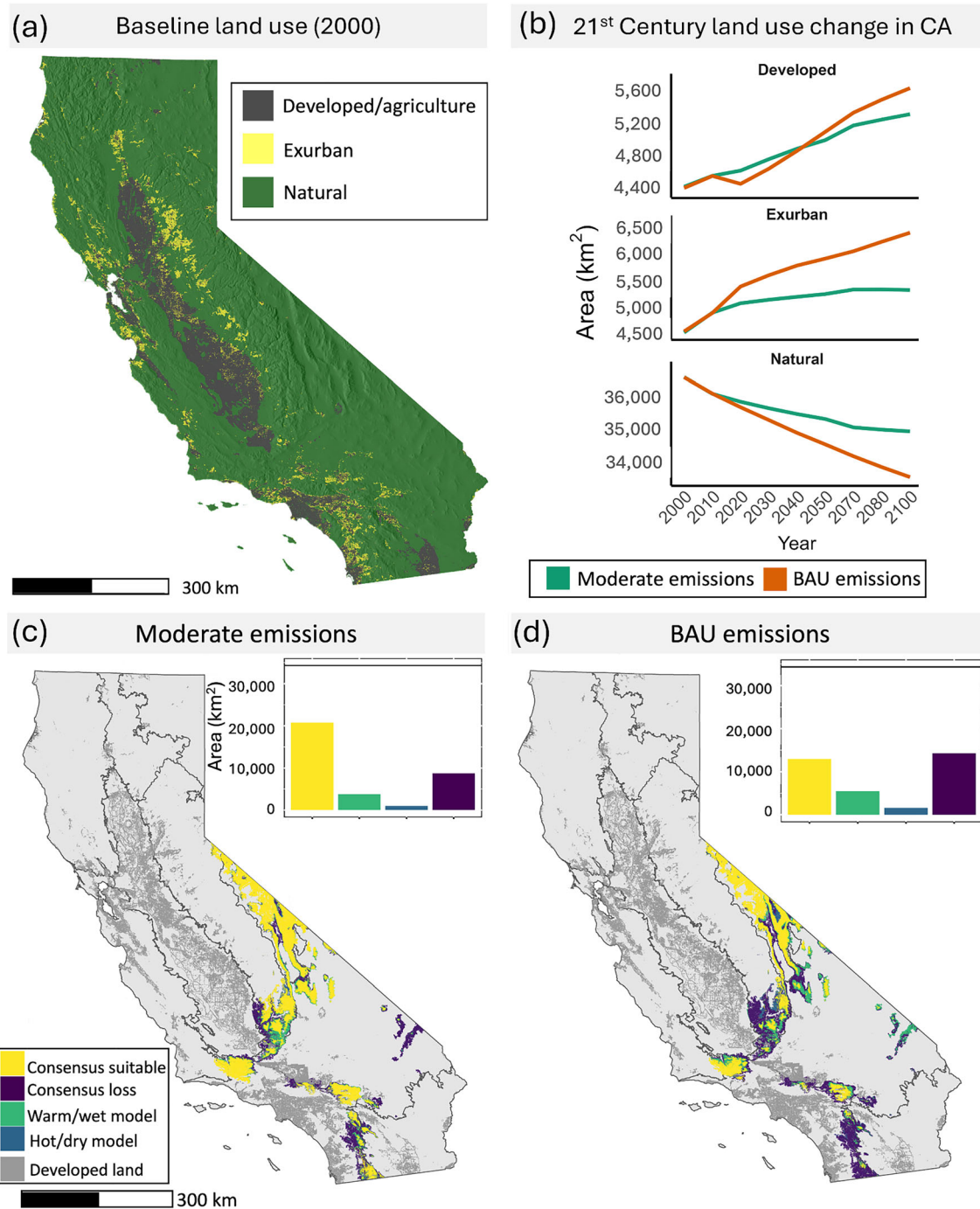


FIGURE 2 Baseline land use in California (2000) for three general categories included in this study (natural, exurban, and developed) (a) and the predicted area trajectories for each in the future based on the Integrated Climate Land Use Scenarios (ICLUS) projections (Theobald, 2005; Bierwagen et al., 2010) (b). Example of predicted habitat change dynamics for single-leaf piñon pine (*Pinus monophylla*) under future climate and land use change under moderate (RCP 4.5) (c) and business-as-usual (RCP 8.5) (d) greenhouse gas concentration scenarios for the late century time period (2070–2099). Consensus suitable and consensus loss represent areas where both climate models (warm/wet and hot/dry) predict habitat to be suitable or become unsuitable by the end of the century, respectively. Green and blue represent areas that will be suitable for only one climate model but not the other. Predictions are restricted to changes within the species baseline estimated distribution (‘no dispersal’).

(suitable under both models), (2) *consensus loss* (unsuitable under both), (3) *warm/wet model only* (suitable only under CNRM-CM5), and (4) *hot/dry model only* (suitable only

under HadGEM2-ES), under a given RCP scenario. An example of these categories is shown in Figure 2c,d for *Pinus monophylla* within its current range.

TABLE 1 Species attributes of sensitivity versus adaptive capacity to climate change and associated potential changes to fire regime.

Metric	1—Most sensitive/least adaptive	2	3	4	5—Least sensitive/most adaptive
Habitat breadth ^a	Narrow	Narrow-moderate	Moderate	Moderate-broad	Broad
Seed longevity	Short	Short-medium	Medium; unknown	Medium-long	Long
Recruitment mode/fecundity	Low		Medium Low-high Low and episodic Unknown	Episodic	High
Fire adaptive capacity (regeneration mechanisms)	No adaptive capacity		Weak sprouter Unknown	Fire-hardy	One mechanism: high sprouter or seeds germinate with heat
Reproductive lifespan	1–10 years	1 year (annual); 10–100 years	10–200 years	10–300 years	10–350 years
Mode of dispersal	Gravity	Gravity +1 mode (not wind)	Gravity + wind Gravity +2 modes Unknown	Gravity +1 mode + wind	Gravity +3 or more modes
Germination agent	Inundation High moisture Winter Scarification	Winter/cold Sufficient moisture Winter/cold + Summer/ Heat Scarification and seed dehulling by rodents; soil disturbance	Chemical/heat Unknown	Heat	
Fire sensitivity	Fire-sensitive Thin epidermis High flammability Canopy architecture susceptible	Fire-sensitive Thin epidermis High flammability	Not known	Fire-hardy Thick epidermis Canopy structure susceptible	Fire-hardy Thick epidermis Canopy architecture resistant Low flammability

Note: Each attribute was scored on a scale of 1 (high sensitivity, low adaptive capacity) to 5 (low sensitivity, high adaptive capacity), and scores were averaged across attributes (Dataset S1).

^aScores calculated from mean squared PCA environmental distances and rescaled using Jenks natural breaks.

We adopted a framework that integrates different aspects of species vulnerability and resilience to climate change by distinguishing *exposure* and *sensitivity* as components of vulnerability, and *adaptive capacity* as characteristics that can ameliorate sensitivity (Chevin et al., 2010; Dawson et al., 2011; Foden et al., 2019; Williams et al., 2008). *Exposure* to climate change is often measured by the degree to which climate is projected to change within a species' range. Sensitivity and adaptive capacity are both defined in terms of species' intrinsic properties, including aspects of their ecology, physiology, genetic diversity, disturbance responses, and dispersal ability. These are generally measured using knowledge about species' traits that are known or believed to impact

their ability to tolerate or adapt to changing environmental conditions (Foden et al., 2019).

Exposure was measured as consensus habitat loss projected by SDMs under climate and land use change (as in Rose et al., 2023) and reflects currently suitable habitat predicted to become unsuitable by both GCMs by the end of the 21st century. We compared habitat loss under Moderate and BAU emissions scenarios to highlight potential results of climate mitigation. To help us interpret these projections, we applied the International Union for Conservation of Nature (IUCN) Red List Criterion A3 (Mancini et al., 2024) and assumed a linear relationship between projected habitat loss and population decline. We used the following thresholds to assign

risk: Critically Endangered ($\geq 80\%$), Endangered ($\geq 50\%$), Vulnerable ($\geq 30\%$), and Near Threatened (20%–30%). Although the IUCN does not define a quantitative threshold for Near Threatened, we followed Mancini et al. (2024) in assigning this category to species with 20%–30% projected habitat loss.

Sensitivity and *adaptive capacity* were assessed using seven species life-history traits derived from the California Manual of Vegetation (MCV; Sawyer et al., 2009, online version, California Native Plant Society), following methods from Thorne et al. (2016). Traits included fire sensitivity, germination agent(s), mode(s) of dispersal, reproductive lifespan, adaptability to fire, mode and level of recruitment, and seed longevity. Each trait was scored from 1 (most sensitive/least adaptive) to 5 (least sensitive/most adaptive) (Table 1). Fire is an important driver of ecosystem dynamics in California where plant species respond to fire regimes via their traits. While climate-driven wildfire has burned considerable areas of California in recent decades (Williams et al., 2019), the impacts of future climate change on fire regimes are highly uncertain (Keeley & Syphard, 2016). Therefore, both sensitivity and adaptability traits were scored to characterize species resilience to altered fire regimes. In general, species with thin epidermis, high flammability, and lacking the capacity for regeneration following fire are assigned a fire-sensitivity score of 1, indicating that they are sensitive to or lack the adaptive capacity to respond to fire. Fire adaptability, on the other hand, is scored based on post-fire regeneration mechanism. A plant with more dispersal modes may be less sensitive to climate and land use change because of increased chances to disperse, incurring a higher dispersal score. Plants with longer reproductive lifespans tend to be less sensitive to environmental change, given that a species will have increased opportunities for reproduction. However, for some fire-adapted perennials and annuals, shorter lifespans may serve as an adaptive advantage if recruitment following a disturbance is high. For this lifespan category, shorter lifespans were associated with higher sensitivity, except for annuals which were scored as 2. Germination agents affect seed germination and represent a direct response (or lack thereof) by a plant to environmental conditions. These can be related to temperature, precipitation, fire, seed consumption, or chemical drivers. Lower scores for germination agents (closer to 1) represent more specific/sensitive germination requirements, such as inundation by water, while higher scores correspond to more general agents such as heat. Scores were available for 24 of our study species from the Thorne et al. (2016) assessment and for the 26 species in our study that were not included in Thorne et al. (2016), scores were assigned by MBR and JF based on the MCV, and reviewed by all authors.

To further account for species-specific environmental sensitivity, we added a niche trait, habitat breadth (range of environmental tolerance), not previously considered in the MCV assessment. We calculated species' habitat breadth using the same hydroclimatic and soil variables used to build SDMs, adapting methods from Vela Díaz et al. (2020). Variables were standardized across California, and separate principal component analyses (PCA) were performed for soil and climate. For each species, we calculated the mean squared environmental distance of occurrences from the species' centroid. These values (range: 2.9–10.6) were rescaled from 1 (narrow environmental range) to 5 (broad environmental range) using Jenks natural breaks (Jenks, 1967).

We grouped species into eight broad habitat associations for the purpose of comparing vulnerability among species that are likely to be found in the same ecological communities and landscapes, and perhaps would be cared for using similar cultural land-tending practices. Those plant communities were: chaparral, coastal sage scrub (CSS), conifer forest, desert scrub, oak woodland, piñon-juniper woodland, riparian woodland, and sagebrush scrub (e.g., Mooney & Zavaleta, 2016).

RESULTS

Projected habitat change—Species exposure

Overall, the SDMs performed well across the 50 species: area under the curve (AUC) = 0.89 ± 0.04 SD, true skill statistic (TSS) = 0.69 ± 0.09 , and omission rate = 0.11 ± 0.05 (Figure S1). When accounting for both climate and land use change, the average projected habitat loss by the end of the 21st century across the 50 study species was higher under BAU RCP 8.5 (mean = 26%, SD = 20%) than under Moderate RCP 4.5 (mean = 17%, SD = 14%) (Figure 3). Although this pattern held for most species, a few showed greater projected habitat loss under RCP 4.5 than RCP 8.5, including honey mesquite (*Prosopis glandulosa*), sugar pine (*Pinus lambertiana*), buckhorn cholla (*Cylindropuntia acanthocarpa*), teddy-bear cholla (*Cylindropuntia bigelovii*), deer grass (*Muhlenbergia rigens*), Mohave yucca (*Yucca schidigera*), canyon oak (*Quercus chrysolepis*), and incense cedar (*Calocedrus decurrens*).

Based on the application of the IUCN Red List criteria for projected habitat loss, most species under RCP 4.5 would be classified as Least Concern ($n = 34$), followed by Near Threatened ($n = 8$), Vulnerable ($n = 6$), and Endangered ($n = 2$). Under RCP 8.5, the distribution shifted toward higher risk categories: Least

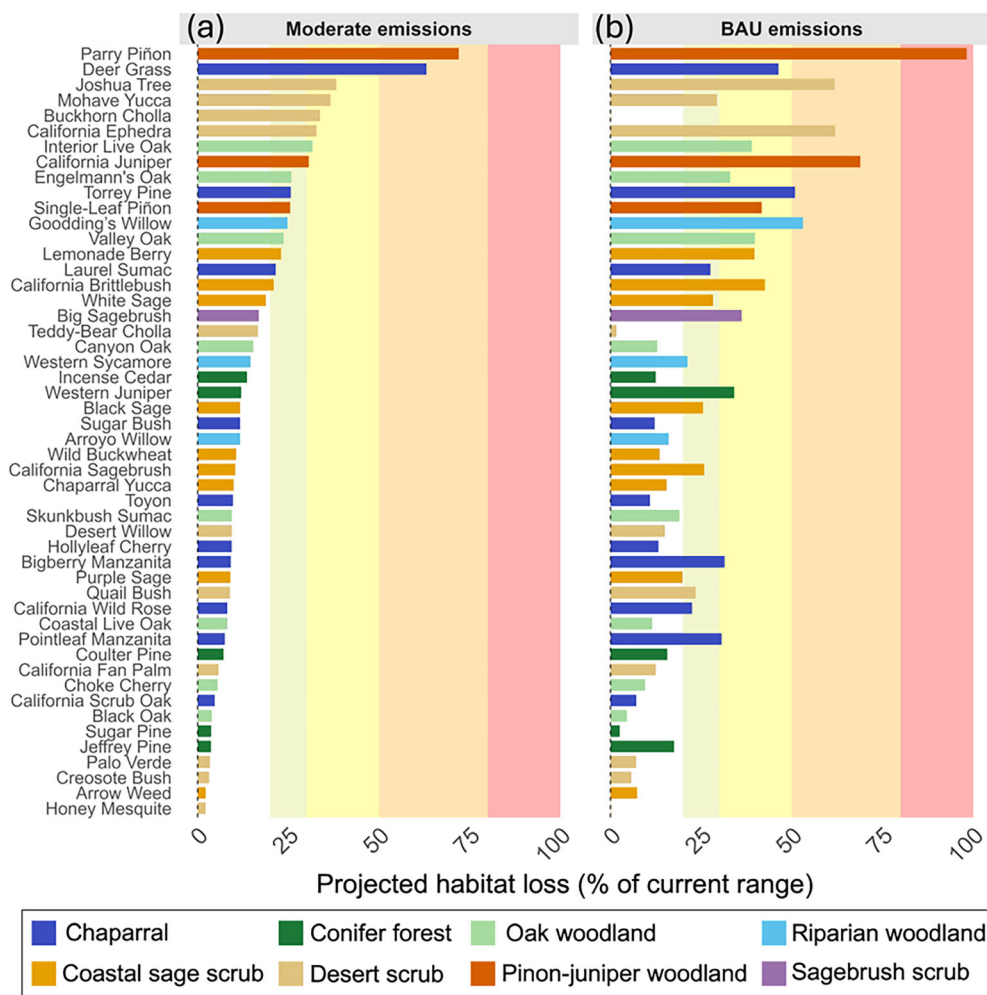


FIGURE 3 Species-level projections of consensus habitat loss relative to baseline range size by end-of-century due to both climate and land use change for the moderate (a) and business-as-usual emissions (b) scenarios. Bar colors correspond to each species' primary plant community association. Background colors represent the thresholds for threat categorization under IUCN criterion A3c. Green = Near Threatened (20%–30% habitat loss); Yellow = Vulnerable (30%–50% habitat loss); Orange = Endangered (50%–80% habitat loss); and Red = Critically Endangered (>80% habitat loss). Species are ordered from greatest to least habitat loss under the moderate emissions scenario.

Concern ($n = 25$), Near Threatened ($n = 8$), Vulnerable ($n = 11$), Endangered ($n = 5$), and Critically Endangered ($n = 1$; Figure 3). In total, 22 species were predicted to fall into a higher risk category under RCP 8.5 compared to RCP 4.5.

For example, Parry piñon (*Pinus quadrifolia*) was projected to lose substantially more habitat under increasing emissions, escalating from Endangered to Critically Endangered. Several other species shifted from Least Concern or Near Threatened under RCP 4.5 to Vulnerable or Endangered under RCP 8.5. On the other hand, eight species showed the counterintuitive pattern of greater habitat loss under RCP 4.5 than RCP 8.5. These differences were minor for four of these species (<4% difference in proportional habitat loss), while the remaining four species (Mojave Yucca, Buckhorn Cholla, Teddy-

Bear Cholla, and Deer Grass) may be less negatively affected under the warmer conditions generally expected under RCP 8.5 as they are generally associated with desert or hot-climate regions.

When aggregating habitat loss by primary plant community, average projected loss was consistently higher under RCP 8.5 than RCP 4.5, though variability in projected habitat loss among species within each plant community was high (Figure 3). Piñon-juniper woodland species ($n = 3$) showed wide variation in habitat loss under both RCP 4.5 and 8.5 (26%–72% and 42%–98%, respectively). Chaparral species ($n = 10$) also showed substantial loss (17% under RCP 4.5; 25% under RCP 8.5), with a broad range (5%–62% and 7%–51%). California scrub oak (*Quercus dumosa*) was projected to lose the least habitat among chaparral

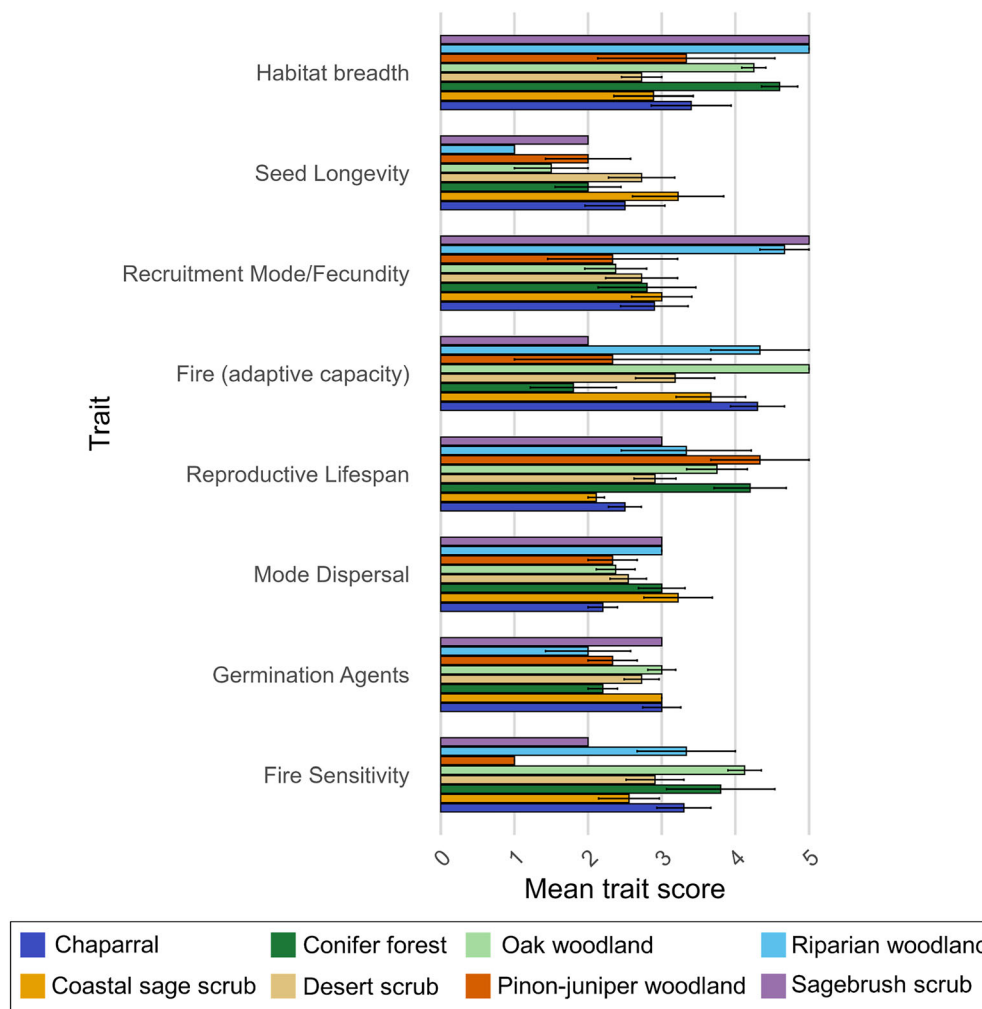


FIGURE 4 Mean sensitivity and adaptive capacity scores for plant species included in this analysis. Traits include habitat breadth, seed longevity, recruitment mode/fecundity, fire adaptability (regeneration mechanisms), reproductive lifespan, dispersal mode, germination agents, and fire sensitivity. Bars represent the mean trait score for species occurring in each habitat type (represented by different colors), with higher scores indicating lower sensitivity or greater adaptive capacity (1 = most sensitive/least adaptive; 5 = least sensitive/most adaptive). Error bars show standard errors of the mean, where applicable.

species, while deer grass (*Muhlenbergia rigens*) and Torrey pine (*Pinus torreyana*) were projected to lose the most.

CSS species had lower average projected losses than chaparral species (13% under RCP 4.5; 24% under RCP 8.5), with relatively low variation between species (2%–23% and 7%–43%). Desert scrub species ($n = 11$) had moderate average losses (17.4% under RCP 4.5; 19.9% under RCP 8.5), but wide variation among species (2%–38% and 0%–62%), indicating substantial heterogeneity in projected habitat change among these species. Conifer forest species exhibited the lowest average loss across both scenarios (8% under RCP 4.5; 17% under RCP 8.5), with relatively low variability between species (4%–14% and 3%–34%).

Species vulnerability assessment

We observed substantial variability in the sensitivity and adaptive capacity of the 50 study species based on the assessed life-history characteristics (Figure 4; Dataset S1). In terms of fire sensitivity, species within oak woodlands were the least sensitive (mean = 4.1), whereas those within piñon-juniper woodlands exhibited the highest sensitivity (mean = 1.0). Regarding fire regeneration, oak woodland species again demonstrated the highest regenerative capacity after fire, for example, owing to strong resprouting ability (mean = 5.0), while conifer forest species without resprouting ability or serotinous cones had the lowest (mean = 1.8). For dispersal, CSS species exhibited the highest mean score (3.2), while chaparral

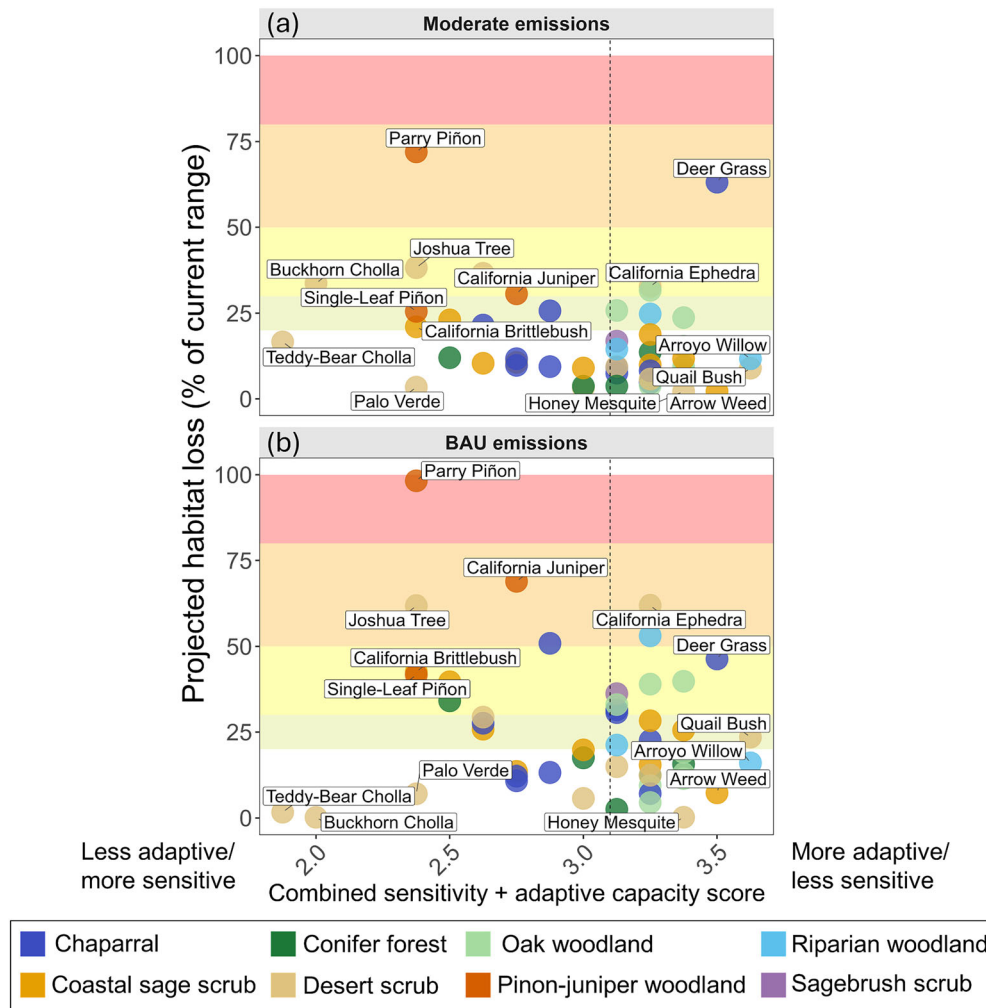


FIGURE 5 Relationship between projected consensus habitat loss by end-of-century under the moderate (a) and business-as-usual emissions (b) scenarios (y-axis) and the mean sensitivity and adaptive capacity score (x-axis). Each point represents a species, and colors correspond to habitat association. Background colors represent the thresholds for threat categorization under IUCN criterion A3c. Green = Near Threatened (20%–30% habitat loss); Yellow = Vulnerable (30%–50% habitat loss); Orange = Endangered (50–80% habitat loss); and Red = Critically Endangered (>80% habitat loss). The dotted vertical lines reflect the median combined sensitivity and adaptive capacity score for the study species (3.1). Fourteen species with the highest and lowest values of projected habitat loss and/or combined sensitivity and adaptive capacity are labeled.

species had the lowest (mean = 2.2). Species in sagebrush scrub ($n = 1$) and riparian woodlands showed the highest capacity for recruitment and fecundity (5.0 and mean = 4.7, respectively), while species in piñon-juniper woodlands showed the lowest (mean = 2.3). However, piñon-juniper woodland species scored the highest for reproductive lifespan (mean = 4.3), while CSS species scored the lowest (mean = 2.1). CSS species did exhibit the highest seed longevity (mean = 3.2), while riparian woodland species had the lowest (mean = 1.0). Chaparral species required the least specific germination agents (mean = 3.0), while riparian species required the most specific (mean = 2.0). In terms of habitat breadth, riparian woodland and sagebrush scrub species had the broadest

environmental tolerances (mean = 5.0), while desert scrub species had the narrowest (mean = 2.7). Overall, species from riparian and oak woodlands were the least vulnerable across all attributes (mean = 3.3), while species from desert scrub and piñon-juniper woodlands were the most vulnerable (means = 2.8 and 2.5, respectively).

When examining vulnerability in the context of both exposure due to habitat loss and combined sensitivity and adaptive capacity, several species emerged as particularly vulnerable or resilient (Figure 5). Parry piñon (*Pinus quadrifolia*) exhibited the highest levels of projected habitat loss under both emissions scenarios and was identified as vulnerable based on a lower-than-average adaptive capacity/sensitivity score. We observed a general

trend, especially under RCP 8.5, where species projected to experience greater habitat loss also tended to have higher sensitivity and lower adaptive capacity. Notably vulnerable species under RCP 8.5 included California juniper (*Juniperus californica*), Joshua Tree (*Yucca brevifolia*), California brittlebush (*Encelia californica*), and single-leaf piñon (*P. monophylla*). On the other hand, species with relatively high projected habitat loss but low sensitivity/high adaptive capacity, such as California ephedra (*Ephedra californica*) and deer grass (*Muhlenbergia rigens*), were also identified. In contrast, several desert species showed low habitat loss but high sensitivity and low adaptive capacity: teddy-bear cholla (*Cylindropuntia bigelovii*), buckhorn cholla (*Cylindropuntia acanthocarpa*), and palo verde (*Parkinsonia florida*). Finally, some of the most resilient species based on the evaluated vulnerability axes included honey mesquite (*Prosopis glandulosa*), arrow weed (*Pluchea sericea*), arroyo willow (*Salix lasiolepis*), and quail bush (*Atriplex lentiformis*).

DISCUSSION

Our vulnerability assessment is an important outcome of the codeveloped research, directly supporting the overarching goal of advancing Tribally led climate adaptation planning and informing stewardship and restoration strategies (Chief et al., 2014). By integrating species distribution model (SDM) predictions of habitat loss (exposure) with trait-based assessments of sensitivity and adaptive capacity, our findings suggest detailed, actionable guidance for stewardship and restoration efforts under changing environmental conditions.

Our research contributed several of the results presented here to the ecological modeling component of the Resilient Restoration Project. The habitat models were integrated into the web-based, GIS-enabled Data Portal for Tribal partners to use as a decision-support tool. Through a collaborative process, we synthesized these modeling outputs into an interactive adaptation menu (Jennings et al., 2025). This menu supports selecting specific on-the-ground restoration actions, providing the TWG with data-informed strategies for implementing their stewardship practices.

The assessment enables the TWG to prioritize management efforts by providing information on the relative magnitude of global change versus other potential threats. For instance, species projected to lose substantial habitat under high-emission scenarios (RCP 8.5) and simultaneously exhibit low adaptive capacity would be targeted for enhanced conservation and restoration efforts focusing on habitat refugia (Morelli et al., 2016; Rose et al. 2026). Conversely, species with high projected

habitat loss but high adaptive capacity, such as California ephedra or deer grass, might require different management approaches focused on human-assisted dispersal of plants into more resilient populations within or outside of the species' current range (Hällfors et al., 2016; Twardek et al., 2023). Our results offer insights into the differential impacts of climate change across Southern California's ecological communities, directly aligning with Tribal goals focused on conserving these region's ecosystems.

Interpreting results for specific communities

Piñon-Juniper woodland vulnerability

We identified species within the piñon-juniper woodland community to have the highest average projected habitat loss (43% under RCP 4.5 and 70% under RCP 8.5) and were generally the most vulnerable across all assessed traits. Piñon-juniper species also exhibited the highest fire sensitivity and lowest recruitment capacity among the communities studied. These results are supported by empirical observations of drought-related tree mortality and subsequent insect-infestation in piñon-juniper woodlands across the western United States (Breshears et al., 2009; Gaylord et al., 2013). This indicates that species like Parry piñon (projected to escalate to Critically Endangered under RCP 8.5) and California juniper are highly exposed and vulnerable to environmental stress. For the TWG, these results highlight the need for focused strategies potentially involving fire mitigation, assisted establishment in future suitable habitats (Redmond et al., 2023; Whitehair et al., 2024), or genetic conservation (Buck & Flores-Rentería, 2022) to address the threat to this community.

Threats and vulnerability in CSS

CSS is one of California's most threatened ecosystems due to its coastal distribution (losses to land use change) and ongoing degradation from nitrogen deposition, invasive species (Cleland et al., 2016), and illegal poaching of species such as white sage (Montgomery, 2023). CSS species exhibited lower projected habitat loss than chaparral or piñon-juniper communities, with mean losses of 13% under RCP 4.5 and 24% under RCP 8.5 (7%–43% for individual species). Trait assessments indicated relatively high adaptive capacity. CSS species had the highest mean dispersal and seed longevity scores, but also a notable vulnerability in reproductive lifespan. Integrating

sensitivity and exposure, California brittlebush emerged as particularly vulnerable. These findings highlight the need for invasive species control (Allen et al., 2019), protection of species such as white sage, and targeted restoration of vulnerable species such as brittlebush.

Resilience in oak and riparian communities

Oak and riparian species generally showed high resilience and adaptive capacity (Hammett et al., 2017; Selmants et al., 2023). Oak woodland species demonstrated the least sensitivity to fire and the highest regenerative capacity after fire (e.g., strong resprouting ability). These communities were identified as the least vulnerable overall. This information may guide Tribal stewardship efforts toward strategies that leverage the natural resilience of these systems, perhaps focusing on monitoring, preserving existing forest structure, or conducting cultural burns to maintain ecosystem health, rather than large-scale, costly active restoration (planting) projects (Thoreson et al., 2024).

Trait-driven sensitivity in desert scrub

The assessment revealed a nuance within the desert scrub community. While many desert species exhibited only moderate habitat loss projections (an exception being Joshua Tree), and some were even projected to lose less habitat under the extreme (RCP 8.5) scenario than the more moderate (owing to their heat and drought tolerance), several, including the teddy-bear cholla, buckhorn cholla, and palo verde, showed low adaptive capacity and high sensitivity based on their intrinsic traits. This finding emphasizes that even if habitat loss is modest, these species may still be susceptible to environmental stress due to poor dispersal or specific germination requirements. Tribal stewards can use this information to focus stewardship actions that directly address these trait limitations, such as protecting specific microclimates or managing local disturbances, such as fire or non-native species encroachment (Underwood et al., 2019).

Value in linking SDM with trait-based analysis

The methodological approach of pairing SDM-derived exposure risk with trait-based analysis of sensitivity and adaptive capacity significantly enhances the utility of the assessment for supporting resilience. By integrating these

two vulnerability axes, the study moves beyond predicting where species might lose habitat (exposure) to understand why a species is vulnerable and what intrinsic characteristics might buffer or exacerbate that risk (Willis et al., 2015).

This integrated framework allows for the identification of two critical management categories. The first is High Exposure/Low Adaptive Capacity. These species (e.g., Parry piñon) face severe habitat loss and lack the intrinsic traits (such as broad dispersal or high recruitment) necessary to cope, requiring proactive, interventionist management. The second is Low Exposure/High Sensitivity, and these species (e.g., certain desert chollas) might appear secure based on habitat projections alone, but are fragile due to their life-history traits. Stewardship efforts here can be highly effective, focusing on mitigating specific local environmental pressures such as grazing or illegal collecting (Martorell et al., 2015).

This linkage ensures that the resulting adaptation menu is both spatially explicit (based on habitat modeling) and biologically relevant (based on species traits), ultimately maximizing the effectiveness of stewardship strategies. The integration of SDM exposure data with sensitivity traits acts as a triage system, where the habitat loss (exposure) is the immediate injury, but the trait analysis (sensitivity/adaptive capacity) is the underlying profile of the level of health. This dual assessment ensures that limited resources are applied effectively, not just to the most exposed, but also to those with the least resilience capacity.

Future directions and contextual constraints

Further stressors affecting plant populations include the interruption of long-standing stewardship practices. Jurisdictional and legal constraints often limit Tribal peoples' access to steward their ancestral landscapes and maintain reciprocal relationships with plant communities (Hankins et al., 2025). The interruption of practices, including cultural burning, seed gathering, thinning, and coppicing, contributes to reduced plant population health, resilience, and distribution (Anderson, 2005; Hankins, 2024). Academic literature documents that these Tribal stewardship practices have direct relevance to plant habitat suitability. For instance, cultural burning utilizes low-intensity fire to promote the health of fire-adapted species (e.g., *Quercus* spp.) and influences species abundance and spatial patterning (Long et al., 2021).

To improve future assessments that support Tribally led climate adaptation, incorporating stewardship practices directly into habitat models would provide an

essential layer of insight (e.g., Skroblin et al. 2021). However, modeling plant resilience across multiple climate scenarios while accounting for fine-scale stewardship practices remains a challenge due to the limited availability of spatially explicit data (Requena-Mullor et al., 2019). Other methodologies for integrating knowledges may be needed (e.g., Mucioki et al., 2022). Accomplishing this work requires sustained collaboration with Tribal stewards and careful attention to relationships that honor cultural protocols and data and knowledge sovereignty (Whyte, 2018). In doing so, this collaborative work will continue to be defined by this shared commitment.

AUTHOR CONTRIBUTIONS

Connor Magee: Conceptualization; funding acquisition; methodology; resources; writing – original draft. **M. Brooke Rose:** Conceptualization; data curation; formal analysis; methodology; software; visualization; writing – original draft. **Janet Franklin:** Conceptualization; funding acquisition; methodology; project administration; resources; supervision; writing – review and editing. **Gregory A. Backus:** Conceptualization; writing – original draft; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

All data and code used in the vulnerability analysis presented here are included in the [Supporting Information](#) or can be found in this Github repository (https://github.com/mrose048/vulnerability_assessment.git). To ensure the confidentiality of individuals and knowledge shared, we omitted sensitive information from the research process. Geographical locations, traditional gathering techniques, and further sensitive information were omitted while delivering inputs to the models. We achieved this by developing relationships based on trust between all parties and a mutual understanding of the unique requirements to protect Tribal data. This paper does not share any sensitive information relative to the Tribes involved, nor does it infringe on the TWG Knowledge Sovereignty Policy. Only publicly available data were used in modeling.

ETHICS STATEMENT

The authors have produced this article following the ESA Code of Ethics.

ORCID

Connor Magee  <https://orcid.org/0009-0006-6320-8281>
M. Brooke Rose  <https://orcid.org/0000-0001-5269-3759>
Janet Franklin  <https://orcid.org/0000-0003-0314-4598>
Gregory A. Backus  <https://orcid.org/0000-0003-3695-8168>

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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