RAD Decisions in Rad Landscapes:

Climate Adaptation for Sonoran Pronghorn

Final Report

Kira Hefty, Jaclyn Fox Rushing, Katherine Zeller, Greta Schmidt, Jill Bright, Paul Sitzmann, Jennifer Wilkening, Stephanie Fuest

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Aldo Leopold Wilderness Research Institute, Rocky Mountain Research Station, USDA Forest Service

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Executive Summary

Climate change is contributing to unprecedented rates of ecological transformation worldwide. Shifts in species composition and habitat have implications for ecosystem function and human relationships. The 1964 Wilderness Act was passed to preserve undeveloped landscapes and to sustain opportunities for people to experience and enjoy "natural" places. Nevertheless, wilderness is still vulnerable to the direct and indirect impacts of climate change. Using active management to respond to climate change in wilderness is complicated by the very protections afforded to wilderness that limit human impacts. This dichotomy manifests as a wicked problem for land stewards who are grappling with how to prepare for or respond to climate change-driven ecological transformation.

In the southwestern United States, climate change is contributing to rapid transformations in desert plant communities. Sonoran pronghorn (*Antilocapra americana sonoriensis*) is a federally endangered species threatened by ongoing habitat degradation and fragmentation associated with human development, drought, and increasing temperatures. Much of the current range of Sonoran pronghorn (herein, pronghorn) overlaps with wilderness, which further complicates recovery efforts. This report summarizes research and activities relevant to the *RAD Decisions in Rad Landscapes: Climate Adaptation for Sonoran Pronghorn* case study. The overarching goal of this case study was to provide United States Fish and Wildlife Service (FWS) staff and their partners with knowledge and tools to support intentional and transparent decision-making for pronghorn through climate change-driven ecological transformation. Scientists from the Aldo Leopold Wilderness Research Institute (ALWRI) conducted research to illuminate the potential ecological consequences of climate change for pronghorn as well as managers' perceived ability to respond to ecological change. Additionally, scientists at ALWRI facilitated a 2-day workshop which engaged FWS staff, state agency managers, and non-profit partners in an adaptive management process to clarify values and desired conditions, generate decision alternatives under the resist-accept-direct (RAD) framework, and evaluate the potential social, legal, and ecological implications of alternatives for pronghorn.

Workshop activities and discussions were informed by biological and social science research conducted prior to the workshop. Biological analyses included assessment of current and mid-21st century habitat selection and connectivity for pronghorn. In the absence of wildlife guzzlers maintained by managers, highly suitable habitat is expected to shift outside current management areas by mid-21st century in accordance with shifting climate. Additionally, the likelihood that active management will need to occur in wilderness is expected to increase if current management strategies continue to be employed. Interviews with managers and their partners indicated that observed warming and increasingly unpredictable monsoonal rainfall threaten pronghorn persistence. The most salient challenges to recovering pronghorn amid these threats included lack of staff capacity, lack of funding, vast landscapes, limited opportunities to act outside wilderness, and extreme climate conditions.

During the in-person workshop, attendees participated in a range of facilitated discussions and activities as part of an iterative process to generate and evaluate decision alternatives to address climate change challenges for pronghorn. When exploring the RAD framework, participants generated alternatives to either support pronghorn (e.g. captive breeding) or improve habitat availability (e.g. planting key forage species and assisted migration of plant species). Participants overwhelmingly generated alternatives that either resisted or accepted ecological change expected to impact pronghorn persistence. Participants further evaluated the positive and negative consequences of three alternatives: add more wildlife guzzlers to historical habitat in wilderness (resist), engage in outreach and education (accept), and translocate pronghorn to a currently unoccupied proposed 10(j) zone in southern California where climatic conditions may be more suitable in the future (direct). The perceived feasibility and efficacy of these alternatives varied among participants based on professional, cultural, and regional affiliations. Overall, participants agreed that a combined strategy may be most useful, however, resources to implement new activities may be prohibitive without engaging additional partners.

The process and tools introduced in the workshop were created to support forward-thinking and intentional decision-making regarding climate change-driven ecological transformation affecting Sonoran pronghorn in wilderness. Specific recommendations were not provided as part of this workshop with the intention that practitioners, land stewards, and partners can use this process in a way that best fits their unique needs and limitations. Following a standardized process that explicitly integrates the evaluation of RAD alternatives can foster collaboration and increase transparency in decision-making for wilderness in an era of climate change.

Key take-aways

- Suitable climatic habitat is expected to shift outside current management zones for Sonoran pronghorn
- Managers perceive that the Sonoran Desert is getting hotter and bimodal rainfall patterns are becoming increasingly unpredictable
- Current management strategies may allow pronghorn to persist within their historical range, but management intensity may need to intensify within and outside wilderness to remain effective
- Although trammeling of wilderness was a concern, some participants felt it was necessary to recover pronghorn and ensure personnel safety
- There was shared desire among participants to resist ecological change but also a desire to adopt more proactive planning approaches to adequately address future change
- Strong partnerships and relationships with private, Tribal, and agency entities will be important to pursue adaptation planning

RAD Decisions in Rad Landscapes: Project Background

Ecological Transformation

Climate change has contributed to unprecedented shifts in ecological patterns and processes (McElwee et al. 2023). These changes directly and indirectly impact relationships between people and the environment. When compounded by existing stressors and threats such as wildfire, pests, disease, invasive species, and human development, it is particularly likely that ecological change can become irreversible. Ecological transformation, or the emergence of new ecosystem states that differ from known historical conditions (Crausbay 2022), makes it difficult for land stewards and partners to delineate management goals and adhere to current management strategies (Stein et al. 2013). Growing concern and recognition that traditional or familiar stewardship strategies may no longer support resilient ecological communities has driven land stewards and their partners to seek alternative solutions to address complex problems under climate change (Magness et al. 2012; Schwartz et al. 2012; Schuurman et al. 2020; 2022).

Managing for Climate Change in Wilderness: A Wicked Problem

Climate change-driven ecological transformation is a diffuse and complex issue impacting landscapes globally, regardless of jurisdiction and protection status. In the United States, the National Wilderness Preservation System (NWPS) includes over 100 million acres of land afforded the highest level of protection of all public lands in the United States. Guiding policy under the 1964 Wilderness Act mandates that lands designated as part of the NWPS be preserved in their natural state, wherein the character of the landscape is primarily influenced by the forces of nature and absent of human development or trammeling (Public Law 88-577; Wilderness Act 1964). In addition, the NWPS is managed to preserve opportunities for solitude or primitive recreational experiences and other features of value, such as ecological processes and cultural features that existed upon designation (Table 1). Nevertheless, despite these high levels of protection, the NWPS remains susceptible to climate change-driven challenges such as increasing temperatures, altered precipitation events, and altered disturbance regimes. Challenges related to climate change threaten several qualities of wilderness character, including the natural condition of wilderness, or the quality of an ecological system to be free from the impacts of modern civilization. These climate change-driven threats were not anticipated when the 1964 Wilderness Act was signed into law. Lack of guidance and sometimes competing priorities outlined under the Wilderness Act have created a conundrum for land stewards, rightsholders, and partners attempting to address climate change-related impacts within the NWPS. Furthermore, the same high levels of protection afforded to wilderness to protect lands from direct human impacts are often dually perceived as constraints on addressing climate change-driven threats, including ecological transformation. Whether or not to pursue active management, which may involve trammeling, to address transforming wilderness systems presents a “wicked problem”, or a problem that is seemingly intractable due to the high degree of complexity and uncertainty associated with balancing sometimes competing mandates, objectives, and values (Head 2019; Rittel & Webber 1973).

Table 1: Descriptions of wilderness character qualities and examples of ways in which they can be degraded are selected from Keeping it wild 2: An updated interagency strategy to monitor trends in wilderness character across the National Wilderness Preservation System (Landres et al. 2015).

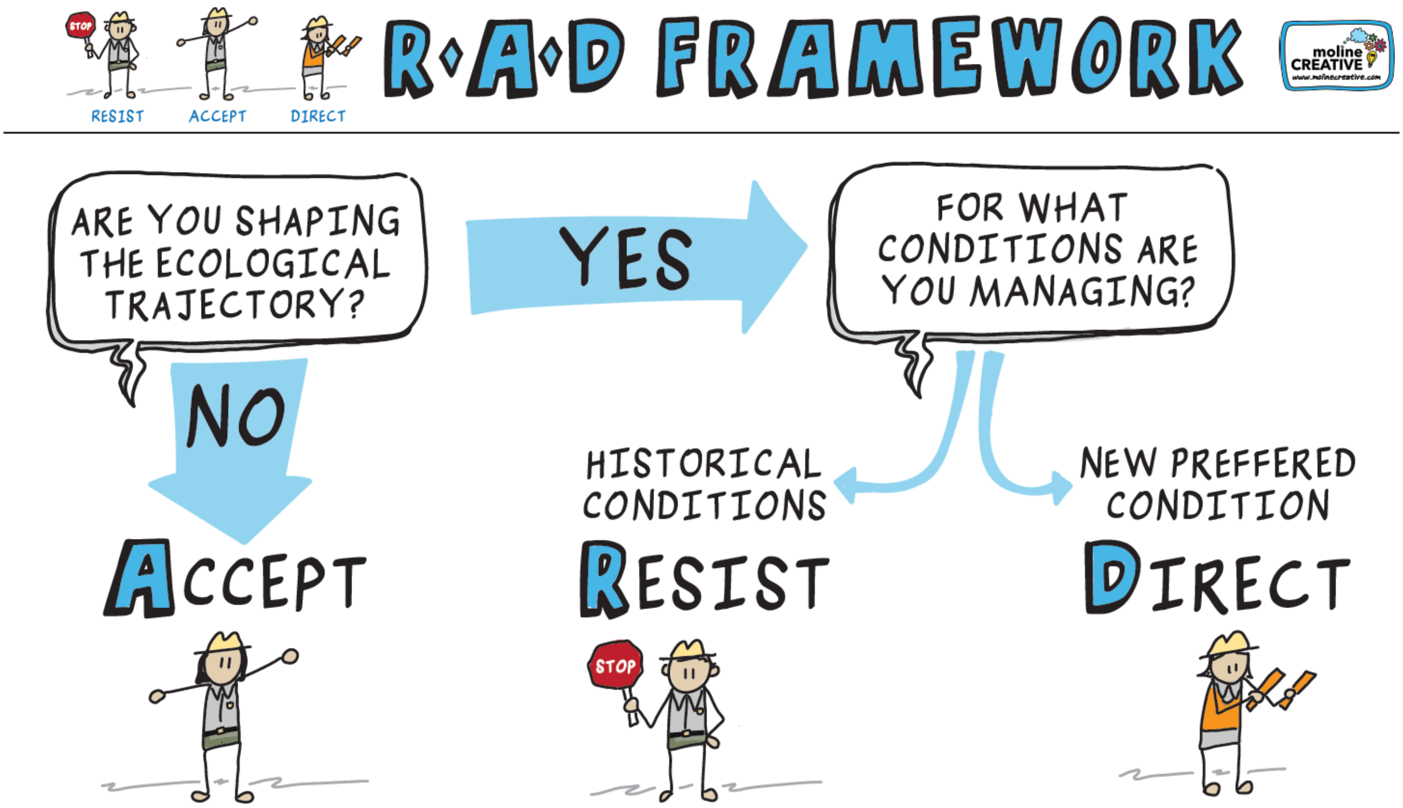
Wilderness Character Quality	**Definition**	**Example Measures that Detract from Quality**
Natural	Wilderness patterns and processes are largely free from the influence of modern civilization	Presence of non-native species, air pollutants, water pollutants
Untrammeled	Wilderness is free from the impacts of human activity or manipulation	Mechanical forest treatments, wildfire suppression, fish stocking
Undeveloped	Wilderness does not contain structures, installations, or other evidence of human presence or occupation	Dams, use of motorized or mechanized equipment, recreational kiosks
Solitude or Primitive and Unconfined Recreation	Wilderness provides opportunities for solitude and primitive recreational experiences unhindered by the impacts of modern civilization	Light pollution, recreation facilities, user-created campsites and trails
Other Features of Value	Wilderness preserves ecological, geological, or other features of scientific, educational, scenic, or historical value	Vandalism of existing cultural features, loss of iconic plant or animal species, deterioration of iconic geological features

Untangling the Wicked Problem: RAD

The resist-accept-direct framework (RAD) helps users explore the full range of available choices for addressing expected or observed ecological transformation: 1) Resist the transformation by maintaining historical conditions through efforts to prevent a transformation or engage in restoration to reverse the process, 2) Accept the transformation by intentionally allowing ecological structure and function to change autonomously, or, 3) Direct the transformation by actively shaping ecological change toward a preferred new condition (Schuurman et al. 2022;

Figure 1). RAD has a unique advantage for wilderness managers because of its incorporation of acceptance as a possible strategy, which supports wilderness as untrammeled. Interagency guidance describes the untrammeled quality of wilderness character as the “first among equals” (Landres et al. 2015, p. 80), which may lead some managers to prioritize the untrammeled quality of wilderness over others such as naturalness. However, instead of accepting ecosystem change implicitly to support the untrammeled quality, RAD provides a decision space wherein the relative value of acceptance can be fully examined and compared to alternative resist or direct strategies. Explicit and intentional planning fosters transparency in decision-making, a quality which is particularly important in federally designated wilderness where active management is highly scrutinized (Miller et al. 2025). By intentionally choosing to resist, accept, or direct observed or anticipated ecological change, land stewards can begin to generate defensible solutions for addressing climate change challenges in wilderness.

Figure 1: Decision points to guide the use and implementation of the resist-accept-direct (RAD) framework for responding to observed or expected ecological transformation under climate change.



Project Objectives

To unravel the wicked problem of addressing climate change in federally designated wilderness, scientists at the Aldo Leopold Wilderness Research Institute (ALWRI) led an effort that used the RAD framework as a tool to illuminate a decision-space when addressing climate change-driven ecological transformation for four case studies, one per wilderness-administering agency. Sonoran pronghorn was nominated by U.S. Fish and Wildlife (FWS) staff as a case study that represented common challenges staff face when attempting to address climate change impacts in wilderness. Through this project and workshop, a process was developed to illustrate the utility of the RAD framework for adaptive decision-making for Sonoran pronghorn. Scientists at ALWRI worked with FWS staff and their partners to identify values and desired conditions, explore the RAD decision space to meet those desired conditions, and evaluate social-ecological trade-offs inherent in pursuing RAD strategies.

The *RAD Decisions in Rad Landscapes* project had three primary goals:

1) **Generate a widely applicable process of how to use the RAD framework in designated wilderness.**

2) **Provide science and decision support for management challenges related to climate change in wilderness.**

3) **Advance our understanding of the trade-offs, uncertainties, opportunities, and limitations for addressing climate change impacts within designated wilderness.**

Project Stages

To accomplish overarching project goals, four project stages were completed for all four case studies (Table 2): 1) gather information to identify case study partners and to better understand current conditions within wilderness and challenges impacting wilderness management, 2) investigate biological and social impacts of climate change-driven transformation in wilderness, 3) facilitate workshops to clarify values and desired conditions as well as evaluate a RAD decision-space for current and future climate change challenges, 4) produce deliverables to summarize results of science analyses and comprehensive summaries of workshop activities. Each stage of the project was designed to inform and contribute to an adaptive management process using RAD as a tool to support intentional decision-making around climate change-driven transformation. This report summarizes the first three stages of the project specific to the Sonoran pronghorn case study.

Table 2: Project stages and descriptions for the RAD Decisions in Rad Landscapes project, 2022-2025.

Information Gathering	Investigate Transformation	Apply RAD to Planning Process	Final Reporting
Build Advisory Team **Synthesize Current Methods and Processes** **Establish Partners** **Site Visits** **Select Case Studies**	**Social Implications of and Perspectives Around Climate Change** • Interviews with managers, rightsholders, partners, and decision-makers **Biological Forecasts Under Climate Change** • Climate change and landscape change modeling • Clarify ecological transformation(s)	**Workshop to Apply and Evaluate RAD Decision Alternatives** • Identify and evaluate values and desired conditions • Generate RAD alternatives • Illuminate socio-ecological consequences of alternatives for wilderness management	**Post-Workshop Reports** **General Technical Report** **Peer-Reviewed Publications**

Information Gathering
Sonoran Pronghorn

The Sonoran Pronghorn Case Study

The federally endangered Sonoran pronghorn (*Antilocapra americana sonoriensis*; herein, pronghorn) is endemic to arid desert landscapes in the southwestern United States (U.S.) and northwestern Mexico. Historically, the range of Sonoran pronghorn in the U.S. extended east from the Salton Sea in California to Tucson and Nogales in Arizona and extended south from the Salton Sea and Phoenix, Arizona, to the border with Mexico (Phelps and Webb 1981, Krausman et al. 2005). Factors that contributed to the decline of pronghorn include habitat fragmentation, livestock grazing, and historical unregulated hunting. More recently, prolonged drought has been linked to severe acute mortality events. In 2002, the pronghorn population in the U.S. declined to just 21 individuals. To support species recovery, managers have implemented a range of intensive management actions such as construction of water storage tanks and drinkers (herein, guzzlers), captive breeding, translocation, provision of supplemental feed, and irrigation of forage (USFWS 2016). All active management in the U.S. is concentrated in southwest Arizona, which includes the endangered population of pronghorn in the Cabeza Prieta National Wildlife Refuge (NWR) and two non-essential experimental populations in the Kofa and the Sauceda management units (Section 10(j), Endangered Species Act; Box 1). Current recovery activities have been successful in reversing population decline over the past two decades. Nevertheless, climate change poses a significant threat to long-term species persistence.

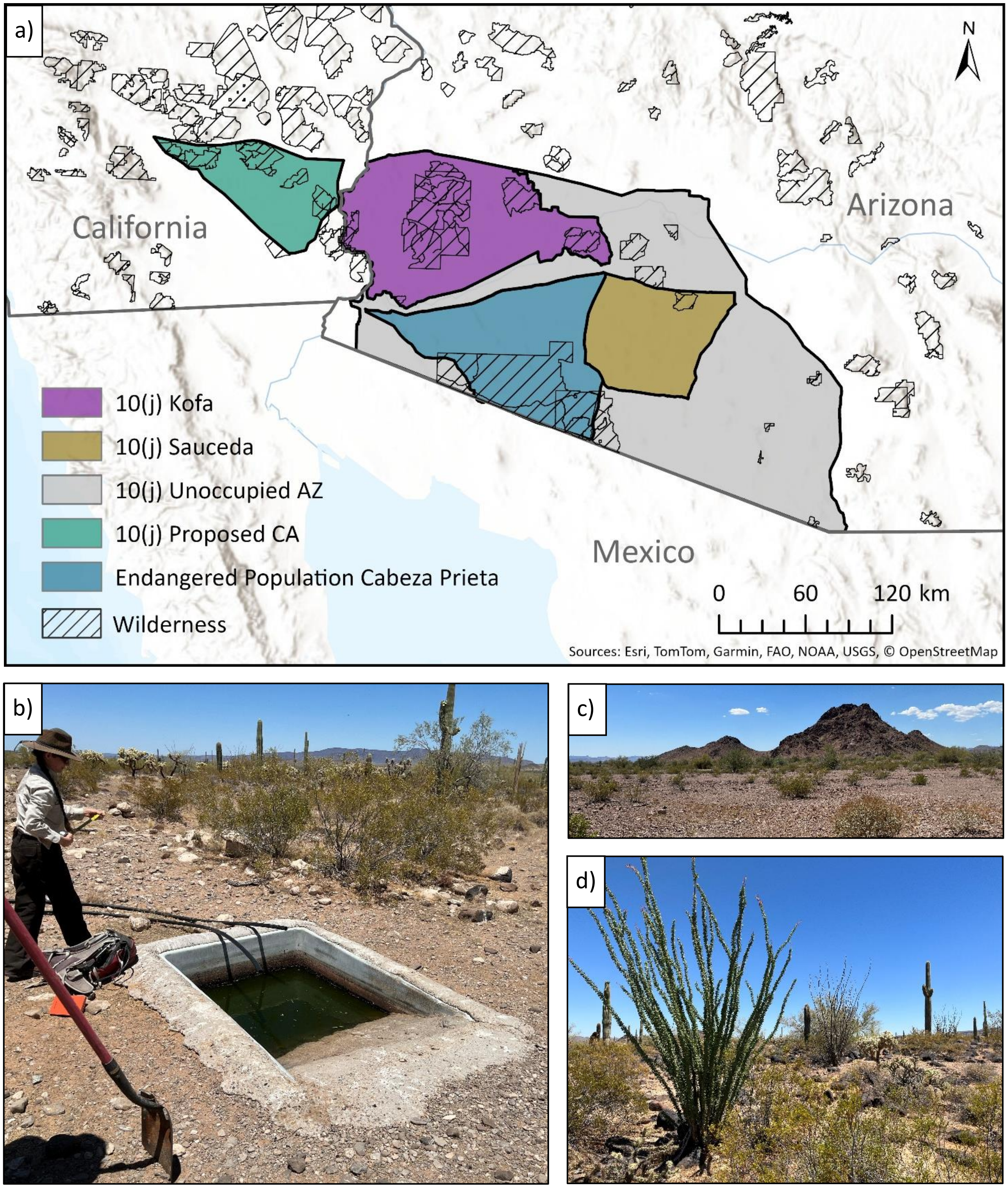
Climate change impacts to Sonoran pronghorn and their habitat

All climate models agree that temperatures in the Sonoran Desert region will increase between 3-9^{o}F by the end of the century and precipitation patterns are expected to fluctuate (Munson et al. 2011; Brown et al. 2023). Despite shifts in precipitation patterns, conditions are expected to become drier overall. Potential for increased precipitation amount in the northern and western Sonoran Desert may delay ecological transformation of pronghorn habitat, allowing pronghorn to persist in these areas for longer. Nevertheless, plant communities important to pronghorn are expected to undergo changes in the prevalence of forb, shrub, and cactus cover (Munson et al. 2011; Gedir et al. 2015; Hantson et al. 2021; Brown et al. 2023). Two plant community types that are particularly important to pronghorn include creosote-bursage desertscrub and palo verde-mixed cacti. Creosote-bursage communities often have an abundance of forbs during cool, wet seasons and the low-growing structure of plants in these communities provide adequate viewsheds for pronghorn to detect predators. Palo verde-mixed cacti communities have greater structural diversity and can provide shelter for pronghorn. Furthermore, chainfruit cholla in these mixed cacti communities provide important sources of water during dry seasons.

In hotter and drier future conditions, it is expected that forb cover will decrease in both these plant community types. In palo verde-mixed cacti communities, tree and shrub cover is also expected to decrease and be replaced by cacti. Loss of forbs and overhead cover from shrubs and trees will negatively impact pronghorn by reducing forage availability and shelter during the hottest months. Although increasing cacti abundance may lead to greater water availability, cacti have very little nutritional value and cannot replace forbs as a food source (Bright & Hervert 2005).

Sonoran pronghorn and wilderness

Recovery for pronghorn is further complicated by policy pursuant to the 1964 Wilderness Act. Approximately 50% of the current range of the endangered population of pronghorn is designated as wilderness, including: 93% of the Cabeza Prieta NWR, 95% of Organ Pipe National Monument (ORPI), and 82% of Kofa NWR. Managers have noted they currently have few remaining opportunities to engage in active management to recover pronghorn outside wilderness (USFWS 2016). While most guzzlers have been installed outside wilderness, some currently occur within wilderness where core pronghorn habitat has been identified. Construction and maintenance of guzzlers degrades the untrammeled and undeveloped qualities of wilderness. Previous litigation concerning the construction of new guzzlers for bighorn sheep in wilderness in Kofa NWR has created a hesitancy to engage in actions which may be necessary to meet recovery goals (Pugh 2013; personal communication). In Wilderness Watch v. U.S. Fish and Wildlife (629 F.3d 1024; 9th Cir. 2010) courts determined that the FWS must consider numerous decisions alternatives and select the alternative which best meets the minimum requirements to achieve conservation goals and accrues the least amount of disturbance to wilderness qualities. Managers must therefore carefully weigh the trade-offs among competing alternative strategies prior to engaging in recovery actions in wilderness to benefit pronghorn.



Box 1: Current and proposed Sonoran pronghorn management units and their overlap with federally designated wilderness in the Unites States (a), a guzzler used to provide water to pronghorn in Cabeza Prieta NWR (b), creosote habitat in Kofa NWR (c), and a forage enhancement plot on Cabeza Prieta NWR showing a leafy green ocotillo in the foreground that is included in the plot and a leafless ocotillo in the background excluded from the plot (d).

Investigate Transformation

Sonoran Pronghorn

Predicting Habitat Suitability and Landscape Connectivity for Sonoran Pronghorn

Methods

We defined our study area to the 35th latitude line in the north (approximately 150 km from the northern boundary of the historic range) and to the 110th longitude line in the east and the 117th longitude line in the west (an extension in both directions of approximately 100 km; Fig. 1). The study area measured 204,330 km^2.

Distinct seasons in the desert southwest are delineated by annual patterns of rainfall and temperature. We used recommendations from Bright and Hervert et al. (2005) as well as rain gauge data collected within the historical range of Sonoran pronghorn to identify four seasons: winter rain (December-March), hot/dry (April-June), summer monsoon (July-September), and cool/dry (October-November). These seasons were used to subset GPS data from pronghorn and examine any shifts in habitat preferences and connectivity throughout the year.

Sonoran Pronghorn Data

We used GPS data collected from Sonoran pronghorn in southern Arizona between 2008-2023 to inform our modeling. We included both adult males (n=90) and females (n=88) in the analysis. Individuals were collared in holding pens on both Cabeza Prieta and Kofa National Wildlife Refuges. The Cabeza Prieta management unit includes the endangered population of Sonoran pronghorn, whereas Kofa and Sauceda management units include the non-essential experimental populations designated under Section 10(j) of the Endangered Species Act (ESA). GPS points were logged approximately every 12 hours for most individuals. For individuals which had higher fix rates, we subset the GPS data to align with the 12-hour intervals of the rest of the individuals. We also removed individuals that had a fix schedule longer than 12 hours.

Habitat Suitability Modeling

We evaluated habitat suitability for Sonoran pronghorn in two ways: 1) home range selection, and, 2) within home range selection and movement. The former was modeled using a Level II resource selection function (RSF) and the latter was modeled using a Level III RSF—an integrated step selection function (iSSF). Each model was parameterized with a suite of geospatial variables known to affect pronghorn habitat use, movement, and survival. Variables included water resources (natural and constructed), topography, climate, and development

(Table 3). Vegetation indices, including the enhanced vegetation index (EVI), were initially considered for analysis given the importance of seasonal forage availability for pronghorn, however, because we were interested in future forecasting of data, we did not include EVI in our analysis. Instead, we used topographic and climatic variables that in concert may dictate availability of vegetation across the landscape.

Table 3: Geospatial variables used in analyses of habitat suitability and connectivity for Sonoran pronghorn in southern Arizona and California, USA.

	Variable	Derivative(s)	Data Source
Water Resources	*Ephemeral streams and rivers*	• Density per kilometer • Distance from	National Hydrography Dataset
	Canals and ditches	Whether step crosses or not	National Hydrography Dataset
	Guzzlers and reliable tinajas	Distance from	Merged locations of established guzzlers, tinajas from ORPI, and tinajas from Kofa that were classified as having moderate to high reliability. Then calculated distance to these resources
Topography	*Aspect*	None	Derived from USGS DEM- used solar radiation aspect from spatialEco package. Continuous and ensures a value of 0 at coolest wettest NNE aspect and a 1 at hottest driest SSW aspect
	Slope	None	Derived from USGS DEM
	Heat load index	None	Calculated with the 'hli' function in SpatialEco (uses McCune, B., and D. Keon (2002); McCune, B. (2007))
	Ruggedness 270m	None	Derived from USGS DEM at two scales – used Dilts et al. 2023 corrected VRM measure at a 270m scale
	Ruggedness 1000m	None	Derived from USGS DEM at two scales – used Dilts et al. 2023 corrected VRM measure at a 1000m scale
	Ruggedness 2000m	None	Derived from USGS DEM at two scales – used Dilts et al. 2023 corrected VRM measure at a 2000m scale

Table 3 (continued): Geospatial variables used in analyses of habitat suitability and connectivity for Sonoran pronghorn in southern Arizona and California, USA.

	Variable	Derivative(s)	Data Source
Development	*Agriculture*	None	Landscape Change Monitoring System, annual
Development	*Developed*	None	Landscape Change Monitoring System, annual
Development	*Building footprints*	Density per kilometer squared	Calculated as density per square kilometer from Microsoft Buildings data set
Development	*Primary roads*	Whether a step crossed or not Density per kilometer squared	Open Street Map
Development	*Secondary roads*	Whether a step crossed or not Density per kilometer squared	Open Street Map
Development	*Tertiary roads*	Whether a step crossed or not Density per kilometer squared	Open Street Map
Development	*Railways*	Whether a step crossed or not	Open Street Map
Climate	*Mean average monthly temperature*	None	ClimateNA. Calculated for each season/year
Climate	*Mean maximum monthly temperature*	None	ClimateNA. Calculated for each season/year
Climate	*Mean minimum temperature*	None	ClimateNA. Calculated for each season/year
Climate	*Mean of the number of degree days under 18°C*	None	ClimateNA. Calculated for each season/year
Climate	*Mean climatic moisture deficit*	None	ClimateNA. Calculated for each season/year
Climate	*Sum of seasonal precipitation*	None	ClimateNA. Calculated for each season/year

Home Range Selection

For the Level II RSF, we used a Home Range Selection Function (HRSF), which compares points within each individual's home range to points in buffers around each home range. For the HRSF, to capture full annual home ranges we used only individuals with at least one year's worth of data (n=86). For each individual, we calculated 95% kernel density home ranges. Within the home ranges, we randomly sampled 1,000 points per individual and assigned these used points a weight of one in the model. We used 1,000 because this was the approximate number of points used per individual to estimate the home range polygons. We then calculated the maximum distance between any two points in an individual's home range and identified the 90th percentile of this distribution across the individuals. This distance was used to buffer the home ranges. We then sampled 10,000 points per individual in the home range buffers as our 'available' points, and assigned these points weights of 5,000 (Fieberg et al. 2021). We sampled points on variables listed in Table 3 and then z-score standardized the data at the sampled points for each variable.

We first ran univariate models to determine the strength of relationship between individual variables and home range selection. We included an interaction with elevation for all climate variables. We identified variables that were significant in the univariate models and carried those forward for consideration in the multiple regression model. For any pair of variables under consideration that were correlated, we retained the variable that resulted in a lower model AIC value. We then ran a multiple regression with the final set of variables. All models were run in a generalized linear mixed modeling framework (GLMM) with individual pronghorn as a random effect.

Integrated Step Selection Function

We used integrated step selection functions (iSSFs) to model Level III selection (within home range resource selection and movement) for each of the four seasons. First, we filtered the pronghorn data by our seasonal dates. We further filtered out any individual with less than 21 days of data for a season, which resulted in 67 individuals for the cool/dry season, 138 individuals for the winter rains season, 115 individuals for the hot/dry season, and 85 individuals for the summer monsoon season. For each used step, iSSFs require random points to be drawn from the empirical distribution of step lengths and turning angles to serve as the available steps. Therefore, for each season, we fit a gamma distribution to used step lengths and randomly sampled 10 points from these distributions for our available locations. We extracted values of our variables at each used and available point, matching our temporally varying variables to the year and season of the used points.

We followed the same procedure as for our HRSF models and first ran univariate models. All models were run in a GLMM framework as a conditional Poisson regression following Muff et al.

(2019). We included stratum as a random intercept with a fixed large variance, and a random slope for each individual for each variable in the model. We included interactions with elevation when these interactions were significant.

Climate Modeling

We generated predictions for both current and future (mid-21st century) habitat suitability and connectivity. We used ClimateNA to download current climate surfaces, derived from PRISM, as well as climate projections for the year 2060 for each of the significant climate metrics from the current Level II and Level III RSF analyses. Future climate metric values were derived from an 8-model ensemble mean which used the latest projections from the Coupled Model Intercomparison Project (CMIP6). The 8-model ensemble excluded models at the hottest extreme of projections (>5^{o}C increase) and models which were outside of the range of projections that the Intergovernmental Panel on Climate Change (IPCC) deem as "very likely". Additionally, we selected models with a Shared Socioeconomic Pathway (SSP) level of 245, which represented a future with growing societal inequality in development and economic growth as well as moderate increases in greenhouse gas emissions (Riahi et al. 2017).

Predicted Surfaces

We predicted relative habitat suitability surfaces for the HRSF and the iSSF models using the fixed effects model coefficients. We then truncated the predicted surfaces at the 2.5 and 97.5 percentiles following Sells et al. (2022) and Hyson et al. (2025), and quantile rescaled the surfaces to a 0-1 value range to represent relative habitat suitability for Sonoran pronghorn. To simplify our evaluation of results, we referred to "high quality habitat" as areas where relative suitability scores were ≥0.7. We evaluated the performance of our models using the Boyce index and by comparing our predictions to a novel dataset which included very high frequency (VHF) data collected on Sonoran pronghorn between 2009-2022.

Connectivity

We modeled connectivity with cumulative resistant kernels (hereafter 'resistant kernels'). Resistant kernels calculate cost and distance away from source points distributed across the landscape, and when combined, estimate the predicted density of dispersing individuals across the landscape. Resistant kernels have been shown to outperform other connectivity models in capturing animal movement, especially when destination locations are unknown (Atzeni et al. 2024).

We ran connectivity models for each season for each time step. We transformed each suitability surface to resistance by taking the inverse of suitability values and rescaling to a 1 to 100 value range, with higher values indicating higher resistance. For the source points, we sampled 2000 points probabilistically on the HRSF surface for the corresponding time step and set the cost distance threshold for the resistant kernel spread to 150,000. We used UNICOR software (Landguth et al. 2012) to produce the cumulative resistant kernel surface. We then took the log of raw connectivity values to highlight differences in the mapped output. Because resistant kernels cannot spread far from the source points in areas of high resistance, sometimes the output produces small individual clumps of pixels. To ease visualization, we removed any clump measuring less than 0.5 km^2.

Management Scenarios

To understand how management intervention may influence habitat distribution and connectivity for pronghorn, we used the RAD (resist-accept-direct) framework to design and simulate competing management scenarios for our modeling (Figure 2). The RAD framework was developed as a tool to address climate change-driven ecological transformation and presents three avenues for responding to transformation: 1) resist transformation by implementing active management to retain historical baselines for ecological conditions, 2) accept transformation and do not engage in active management, and, 3) direct transformation by using active management to shape the ecological trajectory toward a more desirable outcome (Schuurman et al. 2022). In our habitat and connectivity modeling (see below), we manipulated the amount and placement of guzzlers to simulate opposing RAD scenarios as ecological conditions transform under climate change. To resist observed and anticipated ecological change, we explored two scenarios: 1) a **business-as-usual** scenario to maintain all current guzzler locations (n=63), and 2) a **business-as-usual intensified** scenario which involved maintaining all current guzzler locations and adding 40 new guzzler locations in current managed areas for pronghorn (Cabeza Prieta, Kofa, and Sauceda). To accept anticipated ecological change, we simulated a **no intervention** scenario, wherein we removed all guzzlers from our models and set the distance to guzzlers for each individual location as the current maximum distance to a guzzler from anywhere within our study area. To direct ecological change, we simulated an **adaptive** scenario by removing current guzzler locations and placing 40 new guzzlers in habitat for pronghorn based on results from our 2060 Level II resource selection model (see below) without guzzlers. All new guzzlers were randomly generated within areas that met the following criteria: elevation lower than 1400 m, slope ≤ 5%, located on public or Tribal land, and located in the top 30% of predicted relative habitat use from fitted Level II selection models. New guzzlers were allowed to occur within or outside wilderness.

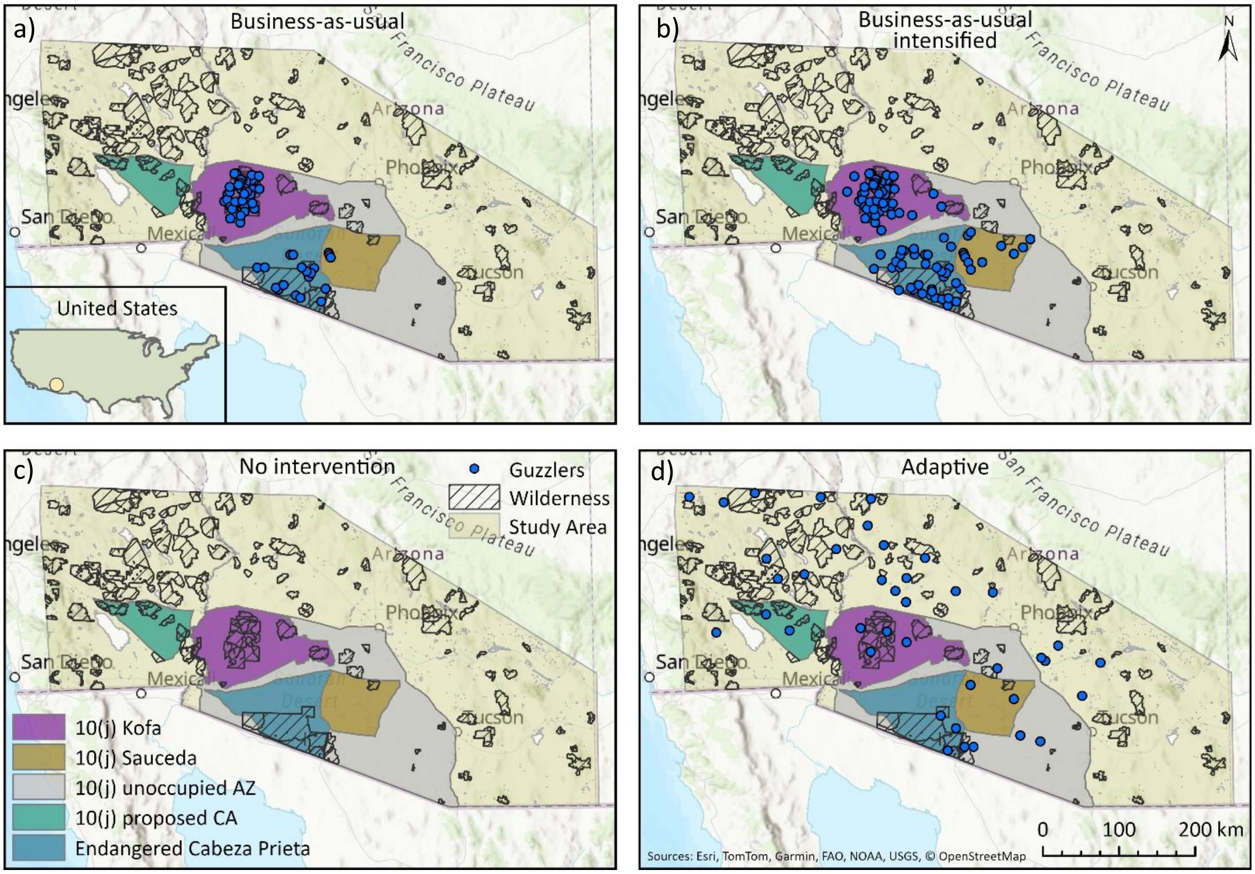


Figure 2: Management scenarios for a study of habitat suitability and connectivity for Sonoran pronghorn for current and proposed pronghorn management units in southern AZ and CA. Scenarios included the manipulation of the placement and amount of water tanks: business-as-usual (a), business-as-usual intensified (b), no intervention (c), and adaptive (d).

Results

Model and Prediction Uncertainty

The following summaries are presented as plausible futures that are subject to further discussion with continued advances in our understanding of climate change trends and subsequent impacts to habitat suitability for Sonoran pronghorn. Model predictions were generated with the best available data and knowledge, however, uncertainty in direct and indirect causal relationships persist. Unanticipated interactions or events may alter future outcomes for Sonoran pronghorn and their habitat. The predictions summarized here are meant to be used as reference points for further refinement as new knowledge and data sources become available.

Current Habitat Suitability and Connectivity

Home Range Selection

From 2008-2023, 90% home range sizes for the individuals in our study ranged from 99 km^2 to 6,717 km^2 (mean = 795, median = 333). The highest proportion of total available Level II habitat (i.e. Level II selection value ≥ 0.7, herein: Level II habitat) among Sonoran pronghorn management units occurred within the 10(j) unoccupied reintroduction area in southern Arizona (25%) followed by the Kofa management unit (20%). 27% of available Level II habitat in our study area occurred in areas not currently managed for pronghorn. Units currently managed for pronghorn (Cabeza Prieta, Kofa, Sauceda) were nearly fully composed of predicted Level II habitat (98-99%). Occurrence of agriculture and building density were negatively associated with home range selection (Table 4). Additionally, pronghorn selected areas that were closer to guzzlers and ephemeral streams as well as areas with lower terrain ruggedness. There was a statistically significant interaction between elevation and mean annual temperature and mean temperature of the coldest month. At lower elevations, Level II suitability increased with decreasing mean annual temperature and lower mean temperature of the coldest month. Mean annual precipitation did not have a statistically significant effect on home range selection. The predicted surface had a Boyce Index of 0.925, indicating good model fit.

Table 4: Home Range Selection Function model results for a study of habitat suitability for Sonoran pronghorn, 2008-2023, in southern Arizona and California, USA.

Predictors	**Coefficient**	**SE**	**CI**	**P-value**
Agriculture	-0.61	0.09	-0.79 – -0.44	<0.001
Building density	-0.29	0.04	-0.37 – -0.21	<0.001
Distance from guzzlers	-1.51	0.01	-1.52 – -1.49	<0.001
Distance from ephemeral streams	-0.5	0.01	-0.52 – -0.48	<0.001
Ruggedness, 2000m	-0.38	0.01	-0.39 – -0.37	<0.001
Elevation	0.05	0.02	0.02 – 0.09	0.005
Average temperature	-0.27	0.03	-0.33 – -0.22	<0.001
Mean coldest month temperature	-0.39	0.02	-0.43 – -0.35	<0.001
Average temperature * Elevation	0.92	0.01	0.90 – 0.94	<0.001
Mean coldest month temperature * Elevation	-0.2	0.01	-0.22 – -0.18	<0.001

Integrated Step Selection Function

The distribution of Level III habitat predicted using integrated step selection functions differed among our four seasons (Figure 3). Areas currently managed for Sonoran pronghorn (Cabeza Prieta, Kofa, and Sauceda) had high proportional coverage of habitat among all seasons (≥80%). Within-unit coverage was highest during the summer monsoon season (mean=99%) and lowest in the cool/dry (October-November) and hot/dry (April-June) seasons (mean=91% and 92%, respectively). In all four seasons, pronghorn selected Level III habitat near guzzlers, in areas of less rugged terrain, and in areas without primary roads (see Supplementary material). However, selection for areas near guzzlers was slightly less strong in the cool/dry and winter rain (December-March) seasons (coefficient: -0.56, SE: 0.23, p=0.014 for cool/dry; coefficient: -0.83, SE: 0.17, p<0.001 for winter rain). During the hot/dry season, pronghorn selected areas with lower minimum temperatures (i.e., cooler areas) and lower deficits in climatic moisture (i.e., wetter areas; see Appendix A). In contrast, pronghorn selected drier areas in the summer monsoon (July-September), cool/dry, and winter rain seasons. In the summer monsoon season, pronghorn also had a negative association with crossing canals and railways (coefficient: -0.63, SE: 0.23, p=0.007 for canals; coefficient: -2.43, SE: 0.61, p<0.001 for railways), and in the winter rain season pronghorn had a negative association with crossing railways (coefficient: -1.03, SE: 0.28, p<0.001). Pronghorn avoided areas with higher building density during the hot/dry season (coefficient: -1.52, SE: 0.52, p=0.003). During the winter rain season only, pronghorn avoided agricultural areas (coefficient: -7.56, SE: 2.7, p=0.005).

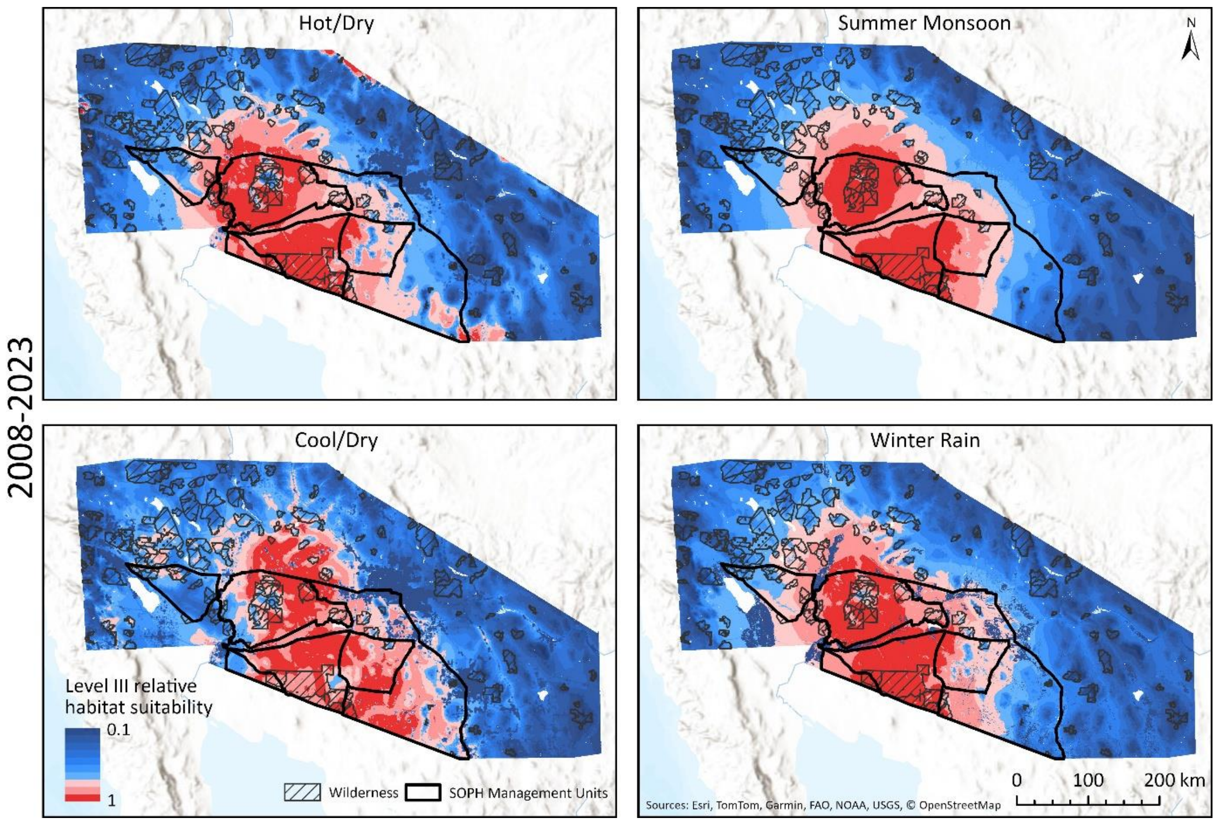


Figure 3: Level III (within home range and movement) relative probability of use calculated using an integrated step selection function (iSSF) for Sonoran pronghorn in southern AZ and CA, USA, 2008-2023. Results are displayed for four seasons: hot/dry (April-June), summer monsoon (July-September), cool/dry (October-November), and winter rain (December-March). Warmer colors (≥0.7) indicate higher quality habitat.

Connectivity

Because guzzlers were strong predictors of Level III habitat selection for Sonoran pronghorn, they also influenced landscape connectivity among all seasons (Figure 4). Connectivity among seasons shifted on the landscape relative to the Level III suitability results, showing strong connectivity centered around Cabeza Prieta and Kofa management units among all seasons (Cabeza Prieta: $1.258e^{-5}$ mean ± $0.882e^{-5}$ SD; Kofa: $1.236e^{-5}$ mean ± $1.298e^{-5}$ SD; Sauceda: $0.275e^{-5}$ mean ± $0.436e^{-5}$ SD). Additionally, connectivity was greater in both the Cabeza Prieta and Kofa management units as compared to the overall mean across our study area (study area: $0.517e^{-5}$ mean ± 0.996^{-5} SD). Connectivity was highest during the wet seasons for both the Cabeza Prieta and Kofa management units (Cabeza Prieta winter rain: $2.351e^{-5}$ mean ± $1.397e^{-5}$ SD; Kofa summer monsoon: $1.924e^{-5}$ mean ± $1.714e^{-5}$ SD). In all current management units, connectivity was lowest during the cool/dry season ($0.690e^{-5}$ mean ± $0.881e^{-5}$ SD). The hot/dry season in the proposed 10(j) management unit in CA was predicted to have the lowest connectivity among all management units and seasons ($0.045e^{-5}$ mean ± $0.067e^{-5}$ SD).

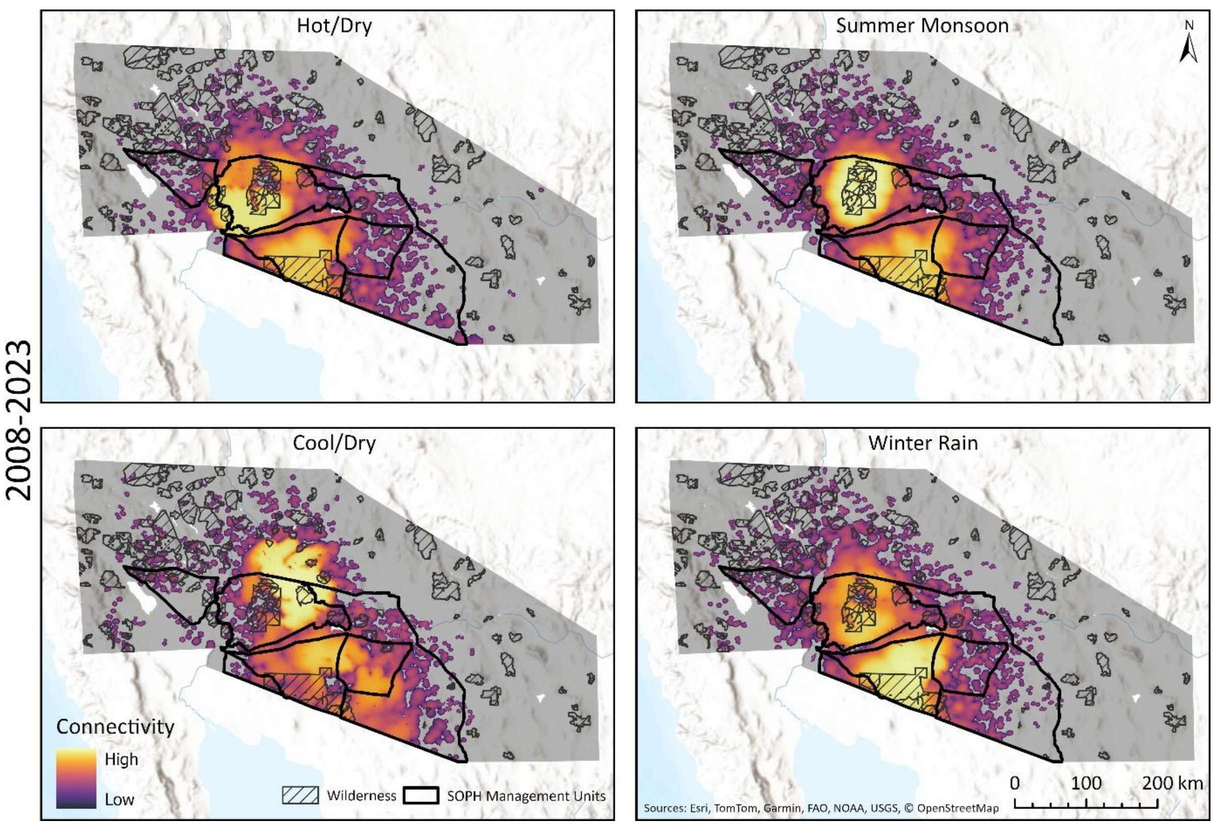


Figure 4: Landscape connectivity for Sonoran pronghorn in southern AZ and CA, USA, 2008-2023. Resistant kernel results were estimated for a hot/dry season (a), summer monsoon season (b), cool/dry (c), and winter rain season (d).

Mid-21st Century Habitat Suitability and Connectivity

Management scenarios influenced the distribution of home range habitat and connectivity over time (Appendices II-VI). Overall, if management scenarios included guzzlers, home range habitat and connectivity were closely associated with locations of guzzlers. Nevertheless, presence of guzzlers did not necessarily prevent management units from losing home range habitat over time (Figure 5). Notably, predicted home range habitat declined in the Cabeza Prieta and Kofa management units by 2060, irrespective of management strategy. Seasonally, the proportion of movement habitat contained within all current and proposed management units was lowest during the hot/dry season by 2060 (mean movement habitat ≤19% among all management scenarios).

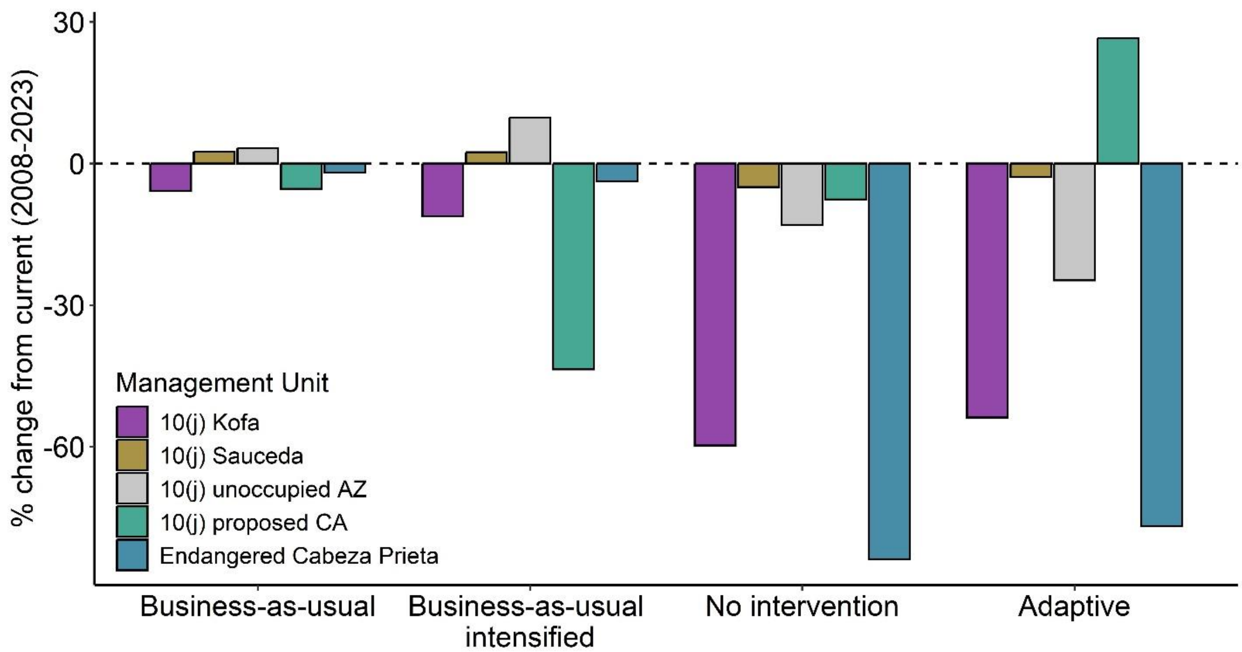


Figure 5: Percent change in proportional coverage of home range habitat for Sonoran pronghorn located within distinct management units in southern AZ and CA, USA. Results were estimated using a home range selection function between two time steps (current and 2060) and four management scenarios.

Business-as-usual

Under the *business-as-usual* scenario, predicted distribution of Level II habitat in 2060 remained closest to the current distribution among all management units (Figures 5,6). The predicted amount of Level II habitat declined slightly in the Kofa and Cabeza Prieta management units and made small gains in the Sauceda and proposed 10(j) region within southern Arizona. Seasonally, mean proportion of Level III habitat available within all current and proposed management units by 2060 was ≥ 70% for the summer monsoon, cool/dry, and winter rain seasons. Proportion of Level III habitat among all management units was lowest in the hot/dry season (mean proportion among all units: 7%). Among all scenarios, the proportion of Level III habitat available within all management units changed the least from 2020 to 2060 under the *business-as-usual scenario* (-11% Δ). Study area-wide landscape connectivity was consistently lower than connectivity within currently occupied pronghorn management units (e.g., across-season mean connectivity: $0.726e^{-5} \pm 0.558e^{-5}$ SD for the endangered Cabeza Prieta population; $0.389e^{-5} \pm 0.699e^{-5}$ SD study area-wide). Although patterns of connectivity for the hot/dry season differed dramatically from current predicted patterns, overall, connectivity in 2060 remained most similar to connectivity in 2020 under the *business-as-usual* scenario among all seasons.

Business-as-usual intensified

Increasing the amount of guzzlers in current pronghorn management units did not reduce predicted loss of Level II habitat in the Cabeza Prieta and Kofa management units and these declines surpassed those in the *business-as-usual* scenario. Declines in Level II habitat were also notable for the proposed 10(j) reintroduction area in southern California. The Sauceda unit and proposed 10(j) area in southern Arizona experienced slight increases in predicted Level II habitat. Level III habitat within all management units still declined under this scenario (-24% Δ from 2020 to 2060 among all management units and seasons), though not as much as the *no intervention* and *adaptive* scenarios. Seasonally, the mean proportion of Level III habitat available within all management units by 2060 was highest during the summer monsoon and winter rain seasons (>70%) and lowest in the hot/dry season (5%). Similar to the *business-as-usual* scenario, study area-wide landscape connectivity was consistently lower than connectivity for currently occupied pronghorn management units (e.g., mean across-season connectivity: $0.408e^{-5} \pm 0.300e^{-5}$ SD for the endangered Cabeza Prieta population; $0.334e^{-5} \pm 0.574e^{-5}$ SD study area-wide).

No intervention

The Cabeza Prieta management unit received the greatest reductions in predicted Level II habitat from 2020 to 2060 when guzzlers were removed from the study area (-84% Δ). The amount of Level II habitat in the Sauceda, unoccupied 10(j) reintroduction area in Arizona, and the proposed 10(j) reintroduction area in California were also estimated to decline in this scenario. This was the only scenario where all current management units were expected to experience declines. Overall, Level III habitat changed the most under the *no intervention* scenario among all management units and seasons (-69% Δ from 2020 to 2060). Seasonally, the mean proportion of Level III habitat available within all management units by 2060 was highest during the summer monsoon season (41%) and lowest in the hot/dry season (3%). This scenario had the lowest connectivity for the Cabeza Prieta unit as compared to all other scenarios. Additionally, unlike the *business-as-usual* and *business-as-usual intensified* scenarios, study area-wide mean connectivity was higher than any individual current management unit (e.g. across-season mean connectivity of the individual management unit displaying the highest connectivity was $0.058e^{-5} \pm 0.059e^{-5}$ SD vs. $0.134e^{-5} \pm 0.237e^{-5}$ SD study area-wide).

Adaptive

By moving guzzlers to new areas expected to be more climatically suitable by 2060, Level II habitat is expected to decline sharply in the Cabeza Prieta and Kofa units (-75% and -54%, respectively), although not as much as in the *no intervention* scenario. Level II habitat in the Sauceda unit and proposed 10(j) reintroduction area were also expected to decline by 2060. In contrast, Level II habitat is expected to increase approximately 27% in the proposed 10(j) reintroduction area in southern California. Seasonally, the mean proportion of Level III habitat available within all management units by 2060 was highest during the summer monsoon (50%) and winter rain (55%) seasons and lowest in the hot/dry season (5%). Adding new guzzlers under the *adaptive* scenario marginally increased mean connectivity as compared to the *no intervention* scenario study area-wide (mean connectivity *no intervention*: $0.134e^{-5} \pm 0.237e^{-5}$ SD; mean connectivity *adaptive*: $0.169e^{-5} \pm 0.278e^{-5}$ SD). Connectivity was generally greater nearer to guzzler locations as compared to areas where guzzlers were absent.

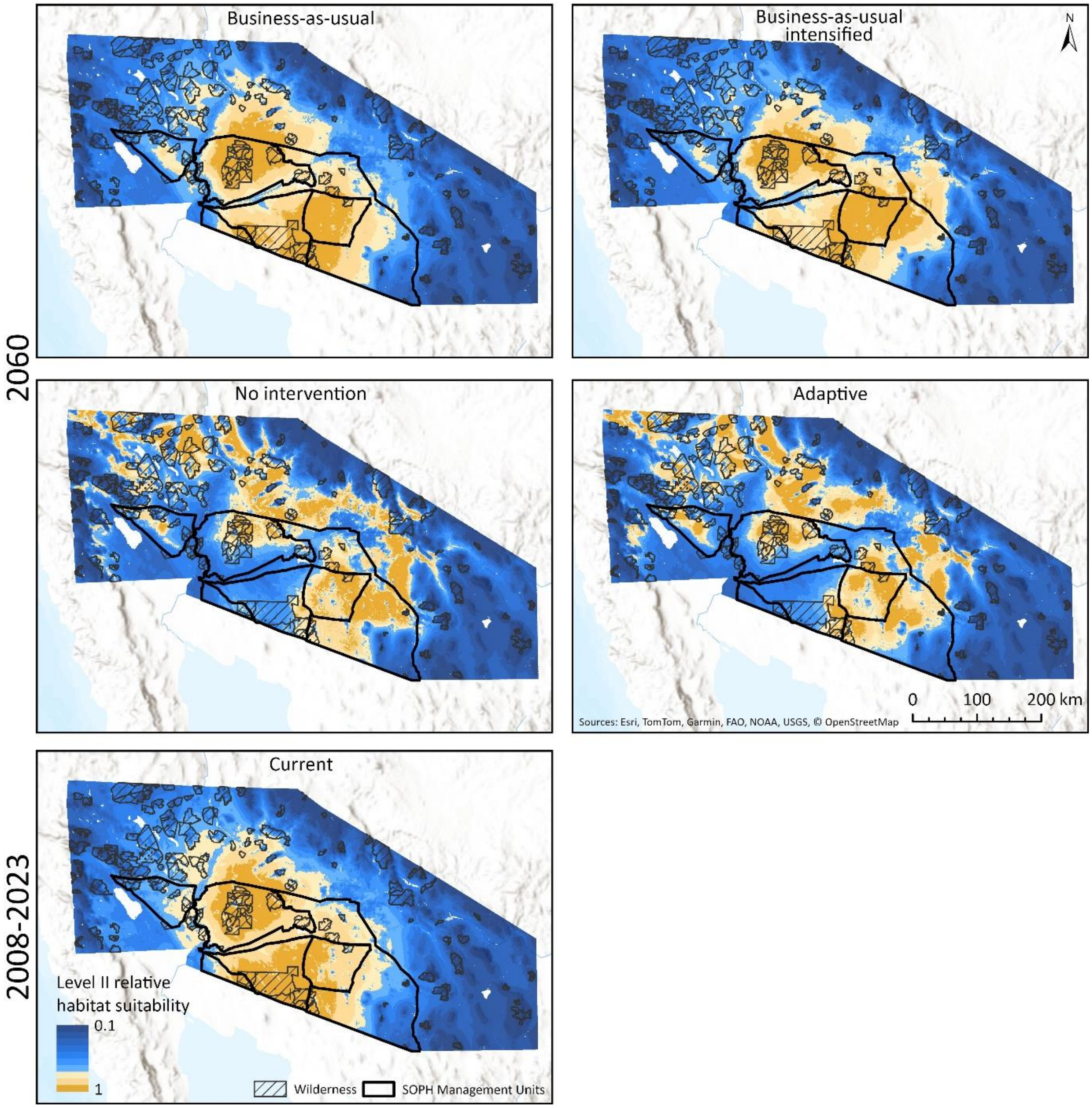


Figure 6: Current (2008-2023) and mid-century (2060) relative home range habitat suitability calculated using a Level II home range selection function for Sonoran pronghorn throughout southern AZ and CA, United States, and for four management scenarios. Warmer colors (≥0.7) indicate higher quality habitat.

The Role of Wilderness for Sonoran Pronghorn Recovery

Within current pronghorn management units (Cabeza Prieta, Kofa, and Sauceda), wilderness contained approximately 25% of all Level II (home range) habitat predicted for 2008-2023 (Table 5). Study area-wide, wilderness is currently estimated to contain 17% of Level II habitat. By 2060, the importance of wilderness is expected to remain similar to current predictions under the *business-as-usual* scenario for both current management units and study area-wide. Additionally, at both scales, removing guzzlers decreased the estimated proportion of Level II habitat available in wilderness as compared to current estimates. For both current management units and study area-wide, the proportion of Level II habitat in wilderness is expected to be highest in the *business-as-usual intensified* scenario (26%). The proportion of Level II habitat in wilderness was lowest for the no intervention strategy (22% within current management units and 12% study area-wide).

Table 5: Proportion of all habitat for Sonoran pronghorn located within wilderness, estimated for current pronghorn management units (Cabeza Prieta, Kofa, and Sauceda) and study area-wide.

Region	Year	Scenario	Area km^2	% of Total Available Level II Habitat in Wilderness
Current Management Units	Current	-	6850	24.82
	2060	BAU	6794	25.29
	2060	BAU intensified	6773	26.01
	2060	No intervention	2704	22.31
	2060	Adaptive	3463	22.48
Study Area-Wide	Current	-	10274	17.12
	2060	BAU	10563	17.60
	2060	BAU intensified	9266	15.44
	2060	No intervention	9160	12.22
	2060	Adaptive	10433	17.38

*Relative habitat suitability was estimated using Level II home range selection functions and for two timesteps (recent [2008-2023] and mid-21st century [2060]) and four management scenarios: 1) business-as-usual (BAU), 2) BAU intensified, 3) no intervention, and, 4) adaptive.

Conclusion

Climate change is continuing to alter the distribution and availability of habitat for Sonoran pronghorn. Habitat improvement efforts, including water provision, may buffer pronghorn populations from the impacts of climate change-driven ecological transformation, however, the amount of habitat will continue to decline in currently occupied management units, particularly for the endangered population. Without continued management intervention, habitat may shift to areas outside the historical range of pronghorn, particularly toward eastern Arizona and southern California. Additionally, maintaining guzzlers in current pronghorn management units will continue to put pressure on wilderness areas where management actions are meant to be restrained. Guzzlers will remain an important conservation tool for pronghorn and other desert species, however, continuing a business-as-usual management strategy may discourage long-range movements, potentially inhibiting adaptive capacity as the distribution of habitat shifts under climate change. A combined strategy that includes maintenance of existing guzzlers to continue to preserve the endangered population of pronghorn as well as installation of new guzzlers and assisted translocation beyond the current occupied range may be necessary to increase habitat available to pronghorn.

Understanding Manager Perceptions of Climate Change and Feasibility of Response Actions

To learn how managers are experiencing climate change and ecological transformation, as well as their perceptions of response options for Sonoran pronghorn, we conducted six semi-structured interviews with managers from the USFWS, National Park Service (NPS), and Arizona Game and Fish Department (AZGFD). A semi-structured interview approach uses the same list of questions (or interview guide) for all participants and allows room for exploration into unique topics brought up by each participant. This approach ensures comparable results across participants while also allowing for unique insights and freedom of response (Kvale & Brinkmann 2009). In particular, we were interested in understanding perceptions of, 1) how climate change is affecting southwestern Arizona and pronghorn, and 2) feasibility of management actions to support pronghorn recovery including real and perceived constraints and opportunities for climate change adaptive actions in wilderness.

All interviews were conducted virtually between December 8, 2023, and January 31, 2024, and lasted an average of 53 minutes. Interviews were recorded and transcribed verbatim. Identifying information was removed from all transcripts to ensure participant confidentiality. All deidentified transcripts were uploaded into NVivo—a qualitative data analysis software, which helps researchers organize data. Qualitative thematic analysis was conducted with open or inductive coding in which the researcher identifies distinct concepts and themes for data categorization (Williams & Moser 2019). These concepts and themes were then considered together as they relate to larger trends across the data (Braun & Clark 2012). See Appendix B for interview quotes that pertain to each theme.

Perceived effects of climate change in southwestern Arizona and impacts on Sonoran pronghorn

Managers perceived that weather in the desert southwest was becoming increasingly variable and unpredictable, particularly amount and timing of precipitation. Managers noted several seasonal changes in summers, monsoons, and winters. A few managers shared that monsoons used to be very consistent and predictable, whereas now, the rains are often coming later in the season but that the intensity of the storms is increasing (i.e. more precipitation in a single storm). Although summer monsoon storm intensity is increasing, managers stated that, overall, they had been observing more extreme heat and drought events. In particular, managers are observing less rainfall in the winter and a lengthening of the dry period between winter rains and summer monsoons was lengthening. Managers connected the general drying trend to declining surface and ground water levels.

Managers felt that increasing temperatures, drought, and weather variability had several implications for pronghorn. First, hotter spring temperatures, especially extreme heat events, are stressful for pronghorn and could result in overall increased fawn mortality as well as adult mortality in areas with limited or no access to supplemental water. Secondly, increased frequency and length of drought periods could also decrease fawn recruitment through reduced water and forage availability. Although managers are already trying to mitigate reduced water availability by constructing and maintaining guzzlers, they reflected that reduced forage quality is more difficult to manage than water availability and that there may be a need to increase supplemental forage in the future. Finally, some managers felt that reduced water and forage availability coupled with habitat fragmentation may lead pronghorn to concentrate in higher numbers around high quality resources which may cause stress to the animals.

Feasibility of management actions to support Sonoran pronghorn recovery in wilderness

Several management actions are currently underway to recover pronghorn within wilderness. Pronghorn were reintroduced directly outside several wilderness areas throughout their historical range. To ensure population health, many guzzlers have been installed in Cabeza Prieta and Kofa wilderness areas, several of which are regularly refilled throughout the dry season. Additionally, game cameras are installed at the guzzlers to monitor fill level, guzzler usage, and predator presence and behavior. If problem mountain lions are identified, then they may be lethally removed, including in wilderness. Managers also mentioned some removal of invasive plant species—particularly Malta starthistle which has potentially negative impacts for pronghorn, that has been very successful. In addition to reintroduction and other efforts to maintain and recover pronghorn, there are several ongoing monitoring efforts in wilderness including pronghorn population monitoring (typically through GPS collars and overflight VHF telemetry), disease monitoring, and climate monitoring through rain gauges and weather stations.

Limitations to climate adaptation in wilderness

Managers identified several institutional and physical constraints to climate adaptive recovery actions in wilderness. First and foremost, managers reported that staff capacity was low. For example, at the time of the interviews, Kofa National Wildlife Refuge had only one full-time permanent staff member. All managers acknowledged that although staff and funding are limited, they do the best they can with available resources and interagency partnerships. Additionally, one manager shared that there is a strong volunteer base, which can help supplement capacity constraints. Another institutional constraint is that work in wilderness requires extensive planning, which can be difficult when staff capacity is limited.

In addition to limited capacity and large planning needs, managers felt that limited place-based climate and precipitation projections hampered their ability to proactively plan for climate change. Although regional climate models are available, managers emphasized that they are not able to capture the microclimates and precipitation events that occur throughout the region and have important implications for pronghorn. Therefore, managers shared that having long-term rain gauge and weather data to inform localized models would better help them plan climate adaptive recovery efforts.

Managers also discussed how physical constraints associated with the wilderness landscape interact with limited capacity to implement climate adaptive recovery actions. All managers mentioned how physically difficult the wilderness landscapes are to navigate and work in. Each wilderness area is immense and rugged, so it takes several hours to access field sites, which can be dangerous in extreme heat conditions. Additionally, managers shared that traveling for field work is hard on equipment, which often breaks, and requires time and skill to fix in the field.

Opportunities for climate adaptation in wilderness

Despite the perceived constraints, managers felt that there were opportunities to engage in new and continued efforts to recover pronghorn in wilderness. First and foremost, managers wanted to continue to strengthen international, federal, and state partnerships, which are critical to support current and future recovery work. Further, managers discussed how being granted access to Border Patrol roads for vehicle use would significantly reduce capacity constraints and allow them to complete necessary work like water hauling much more efficiently. Lastly, managers identified several potential future climate adaptive recovery actions they could pursue, including: adding and/or moving guzzlers, sowing native seeds, reintroducing pronghorn to southern California through assisted migration, additional research and monitoring, and, if necessary, additional efforts to protect pronghorn from predators and visitors.

Managers emphasized that guzzlers are vitally important for pronghorn survival during frequent seasonal droughts. Additionally, managers shared that many of the guzzlers in wilderness were built for desert bighorn sheep in the mountains and outside pronghorn habitat. Therefore, managers suggested that building more and larger guzzlers in pronghorn habitat and/or repairing existing guzzlers could help pronghorn survival and recovery. Additionally, a couple of managers felt that plant community restoration in areas previously grazed or burned could help increase forage availability for pronghorn.

In addition to restoring and adding guzzlers, one manager felt that additional research and monitoring of predators, guzzlers, and fawn mortality would help ensure continued species recovery. Potential predator research could include GPS tracking of mountain lions in wilderness to better understand their behavior. Although managers already monitor the guzzlers with game cameras, one manager shared that they are working toward having a programmatic minimum requirements analysis (MRA) for guzzler monitoring, maintenance, and water hauling. Lastly, research on fawn recruitment could elucidate drivers of fawn survival and mortality and inform future recovery efforts.

Managers also discussed assisted migration of pronghorn within their historical range. One manager reflected that habitat fragmentation by highways, roads, and canals limits pronghorns’ occupation of other areas within their historical range. They felt that, in light of climate change, they would support facilitating pronghorn movement to areas such as southern California or central or northern Arizona, which might be more climatically suitable in the future.

Although managers felt like these actions were last resorts, or only to be used as necessary, managers noted that they could limit visitor access to sensitive habitat during fawning or extreme heat events. Similarly, to protect pronghorn in wilderness, managers reflected that they could engage in additional predator control within wilderness, but they acknowledged they would need more research to support any predator control actions and that most predation occurs outside wilderness boundaries.

Apply the RAD Framework to Climate-Informed Adaptation Planning in Wilderness

Sonoran Pronghorn

Learning Objectives

A 2-day, in-person workshop was implemented to support overarching project goals to inform and evaluate a decision space using the RAD framework and to support climate-informed adaption planning in wilderness. During the workshop, participants followed a generalized adaptation planning process incorporating the RAD framework to generate and evaluate decision alternatives for Sonoran pronghorn under a changing climate. The workshop was structured around four learning objectives:

1) Orient the Sonoran pronghorn case study in the broader challenge of wilderness management in an era of climate change
2) Identify desired conditions surrounding the focal ecological transformation that reflects all perspectives
3) Understand the utility of RAD as a tool for responding to ecological transformation in wilderness
4) Develop a feasible and repeatable workflow to evaluate RAD decision alternatives

Each learning objective was achieved through a combination of scientific inquiry (described above), facilitated discussion, and small group activities. Both biological and social science investigations were leveraged to better understand how ecological conditions may change for Sonoran pronghorn and how land stewards and their partners perceive this change and their ability to prepare for or respond to climate change-driven transformation. Preliminary and final results of science investigations were shared with workshop participants to characterize potential ecological transformation of habitat for Sonoran pronghorn and to encourage further discussion concerning real and perceived constraints and opportunities to conserve current ecosystem conditions. Facilitated small-group activities and discussion encouraged co-production of ideas and decision alternatives that were examined further with additional decision-support tools.

Workshop Participants

Workshop participants included staff from the U.S. Fish and Wildlife Service (FWS), the National Park Service (NPS), the Bureau of Land Management (BLM), the Arizona Game and Fish

Department (AZGFD), and the Living Desert Museum in California. In total, 10 individuals attended the workshop.

Applying the RAD Framework

The RAD framework is a tool meant to be used during a planning process to support decision making in an era of ecological transformation under climate change (Schuurman et al. 2025). Using the RAD framework, land stewards can generate a broad range of decision alternatives to deliberately intervene or not intervene to address climate change threats (Crausbay et al. 2022; Schuurman et al. 2022). During the workshop, a generalized planning process based on adaptive management was used to increase the applicability of the RAD framework as tool for strategic planning and project management (Figure 7). Adaptive management is an iterative, structured decision-making process used to clarify and address uncertainty associated with implementing divergent management strategies, particularly through climate change (Johnson 1999). Incorporating RAD into an adaptive management process is consistent with previous efforts by Lynch et al. (2022) and Crausbay et al. (2022).

> In a rapidly changing landscape where information is limited and the future is uncertain, adaptive management helps land stewards move forward by incorporating learning into decision-making (McFadden et al. 2011). By critically evaluating RAD decision alternatives and monitoring the successes and shortcomings of decisions to meet desired conditions, knowledge is generated along each revolution of the adaptive management wheel. During the workshop, we sought to complete five stages (out of seven) of an iterative adaptive management approach (Figure 3): 1) Clarify observed climate change threats and persistent ecological stressors, 2) Identify values and desired conditions, 3) Clarify potential ecological transformation(s) that threaten values and desired conditions, 4) Generate a suite of decision alternatives to address transformation using the RAD framework, and 5) Evaluate the potential socio-ecological consequences of choosing to resist, accept, or direct perceived climate change-driven threats. Subsequent stages of adaptive management, including implementing a decision alternative(s) and monitoring action effectiveness, are next steps to be completed beyond the workshop.

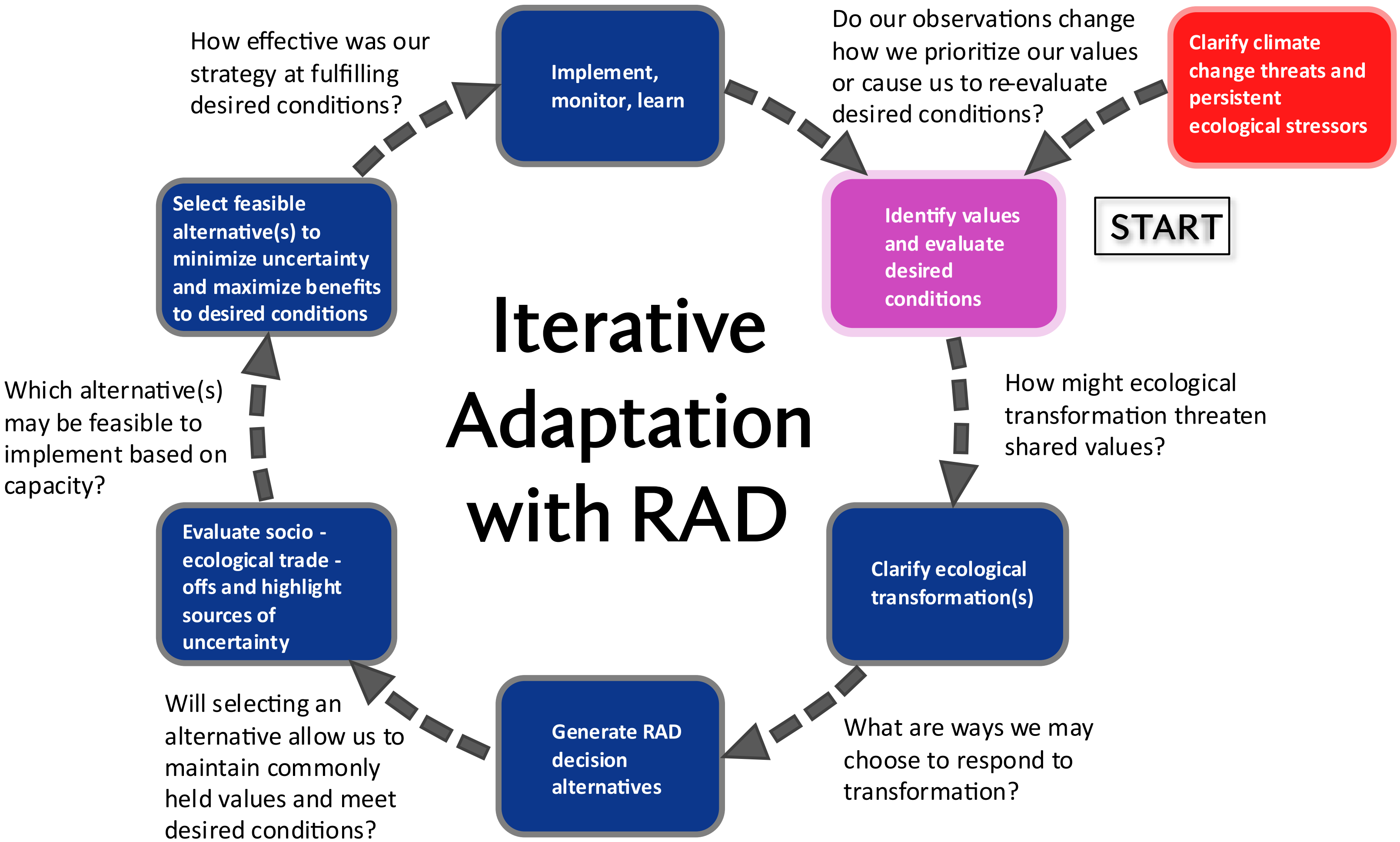


Figure 7: Iterative planning process using the resist-accept-direct (RAD) framework as a tool for climate-informed adaptation for federally designated wilderness.

Learning Objective 1: Orient Sonoran Pronghorn in the Broader Challenge of Wilderness Management in an Era of Climate Change

To orient workshop participants to the broader challenge of managing wilderness in an era of climate change, ALWRI scientists discussed how specific challenges faced by Sonoran pronghorn represent a wicked problem. Facilitators identified existing and anticipated ecological stressors that may contribute to ecological transformation and shared preliminary results from the semi-structured interviews described above to summarize how managers perceive the feasibility of implementing actions to respond to transformation. Since not all workshop participants participated in an interview, sharing this information helped lay a foundation of shared knowledge about conditions affecting Sonoran pronghorn and how they relate to national-level challenges.

The Wicked Problem Statement: Sonoran Pronghorn

Endangered species conservation in an era of climate change is a complex task. Restoring or expanding habitat availability to promote species recovery becomes particularly challenging as baseline ecological conditions transform in response to changing climatic conditions. Additionally, when current or historical habitat exists within designated wilderness, the use of active management to improve habitat conditions in alignment with objectives of the 1973 Endangered Species Act (ESA) may conflict with pre-existing laws pertaining to the 1964 Wilderness Act. In southern Arizona, habitat for the federally endangered Sonoran pronghorn exists both outside and within designated wilderness. Recovery efforts have primarily focused on improving habitat conditions outside wilderness and explicitly within the bounds of the historical range of the species. However, as climate conditions change and plant communities shift, managers are increasingly challenged to both increase active management of populations within historical wilderness habitat as well as explore more adaptive responses outside the historical range. Fulfilling recovery criteria within the historical range while minimizing impacts to wilderness character will necessitate careful consideration of tradeoffs and cross-boundary collaboration among land managers, scientists, rightsholders, and stakeholders.

Learning Objective 2: Identify Desired Conditions Surrounding the Focal Ecological Transformation that Reflects all Perspectives

How individuals perceive and understand ecological transformation and contribute to a decision space is influenced by unique life experiences and values. Several internal and external factors inform individual perspectives and values including personal worldviews, cultural norms and traditions, and institutional demands or constraints (Clifford et al. 2022). Desired conditions in place-based adaptation planning may differ substantially among participants involved in planning efforts (Stern et al. 2023). Discussing solutions to climate change-driven ecological transformation can therefore become contentious when someone's values are impacted by proposed management actions or inaction. By engaging with and illuminating the multi-faceted values of impacted stakeholders and rightsholders, land stewards can build a decision space that is inclusive of the diverse perspectives of affected groups and increase transparency in decision-making. Additionally, new vulnerabilities and opportunities may emerge that may strengthen strategic planning and generate new decision alternatives that were not previously considered (O'Brien et al. 2024). Such co-production efforts can accelerate knowledge transfer and promote sustained interest and support for continued planning as environmental conditions change and new threats emerge (Stern et al. 2023). With climate change-driven transformation, achieving or maintaining previously held desired conditions may no longer be feasible or prioritization of values or desired conditions may shift. Appropriately communicating future uncertainty and re-evaluating the dynamic feasibility to achieve desired conditions under climate change remains a critical component of decision making.

Activity: Values and Desired Conditions

To establish a participatory decision space inclusive of the diverse perspectives of land stewards as well as impacted stakeholders, workshop participants were asked to contribute their unique values and desired conditions for Sonoran pronghorn and their habitat in wilderness during a facilitated, small-group discussion. Values and desired conditions were recorded by workshop facilitators prior to presenting findings of the biological science analyses described above. Following small group discussions, facilitators worked with participants to generate a list of commonly held desired conditions during a large group discussion. After results of the biological analyses were presented, workshop participants were asked to revisit the list of desired conditions to evaluate whether they believed these conditions were threatened by climate change and if new desired conditions emerged.

Values for Sonoran pronghorn and their habitat in wilderness

Workshop participants highlighted the ecological, cultural, and symbolic importance of pronghorn and the critical role of wilderness in its survival (Table 6). Participants emphasized that pronghorn functions as a flagship species—a charismatic animal whose conservation helps draw attention and resources to broader desert ecosystem protection. Public fascination of pronghorn further draws in visitors and engagement in desert conservation. In Organ Pipe National Monument (ORPI), one participant noted that "people come to see pronghorn". As compared to American pronghorn, participants mentioned it is rare to see Sonoran pronghorn and that pronghorn "have a mystery to them and people get really excited when they get to see them".

Participants also valued pronghorn's unique adaptation to the Sonoran Desert, noting that its survival is closely linked to the desert landscape. This specialization contributes to its intrinsic value as an ancient and rare species. One participant noted, "it's very special that we have this ancient animal" and "it would be sad for them to be gone forever."

Participants noted that wilderness areas, though not encompassing all pronghorn habitat, surround key use areas and act as essential buffers against human development and intrusion. As such, important cultural and archaeological sites are better preserved and protected. Further, participants also valued wilderness areas as refugia, not only for pronghorn, but for many species and resources. For example, one participant felt that stricter regulations in wilderness (e.g., motor vehicle use restrictions) would benefit all desert species. Additionally, participants viewed wilderness areas as a "control" against ecological disruption, wherein wilderness landscapes could be used in experimental research to assess the impacts of activities and events on less protected lands.

Finally, the discussion celebrated the "quite unique" interagency collaboration supporting pronghorn recovery and the shared drive to protect both species and its habitat. The presence of pronghorn adds motivation and meaning to conservation efforts, "driving land protection and restoration" in ways that benefit the broader ecosystem and reinforce the purpose of wilderness as a space for biodiversity protection.

Table 6: Social and ecological values for Sonoran pronghorn and federally designated wilderness in the southwestern United States shared by federal agency staff, state agency staff, and collaborators during a workshop in Yuma, Arizona, in February 2025.

	Value Theme	Illustrative Quote
Sonoran Pronghorn	Intrinsic value	"It's a unique species, it's been around for a really long time, it's got some intrinsic value just existing."
	Role in supporting biodiversity conservation	"The added drive to protect the land and restore it because of the pronghorn I think is quite valuable to other species."
	Draw for visitors and recreationists	"[Pronghorn] have a mystery to them and people get really excited when they get to see them."
	Driver of unity and collaboration	"[Pronghorn is] kind of a unifying thing…border patrol also get excited about pronghorn, they also care about pronghorn."
	Symbol of wild and remote places	"Going to Lake Havasu and seeing American pronghorn or just driving north, it would probably be a different experience [to see Sonoran pronghorn] --more difficult…it's very rare to see them."
Wilderness	Species preservation	"Wilderness areas are one of the last areas where we're going to be able to hold on and retain some of these species."
	Scientific investigation	"[Wilderness is] also kind of like a lab…many of the ecological processes still happen without human intervention…we can…observe how those processes work and we can use [lessons learned] in other places."
	Unique recreational opportunities	"Wilderness can be intimidating for members of the public because a lot of them are accustomed to [managed] trails."
	Preservation of important cultural and archaeological sites	"I found a projectile point that was 5-7 thousand years old…[the wilderness designation] protects that stuff, keeps people from driving on it."
	Direct protection from human trammeling	"I think if we didn't have wilderness designations, despite not a lot of people coming out, I think there would be a lot of impacts and change everything."

Desired conditions for Sonoran pronghorn and their habitat in wilderness

Discussion of desired conditions among workshop participants centered on balancing effective recovery of pronghorn with the values and constraints of wilderness (Box 2). One participant noted that "wilderness should not be detrimental to the recovery of endangered species," emphasizing that conservation actions—though potentially constrained by wilderness policy—must still support species survival. Nevertheless, perspectives on what desired conditions might encompass for species recovery in wilderness under climate change varied among participants.

One major topic was water provisioning. Participants acknowledged logistical and safety challenges for maintaining guzzlers in wilderness, noting that it can take several hours to multiple days to access and fill guzzlers. Participants therefore desired to gain the ability to more efficiently and safely fill guzzlers in wilderness. This sparked further reflection on whether current management strategies are sustainable given climate change. One participant mentioned, "we know we need more, but do we need more of the same?"

Participants recognized that "with climate change, it gets kind of tricky" when cultivating desired conditions for pronghorn. Some participants noted that restoration efforts may need to shift from recreating past conditions to "more like a climate adaptation strategy". Acknowledging that preserving the historical range of ecological variation may no longer be realistic, one participant mentioned that they "don't think it's possible for [pronghorn] to remain within their historic range". Still, there was strong sentiment against abandoning recovery efforts within the historical range of pronghorn. After reviewing the modeling results, one participant emphasized that, "this is one model…will it happen, I don't know…I don't think we just give up because we've got one model that says they can't live here". There was further discussion concerning the definition of historical range for pronghorn. One participant described the historical range of pronghorn as being tied to a specific geographic location, while another participant mentioned the range of pronghorn being defined by the extent suitable habitat more generally irrespective of historical location. Overall, however, participants did agree that they would like to strive to keep pronghorn within their current geographically-defined historical range for as long as possible.

Despite having the desire to maintain pronghorn where they occur today, participants expressed the desire to facilitate the movement of pronghorn "to new areas if and when habitat shifts". As such, connectivity among wilderness areas and suitable habitat was highlighted as a vital desired condition. The group also mentioned the desire to maintain and build strong interagency partnerships, noting that "we've got a good thing going with our partners". Another participant mentioned the desire to increase volunteer engagement and Tribal relations to enhance capacity for monitoring and management.

Participants also viewed pronghorn recovery as inherently tied to the desire to retain recreational opportunities, protect important cultural sites, and preserve biodiversity. As the potential range of pronghorn expands into new areas under climate change, preservation of pronghorn may come into conflict with existing land uses that may otherwise endanger pronghorn. Participants mentioned off-road vehicle use and discussed the desire to maintain a balance for multiple uses with pronghorn preservation. Other participants discussed the desire to see overall prioritization of biodiversity, using the fluctuating range of pronghorn as a driver to conserve whole ecosystems under climate change.

Overall, participants voiced a desire for flexibility, collaboration, and creative thinking in pronghorn recovery. While recognizing the challenges of working withing wilderness and a changing climate, they discussed the desire to become more proactive in planning for ecological change to better adapt future landscape and give pronghorn the best chance of long-term survival.

Desired Conditions for Sonoran Pronghorn

1) **Sustain and grow Sonoran pronghorn populations and other wildlife species within wilderness in their geographic historical range for as long as possible**
   - Have wilderness not be detrimental to species recovery
   - Support and/or facilitate movement if and when distribution of habitat shifts
2) **Have high quality, intact, and well-connected Sonoran pronghorn habitat**
3) **Have safe accessibility for staff to maintain waters**
4) **Intact hydrologic function, soil and site stability (ecosite), and geomorphic and biological integrity**
5) **Landscape-level conservation approach achieved through multi-agency partnerships and collaborations with private landowners and other stakeholders and rightsholders**
6) **Sustained opportunities for the public to respectfully visit and experience wilderness**
7) **Cultural values remain intact**
   - Intrinsic value
   - Cultural resources and artifacts
8) **Holistic consideration of development impacts to biodiversity (including Sonoran pronghorn) outside wilderness**
9) **Balanced opportunities for motorized recreation and Sonoran pronghorn conservation**
10) **Shift towards proactive planning supported by science research**
11) **Adequate capacity to successfully implement recovery strategies within wilderness**
    - Staffing, funding, partnerships

Box 2: Desired conditions for Sonoran pronghorn in federally designated wilderness in the United States. Conditions were generated by federal agency staff, state agency staff, and collaborators during a workshop in Yuma, Arizona, in February 2025.

Learning Objective 3: Understand the Utility of RAD as a Tool for Responding to Ecological Transformation

Since European settlement, ecological systems within the United States have been managed under the assumption of stationarity, or the tendency of environments to fluctuate within a range of historically known conditions (Jackson & Hobbs 2009; Magness et al. 2022; Young & Duchicela 2020). With this understanding, environmental properties may change in response to disturbance events, such as wildfire, but also return to a known reference or stable state following disturbance. Increasingly, however, land stewards are observing a shift in ecosystem state beyond a historical natural range of variability (Schuurman et al. 2022). Once ecological communities have crossed a threshold, it is often infeasible to restore historical ecosystem structure, composition, or function (Milly et al. 2008; Suding and Hobbs 2009). Management techniques that may have been previously employed to restore ecosystems following perturbation or strategies to promote resiliency through disturbance may no longer be effective at achieving desired conditions. Land stewards are therefore increasingly challenged to generate novel solutions to meet management mandates and objectives as the character of the landscapes they manage transform.

Responding to and preparing for climate change in wilderness

The RAD framework was developed in response to the need to expand the decision space around ecological transformation under climate change. Rather than defaulting to familiar actions or strategies, the RAD framework provides a space for land stewards to evaluate the opportunities and costs of choosing to deliberately act to intervene (resist or direct) alongside the deliberate decision to not intervene (accept) with observed climate change-driven ecological transformation. This is particularly pertinent for federally designated wilderness, where accepting ecological change may be a familiar strategy due to real and perceived barriers to using active management (Cravens et al. 2024). Nevertheless, although active management is highly scrutinized in wilderness, such activities are not strictly prohibited. In some instances, resist strategies may be necessary to preserve or recover special status species, such as those listed under the Endangered Species Act. Direct strategies are often less familiar and may be viewed as high-risk strategies because few real-world examples exist outside manipulative experimental trials such as common garden and greenhouse experiments (Cravens et al. 2024). By carefully considering all potential alternatives and their implications for wilderness character qualities, land stewards may justify the use of minimum allowable tools to meet desired conditions in rapidly changing wilderness landscapes.

Activity: Generating RAD Alternatives

Decision alternatives for Sonoran pronghorn

Before introducing the RAD framework, workshop participants were divided into two smaller groups and asked to generate potential management responses to transformation of habitat for Sonoran pronghorn. Participants were encouraged to freely generate decision alternatives, regardless of capacity limitations, constraints, or risks. Seven themes of alternatives emerged from exercises and ensuing conversations: water availability, connectivity, habitat restoration and improvement, direct population support, predator and competitor management, climate adaptation research and monitoring, and collaboration and public engagement (Table 7).

Both groups emphasized the importance of water provisioning for pronghorn survival. One group discussed expanding water tank storage to reduce the frequency guzzlers would need to be refilled, coordinating with the Marine Corps and solar companies to help maintain or create new guzzlers, and exploring novel technologies like atmospheric water generators. The other group proposed using drones to refill water sources or drop alfalfa and discussed passive water harvesting structures (e.g. beaver dam analogs) to increase infiltration of water run-off into guzzlers. Both groups highlighted the complexity of water rights and diminishing availability of Colorado River water as growing concerns.

In addition to water availability, vegetation condition and habitat connectivity was a primary concern for continued pronghorn recovery. One group emphasized working with private landowners and Tribes to reserve land for biological corridors, restore degraded areas, and limit development surrounding protected areas. Restoration strategies included planting drought-tolerant species such as chainfruit cholla and creosote, even with acknowledged difficulty of growing plants in the desert. Seeding sourcing tools such as the USGS Seed Mapper were discussed to identify and source seeds from seed zones that may be better adapted to changing climatic conditions. The other group echoed these concerns and added that managing invasive species, limiting wildfire, and maintaining microsites with relict forage species would be essential to retain habitat and allow pronghorn time to shift their range as conditions change.

Both groups recognized that climate change is already shaping the Sonoran Desert ecosystem and called for adaptive planning. One group discussed the value of identifying ecological “triggers” for action (e.g., habitat decline, vegetation shifts, population change) that would prompt translocation of pronghorn. Participants debated the ethical and logistical implications of assisted migration, with caution expressed about moving pronghorn into areas like Tucson, where American pronghorn already exist and predators such as jaguars and mountain lions pose risks. Furthermore, participants discussed that identifying the appropriate time to translocate pronghorn was difficult without further on-the-ground research on habitat change over time. The other group noted recent policy changes at USFWS that allow for translocations outside historical ranges and emphasized a long-term view of pronghorn conservation.

Both groups agreed that captive breeding pens will remain an important tool, particularly when considering translocating pronghorn to new areas outside their historical range. However, participants felt that breeding pens could be paired with behavioral conditioning to improve release success. One group debated the philosophical and practical value of maintaining zoo populations, with some participants emphasizing the importance of keeping the species viable in the wild and others pointing to the success of zoo-based efforts for species like the black-footed ferret. Both groups agreed that the current genetic diversity of pronghorn is sufficient, and translocations from Mexico for genetic reasons aren't urgently needed. However, one group did discuss genetic banking and selecting pronghorn with resistance to disease for potential future translocation into areas where American pronghorn may exist.

Although captive breeding has been effective, participants mentioned that released individuals may have a higher rate of mortality than wild individuals. Both groups identified predator control and behavioral conditions of captive-bred individuals to reduce mortality. One group also mentioned radio-collaring mountain lions to better understand predator movement and behavior. Both groups also mentioned the ecological and legislative challenges posed by wild horses and burros, with one group discussing policy reform to facilitate management.

To maintain current management strategies or engage in new actions, such as assisted migration, both groups emphasized the value of partnerships. One group suggested leveraging social media to build public interest and encourage private landowner involvement, including establishing conservation easements and land purchases. They also discussed working with off-road recreation groups and using incentives or restrictions to reduce disturbance during sensitive times, such as fawning season. The other group highlighted the importance of research partnerships with universities and leveraging new and existing models and tools to better understand landscape dynamics. One participant also mentioned the University of Arizona and the Biosphere 2 research facility to experiment with planting native vegetation in different climatic conditions.

Overall, there was a shared sense of urgency to address climate change challenges, but also realism about adopting new adaptation strategies. As one participant stated, "Obviously we want to do the best we can for as long as we can, but…it's going to change…we have to adapt." Participants acknowledged the intrinsic value of pronghorn and emphasized that recovery must involve creative thinking, interagency coordination, and a willingness to challenge traditional approaches in the face of accelerating environmental change.

Applying the RAD framework to alternatives for pronghorn in wilderness

Participants engaged in thoughtful and at times challenging conversation about applying the RAD framework to alternatives generated for pronghorn recovery. Conversation revealed a mix of practical insights, philosophical reflections, and a desire for clarity when defining the intent behind management actions in wilderness.

After sorting the alternatives they generated into resist, accept, and direct categories, participants agreed that resist strategies were the most familiar and commonly implemented for pronghorn recovery. As one participant noted, “I think we’re really good at resistance.” Most actions that fell into the resist category involved activities aimed to retain Sonoran pronghorn within their historical range for as long as possible and included existing management activities such as providing supplemental forage, captive breeding, and habitat restoration.

Despite the comfort with resist strategies, participants acknowledged that many actions could fall into multiple RAD categories depending on intent. For example, strategies typically used to resist change, such as captive breeding or water provision, could be considered direct strategies if used to facilitate the establishment of pronghorn outside their historical range. This highlighted the importance of clarifying the objective behind an action—whether to hold the line (resist) or shape a new trajectory (direct).

There was some confusion about when an alternative shifted from resist to direct and a broader hesitation to make that transition. Participants expressed a desire to identify ecological tipping points or clear indicators that would justify moving from resisting change to directing it. This uncertainty created a reluctance to move into less familiar territory.

Overall, there was widespread recognition that direct strategies are more abstract and harder to plan for. Several participants acknowledged the discomfort with forward-looking approaches. One participant noted, “I see direct as kind of being in the future and the future is very unpredictable.” Another participant said, “I also think when there’s a new idea, it’s always harder for everybody to…go for it.” Directing change, such as relocating pronghorn to new suitable habitat or planting transformed landscapes with novel plant species, was seen as valuable but conceptually challenging.

Participants generated several accept alternatives which focused on research, building partnerships, and outreach and education. These alternatives did not directly address transforming landscapes or use active management, however, participants noted that these activities were essential to inform active management. In particular, when identifying tipping points to shift from resist or direct activities, participants noted that it would be critical to have data on vegetation change and strong partnerships and public support.

Several participants noted that the RAD framework, while helpful in theory, doesn’t always map neatly onto real-world decisions. As one participant noted, “When you were deciding between the three of them…they didn’t totally fit those definitions.” Nevertheless, the RAD framework also helped participants better clarify the intent behind each proposed alternative. Participants agreed that it was important to be mindful and provide clear justification for active management in wilderness.

Table 7: Decision alternatives generated by land stewards and their partners and categorized using the Resist-Accept-Direct framework in a workshop to assess climate adaptation strategies for Sonoran pronghorn in the southwestern United States.

Strategy Theme	Decision Alternative	Resist	Accept	Direct
Water Availability	Install more drinkers in current management units	X		
	Work with solar companies and private landowners to supply water	X		X
	Use drones or helicopters to deliver water to existing guzzlers	X		
	Restore access to historical water sources (i.e., Gila and CO Rivers)	X		
	Mitigate evaporation from existing guzzlers	X		
	Engineer passive water collection (e.g. beaver dam analogs)	X		
	Enlarge water storage capacity	X		
	Desalinated water delivery	X		X

Table 7 (continued): Decision alternatives generated by land stewards and their partners and categorized using the Resist-Accept-Direct framework in a workshop to assess climate adaptation strategies for Sonoran pronghorn in the southwestern United States.

Strategy Theme	Decision Alternative	Resist	Accept	Direct
Connectivity	Private landowners provide corridors through vegetation management			X
	Farming for wildlife (i.e., create biological corridors through agricultural lands)			X
	Establish conservation easements	X		X
	Work with solar companies to provide corridors within historical range	X		
	Restrict land development surrounding protected areas	X		X
Plant Community Restoration and Improvement	Irrigation of the desert	X		
	Remove and control invasive plant species	X		X
	Plant chainfruit cholla outside historical range			X
	Source new drought-tolerant plants that pronghorn will eat	X		X
	Assisted migration of Sonoran plants	X		X

Table 7 (continued): Decision alternatives generated by land stewards and their partners and categorized using the Resist-Accept-Direct framework in a workshop to assess climate adaptation strategies for Sonoran pronghorn in the southwestern United States.

Strategy Theme	Decision Alternative	Resist	Accept	Direct
Direct Population Support	Captive breeding	X		
	Supplemental feeding	X		
	Increase breeding areas and pronghorn numbers on the ground	X		
	Assisted migration of pronghorn to new areas expected to be more suitable in the future			X
	Assisted migration of pronghorn within historical range	X		X
	Breed for drought and disease resistance	X		X
Predator and Competitor Management	Remove feral horses and burros	X		
	Change Wild Horse and Burro Act so you can better manage populations		X	
	Predator control	X		
	Predator behavioral conditioning for captive-bred individuals	X		
	Collar predators for monitoring		X	

Table 7 (continued): Decision alternatives generated by land stewards and their partners and categorized using the Resist-Accept-Direct framework in a workshop to assess climate adaptation strategies for Sonoran pronghorn in the southwestern United States.

Strategy Theme	Decision Alternative	Resist	Accept	Direct
Climate Adaptation Research and Monitoring	Greenhouse experiments		X	
	Identify areas for potential habitat and identify triggers		X	
	Research on diet breadth of pronghorn under changing plant communities		X	
	Monitor climate trends		X	
	Genetic banking		X	X
	Wildfire recovery		X	
	Research pros and cons of drinkers under changing climatic conditions		X	
Collaboration and Public Engagement	Manage visitor use access	X		
	Increase outreach to recreational groups/users		X	
	Partner with other agencies and Tribes		X	
	Citizen science to increase awareness of problems and advocacy		X	
	Social media campaign		X	

Learning Objective 4: Develop a Feasible and Repeatable Workflow to Evaluate RAD Decision Alternatives

Selecting and applying decision alternatives generated using the RAD framework can be challenging if the ecological transformation is poorly understood or if institutional constraints impact the ability of managers to feasibly pursue certain alternatives. Ecological modeling and experimentation may help to characterize potential transformation, however, uncertainty often persists. Despite constraints and sources of uncertainty, land stewards are tasked with responding to ecological transformation to fulfill institutional mandates and objectives.

Balancing social-ecological trade-offs

In addition to grappling with uncertainty, wilderness stewards must also balance social-ecological trade-offs inherent in decision-making under climate change. These trade-offs are a negotiation of the unique values each member of the planning or project team contributes balanced with policy requirements under guiding strategic management plans and legal documents, such as the National Environmental Policy Act (NEPA) and the Wilderness Act. In federally designated wilderness, selecting and implementing a decision alternative should minimize undesirable outcomes as well as impacts that may degrade wilderness character. For example, preserving special status, iconic species may be considered a high priority for managers to fulfill requirements pursuant to the Endangered Species Act (16 U.S.C. 1531-1544) as well as to maintain or preserve the natural quality of wilderness (see Table 1 for definitions of wilderness character qualities). Nevertheless, the type of management action pursued to support species persistence may conflict with policy under the Wilderness Act. Management actions that seek to halt or reverse ecological change for single-species preservation align most closely with a resist strategy. However, resist actions often require trammeling of wilderness to meet necessary targets for viable populations. Furthermore, under climate change, it is becoming less common that single actions will be sufficient to support species persistence, thereby necessitating more intensive management efforts, and thus greater trammeling (Evans et al. 2016). In the long-term, a resist strategy may reduce undesirable outcomes associated with species loss, but this strategy may also degrade wilderness character through multiple acts of trammeling. Under an accept strategy, where no active management takes place, wilderness character may not be degraded by trammeling; however, the natural quality of wilderness may be compromised if an iconic species is lost. Finally, under a direct strategy, individuals or populations may be translocated to other areas of the landscape where they may persist autonomously as habitat conditions shift under climate change. Trammeling may be required to translocate the species to more suitable habitat within or outside wilderness, however, unlike the resist strategy, it may be less likely that this strategy will entail repeated acts of trammeling to meet target population requirements if the species can be self-sustaining within its introduced range. For management decisions to be defensible, it is critical to explicitly account for all potential impacts of implementing a decision alternative.

The Futures Wheel: An exercise to illuminate trade-offs

To help clarify sources of uncertainty and socio-ecological trade-offs inherent in climate change-informed decision-making, we used the Futures Wheel tool to evaluate the potential consequences (positive, negative, or neutral) and tradeoffs of a resist, accept, and direct strategy for Sonoran pronghorn and their habitat. The Futures Wheel is a structured brainstorming tool used to describe multi-level consequences of addressing social-ecological change (Bengston 2015; Bengston et al. 2022). The Futures Wheel has been applied in a diversity of sectors to analyze consequences of many types of change, but it has rarely been used in climate adaptation planning. Considering climate adaptation actions in wilderness demands a transparent process to understand the potential consequences of decisions to act, or not to act. There are many ways to design and apply the Futures Wheel, however, in its basic structure, it requires users to define multiple arcs of consequences that stem from a central problem or event. Individual arcs describe a hierarchy of connected consequences. First order consequences occur as a direct result of the central decision point or event. Second order consequences are triggered by first order consequences. Third order and all subsequent consequences are directly informed by the preceding order. Arcs are extended as far as necessary, such that all potential consequences have been identified for each arc. The purpose of building arcs is to clarify all potential impacts, likely or unlikely, that stem from a central problem or event. By following this process, users can reduce unforeseen impacts and identify consequences that may be particularly beneficial or catastrophic (Bengston et al. 2022). Furthermore, by explicitly describing and recording all potential implications of implementing a decision, this process fosters transparency in decision-making. After all arcs have been completed, users can score each consequence by the likelihood that it may occur and its perceived desirability (Table 8). Final scores can then be summarized across the wheel to generate a quantitative understanding of the drawbacks and opportunities of a central problem or event.

Activity: Applying the Futures Wheel to RAD Decision Alternatives

To further evaluate decision alternatives generated during the workshop, Futures Wheels were used to illuminate all potential consequences (positive, negative, or neutral) of selecting either a resist, accept, or direct action to address ecological transformation for Sonoran pronghorn and their habitat in the United States. Workshop participants were divided into two small groups which represented a range of positions, tenure, and affiliations. Each group constructed one wheel focused on either a resist, accept, or direct alternative (Box 3). Decision alternatives were placed at the center of each wheel such that subsequent arcs described direct and indirect implications associated with implementing each alternative. Workshop participants were encouraged to consider a range of potential consequences, including social, legal, and ecological consequences. Participants then scored each unique consequence by its likelihood and desirability (Table 8). Likelihood described the perceived possibility that each consequence would come to pass and was scored on a scale from 1-9. Desirability described perceived appeal of each potential consequence and was scored along a weighted scale such that perceived catastrophic consequences received a score of -50 and triumphant consequences received a score of 50. Workshop participants used the scores to gather a general sense of whether each alternative felt desirable and whether the cascading consequences were certain.

Table 8: Scoring method for a Future's Wheel activity examining the implications of choosing to resist, accept, or direct ecological transformation for Sonoran pronghorn and their habitat in the southwestern United States.

Likelihood		**Desirability**	
9	Extremely likely	50	Triumph
8	Very likely	5	Extremely desirable
7	Likely	4	Very desirable
6	Somewhat likely	3	Desirable
5	Uncertain	2	Somewhat desirable
4	Somewhat unlikely	1	Minimally desirable
3	Unlikely	0	Neutral
2	Very unlikely	-1	Minimally undesirable
1	Extremely unlikely	-2	Somewhat undesirable
		-3	Undesirable
		-4	Very undesirable
		-5	Extremely undesirable
		-50	Catastrophe

RAD Alternatives: Sonoran Pronghorn

To better envision social-ecological trade-offs inherent in choosing among competing RAD alternatives, workshop participants were asked to further discuss cascading consequences of the following.

RESIST: Install more guzzlers

More guzzlers would be added to historical wilderness habitat. Tools to construct guzzlers would include motorized vehicles, backhoes, power tools, and generators. Permanently constructed features would include collection dams, underground pipes, and ground level troughs. Game cameras would be permanently installed to monitor use of guzzlers by wildlife. Water level monitors would also be permanently installed. Maintenance of guzzlers would primarily be accomplished with non-motorized means, however, motorized vehicles may be used to refill difficult-to-access guzzlers. If predation of Sonoran pronghorn becomes problematic at guzzler locations, vegetation may be cleared from the bottom branches of larger trees/shrubs and understory brush maybe be removed within 50 yards of the guzzler. Lethal removal of collared problem predators may be authorized if deemed necessary.

ACCEPT: Outreach campaign

Outreach and education efforts would be increased within local communities, partnering agencies, landowners, and Tribes to increase support and advocacy for Sonoran pronghorn. Activities would include in-person events and social media campaigns. Outreach content would focus on education about Sonoran pronghorn and developing partnerships to support land improvement for recovery efforts.

DIRECT: Assisted range expansion

Sonoran pronghorn would be captured from captive breeding facilities and transported via truck to a release pen at a site adjacent to a wilderness area in the proposed 10(j) area in southern CA. Release would occur in wilderness areas projected to become or remain more climatically suitable for pronghorn into the future. Pronghorn would reside in the release pen for 3-4 weeks and food and water would be supplied until pronghorn became independent. Release would occur in winter. Pronghorn would be released multiple times (i.e., over multiple years).

Box 3: Alternative actions proposed to resist, accept, or direct anticipated ecological transformation impacting Sonoran pronghorn recovery. Workshop participants discussed the cascading implications of each alternative both in terms of their desirability in achieving desired conditions and likelihood of occurring if the alternative was implemented.

Resist: Install more guzzlers

This resist alternative focused on conservation of Sonoran pronghorn in its historical range by installing more guzzlers in southwestern Arizona wilderness areas. Overall, participants viewed this alternative as desirable and felt that potential consequences, positive or negative, were well known and therefore relatively certain (Figure 8). However, given projected climate and habitat suitability, some participants felt this strategy may become untenable over time. One participant shared that managers will "try to resist until resistance is futile." First order consequences of adding guzzlers included spatial impact to existing wildlife, increased pronghorn survival, removal of vegetation for predator control, introduction of invasive plant species, maintenance of the guzzlers, increase in infrastructure, MRA initiation, improved wilderness character due to increased wildlife, ground disturbance, and both the potential for either increased or decreased need to haul water.

Future climate remained a point of uncertainty and discussion. For example, if the climate became increasingly hot and dry, then installing more guzzlers could require increased water hauls. Alternatively, one participant felt that increasing the number of guzzlers may decrease the need to haul water because there would be less pressure on any one guzzler by pronghorn and other wildlife. Although this scenario could take more agency capacity and resources, participants emphasized that public support for pronghorn is strong, and they doubted the public would think negatively about increased agency spending even as water becomes scarcer. Another participant noted that the cost of water to fill guzzlers may increase in the future as it becomes scarcer, but that wasn't concerning for several managers because partners like Yuma Proving Ground have several wells.

In addition to supporting pronghorn and other wildlife, participants discussed several public recreational benefits of adding guzzlers including increased opportunities for wildlife viewing and for hunting. Participants shared that hunters often hunt near guzzlers (legally allowed one mile away from waters). Although hunting opportunities could be improved by increasing guzzlers and, subsequently, wildlife, one participant shared that it could also improve wildlife survival rates since they would be distributed over a wider geographic area (i.e. fewer animals at each guzzler).

One participant asked if wildlife would become overly dependent on supplemental water sources and abandon natural water sources, however, biologists shared that pronghorn generally prefer natural water sources due to the surrounding vegetation. Additionally, biologists emphasized that pronghorn regularly travel to different water sources across the landscape as they are replenished by rain. Therefore, participants were not concerned that pronghorn would become negatively habituated to human-made water sources. Participants did not reflect much on impacts to wilderness character associated with this strategy aside from impacts to the undeveloped quality as a result of guzzler construction.

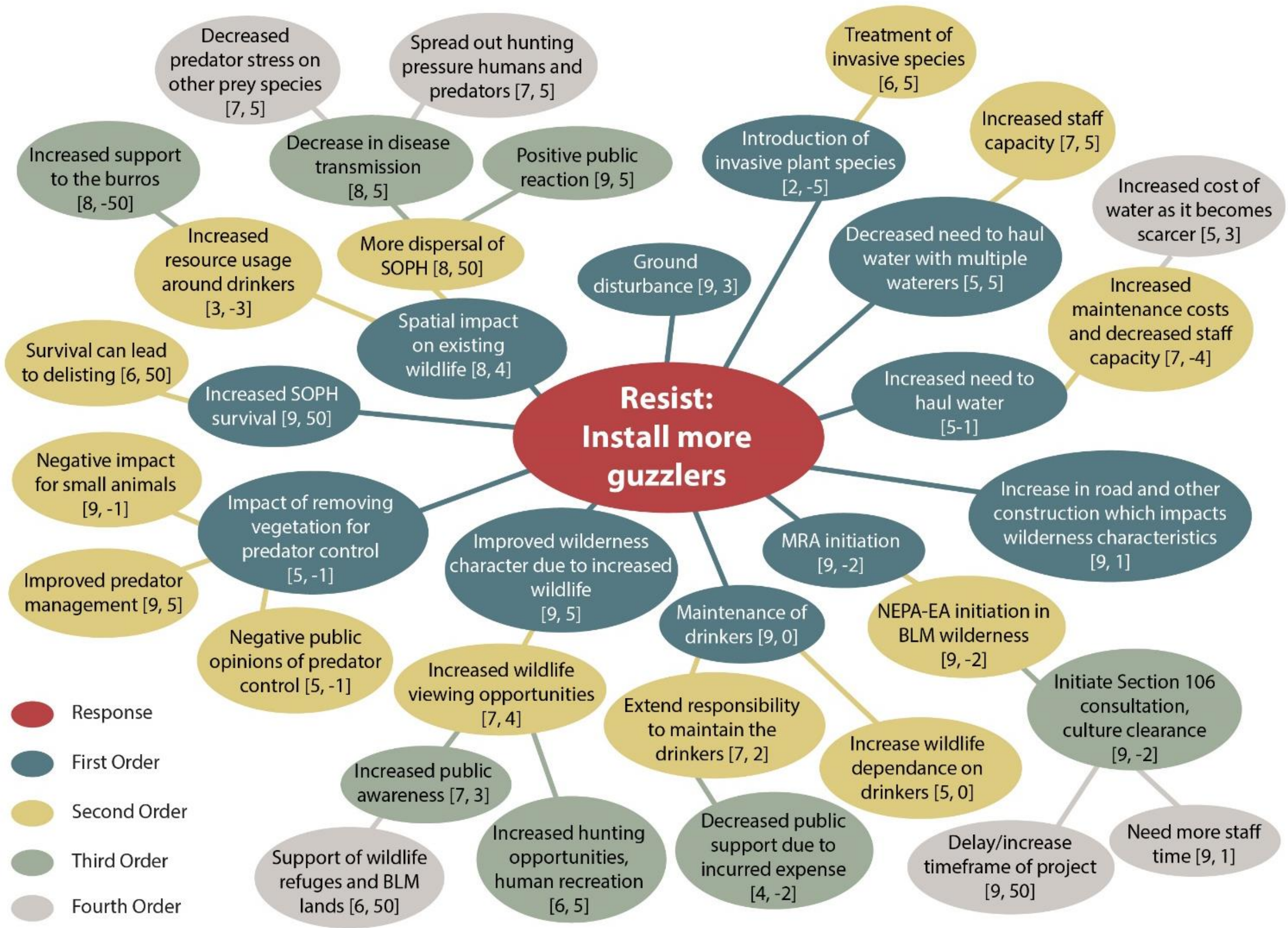


Figure 8: A Futures Wheel used to illuminate the potential cascading implications of choosing to resist anticipated ecological transformation of Sonoran pronghorn habitat in the United States, by installing more guzzlers in wilderness in their historic range. Implications (blue, yellow, green, and grey circles) were scored by the likelihood that they may occur because of the decision (first number in brackets) and by their perceived desirability (second number in brackets).

Accept: Outreach campaign

The accept alternative focused on putting time and energy into an outreach campaign with existing national and international partners, and seeking additional partnerships with other agencies, rightsholders, stakeholders, and the general public (Figure 9). Overall, participants felt that this alternative would have some very desirable outcomes including more public buy-in and collaborative conservation work. However, participants also recognized that if the accept strategy meant ending or reducing active pronghorn management, then pronghorn populations would likely decline, which was considered a catastrophe. First order consequences of accepting the transformation and focusing on an outreach campaign included increased public awareness, more volunteers, loss of species dependent on the guzzlers, reduced need to haul water, lack of progress in establishing pronghorn in the 10(j) area, more collaboration between entities, and no impact to wilderness character (e.g. trammeling). Participants were less certain about implications related to collaboration and increased public awareness than they were about implications of no longer providing supplemental water.

Participants felt that focusing on an outreach campaign would successfully engage the public and foster new partnerships. Participants believed that strengthening these relationships through outreach could result in increased public awareness of Sonoran pronghorn and potentially lead to a broader volunteer base and more funding support for the recovery program. In addition to broader public engagement, participants thought this strategy could lead to new partnerships with private landowners (i.e. farms) adjacent to public lands currently occupied by pronghorn and more consistent engagement with the Tohono O'odham Nation, who have been intermittently involved in the pronghorn recovery team. Importantly, participants were uncertain whether they would be successful in increasing collaboration among the public, stakeholders, and rightsholders. However, if successful, participants anticipated several clear benefits including creation of biological corridors through farmland, increased protected land, and potential for farmers to provide wildlife waters. If these actions came to pass, connectivity could be enhanced and there would be potential for increased biodiversity, resilience, and carbon sequestration.

Engaging more people and partners in pronghorn conservation and recovery would likely lead to longer project timelines to best incorporate diverse values, ideas, and opinions. Participants felt that lengthened project timelines were undesirable and could result in less action over time. However, participants acknowledged that the outcomes of these collaborative decisions may have more public support and result in less litigation. Despite the several desirable implications associated with this accept strategy, participants identified a number of potentially undesirable consequences. First, if the outreach campaign was successful in spreading public interest and awareness, then there would be potential for increased visitation to areas where pronghorn could be viewed. Increased visitation may result in unintended negative impacts to the landscape, and require management action in terms of education, engineering, and enforcement—taking up already limited staff time and resources. Additionally, increased public interest could lead to the spread of misinformation online.

Even if the accept strategy was successful, accepting ecological transformation would result in loss of pronghorn, which participants considered catastrophic. Additionally, other species besides pronghorn rely on guzzlers, and they, along with pronghorn, would likely be negatively impacted if no supplemental water was provided. Participants reflected that ceasing to intervene (i.e. not engage in active management) may not benefit wilderness any more than continuing to resist transformation. For example, participants noted that although accepting transformation would mean less trammeling, naturalness would be degraded in the long-term if species were extirpated from the wilderness areas. Participants in this focus group felt that the loss of species (i.e. naturalness) would be worse than the degradation of wilderness character due to trammeling.

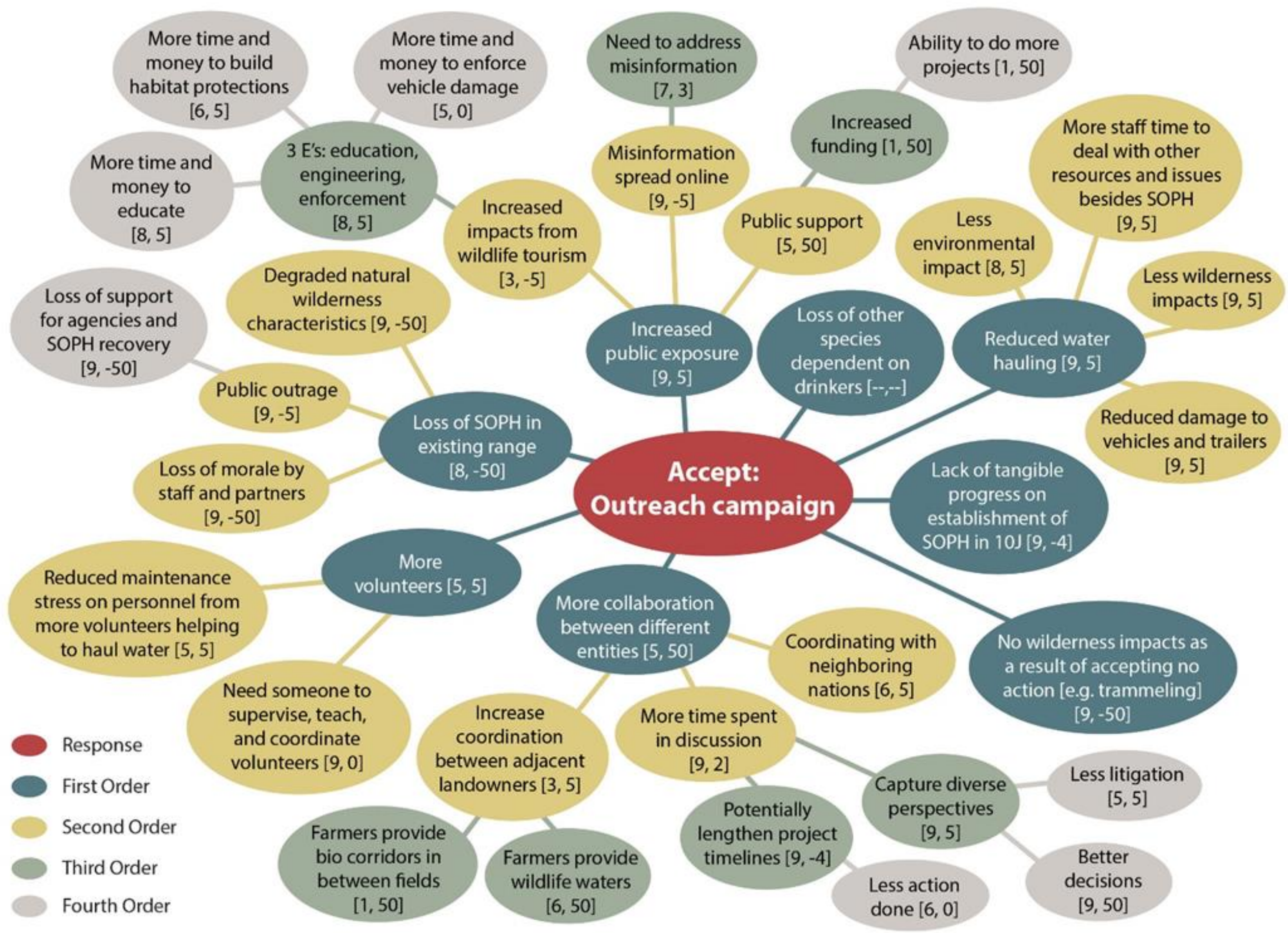


Figure 9: A Futures Wheel used to illuminate the potential cascading implications of choosing to accept ecological transformation of change to pronghorn. Implications (blue, yellow, green, and grey circles) were scored by the likelihood that they may occur because of the decision (first number in brackets) and by their perceived desirability (second number in brackets).

Direct: Assisted range expansion

Using a direct alternative, managers would seek to conserve Sonoran pronghorn by moving individuals into a proposed 10(j) area in southern California (CA), which is both with their historical range and projected to be more climatically suitable in the future (Figure 10). In general, participants felt that more research including vegetation mapping and ground truthing was critically needed before implementing this direct strategy. First order implications of assisted range expansion into southern CA included finalizing the 10(j) area, successful establishment of pronghorn in the 10(j) area, potential mortality of pronghorn associated with capture in AZ and release in CA, less funding for other programs, ability for Californians to experience pronghorn, increased collaboration across states, benefits to resident wildlife from adding supplemental water, potential for pronghorn to leave the 10(j) area, potential for unsuccessful relocation, and likelihood that rain would be sufficient to fill guzzlers.

Participants identified several uncertainties that would need to be addressed if this strategy were to be implemented. For example, national monuments and wilderness areas in the proposed 10(j) area are short-staffed, and agencies would need to work together to determine roles and responsibilities for relocation and recovery efforts across state and jurisdictional boundaries. Further, if lethal predator management were needed in CA, there may be different laws or requirements that managers would need to navigate. Additionally, participants were uncertain if the vegetation and rainfall in the proposed 10(j) area could support pronghorn and if competition and interbreeding with other nearby pronghorn subspecies would become an issue.

Participants were uncertain but hopeful that reintroducing pronghorn to the proposed 10(j) area in CA would have positive cascading consequences for landscape-level conservation. For instance, if CA residents could experience and enjoy pronghorn, support for the species and for the landscapes they live on could grow. Increased public awareness and support could result in more funding for conservation and may make the public value and protect national monuments where pronghorn were released. Participants also acknowledged that adding guzzlers to the area may benefit other game species, and garner local hunter support and volunteerism. However, participants reflected that despite increased outreach efforts for desert tortoise in the region, there was not yet widespread support for species or landscape-level conservation.

Participants acknowledged how this strategy could both degrade and enhance wilderness character in areas where pronghorn are reintroduced, and guzzlers are installed. Certainly, the reintroduction of pronghorn and installation of guzzlers constitute trammeling actions and developments within wilderness. Although participants felt some members of the public would be opposed to these actions and litigation may result, they felt that the enhancement of the natural quality would outweigh the negative impacts to wilderness character.

Participants identified several potentially negative consequences if assisted range expansion efforts failed. Although participants felt that reintroducing pronghorn to the proposed 10(j) would earn some amount of goodwill from the public, they recognized that they could receive severe criticism if the reintroduction failed. Additionally, participants highlighted that potential loss of pronghorn in the 10(j) would negatively impact the species as whole due to loss of individuals and their genetics. In other words, there would be fewer individuals for breeding and species recovery in Arizona. Finally, staff shared their deep emotional investment in the species wellbeing. Several participants indicated that loss of pronghorn, whether in AZ or in the proposed 10(j) in CA, would be devastating for staff.

Overall, participants felt that resistance was the most desirable short-term strategy, they acknowledged that directing pronghorn to more climatically suitable habitats may be necessary for species conservation. Until then, participants identified a number of critical uncertainties that could be addressed as they further develop a plan to establish a 10(j) population in CA.

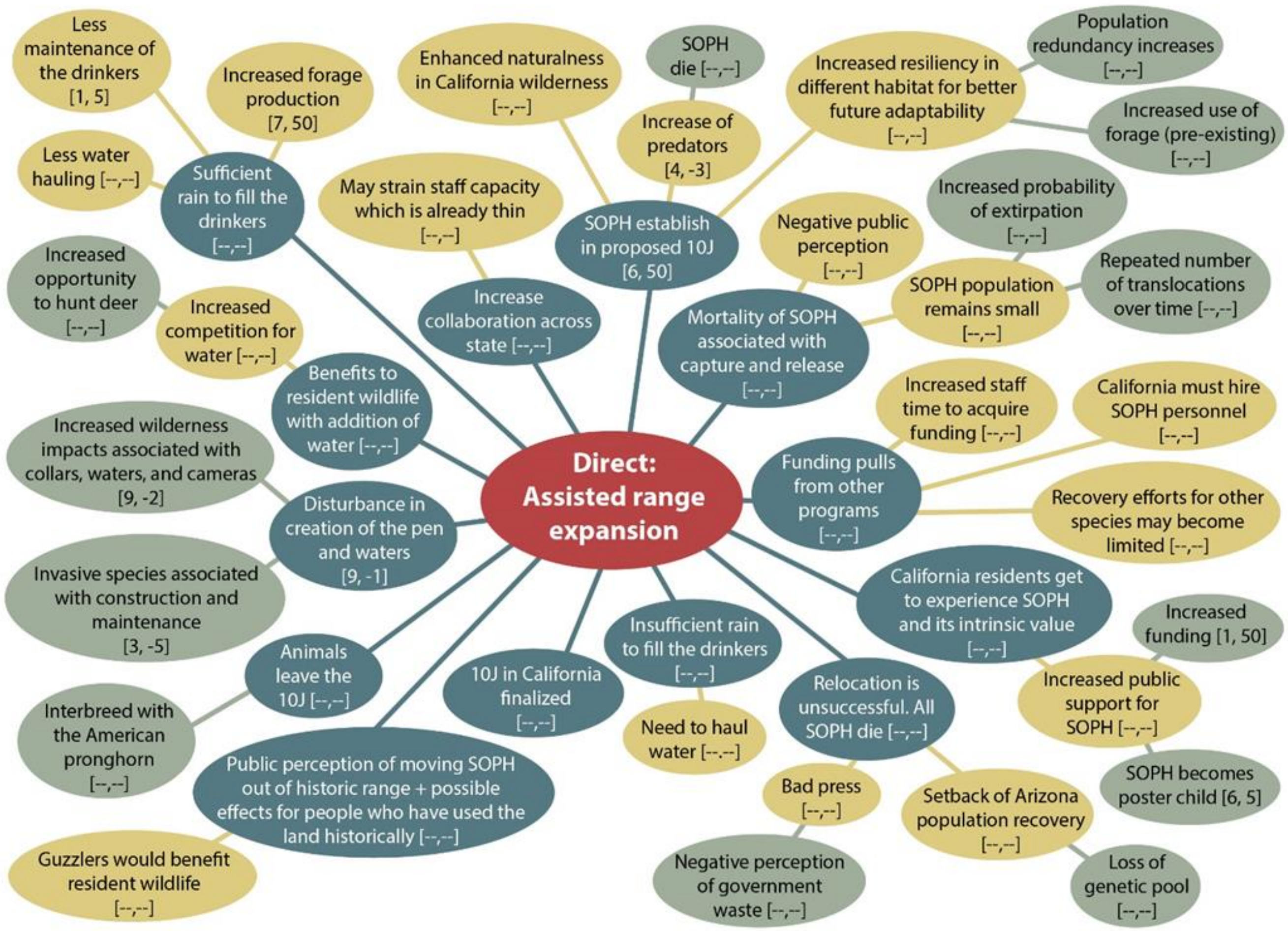


Figure 10: A Futures Wheel used to illuminate the potential cascading implications of choosing to direct ecological transformation of change to pronghorn. Implications (green, blue, and gray circles) were scored by the likelihood that they may occur because of the decision (first number in brackets) and by their perceived desirability (second number in brackets). Dashes within brackets represent missing values, or un-scored implications).

Key take-aways and findings from the Futures Wheel exercise

- In general, participants shared that resisting is their first-choice strategy because they are emotionally and legally tied to maintaining the endangered population of pronghorn in southwestern AZ

- Several participants acknowledged that resisting may become untenable, and described the importance of learning more about future climate and exploring the direct strategy as a potentially necessary future option

- Although participants identified several benefits of an outreach campaign, accepting the transformation and subsequently the loss of pronghorn was seen as catastrophic, a violation of the Endangered Species Act, and not a viable option in isolation

- Participants felt that conserving pronghorn and subsequent enhancement of the natural quality of wilderness character outweighed costs to the untrammeled and undeveloped qualities of wilderness

- Across all three response alternatives, participants felt that widespread public awareness of and involvement in pronghorn conservation could result in more funding and engagement in species- and landscape-level conservation

Conclusions and Considerations for Future Work

Addressing climate change in congressionally designated wilderness is a wicked problem faced by land stewards throughout the United States. The purpose of this project was to begin to untangle this wicked problem by examining the ecological and social impacts of climate change and by demonstrating an iterative process that land stewards and their partners may use to be mindful in their response to climate change-driven ecological transformation. The case study described in this report specifically addresses the challenge of recovering the federally endangered Sonoran pronghorn as their habitat in wilderness transforms under climate change. Scientists at the Aldo Leopold Wilderness Research Institute (ALWRI) researched both the potential ecological consequences of projected climate change for pronghorn habitat and connectivity as well how impacts to pronghorn are observed and currently addressed by land stewards. Following this research, ALWRI scientists facilitated a 2-day workshop with U.S. Fish and Wildlife Service staff (FWS), Arizona Game and Fish Department staff, and partners from non-profits and other federal agencies to introduce an adaptive management process incorporating the RAD framework to generate and evaluate a decision space for addressing climate change-driven transformation.

According to our modeling, habitat for pronghorn is strongly influenced both by climatic factors as well as current management activities. In the absence of water provision in the form of guzzlers, habitat for pronghorn is expected to shift north and east. Continued maintenance of guzzlers may allow pronghorn to persist in their historical range, however, the likelihood that active management will need to occur within wilderness increases if management efforts remain concentrated within current management units. Restoring or conserving a federally threatened species in wilderness is a particularly challenging endeavor and perspectives on when, where, and how these activities should occur in wilderness differed among interviewees and workshop participants. Nevertheless, there was a unified acknowledgement that some action within wilderness may be necessary to meet recovery goals.

Workshop participants expressed that they valued pronghorn intrinsically, as a symbol of wild and remote places, and their propensity to draw in visitors and recreationists. Additionally, participants valued how conservation activities for pronghorn also benefits other species and brings partners together for collaboration. Although participants acknowledged that recovery of pronghorn within wilderness was challenging, participants also valued wilderness for species preservation, scientific investigation, unique recreational opportunities, preservation of cultural and archeological sites, and protection from trammeling.

These values informed several desired conditions that primarily centered on balancing effective recovery of pronghorn within the context of wilderness. Importantly, some participants expressed the desire for the wilderness designation to not impede species recovery, but instead provide high-quality, intact habitat facilitating species recovery, respectful recreation, preservation of cultural values and artifacts, and safe access to guzzlers for staff and wildlife. Further, participants identified continued collaborative landscape-level conservation, adequate capacity to implement recovery, and shifting towards proactive and scientifically supported planning for future management as desired conditions.

Although future climate and habitat projections do not bode well for pronghorn, participants emphasized their deep commitment to the species and their ethical and legal needs to ensure its persistence. Partly due to its listed status and partly due to participants attachment to maintain Sonoran pronghorn in place, most activities participants identified resisted change by focusing on conserving and recovering pronghorn in their current habitat. These “resist” strategies included ensuring water availability, enhancing connectivity, vegetation restoration, providing supplemental forage, predator and competitor management, and managing visitor use in their current range. Participants did not feel that accepting the transformation was a viable option in isolation due to ethical and legal obligations to recover the species, however, participants did discuss several benefits of increasing public awareness through outreach campaigns, engaging in research and monitoring, and maintaining and building upon existing partnerships and collaboratives.

Although resist strategies felt more certain, familiar, and aligned with participants’ desire to maintain pronghorn in their current habitat, several participants acknowledged that resisting change may not be tenable in the long-term. As such, participants identified some strategies to direct pronghorn recovery in response to habitat transformation. “Direct” strategies included enhancing connectivity so pronghorn could access more suitable habitat, planting more drought tolerant forage species, assisted migration of Sonoran plants and/or pronghorn to areas projected to be more climatically suitable in the future, and genetic banking and breeding for drought and disease resistance. Although participants acknowledged the necessary eventuality of assisted migration efforts, participants expressed that more research was needed on habitat suitability in the proposed 10(j) area in CA and elsewhere before translocating pronghorn.

In sum, well-practiced approaches that resisted change, such as population support through captive breeding and provision of supplemental food and water, were viewed more favorably as compared to new practices to direct pronghorn through habitat transformation (e.g. assisted migration). Although participants acknowledged that these resist strategies constituted developments and trammeling actions, they would provide numerous benefits to pronghorn and other wildlife species—enhancing the naturalness of the affected wilderness areas. However, given the future climate trajectory, participants felt it was wise to begin engaging in accept strategies (e.g., research, collaboration, and public engagement) and exploring direct strategies (e.g. visit and ground truth habitat suitability in the proposed 10(j) area) while continuing to resist change within pronghorn’s current range. Knowing when to change strategies from primarily resist to accept or direct was a key topic of discussion. Participants felt they would need to determine some kind of threshold and triggers to change course but were unsure what those might be. Research to determine triggers was identified as an "accept" strategy that could benefit future management directions.

Recovery Criteria in a Changing Landscape

Many workshop participants stated that they valued pronghorn because of the species' unique adaptation to survive in the Sonoran Desert ecosystem. Although our research and similar studies indicate that Sonoran Desert habitat is likely to shift outside the historical range of pronghorn, downlisting and delisting criteria outlined in the most recent pronghorn recovery plan do not explicitly acknowledge or accommodate climate change-driven habitat change. Rather, current targets to reclassify Sonoran pronghorn include establishing three viable populations of pronghorn, two of which must occur within the southern extent of their historical range in the United States (USFWS 2016). Despite widespread recognition that climate change is a leading threat to the recovery to all at-risk species, few recovery plans currently account for projected climate change-driven transformation in their recovery criteria (Weber et al. 2023).

If suitable habitat conditions for pronghorn shifts outside the species' historical range, management efforts to achieve viable populations in the historical range will likely need to continue or intensify in the future. Conservation-reliant species, or species that require management support in perpetuity to retain viable abundance thresholds, are becoming increasingly common in transforming landscapes (Scott et al. 2010). During the workshop, participants acknowledged this challenge and questioned whether the geographically static approach currently used to set population thresholds for pronghorn was still appropriate given observed and anticipated ecological change. Some participants discussed the desire to see population targets that reflected estimates of current and future habitat extent. Furthermore, participants also recognized that efforts to recover pronghorn may need to extend beyond the species itself to the habitat that supports it. Managers proposed several alternatives that might restore habitat or expand habitat through assisted migration. Nevertheless, participants also noted that getting plants to establish in the desert was particularly difficult and capacity constraints may hinder their ability to engage in such activities.

To allow for more flexible recovery strategies as habitat shifts under climate change, the FWS finalized a rule in 2023 that allows nonessential experimental populations to be introduced beyond a species' historical range. For pronghorn recovery to be successful, it may be necessary to employ a combined strategy that resists change to current populations within the historical range and reduces barriers to or facilitates climate-driven dispersal beyond the historical range. Nevertheless, employing novel alternatives that direct population change, such as assisted migration, is inherently risky. Moreover, agencies often lack the resources to implement such large-scale activities. To capitalize on the new opportunity afforded by this recent rule, managers will need to continue to work closely with collaborators and scientists to build capacity, fill knowledge gaps, and develop adaptive approaches to recovery—such as the process introduced during this case study—that might better align with the original intent of the ESA and the changing needs of pronghorn.

Identifying Ecological Thresholds or Trigger Points

When and where to apply RAD alternatives remains a complex topic that requires further consideration. Ecological transformation has been described as a continuum of irreversible change that may increase in magnitude over time (Hillebrand et al. 2020). In that respect, it may be more appropriate for land stewards to identify specific features or ecological processes that, if degraded or lost, might trigger management actions. Limits of acceptable change (LAC) is one example of a tool wilderness managers may use to decide if or when to implement management actions to either resist or direct observed ecological change (Stankey and McCool 1984). LAC was initially developed to inform the management of recreation in wilderness. More recently, the LAC tool has been revisited to understand how it can be applied in a multi-use framework (McCool and Cole 1997). Additionally, others have developed guidance to identify ecological thresholds and trigger points to inform shifts in RAD pathways (Lynch et al. 2025). Wilderness managers may use these tools and guidance or develop their own to decide how much ecological change may be acceptable and to justify when active management may be necessary to minimize undesirable outcomes.

Timelines for Application

For any climate adaptation process to be successful in the long-term, it is important to establish a timeline to revisit and re-evaluate key decisions and desired conditions on a recurring basis (Stein et al. 2014). There are several obstacles that can make it difficult to adhere to re-evaluation timelines, including insufficient resources or capacity, turnover in leadership and staffing, and competing priorities. Some of these obstacles can be overcome by developing and maintaining partnerships, planning ahead to secure appropriate resources and tools, keeping detailed and accessible records, and designating appropriate timelines that may coincide with existing planning revisions or amendments (Månsson et al. 2023). Throughout this case study, land stewards highlighted the need for continued and growing partnerships, identified knowledge gaps and uncertainties for further investigation, and evaluated desired conditions and potential outcomes of divergent decision alternatives to meet desired conditions. To reduce potential redundancy with existing efforts and streamline decision-making, the skills acquired during the workshop can be used to support existing planning and projects.

Incorporating RAD into Existing Planning

The RAD framework design is intentionally simple so that it can be applied to existing planning strategies and processes (Schuurman et al. 2022; 2025). While similar discussions and conversations may already be a part of existing protocols, the process outlined in this report allows land stewards to build a transparent, repeatable process that can be applied in a wide variety of contexts to support defensible decision-making. For example, the RAD framework may be used to structure decision alternatives as required under the National Environmental Policy Act (NEPA). The accept option of RAD aligns well with the no-action alternative for NEPA, whereas the resist and direct options may be considered alternative actions. For a Minimum Requirements Analysis (MRA), RAD may similarly be used to generate divergent decision alternatives for further evaluation. Importantly, including the Futures Wheel exercise as a tool alongside RAD in adaptation planning can illuminate consequences of each alternative when determining whether action may be necessary to achieve specific objectives or improve certain wilderness character qualities. This step can be overlooked in adaptation planning processes, but for the wilderness context, it is essential. In conclusion, the skills and tools explored for this case study and introduced during the workshop are intended to support increasingly complex decision-making in wilderness by integrating adaptation thinking into existing planning processes.

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APPENDIX

Appendix A

Detailed results of the biological analysis of current and future habitat selection and connectivity for Sonoran pronghorn in the southwestern United States.

Appendix B

Key themes about managers' perceptions of climate change, its impact on endangered Sonoran pronghorn, and feasibility of responding to observed and project changes in Kofa and Cabeza Prieta Wilderness Areas, Arizona.

Appendix C

Tabular presentation of the cascading implications of pursuing selected resist, accept, and direct strategies for Sonoran pronghorn (SOPH).

Appendix A

Predicting Habitat Suitability and Landscape Connectivity for Sonoran Pronghorn

Appendix I: Descriptions of transportation variables used for home range selection and step selection function analyses.

Appendices II-V: Level III (integrated step selection function) model results for a study of habitat suitability for Sonoran pronghorn, 2008-2023, in southern Arizona and California, USA.

Appendices VI-IX: Current (2008-2023) and mid-century (2060) relative Level III habitat suitability estimated from an integrated step selection function for Sonoran pronghorn across four seasons for four management scenarios throughout southern Arizona and California, USA.

Appendix X-XII: Current (2008-2023) and mid-century (2060) landscape connectivity estimated from resistant kernels for Sonoran pronghorn across four seasons for four management scenarios throughout southern Arizona and California, United States.

Appendix I: Open street map crosswalk

Open Street Map Class	**Description**	**Final Road Class**
Bridleway	Horse trails	NA
Cycleway	Bike trails	NA
Footway	Walkway	NA
Living street	Residential streets, low speed limits	Secondary road
Motorway	Freeway	Primary road
Motorway link	Onramp	Primary road
Path	Walkway/bikeway	NA
Pedestrian	Walkway that occasionally allows vehicles (e.g. service vehicles)	NA
Primary	Major secondary road, often link large towns	Primary road
Primary link	Onramps for Primary OSM class	Primary road
Residential	Residential	Secondary road
Secondary	Tertiary roads	?
Secondary link	Onramps/roads to Secondary OSM class	?
Service	Access roads/alleys	Secondary road
Steps	Flight of stairs	NA
Tertiary	Tertiary road	Secondary road
Tertiary link	Onramps/roads to Tertiary OSM class	Secondary road
Track	Two-track/dirt road	Tertiary road
Track grade 1	Single lane paved rural road	Tertiary road
Track grade 2	Dirt rural road	Tertiary road
Track grade 3	Dirt / mud rural track	Tertiary road
Track grade 4	Barely a road	Tertiary road
Track grade 5	Barely a road	Tertiary road
Trunk	Highway, usually but not always divided	Primary road
Trunk link	Onramp for OSM Trunk Class	Primary road
Unclassified	Local roads	Teritary road
Unknown		NA
Rail	Railway	Railway

Appendix II: Integrated step selection function model results for a study of habitat suitability for Sonoran pronghorn, 2008-2023, in southern Arizona and California, USA. Results are for the **hot/dry season** (April-June).

Predictors	**Coefficient**	**SE**	**CI**	**P-value**
Slope	-0.96	0.07	-1.10 – -0.82	**<0.001**
Aspect	0.05	0.02	0.01 – 0.08	**0.012**
Heat Load Index	-0.02	0.03	-0.08 – 0.05	0.603
Distance from guzzlers	-1.56	0.33	-2.21 – -0.91	**<0.001**
Building density	-1.52	0.52	-2.54 – -0.51	**0.003**
Density of Primary Roads	0.01	0.03	-0.05 – 0.08	0.651
Elevation	-1.52	0.38	-2.25 – -0.78	**<0.001**
Minimum temperature	-0.49	0.24	-0.97 – -0.01	**0.046**
Climatic moisture deficit	-0.81	0.89	-2.56 – 0.93	0.361
Primary road crossing	-2.3	0.11	-2.52 – -2.09	**<0.001**
Secondary road crossing	-0.6	0.05	-0.70 – -0.51	**<0.001**
Tertiary road crossing	-0.18	0.02	-0.22 – -0.14	**<0.001**
Canal crossing	0.07	0.13	-0.19 – 0.34	0.597
Railway crossing	-0.39	0.2	-0.78 – 0.01	0.056
Step angle	-0.68	0.01	-0.70 – -0.66	**<0.001**
Step length (log)	0.18	0.01	0.17 – 0.19	**<0.001**
Climatic moisture deficit*Elevation	2.22	0.42	1.40 – 3.04	**<0.001**
Minimum temperature*Elevation	-0.88	0.22	-1.31 – -0.44	**<0.001**
Step angle * Step length	0.08	0.01	0.07 – 0.10	**<0.001**

Appendix III: Integrated step selection function model results for a study of habitat suitability for Sonoran pronghorn, 2008-2023, in southern Arizona and California, USA. Results are for the **summer monsoon season** (July-September).

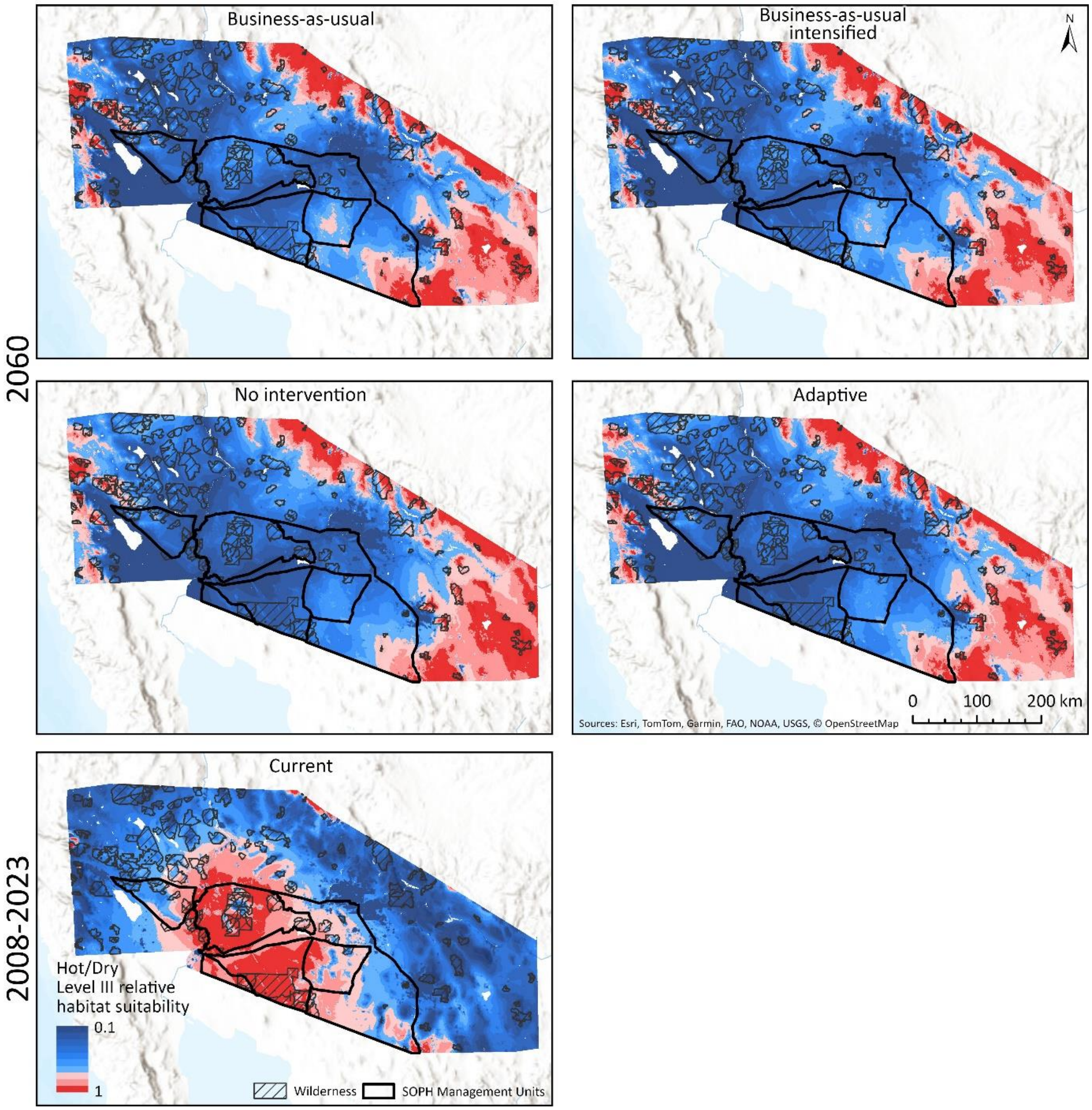
Predictors	**Coefficient**	**SE**	**CI**	**P-value**
Ruggedness 1000m	-2.37	0.25	-2.86 - -1.88	**<0.001**
Aspect	0.09	0.03	0.03 – 0.14	**0.005**
Heat Load Index	-0.04	0.03	-0.09 – 0.01	0.101
Distance from guzzlers	-2.03	0.13	-2.28 – -1.77	**<0.001**
Density of Primary Roads	-0.08	0.03	-0.14 – -0.02	**0.011**
Climatic moisture deficit	1.12	1	-0.83 – 3.08	0.26
Elevation	-0.08	0.46	-0.99 – 0.83	0.859
Degree days under 18°C	0.06	0.07	-0.06 – 0.19	0.328
Primary road crossing	-1.77	0.12	-2.01 – -1.53	**<0.001**
Secondary road crossing	-0.66	0.07	-0.79 – -0.54	**<0.001**
Tertiary road crossing	-0.19	0.02	-0.23 – -0.14	**<0.001**
Canal crossing	-0.63	0.23	-1.08 – -0.17	**0.007**
Railway crossing	-2.43	0.61	-3.62 – -1.24	**<0.001**
Step angle	-0.68	0.01	-0.70 – -0.65	**<0.001**
Step length (log)	0.15	0.01	0.14 – 0.17	**<0.001**
Climatic moisture deficit*Elevation	0.88	0.31	0.27 – 1.48	**0.004**
Degree days under 18°C *Elevation	-0.02	0.07	-0.16 – 0.11	0.746
Step angle * Step length	0.01	0.01	-0.01 – 0.03	0.177

Appendix IV: Integrated step selection function model results for a study of habitat suitability for Sonoran pronghorn, 2008-2023, in southern Arizona and California, USA. Results are for the **cool/dry season** (October-November).

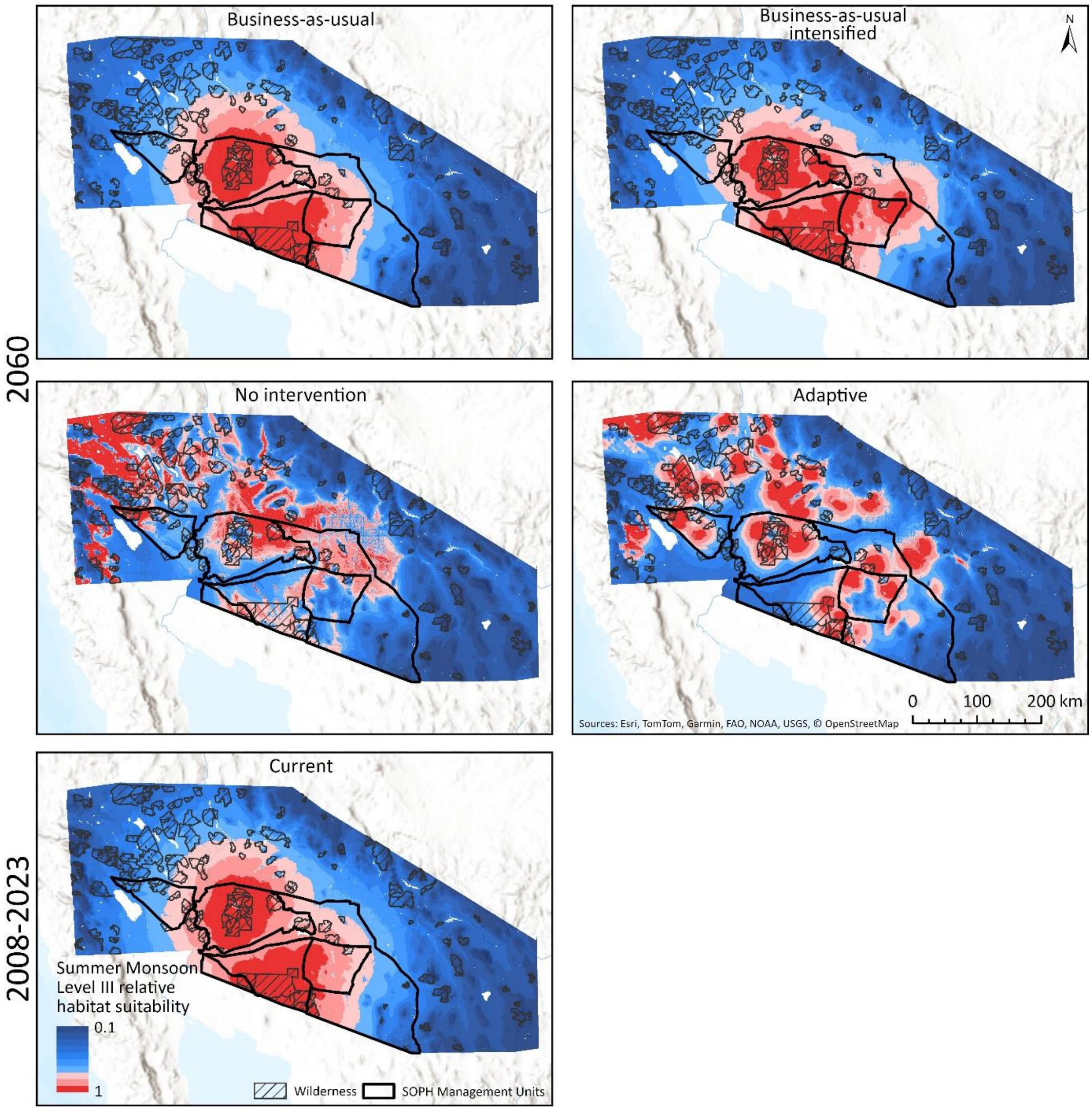
Predictors	**Coefficient**	**SE**	**CI**	**P-value**
Ruggedness 270m	-7.89	1.34	-10.52 – -5.26	**<0.001**
Distance from guzzlers	-0.56	0.23	-1.00 – -0.11	**0.014**
Building density	-0.35	0.18	-0.70 – 0.00	0.051
Density of Primary Roads	-0.14	0.04	-0.22 – -0.06	**0.001**
Minimum temperature	-1.45	0.26	-1.96 – -0.94	**<0.001**
Climatic Moisture Deficit	2.04	0.75	0.57 – 3.51	**0.007**
Elevation	-0.06	0.24	-0.53 – 0.40	0.785
Primary road crossing	-3.3	0.29	-3.86 – -2.74	**<0.001**
Secondary road crossing	-0.08	0.07	-0.22 – 0.05	0.231
Tertiary road crossing	-0.23	0.04	-0.30 – -0.16	**<0.001**
Canal crossing	-1.57	0.56	-2.66 – -0.47	**0.005**
Railway crossing	0.61	0.48	-0.32 – 1.55	0.197
Step angle	-0.21	0.02	-0.24 – -0.17	**<0.001**
Step length (log)	0.1	0.01	0.08 – 0.12	**<0.001**
Minimum temperature*Elevation	0.14	0.12	-0.08 – 0.37	0.218
Step angle * Step length	0.03	0.01	0.00 – 0.05	**0.021**

Appendix V: Integrated Step Selection Function model results for a study of habitat suitability for Sonoran pronghorn, 2008-2023, in southern Arizona and California, USA. Results are for the **winter rain season** (December-March).

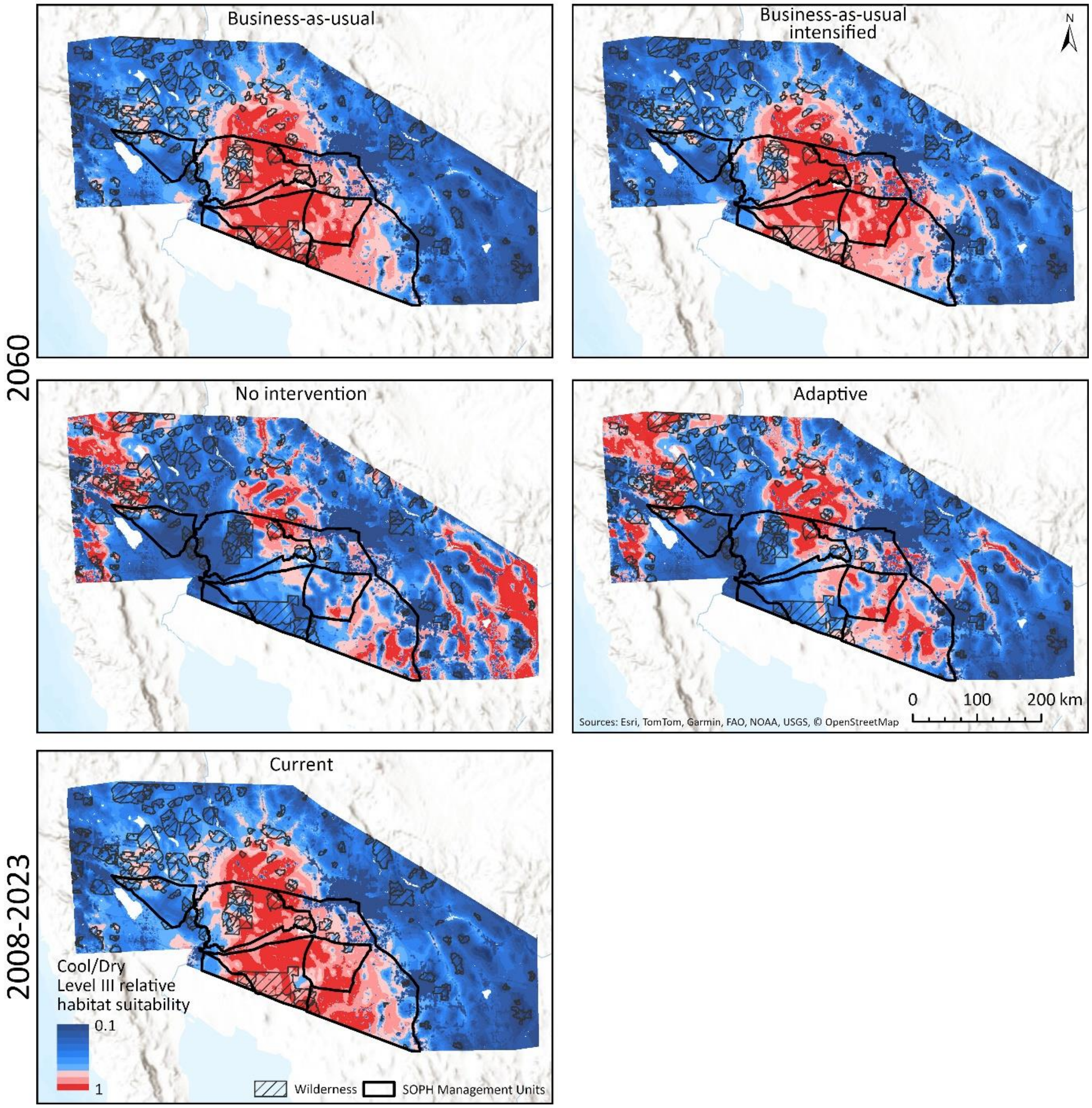
Predictors	**Coefficient**	**SE**	**CI**	**P-value**
Ruggedness 2000m	-1.44	0.15	-1.75 – -1.14	**<0.001**
Distance from guzzlers	-0.83	0.17	-1.16 – -0.51	**<0.001**
Density of Primary Roads	-0.08	0.03	-0.13 – -0.03	**0.001**
Agriculture	-7.56	2.7	-12.86 – -2.27	**0.005**
Minimum temperature	-0.24	0.11	-0.47 – -0.02	**0.035**
Elevation	-0.21	0.18	-0.55 – 0.13	0.23
Climatic Moisture Deficit	0.31	0.38	-0.44 – 1.06	0.419
Primary road crossing	-3.6	0.18	-3.96 – -3.24	**<0.001**
Secondary road crossing	-0.39	0.05	-0.49 – -0.30	**<0.001**
Tertiary road crossing	-0.18	0.02	-0.22 – -0.15	**<0.001**
Canal crossing	0.21	0.13	-0.05 – 0.47	0.12
Railway crossing	-1.03	0.28	-1.59 – -0.47	**<0.001**
Step angle	-0.52	0.01	-0.54 – -0.50	**<0.001**
Step length (log)	0.1	0	0.09 – 0.11	**<0.001**
Minimum temperature*Elevation	-0.08	0.07	-0.23 – 0.06	0.257
Climatic Moisture Deficit*Elevation	0.57	0.1	0.37 – 0.78	**<0.001**
Step angle * Step length	0.04	0.01	0.03 – 0.05	**<0.001**



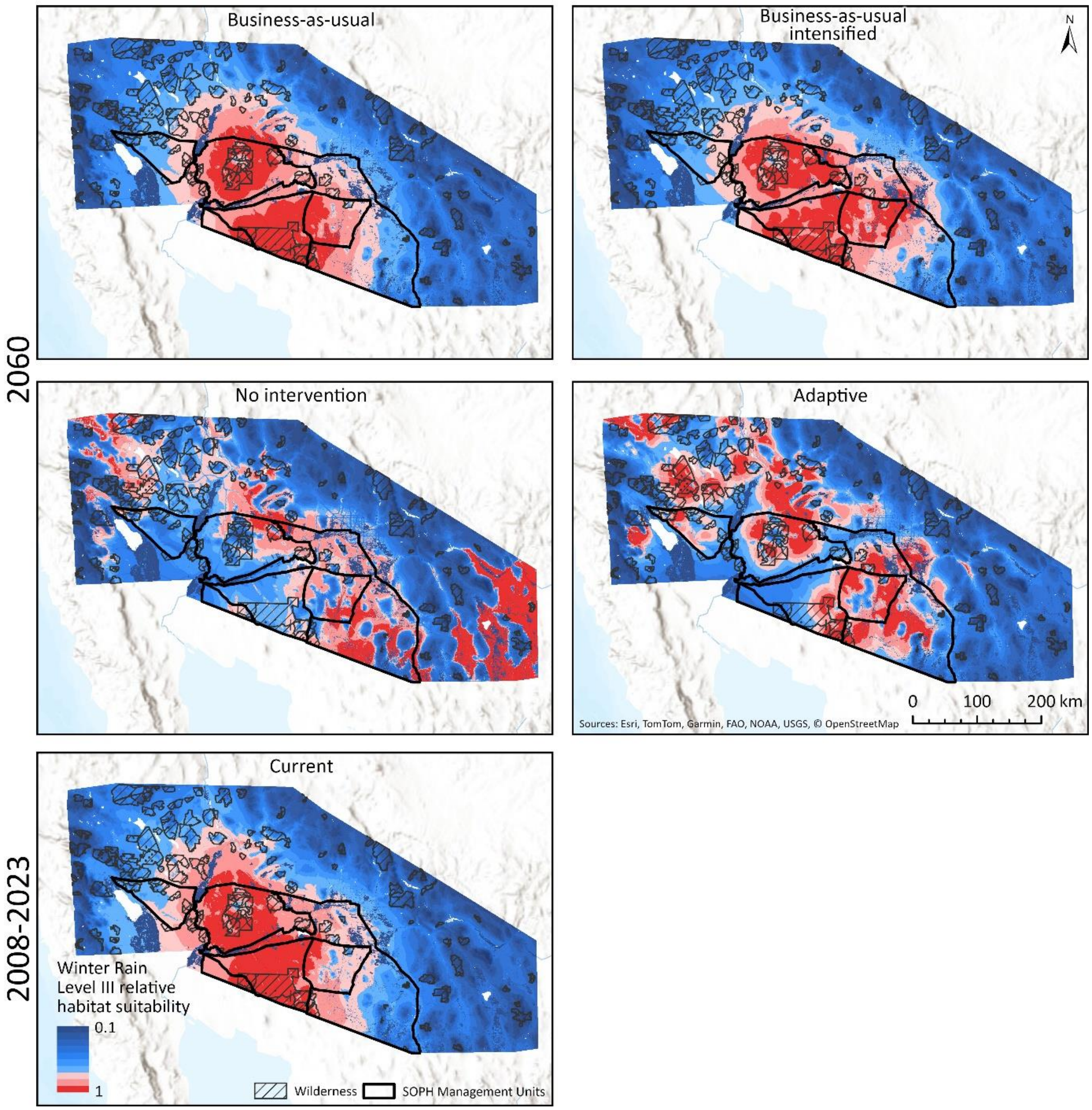
Appendix VI: Current (2008-2023) and mid-century (2060) within home range and movement relative habitat suitability estimated from an integrated step selection function (iSSF) for Sonoran pronghorn during the **hot/dry season** (April-June) throughout southern AZ and CA and for four management scenarios. Warmer colors (≥0.7) indicate higher quality habitat.



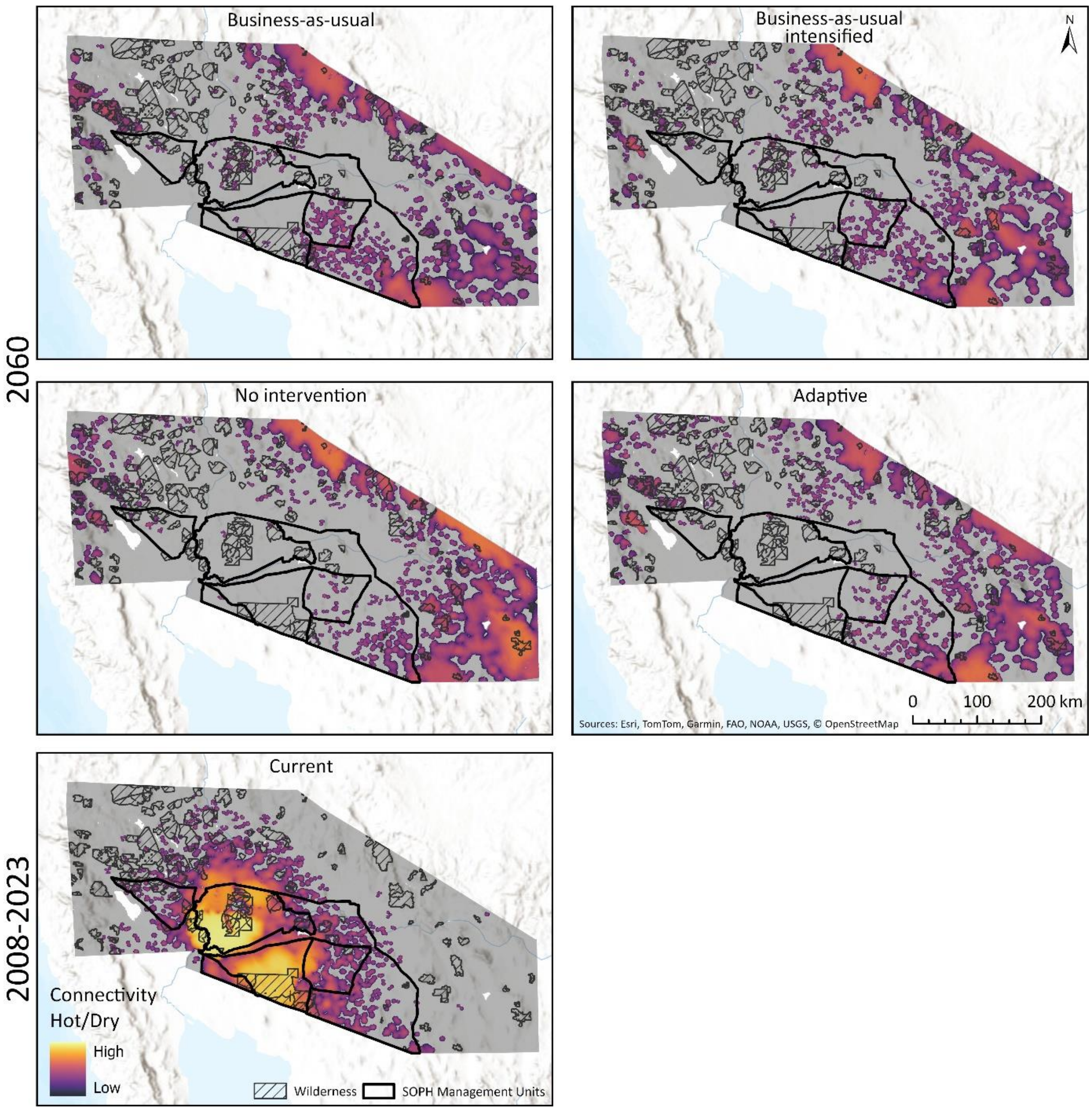
Appendix VII: Current (2008-2023) and mid-century (2060) relative movement habitat suitability estimated from an integrated step selection function (iSSF) for Sonoran pronghorn during the **summer monsoon season** (July-September) throughout southern AZ and CA and for four management scenarios. Warmer colors (≥0.7) indicate higher quality habitat.



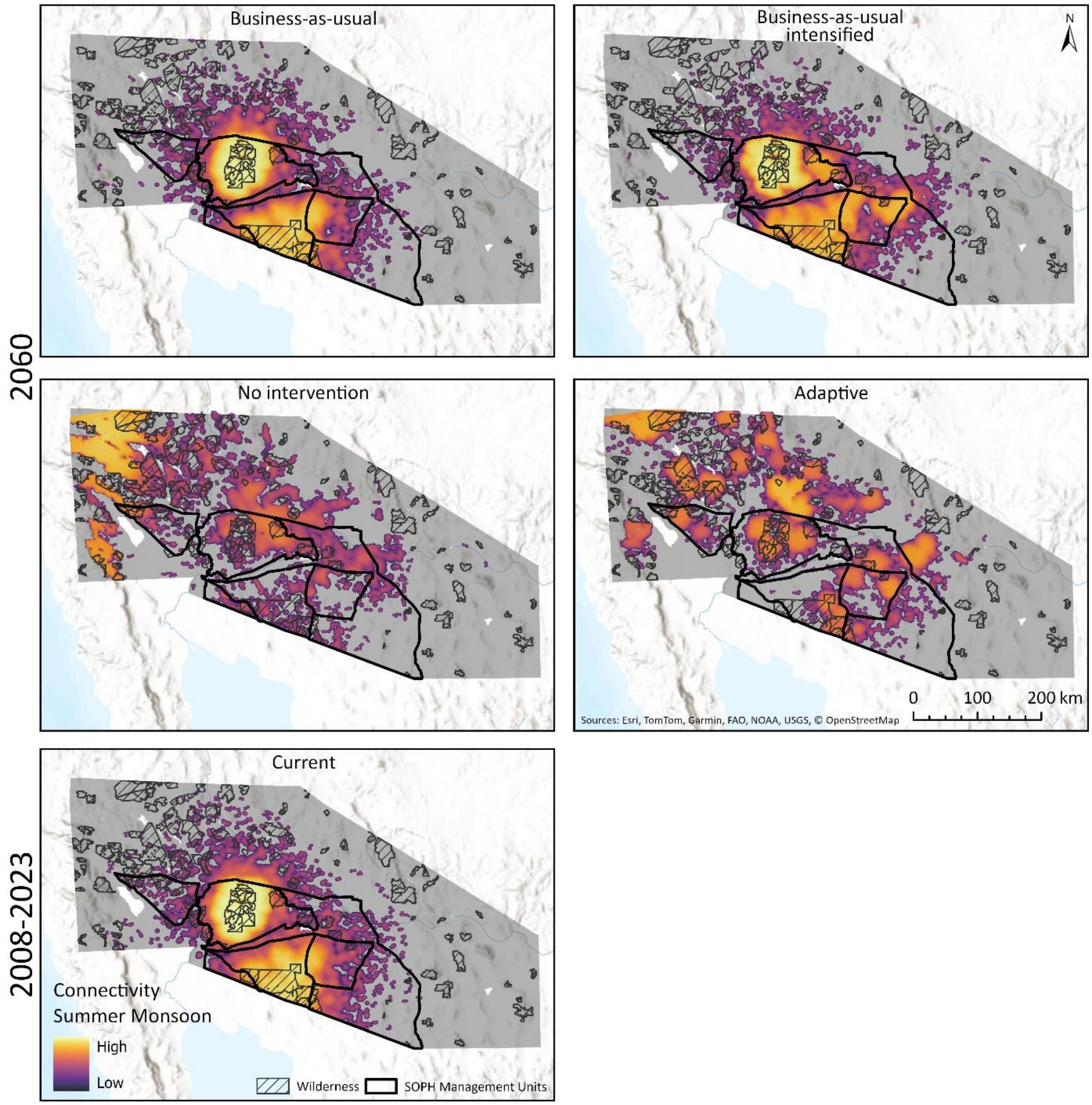
Appendix VIII: Current (2008-2023) and mid-century (2060) relative movement habitat suitability estimated from an integrated step selection function (iSSF) for Sonoran pronghorn during the **cool/dry season** (October-November) throughout southern AZ and CA and for four management scenarios.



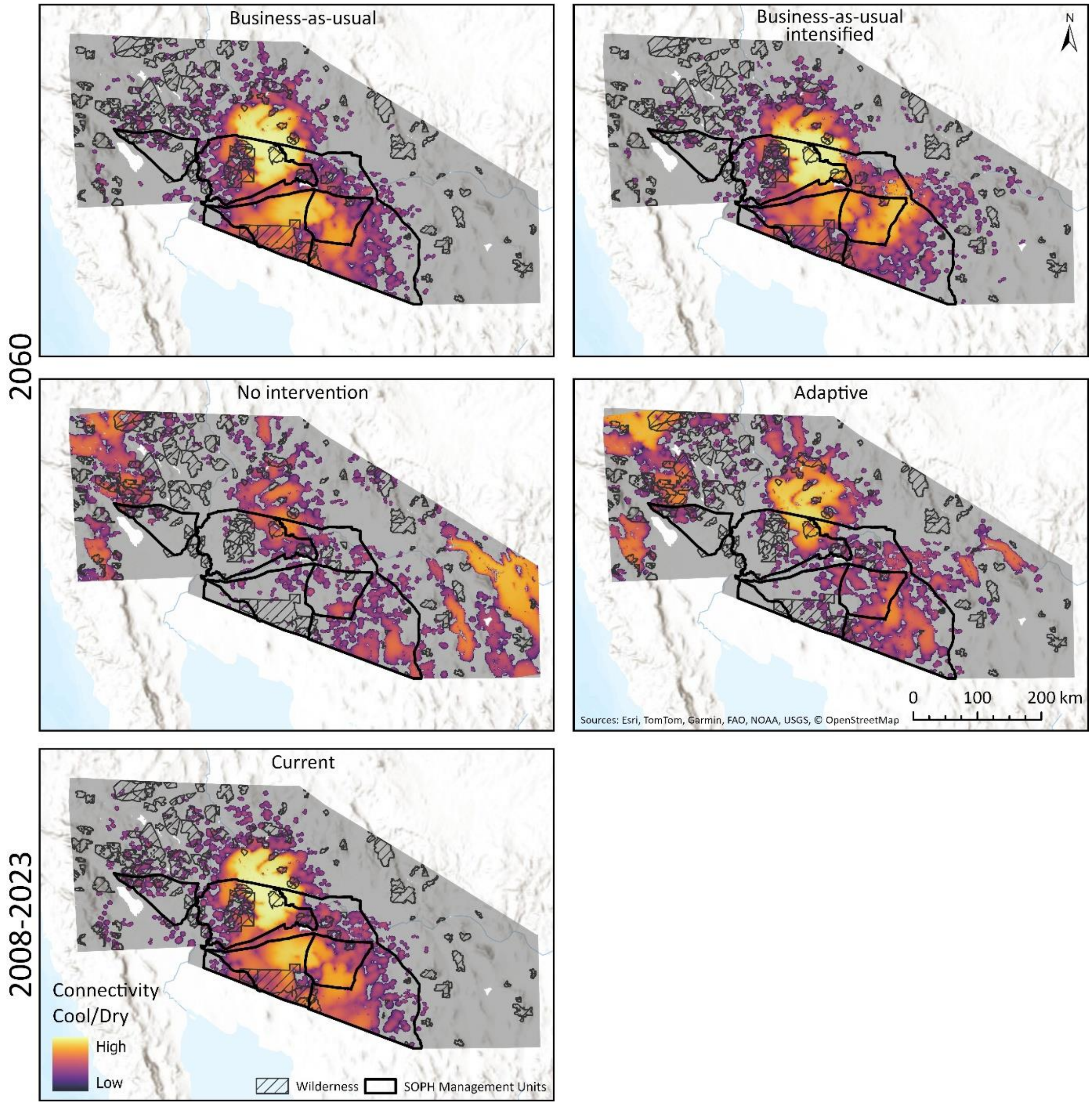
Appendix IX: Current (2008-2023) and mid-century (2060) relative movement habitat suitability estimated from an integrated step selection function (iSSF) for Sonoran pronghorn during **the winter rain season** (December-March) throughout southern AZ and CA and for four management scenarios.



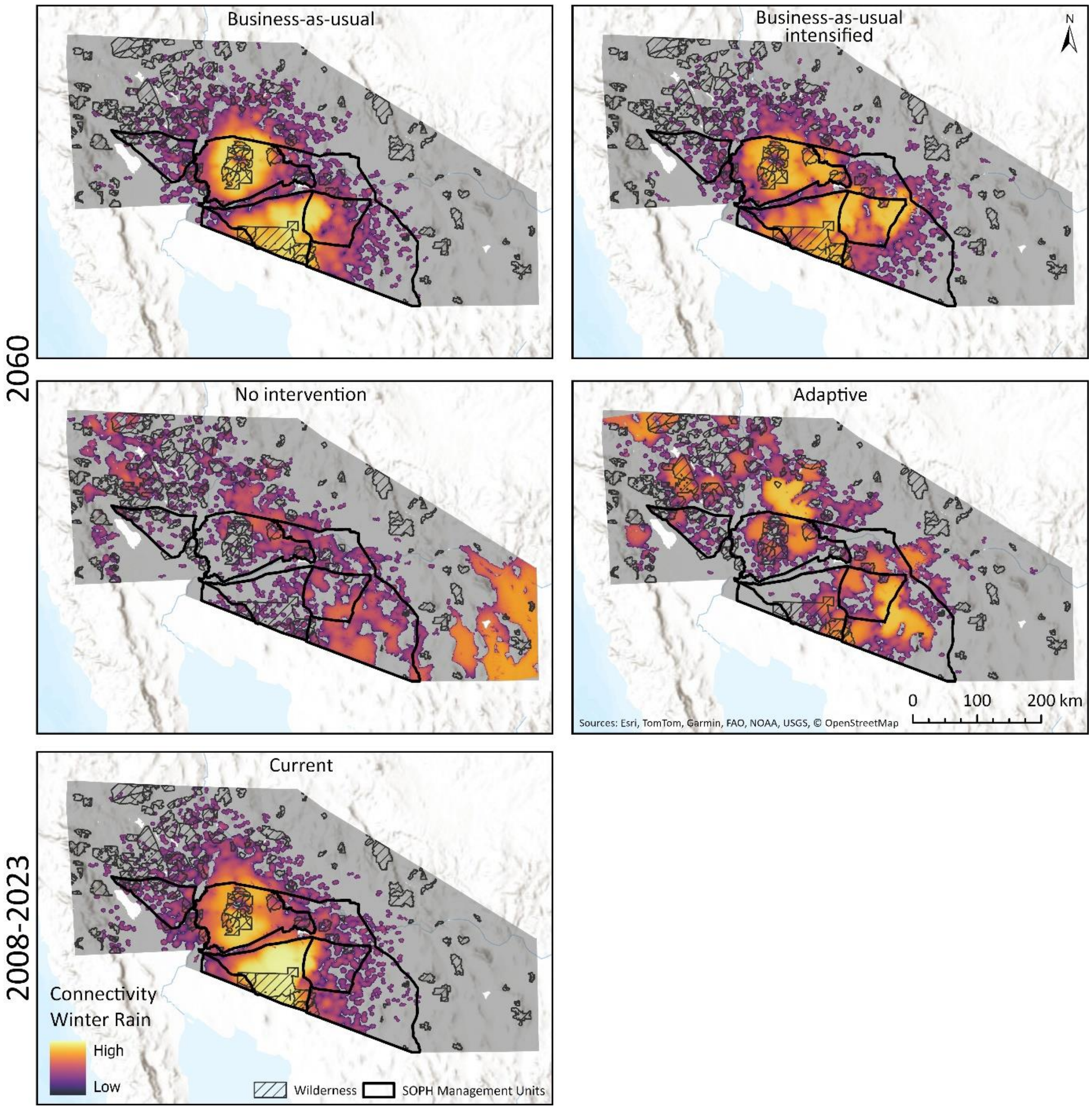
Appendix X: Current (2008-2023) and mid-century (2060) landscape connectivity estimated from resistant kernels for Sonoran pronghorn during the **hot/dry season** (April-June) and for four management scenarios throughout southern AZ and CA, United States.



Appendix XI: Current (2008-2023) and mid-century (2060) landscape connectivity estimated from resistant kernels for Sonoran pronghorn during the **summer monsoon season** (July-September) and for four management scenarios throughout southern AZ and CA, United States.



Appendix XII: Current (2008-2023) and mid-century (2060) landscape connectivity estimated from resistant kernels for Sonoran pronghorn during the **cool/dry season** (October-November) and for four management scenarios throughout southern AZ and CA, United States.



Appendix XIII: Current (2008-2023) and mid-century (2060) landscape connectivity estimated from resistant kernels for Sonoran pronghorn during the **winter rain season** (December-March) and for four management scenarios throughout southern AZ and CA, United States.

Appendix B

Table 1.Key themes about managers' perceptions of climate change in Southwest Arizona derived from six interviews with Sonoran pronghorn managers. To ensure confidentiality, each interviewee was given a code name (e.g., SOPH1).

Theme	Code	Representative Quotation
Managers perceive that weather in the desert southwest is becoming increasingly variable and unpredictable, particularly among and timing or precipitation.	Less predictable	"Climate change has made weather far less predictable overall…some years its better and some years its worse, but the inconsistency, I think, is the greatest challenge that we've seen in regard to climate change." (SOPH2)
		"With climate change, we get much higher variability within rainfall." (SOPH5)
There have been several seasonal changes within summers, monsoons, and winters.	Changing monsoon patterns	"The rain is coming later, I think. I need to get historic data…but typically, monsoon season was considered from like July to August. Now it seems like it's late August and September and like that's it." (SOPH1)
		"One of the things that seems to be occurring, and we're not sure to what extent here, is intensity of monsoon rains. Anecdotally, it seems like the intensity is increasing. You know, increased temperatures carry more water, hotter events, more intense storms. So those storms are difficult to manage, especially when we have all these illegal off-road driving routes that interfere with sheet flows." (SOPH6)
	Drier summers	"A lot drier summers" (SOPH5)
	Hotter summers	"[There is] extreme heat and drought in the middle of summer…Our temperatures have increased substantially…we've been monitoring weather and climate here since 1939, 1940, something like that. We have a number of weather stations…so we have pretty good climate data. So, we're fully aware of the temperature trends and the direction they're heading." (SOPH6)

	Less winter rain	"And, of course, winter rains. We're not getting those. So this year is a good example. The prognosis was we were going to get some wonderful winter rains because of El Niño. We haven't had a drop. We're at the beginning of our winter rains and we haven't had really really a drop of anything even with El Niño. And, right now there isn't any hope for rain in the near future." (SOPH3)
The general drying trend is causing spring water and other surface water decline.	Less available water	"Generally speaking, our springs and wells and things that we monitor have been slowly decreasing…it might be driven by various factors, but it's tightly correlated with climate change…the future is going to be a challenge with that decreased spring production." (SOPH6)

Table 2. Managers' perceptions of climate change impacts on Sonoran pronghorn derived from six interviews with Sonoran pronghorn managers. To ensure confidentiality, each interviewee was given a code name (e.g., SOPH1).

Theme	**Code**	**Representative Quotation**
Hotter temperatures, especially extreme heat events, are stressful and sometimes lethal for fawns or adults in areas with limited or no access to supplemental water.	Hotter temperatures are stressful	"Extreme heat in the summer is a problem, especially in places where we don't have supplemental water, we'll occasionally have some large die offs. You know even things that are heat adapted like swirl cactus and pronghorn have an upper threshold. So, we certainly have concerns with extreme heat and drought in the middle of summer. For an animal that's already operating in the extremes, going just a little bit higher can be very problematic." (SOPH6)
		"The hotter hot especially with the phenology of pronghorn fawning, kind of being towards March, April, May with warmer night temperatures and higher temperatures earlier could put more stress on the fawns in particular. Pronghorn, in general, are delicate, and having those hotter temperatures can definitely result in mortalities, especially if people are out and about scaring them and they run and the mom leaves. Yeah it could be very detrimental." (SOPH1)

Longer periods of drought threaten Sonoran pronghorn recruitment and adult survival.	Longer periods of drought are stressful	"Research by John Hervert and Jill Bright in 2005 demonstrated the importance of both winter rainfall, but more importantly summer rainfall. And what they found was it's that period between the last winter rain and the first summer rain that's really predictive of recruitment…And so having that really short time span between that last winter rain and the first summer rain is important. We're seeing much greater variability in that or a much more extended time period in that with climate change." (SOPH5)
		"It's all about the rain. The timing of the rain with fawning and timing of when fawns are weaned from their mothers' milk. There were years we documented no fawn survival in the population whatsoever, and that's because of the lack of rain. And there were times when even adults were starving to death because of a lack of forage." (SOPH4)
	Forage enhancement is difficult	"As long as these long term droughts continue, I think the plight for all wildlife in this area is going to bet more dire. We can provide water, that's fine and easy, but the browse, you know, where's that going to come from? So, we are facing drilling more wells, creating more forage enhancement plots." (SOPH3)
		"Water is the number one thing: ensuring there's water for them. We can't make it rain. So, there's not a lot we can do about the forage." (SOPH1)

Climate change coupled with habitat fragmentation further threatens pronghorns' ability to adapt and survive.	Fragmentation x climate change	"Climate change combined with fragmentation of the habitat is causing the problem. If you were to dig into our historic park documents going back to the 1940s, they talk about pronghorn being kind of 'the winter arrivers', or something along those lines. They would go into Mexico in the summer and then move up into the park in the winter. And that problem started in the 1940s when barbed wire fence was put on the border for the first time to keep cattle out of the monument and delineate the border. We suspect the pronghorn needs to probably be back and forth from the Rio Sonoita, or the Rio Savanah River Valley and into the park and back and forth. Once that stopped, we kind of eliminated their access to historic water sources. And that's, of course, just gotten worse and worse over the years—more layers of more barriers have been put in place…And so if there's a need for them to move across the landscape to areas with more water, that's going to be very difficult." (SOPH6)
	Crowding	"What are the consequences of having all these pronghorn together through interacting? One of the relationships that we saw was higher stress hormone levels…Because pronghorn are at the drinkers and feed stations, some of these sites have 30 to 40 pronghorn. That's a lot of pronghorn interactions. [But,] you have to take that with a grain of salt…it doesn't necessarily have to be those interactions that are causing those increased stress levels." (SOPH5)

Table 3. Perceived feasibility of climate adaptive management actions within wilderness derived from six interviews with Sonoran pronghorn managers. To ensure confidentiality, each interviewee was given a code name (e.g., SOPH1).

Theme	**Code**	**Representative Quotation**
There are several institutional constraints to climate adaptive recovery actions in wilderness.	Low staff capacity	"It's pretty much myself and an intern, that's pretty much the entire [refuge] staff… I do get spread between the other refuges in the complex because we have been so short staffed…[I do] all things biology…I do a lot of NEPA, section seven consultations. I'm also the GIS person…I'm the cooperative agreements person…and yeah, try not to pull my hair out…but I do the best I can with what I've got." (SOPH1)
	Lack of funding	"Capacity is an issue: resources, money, funding, it's all tied together. Unfortunately the Fish and Wildlife Service is not a well-funded organization." (SOPH3)
		"In very dry summers we'll have to coordinate water hauls with the Arizona Game and Fish Department to some of these more remote sites that might require helicoptering in water because of the wilderness status, which is extremely expensive and just sometimes not within our budget." (SOPH5)
	A lot of planning	"A minimal requirements analysis is something that is done every year, but the content is usually taken from the previous year so it's not a huge time-consuming thing. In the context of the boulders, getting to the guzzlers requires a lot of logistical planning." (SOPH2)
	Need more localized models and data	"Climate models that I've seen tend to be more regional, so it's kind of hard to say what's going to happen exactly locally." (SOPH1)

There are several opportunities to engage in more climate adaptive management in wilderness.	Continue to strengthen international, federal, and state-level partnerships	"Our partners are actively looking to help us out when they can…In the past when we did projects in Cabeza wilderness, we agreed we were going to hand dig and bury the systems. We had Marines there to help us do that hard work. Without their help, we wouldn't have been successful. That's just an example of the level of cooperation." (SOPH4)
	FWS access to Border Patrol roads	"Being able to do water hauls via hose lay in designated wilderness. So being able to utilize some of these routes that maybe just Border Patrol is using, but that's still very well-traveled. So being able to get permission to use those." (SOPH5)
	Add guzzlers	"That's something we see in the future: building more waterers. We definitely need to do that in designated wilderness. And, not just building more waterers, but repairing waterers that are currently there, so that we can minimize the number of water hauls that we have to do. So, minimize future impacts to wilderness." (SOPH5)
	Add native seed	"I talked about supporting doing some native seed, aerial dispersion in areas, of some key forage species…It would be nice to do that to get some of these other species out here in certain areas, particularly burned areas." (SOPH1)
	Predator research	"Understanding mountain lion predation—doing that sort of research project. That wouldn't be completely outside the ball of things that we've done in wilderness before. So, I don't see that being a huge issue." (SOPH5)
	Monitoring guzzlers	"I think the refuge is working towards doing a programmatic MRA [minimum requirements analysis] to include the water monitoring." (SOPH1)
	Fawn mortality research	"I also have a dream study of looking at fawn recruitment and mortality, and what are the primary causes of fawn mortality out in the wild? We don't know that. That's a big question mark for us." (SOPH1)

	Assisted migration	“Personally, I’m a fan of assisted migration, especially in the light of climate change. And if climate conditions start to change and become more favorable in a different area, I jokingly say, ‘these are the pronghorn of the future.’” (SOPH 1)
	Limit visitor access	“Hypothetically we could close down sensitive habitat if we needed to. The biggest period of concern is during fawning, and then when it gets really, really hot. So prior to monsoon season, so kind of like late February, especially early March all the way through now August is when there’s a lot of stress.” (SOPH1)
	Predator control	“One potential idea would be predator control in designated wilderness…but most of mountain lion predation is occurring outside of designated wilderness. I do think we do need to do a lot more research.” (SOPH5)

Appendix C

Tabular presentation of the cascading implications of pursuing selected resist, accept, and direct strategies for Sonoran pronghorn (SOPH).

Resist: Install more guzzlers

- I) Spatial impact of existing wildlife (8/4)
    - a. Increased resource usage around drinkers (3/-3)
        - i. Increased support to the burros (8/-50)
    - b. More dispersal of SOPH (8/50)
        - i. Positive public reaction (9/5)
        - ii. Decrease in disease transmission (8/5)
            - 1. Spread out hunting pressure humans and predators (7/5)
            - 2. Decreased predator stress on other prey species (7/5)
- II) Increased SOPH survival (9/50)
    - a. Survival can lead to delisting (6/50)
- III) Impact of removing vegetation for predator control (5/-1)
    - a. Negative impact for small animals (9/-1)
    - b. Improved predator management (9/5)
    - c. Negative public opinions of predator control (5/-1)
- IV) Introduction of invasive plant species (2/-5)
    - a. Treatment of invasive species (6/5)
- V) Maintenance of drinkers (9/0)
    - a. Extend responsibility to maintain the drinkers (7/2)
        - i. Decreased public support due to incurred expense (4/-2)
    - b. Increase wildlife dependance on drinkers (5/0)
- VI) Increase in road and other construction which impacts wilderness characteristics (9/1)
- VII) MRA initiation (9/-2)
    - a. NEPA-EA initiation in BLM wilderness (9/-2)
        - i. Initiate Section 106 consultation / culture clearance (9/-2)
            - 1. Delay / increase time frame of project (9/50)
            - 2. Need more staff time (9/1)
- VIII) Improved wilderness character due to increased wildlife (9/5)
    - a. Increased wildlife viewing opportunities (7/4)
        - i. Increased hunting opportunities / human recreation (6/5)
        - ii. Increased public awareness (7/3)
            - 1. Support of wildlife refuges and BLM lands (6/50)
- IX) Decreased need to haul water with multiple waters (5/5)
    - a. Increased staff capacity (7/5)
- X) Increased need to haul water (5-1)
    - a. Increased maintenance costs and decreased staff capacity (7/-4)
        - i. Increased cost of water as it becomes scarcer (5/3)
- XI) Ground disturbance (9/3)

Box 6: Potential cascading implications of choosing to resist anticipated ecological transformation of Sonoran pronghorn habitat in the United States, by installing more guzzlers in wilderness in their historic range. Implications were scored by the likelihood that they may occur because of the decision (first number in brackets) and by their perceived desirability (second number in brackets).

Accept: Outreach campaign

XII) Increased public exposure (9/5)
  a. Increased impacts from wildlife tourism (3/-5)
    i. 3 E's – education, engineering, enforcement (8/5)
      1. More time and money to enforce vehicle damage (5/0)
      2. More time and money to build habitat protections (6/5)
      3. More time and money to educate (8/5)
  b. Misinformation spread online (9/-5)
    i. Need to address misinformation (7/3)
  c. Public support (5/50)
    i. Increased funding (1/50)
      1. Ability to do more projects (1/50)

XIII) Loss of other species dependent on drinkers

XIV) Reduced water hauling (9/5)
  a. Less environmental impact (8/5)
  b. Less wilderness impacts (9/5)
  c. More staff time to deal with other resources and issues besides SOPH (9/5)
  d. Reduced damage to vehicles and trailers (9/5)

XV) Lack of tangible progress on establishment of SOPH in 10J (9/-4)

XVI) More collaboration between different entities (5/50)
  a. Increase coordination between adjacent landowners (3/5)
    i. Farmers provide bio corridors in between fields (1/50)
      1. Increased connectivity (8/50)
      2. More protected land (8/50)
        a. Other species' migration routes conserved (e.g., birds, bats) (8/5)
        b. Other species protected (8/50)
        c. Sequester carbon and reduce climate change (1/50)
        d. Increase in biodiversity (8/50)
          i. Ecosystem resilience (8/50)
    ii. Farmers provide wildlife waters (6/50)
  b. Coordinating with neighboring nations (6/5)
  c. More time spent in discussion (9/2)
    i. Potentially lengthen project timelines (9/-4)
      1. Less action done (6/0)
    ii. Capture diverse perspectives (9/5)
      1. Better decisions (9/50)
      2. Less litigation (5/5)

XVII) No wilderness impacts as a result of accepting no action (e.g. trammeling) (9/-50)

XVIII) More volunteers (5/5)
  a. Reduced maintenance stress on personnel from more volunteers helping to haul water (5/5)
  b. Need someone to supervise, teach, and coordinate volunteers (9/0)

Accept: Outreach campaign (continued)

XIX) Loss of SOPH in existing range (8/-50)

a. Loss of morale by staff and partners (9/-50)
b. Public outrage (9/-5)
    i. Loss of support for agencies and SOPH recovery (9/-50)
c. Degraded natural wilderness characteristics (9/-50)

Box 7: Potential cascading implications of choosing to accept anticipated ecological transformation of Sonoran pronghorn habitat in the United States, by pursuing an outreach campaign. Implications were scored by the likelihood that they may occur because of the decision (first number in brackets) and by their perceived desirability (second number in brackets).

Direct: Assisted range expansion

I) 10J in California finalized

II) SOPH establish in proposed 10J (6/50)

  a. Enhanced naturalness in California wilderness
  b. Increase of predators (4/-3)
    i. SOPH die
      1. Engage lethal management of predators if problematic (7/-5)
        a. Negative public perception (8/-4)
        b. Potential funding allocation to contract lethal management (5/-4)
  c. Increased resiliency in different habitat for better adaptability for future
    i. Spreading out on the landscape cam ensure population if a sub-population is wiped out due to disease or predation
      1. SOPH hunting opportunities
      2. Monument status is more secure
    ii. Increased use of forage (pre-existing)
      1. Reduced resources available
      2. Increased competition with other native ungulates

III) Mortality of SOPH associated with capture and release

  a. Negative public perception
  b. SOPH population remains small
    i. Increased probability of extirpation
    ii. Repeated number of translocations over time
      1. Decrease in Arizona SOPH population

IV) Funding pulls from other programs

  a. Increased staff time to acquire funding
  b. California must hire SOPH personnel
  c. Recovery efforts for other species may become limited

V) California residents get to experience SOPH and its intrinsic value

  a. Increased public support for SOPH
    i. Increased funding (1/50)
    ii. SOPH becomes poster child (6/5)
      1. Increased advocacy for ecosystem-level conservation (6/50)

VI) Increase collaboration across states

  a. May strain staff capacity which is already thin

VII) Public perception of moving SOPH out of historic range and possible effects for people who have used the land historically.

VIII) Benefits to resident wildlife with addition of water

  a. Increased competition for water
    i. Increased opportunity to hunt deer
      1. Increased hunter support (e.g. help to refill water tanks)

Direct: Assisted range expansion (continued)

IX) Animals leave the 10J
- a. Interbreed with the American pronghorn

X) Disturbance in creation of the pen and waters (9/-1)
- a. Invasive species associated with construction and maintenance (3/-5)
- b. Increased wilderness impacts associated with collars, waters, and cameras (9/-2)
  - i. Potential for litigation for impacts to undeveloped and untrammeled (8/-5)

XI) Relocation is unsuccessful (all SOPH die)
- a. Bad press
  - i. Negative perception of government waste
    - 1. Potential for program to be shut down
- b. Setback of Arizona population recovery
  - i. Loss of genetic pool

XII) Sufficient rain to fill the drinkers
- b. Less maintenance of the drinkers (1/5)
- c. Less water hauling
  - i. Alleviate pressure on managers to maintain drinkers
  - ii. Less time required by staff (9/5)
- c. Increased forage production (7/50)
  - i. Increased fawn recruitment (7/50)

XIII) Insufficient rain to fill the drinkers
- b. Need to haul water
  - i. Less staff time for other projects

Box 8: Potential cascading implications of choosing to direct anticipated ecological transformation of Sonoran pronghorn habitat in the United States, by translocating pronghorn to the proposed 10-J and providing guzzlers to support translocated animals. Implications were scored by the likelihood that they may occur because of the decision (first number in brackets) and by their perceived desirability (second number in brackets).