Biological Feasibility of Introducing Bighorn Sheep to the Jicarilla Apache Nation

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Prepared for the Jicarilla Apache Nation

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Executive Summary

The biological feasibility of introducing Rocky Mountain bighorn sheep (*Ovis canadensis canadensis*) to the Dulce area of the Jicarilla Apache Nation (JAN) depends on availability and condition of potential habitat and the potential for disease risk, as pneumonia is the largest current threat to wild sheep populations. We modeled quality and quantity of potential bighorn sheep habitat incorporating the three most recent fire scars around Dulce, determined potential winter range within preferred habitat, assessed on the ground vegetation characteristics, and examined potential for disease transmission via risk of contact with domestic sheep and goats. Most of the area of interest for this study has a suitability value ≥ 50%, with approximately 23-29% of the study area considered preferred, or high-quality habitat for bighorn sheep. High-quality habitat for Rocky Mountain bighorn sheep is defined as being within 300 m of escape terrain, within 1.6 km of water, and containing ≤ 30% shrub and tree cover. Of this, approximately 43-56% of potential preferred habitat qualifies as winter range, which is mostly concentrated in the narrow valley bottoms where roads are commonly located and the south-facing slopes surrounding valleys. Analysis of field-collected vegetation data indicates most of the existing forage within the surveyed area to be of moderate or high forage value to bighorn sheep, but horizontal visibility, predominantly in the form of shrubs, is more obscured than what bighorn sheep prefer for most of the area of interest. Maximum shrub and tree cover is also the most limiting factor in the suitability model, primarily due to the prevalence of dense shrub regeneration, particularly Gambel oak, which occurs after high severity burns. The largest quantities of high-quality potential bighorn sheep habitat within the study area occur in unburned areas or those burnt by the predominantly low-moderate severity Amargo fire in 2021. Relative to risk of contact with domestic sheep and goats that can transmit lethal pneumonia-causing pathogens, potentially causing an introduction effort to fail, there is high risk because of the proximity to two hobby-subsistence herds (< 3 km away).

Introduction and Objectives

In 1996—and more recently 2015 and 2021—the area surrounding Dulce, New Mexico experienced fires which altered vegetation communities and promoted an interest in evaluating the feasibility of introducing Rocky Mountain bighorn sheep (*Ovis canadensis canadensis*) to the

Jicarilla Apache Nation (JAN). A preliminary analysis evaluated terrain features characteristic of bighorn sheep habitat and found the area of interest to contain enough escape terrain and suitable slope, but recommended assessment of forage and water availability, conditions which facilitate predation risk (e.g., horizontal visibility), and potential contact with domestic sheep and goats prior to moving forward with introduction efforts (Cain 2017).

It is important to consider the disease risk associated with domestic sheep and goats because pneumonia is considered the biggest threat to wild sheep herds across North America. The respiratory disease can linger in populations for decades or even extirpate entire herds—it directly influences the success and persistence of a bighorn sheep population. Pneumonia is a polymicrobial condition, caused by a variety of pathogens (*Mannheimia haemolytica, Pasteurellaceae* spp., and more), but *Mycoplasma ovipneumoniae* appears to be a necessary primary agent to contract the disease and is host-specific to the Caprinae family (sheep and goats; Foreyt and Jessup 1982, Foreyt 1989, Lawrence et al. 2010, Besser et al. 2014). There are few instances of sheep contracting pneumonia from cattle (Foreyt and Lagerquist 1996, Wolfe et al. 2010), however this is rare (Foreyt and Lagerquist 1996, Besser et al. 2012) and is not typically of concern. The non-laboratory conditions which facilitated the transmission were deep persistent snow with limited winter range and drought, where bighorn sheep were using feed, water, and mineral blocks side-by-side with cattle that were experiencing respiratory issues (Wolfe et al. 2010, O'Brien et al. 2021). Bighorn sheep do not actively seek out cattle, whereas during the rut, wild sheep can be attracted to and seek out domestic sheep, increasing risk of direct contact. *M. ovipneumoniae* is not native to North America, but domestic sheep and goats can be asymptomatic carriers of the pathogen and are usually immune to its effects. It can be lethal to bighorn sheep however, inducing mortality rates ranging from 15-100% (47% on average; Cassirer et al. 2018). While *M. ovipneumoniae* does not survive well outside of a host, it has become endemic in most wild sheep herds of North America in the last two centuries and adult bighorn sheep can transmit the pathogens to lambs, who do not have strong enough immune systems and often do not make it into adulthood once infected. Population declines due to lack of recruitment are often more severe than those from initial outbreak (Foreyt 1990, Coggins and Matthews 1992, Cassirer et al. 2018). Environmental stressors can also increase the susceptibility of bighorn sheep to disease such as unhealthy rangeland (lack of forage from overgrazing or unpalatable invasives), mineral deficiencies, harsh winters, and stress from persistent human activity or predation (Foreyt 1989, Wilder and Pils 2017). There are currently no vaccines to treat *M. ovipneumoniae* persistence and risk of contact and transmission is primarily influenced by proximity to domestic sheep and goats. Additionally, population size, density, demographics, and how established a bighorn sheep herd is also influences risk of contact with pathogens that cause pneumonia (O'Brien et al. 2014, 2021, Sells et al. 2015). In the context of an introduction, bighorn sheep have high site fidelity, which can lead to large forays after relocation, resulting in increased risk of contact with domestic sheep and goats until they become settled in their new range (DeCesare and Pletcher 2006, Morrison et al. 2021).

This report details the evaluation of 4 objectives. 1) Update the 2017 preliminary habitat assessment to include other landscape elements conducive to bighorn sheep selection and determine the amount of potential habitat within the area of interest. 2) Determine potential winter range areas using landscape and climate characteristics. 3) Conduct field assessments for vegetation not captured by satellite data, including abundance of potential forage plants and horizonal obstruction. 4) Assess potential for disease transmission-risk of contact with domestic sheep and goats.

Study Area

The area of interest for the 2017 preliminary assessment was the fire perimeter of the 1996 Archuleta mesa fire (66.6 km^2). In this analysis, we expanded the area of interest to additionally incorporate the 2015 Navajo River fire perimeter and the 2021 Amargo fire perimeter and modified it to exclude swaths of private or state lands to the east and excluded the residential town of Dulce (Fig. 1). A 500 m buffer was then put around the area to account for bighorn sheep potentially using areas up to 500 m away from escape terrain within the area of interest (Gionfriddo and Krausman 1986, Smith et al. 1991, Dicus 2002). The resulting size of the study area was 122.37 km^2/47.25 mi^2.

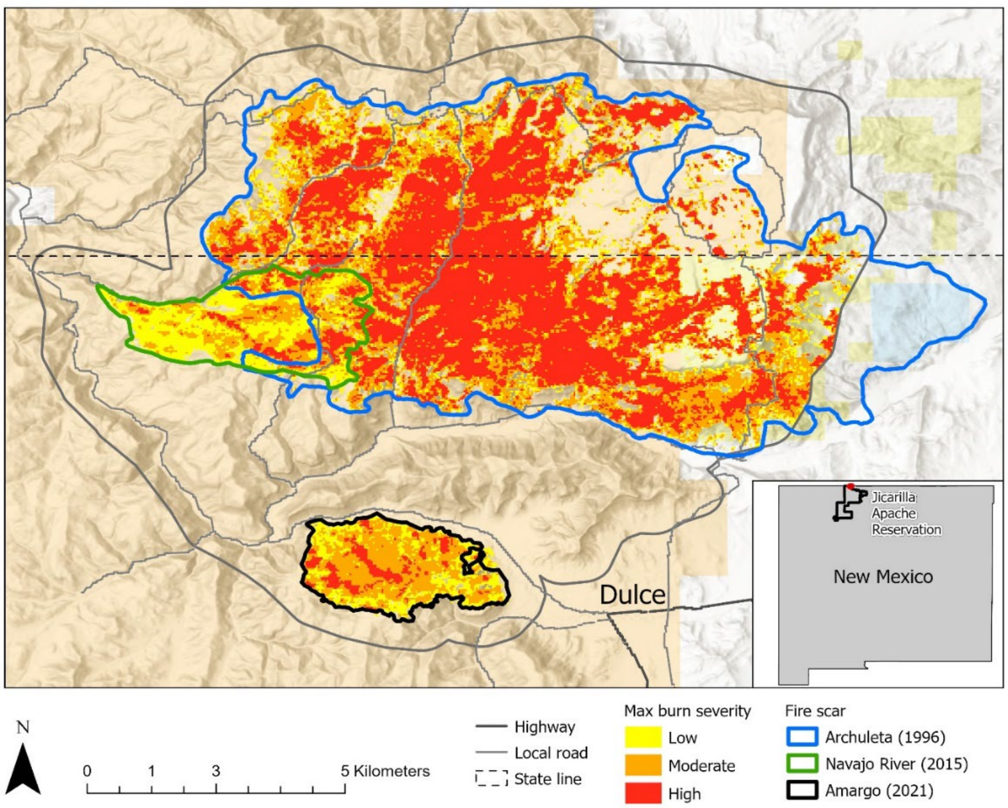


Figure 1. Study area depicting the burn perimeters and severity values of recent fires on the Jicarilla Apache Reservation, New Mexico, USA.

The study area straddles the New Mexico-Colorado border and primarily consists of the JAN, but also incorporates a portion of the Southern Ute Indian Reservation, Bureau of Land Management lands, and a few private parcels. Elevation ranges from 2002−2813 m, with Archuleta Mesa being the highest point and the Navajo River being the lowest point. The area is mountainous, with a few narrow stream and river bottoms dividing up the steep and rocky topography (Fig. 2). Vegetation is dominated by Gambel oak (*Quercus gambelii*), ponderosa pine (*Pinus ponderosa*), Rocky Mountain juniper (*Juniperus scopulorum*), one seed juniper (*Juniperus monosperma*), Douglas fir (*Pseudotsuga menziesii*), Antelope bitterbrush (*Purshia tridentata*), and western snowberry (*Symphoricarpos occidentalis)*, in addition to a variety of cool and warm season grasses interspersed with forbs. Mule deer (*Odocoileus hemionus*), elk (*Cervus canadensis*), black bear (*Ursus americana),* coyote (*Canis latrans*), and mountain lion (*Puma concolor*) are common fauna in the area. Climate is temperate, with precipitation primarily coming from monsoon rains July−September and snow November−March (annual precipitation 50 ± 44 cm; PRISM Climate Group). Dominant land use within the area is hunting, with some cattle grazing occurring at lower elevations and in areas of little to moderate terrain ruggedness.

Figure 2. Aerial view of a portion of the study area during winter 2024. Photo by Kyle Tator, Jicarilla Apache Game and Fish.

Methods

Potential bighorn sheep habitat

The 2017 analysis evaluated slope and escape terrain available to bighorn sheep following a potential introduction. Bighorn sheep use escape terrain for refuge and to evade potential predators. Proximity to or availability of escape terrain is consistently one of the most important predictors of preferred habitat use by bighorn sheep (Geist 1971, Van Dyke et al. 1983, Dicus 2002, Baker et al. 2015). The definition of escape terrain varies in literature, so we evaluated potential habitat using 3 different definitions: areas with ≥ 27° or 51% slope (Geist 1971, Zeignefuss et al. 2000, DeCesare and Pletscher 2006), areas with ≥ 28.8° or 55% slope (ET55; Cain 2017), and areas with ≥ 31° or 60% slope (ET60, most often seen in desert bighorn; Tilton and Willard 1982, Holl 1982, McKinney et al. 2003). However, wild sheep are limited in their ability to scale rock and prefer steep terraced landscapes to sheer cliffs, thus we defined slopes greater than 70° or 274% as unavailable and excluded them from consideration (Lula et al. 2020, Anderson et al. 2022). To identify escape terrain within the study area, we derived slope from 1-m x 1-m LiDAR elevation data (USGS 2018) and reclassified the slope raster three times into three new rasters, one for each escape terrain (ET) definition using the "terra" package in program R (version 4.2.3). We then converted each ET raster into polygons in ArcPro (Esri version 3.2.1) and calculated the area of each ET patch. Because small, isolated patches of escape terrain would be of little benefit for bighorn sheep, we removed patches of escape terrain < 3.5 ha in size unless they were within 100 m of patches ≥ 3.5 ha. Unless transitioning between seasonal ranges or dispersing, bighorn sheep rarely travel > 500 m from escape terrain (Gionfriddo and Krausman 1986, Smith et al. 1991, Dicus 2002). Distance thresholds vary in literature and are likely population specific, but Smith and Flinders (1991) found 95% of bighorn sheep activity occurs within 300 m of ET, while Beecham et al. 2007 reported that 90% of activity occurs within 400 m of escape terrain. Thus, we evaluated potential habitat within 300 m and 450 m away from ET, and buffered ET polygons accordingly. Additionally, we created a distance from escape terrain raster as a component to be used in the habitat suitability raster using the Distance Accumulation tool in ArcPro. We used the ET ≥ 51% polygon for the distance raster because it would result in the most conservative estimate (largest amount of potential preferred habitat) and areas defined as escape terrain based on 51% slope include ET55 and ET60; however in reality, within the study area, there is substantial overlap between all ET polygons so regardless of the ET used, the results would be similar (Fig. 3).

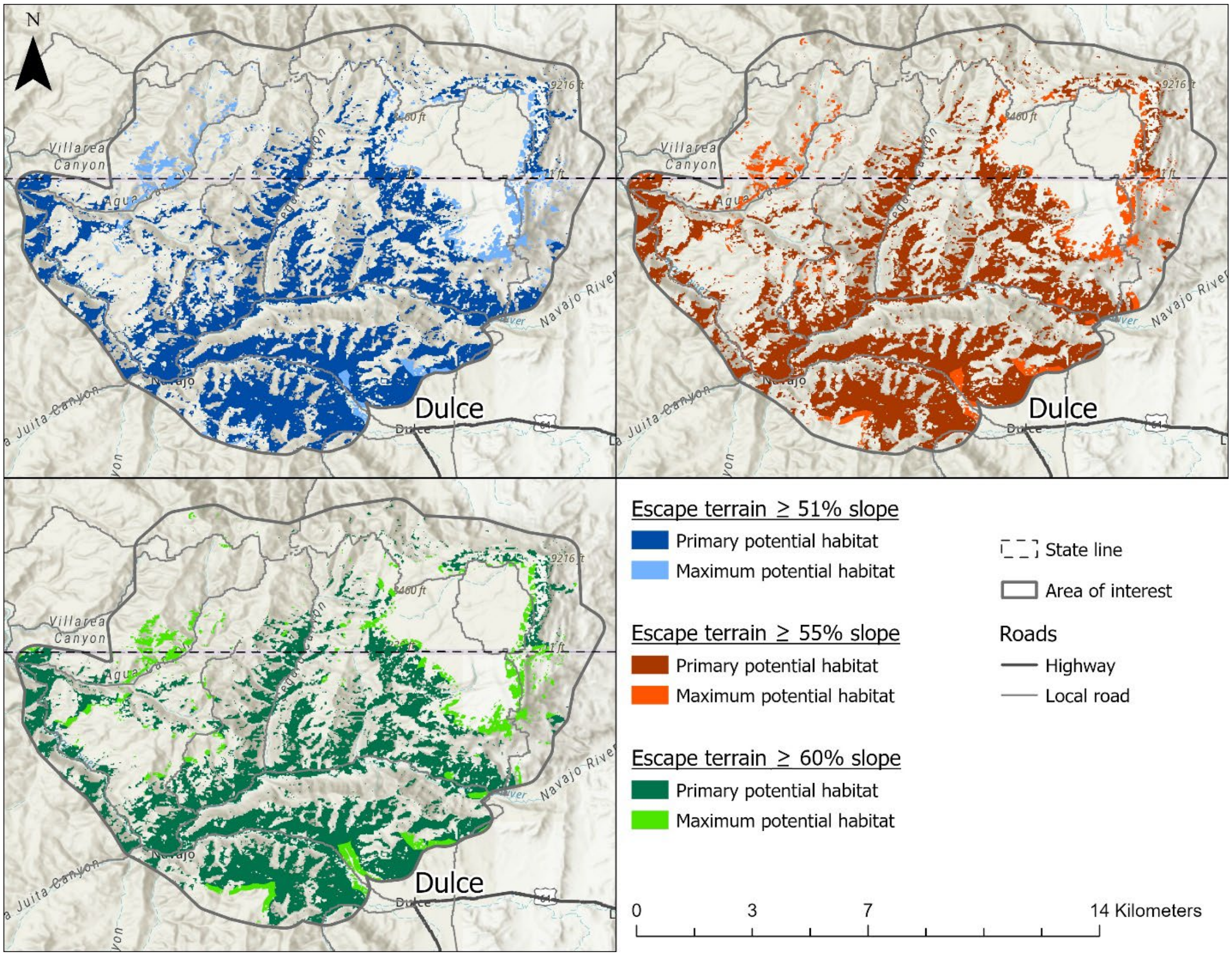


Figure 3. Primary and maximum potential habitat for bighorn sheep within the study area for each escape terrain definition, excluding slopes > 274%.

After proximity to ET, vegetation cover is the second most influential predictor of preferred bighorn sheep habitat (Baker et al. 2015). Bighorn sheep predominantly forage on grass and forbs (but will forage on shrubs) and prefer more open areas for both forage availability and detection of predators. Although slightly variable in literature, Rocky Mountain bighorn sheep prefer areas with ≤ 25-40% shrub or tree cover and regularly use areas with ≤ 30% cover (DeCesare and Pletscher 2004, O'Brien et al. 2014, Baker et al. 2015, Lula et al. 2020). We assessed vegetation cover using Rangeland Analysis Platform (RAP) 30 m x 30 m continuous vegetation cover rasters from 2022 and selected the bands/rasters for shrub and tree cover separately (Appendix A Figs. A1, A2). We then mosaiced the rasters together to create a new raster which represented the maximum cover value present at a pixel (whether tree or shrub). To aid in creating potential habitat polygons, we reclassified the maximum cover raster as preferred cover (≤ 30%) or not preferred cover (> 30%) and converted the raster to polygons.

To assess water availability, we used National Hydrography Dataset from U.S. Geological Survey (USGS 2023) to locate perennial water sources and verified and supplemented data with locations of wildlife guzzlers installed by Jicarilla Game and Fish

Department. We created 1.6 km and 3.2 km buffers around water locations because 85% of bighorn sheep activity occurs within 3.2 km of water, but bighorn sheep use areas < 1.6 km to water even more (Van Dyke et al. 1983). Additionally, we created a distance from water raster to be used as a component to the habitat suitability raster using the Distance Accumulation tool in ArcPro.

To quantify potential habitat, we created maps of intersecting features in ArcPro, delineating primary potential habitat (PPH) and maximum potential habitat (MPH) within the area of interest for each ET definition (Table 1, Fig. 3). We defined PPH as areas within 300 m of escape terrain and 1.6 km of perennial water, and containing ≤ 30% tree and shrub cover. MPH included areas within 450 m of escape terrain and 3.2 km of perennial water, and containing ≤ 30% tree and shrub cover. Using reclassified burn severity data from Monitoring Trends in Burn Severity (MTBS 2022), we then quantified the relationship between PPH and MPH and fire intensity (Table 2). Additionally, to depict the spectrum of suitability and create a habitat preference raster required for the risk of contact analyses (objective 4), we utilized the Suitability Modeler tool in ArcPro (Fig. 4). The user inputs raster layers that are important to the species of interest and assigns weights to each layer identifying how influential each input characteristic is in habitat selection. We used distance to ≥ 51% ET (35% weight), maximum tree/shrub cover (35% weight), distance to water (15% weight), and terrain ruggedness (15%). Terrain ruggedness is important for lambing and predator avoidance (Gionfriddo and Krausman 1986, Lula et al. 2020, Anderson et al. 2022) and is a more fine-scale representation of bighorn sheep's preference of rugged terrain than distance to escape terrain. Each input raster is normalized and transformed by the user to reflect animal preferences for the characteristic (e.g., assigning higher selection values to tree and canopy cover < 35% and/or specifying thresholds at which selection would be zero). There are a variety of transformation functions available to customize; see Appendix A Fig. A3 for the specific transformations and thresholds used to modify landscape variables relative to bighorn sheep preferences for the habitat suitability raster. A panel image of each of the transformed input variables can be found in Figure 5 to aid in identifying limiting variables or specific areas which could benefit from bighorn sheep-specific habitat improvement efforts.

Table 1. Size of calculated primary and maximum potential habitat within the area of interest (AOI) for each escape terrain definition

	Primary potential		Maximum potential	
Escape terrain	Area (km^2)	% of AOI	Area (km^2)	% of AOI
51% slope	31.19	25.49	35.22	28.78
55% slope	29.76	24.32	34.27	28.01
60% slope	28.16	23.01	33.06	27.02

Table 2. Calculated primary potential habitat (PPH) and maximum potential habitat (MPH) relative to burn severity (BS) for each escape terrain (ET) definition.

Burn Severity		**51% slope**		**55% slope**		**60% slope**		
		PPH	**MPH**	**PPH**	**MPH**	**PPH**	**MPH**	**Average**
Unburned	**Area (km^2)**	23.66	26.45	22.51	25.77	21.41	24.88	24.11
	% PH	75.84	75.1	75.63	75.19	76.05	75.26	75.51
	% of BS area	33.18	37.09	31.57	36.14	30.03	34.89	33.82
	% of AOI	19.33	21.61	18.39	21.06	17.5	20.33	19.7
Low	**Area (km^2)**	1.17	1.33	1.13	1.32	0.76	1.23	1.16
	% PH	3.76	3.77	3.81	3.86	2.71	3.72	3.6
	% of BS area	12.22	13.83	11.79	13.75	7.93	12.8	12.05
	% of AOI	0.96	1.09	0.93	1.08	0.62	1	0.95
Moderate	**Area (km^2)**	0.87	1.49	0.84	1.45	0.88	1.35	1.15
	% PH	2.79	4.24	2.83	4.24	3.13	4.09	3.55
	% of BS area	4.9	8.42	4.75	8.19	4.98	7.62	6.48
	% of AOI	0.71	1.22	0.69	1.19	0.72	1.1	0.94
High	**Area (km^2)**	5.49	5.95	5.28	5.73	5.1	5.6	5.52
	% PH	17.61	16.89	17.73	16.72	18.11	16.93	17.33
	% of BS area	23.15	25.05	22.23	24.13	21.49	23.58	23.27
	% of AOI	4.49	4.86	4.31	4.68	4.17	4.57	4.51

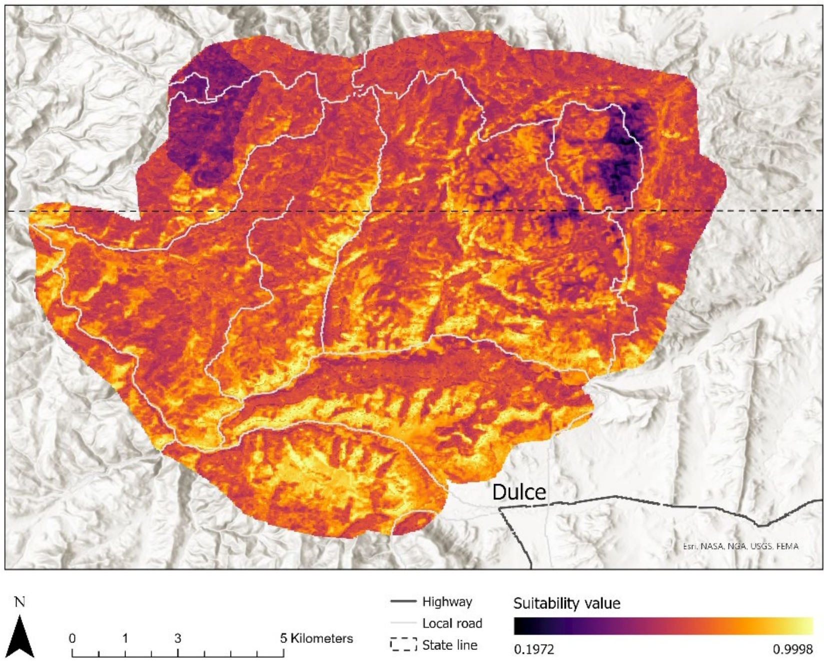


Figure 4. Habitat suitability on a continuous scale for the study area. Values closer to one (yellow) are more suitable for bighorn sheep.

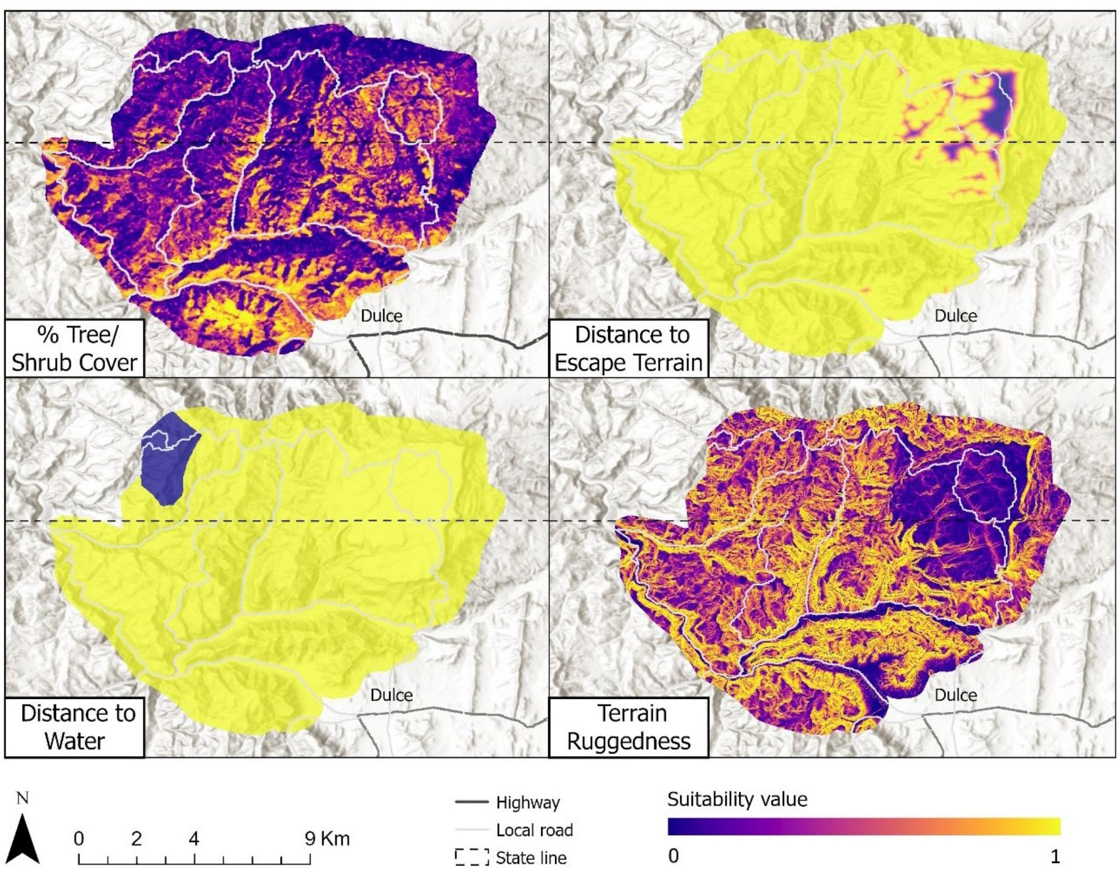


Figure 5. Landscape components used to create the continuous suitability index, transformed to represent preferences of bighorn sheep. Values closer to one (yellow) are more preferred.

Potential winter range

To calculate potential winter range, we utilized the primary and maximum potential habitat polygons and isolated those which had southern aspects and low season-long snow depths which would be preferable to bighorn sheep. We derived aspect from the 1-m x 1-m LiDAR elevation data and reclassified aspects of 120-240° as south facing and suitable for bighorn sheep winter range, in addition to areas with no aspect (i.e., flat terrain). After converting the reclassified aspect raster to a polygon layer, we intersected it with potential habitat polygons to narrow down potential winter range.

To define winter season and severity, we evaluated climatic patterns recorded from a NOAA Western Regional Climate Center weather station near Dulce between November and March (WRCC 2023). Persistent snow depth is likely the most ecologically prohibitive element to bighorn sheep survival in winter as it affects foraging access, energetic costs, and susceptibility to predation, thus, we created winter severity definitions to reflect persistent snow depth. To determine winter severity, we averaged daily maximum temperature and daily total snow depth each month within each "year" (Nov-March) and excluded any years that were not complete (i.e., had < 5 months of data or too much missing data per month; Appendix A Fig. A4). We then averaged these values over each year and subtracted temperature values (°C) from snow depth values (cm). This resulted in years with deeper snow and colder temperatures as having higher winter severity and years with less snow and/or warmer temperatures as having lower values (indicating a mild or more average winter). We evaluated severity thresholds from both a historical (1963-2023) and recent (2003-2023) context to account for the influence of climate change and averaged values across years to get a mean and standard deviation of severity. Severe years had a severity index above the average and mild winters had a severity index one standard deviation below the average (Appendix A Fig. A5). We then downloaded daily 1 km x 1 km SNODAS snow depth data for every year after 2003 (when SNODAS first launched, SNODAS 2004) from November—March for the study area and extracted average daily snow depth values for each potential winter range polygon. Based on the date of the SNODAS data, we labeled these values by severity and then calculated area of polygons or partial polygons which had ≤ 16 cm and ≤ 25 cm of snow for ≥ 60, 75 90, and 100% of the winter season for each severity relative to both recent and historical norms (Appendix A Tables A1, A2). Research indicates bighorn sheep prefer areas with ≤ 16 cm (Lauer and Peek 1976) or ≤ 25 cm of snow (McCann 1956, Tilton and Willard 1982, Smith and Flinders 1991). We isolated polygons or partial polygons with ideal snow conditions for ≥ 60% and ≥ 90% of winter (November—March) to depict on a map (Figures 6, 7).

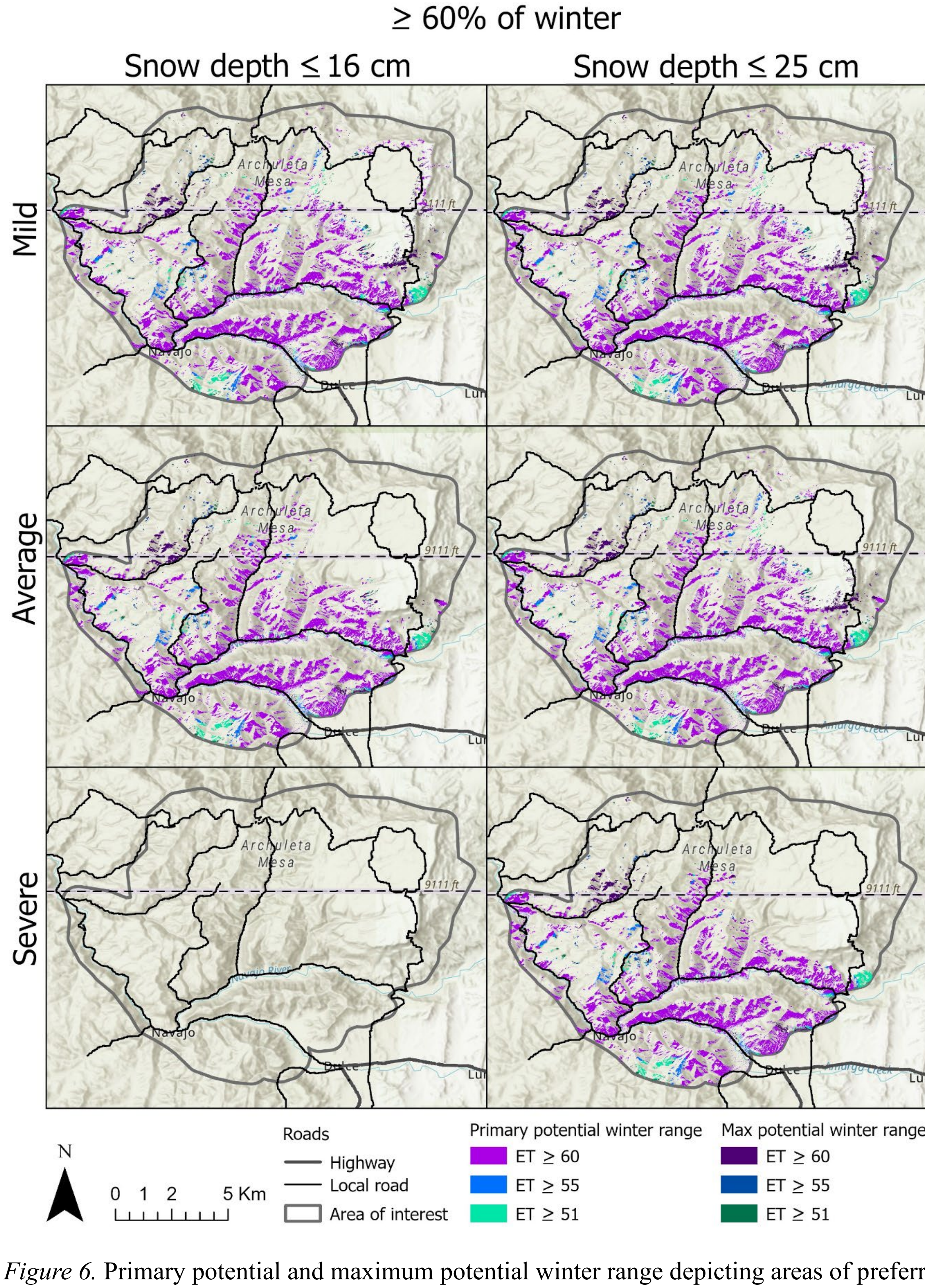


Figure 6. Primary potential and maximum potential winter range depicting areas of preferred habitat and snow depth for ≥ 60% of winter (Nov-March) based on recent normals (past 20 years).

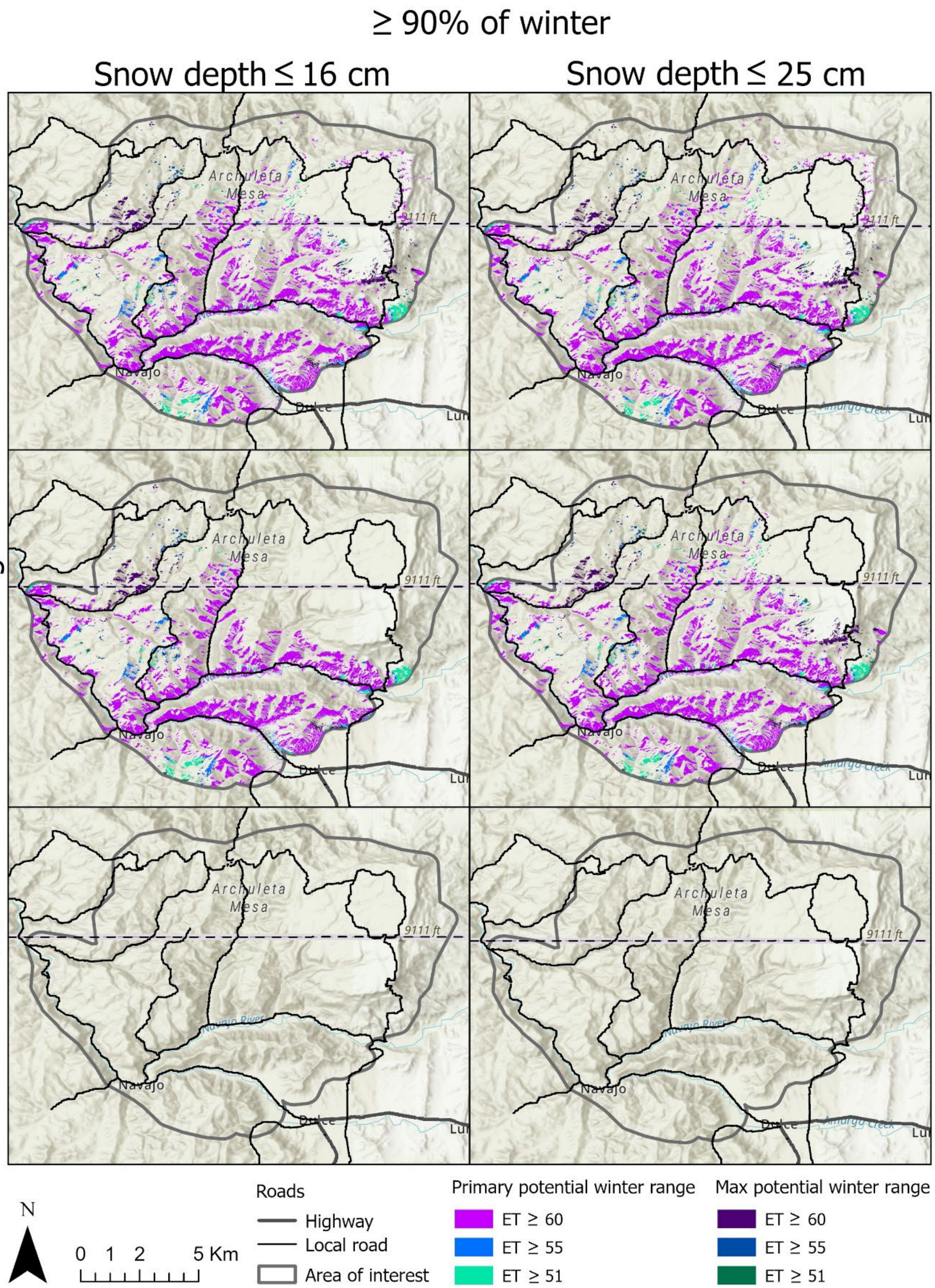


Figure 7. Primary potential and maximum potential winter range depicting areas of preferred habitat and snow depth for ≥ 90% of winter (Nov-March) based on recent normals (past 20 years).

Field assessment of habitat conditions

From June 1st—July 14th, 2023, we surveyed 204, 100 m long vegetation transects within the study area. Transects were randomly oriented and located, spaced at least 500 m away from other transects. Every 10 m along the transect, we measured percent cover within a 1 m^2 Daubenmire frame for the three most dominant species of trees, shrubs, sub-shrubs, and succulents to evaluate forage availability and forage value, vegetation composition, and frequency of species occurrence (Fig. 8a). We defined trees as woody vegetation with clear visibility around the base (typically with one main trunk) and shrubs as woody vegetation in which foliage obscured the base of the plant. Every 20 m along the transect, we recorded the distance to the nearest tree and shrub in four quadrats using a range finder (up to 200 m) to estimate shrub and tree density using the point-center quarter method (Cottam and Curtis 1956, Khan et al. 2016; Appendix B, Fig. B1). Additionally, we measured horizontal visibility every 12.5 m along the transect using the ball and staff method (Collins and Becker 2001, Pop 2020; Fig. 8b). This entails a tennis ball being glued to the top of a 1 m PVC pipe (to represent the height of bighorn sheep) and 8 measurements assessing whether the single point where the ball meets the lip of the PVC pipe can be seen with one eye open are taken from 1-m off the ground in each cardinal and sub-cardinal direction (Appendix B Fig. B2).

Figures 8a (left) and 8b (right). Taking field measurements of forage availability (left) and horizontal cover (right). Photos by Cara Thompson, New Mexico State University.

We summarized field collected data and modeled vegetation data using beta regression to predict horizontal visibility, forage quality, and species frequency across the study area. To assess potential forage quality, we referenced the United States Department of Agriculture (USDA) database of plants and the "importance to wildlife and livestock" section of their Fire Effects Information System, which is based on existing literature (Appendix B Table B1). If no data existed for bighorn sheep, we used the value for domestic sheep as a proxy. We then summarized and modeled the proportion of existing forage present by quality category across transects. To model horizontal visibility, we evaluated both mean and median horizontal visibility across transects as the response variable in model sets. For shrub and tree density estimates, the equations require at least 50 samples (transects), so density is reported at the study area scale, rather than the transect level scale and for shrubs and trees as functional groups, rather than by species. However, we were able to use the shrub and tree density data to estimate species frequency and modeled the frequency of occurrence for the five most common shrub and tree species across the study area. For all summaries and modeling, we pooled sampling points within a transect to get a mean and/or median value per transect and those resulting values became the response variable in the models for each parameter of interest.

Predictor variables for models included years since fire, burn severity (reclassified to none, low, moderate, severe), a binary variable representing if the area had burned or not since 1996, tree cover, shrub cover, aspect, Normalized Difference Vegetation Index (NDVI, Copernicus 2003), dominant vegetation type, vegetation structure, terrain ruggedness, slope, and elevation. We reclassified dominant vegetation type and vegetation structure using 2020 LANDFIRE Existing Vegetation Type data. Vegetation structure data included semi-open woody, closed woods, grassland, open woods, and other (developed) classifications and was meant to represent the landscape in context of horizontal visibility. Dominant vegetation included aspen and mixed conifer, piñon-juniper, Douglas fir, ponderosa, shrubland, grassland, and other as categories. We derived a terrain ruggedness index from the LiDAR elevation model using the package "spatialEco" (Evans and Murphey 2023) in R. Due to the difficulty of maintaining a straight line through thick vegetation, we buffered transects by 10 m on each side to better match field collected data. Thus, we extracted the mean within the buffered transect for continuous landscape variables and the mode for categorical predictors. We ensured variables within models were not collinear by assessing their relationship to one another using Spearman's correlation coefficient (ρ). Any covariates with a $\rho \geq 0.7$ were not included in the same model structures. Additionally, we centered and scaled all continuous covariates. For each parameter of interest, we compared models using Akaike Information Criterion corrected for small sample size (AICc; Appendix B, Table B2) and verified independence among predictor variables in top performing models by conducting a variance inflation factor analysis (VIF) and ensuring all variables had a value ≤ 2. For variables which were highly correlated (e.g., burn severity, fire history, and burn age), we substituted each related predictor in the top performing models and assessed which explained the most variation in models. To test the predictive power of top performing models, we conducted a 10-fold cross-validation repeated 20 times and derived an R^2 value. If the models predicted well across the study area, we would incorporate them into identifying potential habitat for bighorn sheep as part of objectives 1 and 2.

Risk assessment of disease transmission

Because the biggest predictor of pneumonia in bighorn sheep is proximity to domestic sheep and goats (WAFWA 2012 and sources within), we compiled locations of permitted and active federal and state sheep and goat allotments, recorded personal observations of domestics, and gathered information from local biologists and rangeland ecologists to help capture data on hobby farms and private herds within 80 km of the study area. We chose 80 km as the cutoff because while rare, translocated bighorn sheep have been known to disperse this far (Coggins et al. 2000, Arizona Game and Fish Department, personal communication S. Willams & R. Langley, 2021). We calculated distance to these herds from the study area (Fig. 9) and used their locations in two different risk of contact analyses. Currently, the risk of transmission once contact with an infected domestic occurs is unknown, is variable, and likely depends on a variety of factors (duration and type of contact, health of wild sheep, previous exposure.; O'Brien et al. 2014). Thus, the analyses conducted only estimate the risk of contact (RoC) with domestic sheep and are not models of disease transmission, rate of spread, or species persistence.

The Risk of Contact Tool (RoCT; O'Brien et al. 2014, 2021) is widely used by federal agencies to assess the probability of a foraying individual (ram or ewe) contacting a domestic sheep or goat allotment based on habitat preferences, sex ratios, herd size, core home range, and foray behavior. In this context, a foray is any exploratory movement beyond the core home range. We modeled various home range sizes, herd sizes, sex ratios, and foray behaviors to illustrate the influence of each variable on contact risk, because risk of contact and disease transmission is highly dependent on sex ratios, herd size, and how established the population is (O'Brien et al. 2014, 2021). Using the habitat suitability raster developed in objective one and the suitability modeler tool in ArcPro, we identified areas of various sizes to represent the likely core home range of bighorn sheep, if they were introduced to the study area. We specified the suitability modeler tool to prioritize utility (i.e., having the highest suitability values) and connectivity equally when identifying the core home range areas and for each to consist of one polygon. To determine the size of the core home range, we referenced available literature on minimum viable population (MVP) sizes for bighorn sheep and divided the most cited value by population densities reported in research. There is no consensus on MVP for bighorn sheep, with values ranging from 100-188 (Berger 1990, O'Brien et al. 2021), however 125 animals is the most used number in literature (Geist 1975, Van Dyke et al. 1983, Smith et al. 1991, Zeigenfuss et al. 2000). Van Dyke et al. (1983) reported maximum density of bighorn sheep to be 1.9/km^2 in southeastern Great Basin ecosystems, while Zeigenfuss et al. (2000) reported prairie-badland habitat to support an average density of 3.86 sheep/km^2, requiring about 32 km^2 of habitat to support a MVP and Rocky Mountain ecosystems supporting an average of 1.47/km^2, requiring about 85 km^2 of habitat. There are examples of desert bighorn sheep populations persisting while being smaller than MVP numbers in literature, however (Krausman et al. 1993). To incorporate the spectrum of these densities, we created core habitat polygons 32 km^2 and 85 km^2 in size, in addition to 20 km^2, which is the average 95% individual home range size derived from a recently introduced herd in Cochiti Canyon, NM (Appendix C Table C2). The estimates using the 20 km^2 core range allow for insight into what risk of contact may be on a more individual basis or introduced herd that settles quickly.

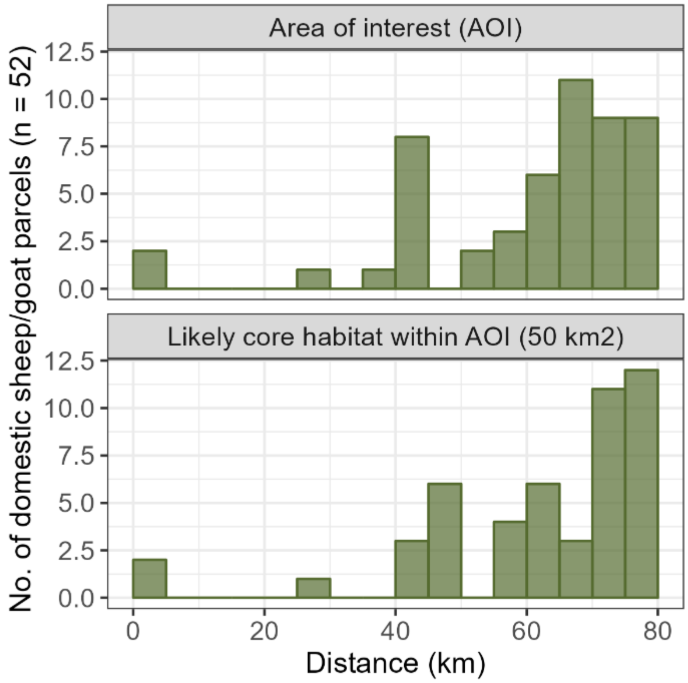


Figure 9: Distance to domestic sheep, goat, or both grazing parcels from the study area and likely core habitat for bighorn sheep within the Jicarilla Apache Nation.

To compare the risk of contact between an established population and a recently reintroduced population, we used sex ratios and foray probabilities from 12 years of data from 12 herds in the Hells Canyon area in Oregon (the default values in the RoCT) and five years of GPS data immediately after introduction of Rocky Mountain bighorn sheep in Cochiti Canyon, NM (i.e., the Jemez population). Similar to the proposed introduction of sheep to the JAN after the 1996-2021 fires, the Jemez population was introduced in 2014 and 2017 by New Mexico Department of Game and Fish (NMDGF) after the 2011 Las Conchas Fire created more suitable habitat conditions for bighorn sheep. To quantify foray behavior for sheep in the Jemez, we created a 90% home range polygon using all available locations from the Jemez population and measured the distance of all GPS points to the core home range polygon, counting the number of locations away from the home range polygon in each 1-km increment (O'Brien et al. 2014, 2021). From this, we were able to calculate the probability of animal-year forays at each distance increment by sex and determine the percent of ewes/rams that leave the core home range in animal-years, which is then input into the RoCT (O'Brien et al. 2014, 2021). It is important to note the foray behavior derived from the Hells Canyon data is only from May-October because those are the only months domestic sheep allotments are active in the area and thus, it does not include larger forays made during the rut or from translocated individuals settling down (O'Brien et al. 2014, 2021). It is also of note the sex ratios of the Jemez herd included more females than males because the goal was to expand the population quickly after introduction.

After foray behavior, demographic and herd parameters, locations of domestic sheep and goats, and the habitat raster and home range polygon are uploaded into the RoCT, contact rates are estimated for each domestic sheep location/allotment within the maximum foray distance. The contact rates are estimated for a single ram, a single ewe, for all rams, all ewes, and for the herd. A contact rate of one indicates the core home range overlaps with or touches a domestic sheep or goat location (O'Brien et al. 2021). Additionally, we estimated time to contact by dividing 1 by the annual herd contact rate and estimated time to outbreak by taking one divided by the annual herd contact rate times a simulated transmission rate (O'Brien et al. 2021). Following the simulations in the RoCT in Appendix H (O'Brien et al. 2021), we simulated a moderate transmission rate of 0.25 (where every 1 in 4 contacts with domestics leads to an outbreak). In reality, transmission rate is extremely variable and influenced by demographics, herd history of pneumonia, and environmental factors like spring precipitation (Sells at al. 2015, Manlove et al. 2017). Thus, the RoCT is not a model of disease transmission, rate of spread, or species persistence, but is intended to provide a general idea of the potential for contact between bighorn sheep and domestic sheep and goats. It also does not account for individuals who foray and do not return.

The second method we used to assess risk of contact with domestics was a cost-distance analysis using the habitat suitability raster made for objective one (Anderson et al. 2022). This method does not take foray behavior or demographics and herd size into account; however, it accounts for connectivity between suitability pixels and topography relative to a 50% core home range to depict landscape use more realistically. The suitability raster is natural-log transformed to best portray the relationship between resistance (connectivity) and suitability (Keeley et al. 2016, Anderson et al. 2022), then multiplied by -1 to get all positive values. We then input the resistance layer into the Distance Accumulation tool in ArcPro and supplied the 1-m x 1-m LiDAR elevation data and a 32 km^2 50% home range polygon created from the suitability raster as described above as the "source" layer, which the bighorn sheep would theoretically be originating from to create the "cost" raster (Anderson et al. 2022). We decided to use the 32 km^2 core range polygon used in the RoCT analysis as the source polygon because it was similar to the 50% home range size of the Jemez population, which shares geographic and situational similarities with the proposed introduction to the JAN (Appendix C). We extended the suitability raster to include an 80 km radius beyond the study area to match the cutoff of domestic sheep and goat parcels we used. Following Anderson et al. (2022), we rescaled the resulting cost raster to reflect values of 0 to 100 and inverted the values, so 100 represented a higher likelihood of use from bighorn sheep with less cost. Areas closer to the source polygon and having higher suitability and connectivity would have larger values in the cost raster. We created suitability and cost rasters for the sheep in the Jemez, then overlaid GPS location data for sheep translocated to the Jemez and extracted cost values at each point to determine cost thresholds. We evaluated cost thresholds relative to release date and calculated thresholds for all locations post-release, locations > 4 months post-release, and for locations > 12 months post-release to capture the settling-in period after an introduction effort. We then overlaid domestic sheep and goat polygons with the cost-distance raster for the study area and extracted the minimum cost value for each location, calculating percentage of parcels that fall within the use thresholds of bighorn sheep.

Results

Potential bighorn sheep habitat

Within the 122.37 km^2 of the study area, 28.16-31.19 km^2 meets the criteria of PPH, depending on the definition of escape terrain used, and 33.06-35.22 km^2 is considered MPH

(Table 1). Thus, approximately 23-29% of the study area has preferred habitat conditions for bighorn sheep. This value does not account for connectivity to preferred habitat patches however, thus is likely an underestimate of the area bighorn sheep would use. The most concentrated area of preferential habitat occurs in the southern portion of the study area, around Amargo Canyon, and the lowest quality habitat occurs in the north-northwest portion of the study area and the interior of Archuleta Mesa (Figs. 3, 4). The reason the northwest portion of the study area is not conducive to providing habitat for bighorn sheep because portions are > 3.2 km from water and shrub and tree cover is higher than that preferred by bighorn sheep (Fig. 4). Most of the study area is within a preferred distance to escape terrain, contains good to moderate terrain ruggedness (except for the interior portion of Archuleta Mesa), and is within ideal distance to water, thus these elements are not limiting to potential bighorn sheep establishment within the area (Fig. 5). Of the landscape elements analyzed, vegetation cover is the most limiting (Fig. 5), with 46.7% of the study area having > 30% tree/shrub cover (max cover) and 30.2% having > 40% max cover (Appendix A Table A3). More dense shrub cover is slightly more prevalent than tree cover with 26.3% of the study area having > 30% shrub cover (15.1% with > 40% shrub cover) and 22.4% of the area having > 30% tree cover (15.2% with > 40% tree cover; Appendix A Table A3). Relative to burn severity, approximately 75.5% of potential habitat occurred in unburned areas, 3.6% occurred in both low and moderate severity, and approximately 17.3% of potential habitat occurred in high severity burns (Table 2). The 1996 Archuleta fire primarily was a high severity burn, the 2015 Navajo River fire was primarily low to moderate intensity, and the 2021 Amargo fire was primarily a moderate intensity burn.

Potential winter range

Using the last 20 years of climate data as reference (i.e., recent winter weather), between 13.1-19.1 km^2 of potential winter range occurs in the study area (depending on ET definition and duration of winter) during mild and average winters when the snow depth threshold is set at a shallower, more conservative threshold of 16 cm (Appendix A, Table A1). This translates to approximately 43-56% of potential habitat also being winter range in these conditions. However, at a snow depth threshold of 16 cm, when severe winter conditions (i.e., when daily maximum temperatures were colder than average and snow depth was deeper or more continuous than average) persist for ≥ 60% of the season, no potential wintering range exists, regardless of escape terrain definition (Appendix A Table A1). Conversely, when the snow depth threshold is 25 cm, winter range only ceases to exist when severe winter conditions persist for ≥ 90% of winter, although the quantity of potential winter range is only around 1 km^2 when severe conditions persist for ≥ 75% of winter but are relatively large (13.6-16.1 km^2) when severe conditions persist < 75% of winter (Appendix A Table A1). Relative to historical winter weather patterns, the available winter range was mostly similar, however no potential winter range existed when severe weather persisted for ≥ 75% of the season regardless of the snow depth threshold (Appendix A Table A2). Generally, climatic patterns are milder in recent years than historically and thus slightly more potential winter range is available when using recent weather trends compared to historical trends (Figs. 6, 7; Appendix A Figs. A6, A7). Most of the winter range is located along the north side of Amargo Canyon, the north side of the River Road, the west side of Archuleta Mesa, and the middle portion of Seguro Canyon (Figs. 6, 7).

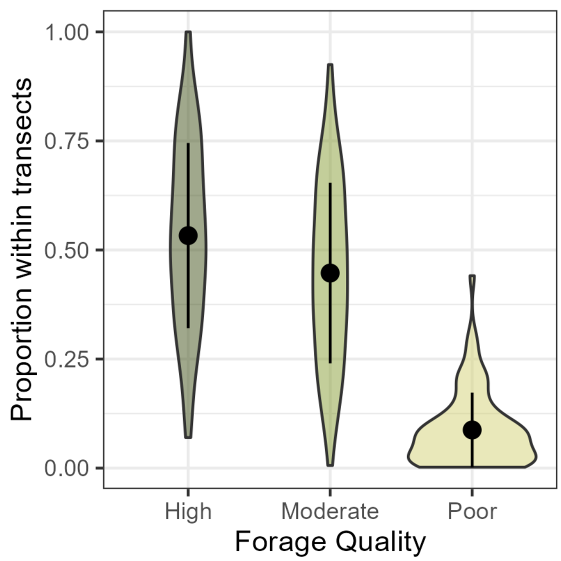


Figure 10: Distribution of forage quality at transects for existing vegetation.

Field assessment of habitat conditions

Overall, assessments of field-collected vegetation data indicated that most of the existing vegetation at transects were species considered to be of moderate or high nutritional value to bighorn sheep, shrub density was moderately high, and horizontal visibility was variable across transects, but averaging on the high end of what bighorn sheep prefer. The mean and median proportion of existing vegetation at transects in each quality category were nearly identical, thus the average nutritional representation at plots was 53% ± 21% high quality, 44% ± 21% moderate quality, and 9% ± 8% poor quality vegetation (Fig. 10). The most common species encountered by far in both forage availability plots and shrub/tree density plots was Gambel oak (*Quercus gambelii*, USDA plant code "QUGA", Table B1), typically in shrub form (Figs. 11 & 12). QUGA is of moderate forage quality (Appendix B Table B1). The next most frequently encountered species were antelope bitterbrush ("PUTR"), Oregon grape ("MARE"), and Oregon boxwood ("PAMY"; Figs. 11, 12). PUTR is a species of high nutritional value, while MARE and PAMY are both of moderate quality (Appendix B Table B1). Most of the poor-quality forage species are trees (Appendix B). All grass and forbs were considered as preferred forage in the analysis and were not separated by species.

Stem densities estimated using the point-center quarter method can be compared to maximum stand density indices (SDI_{max}), which indicate the theoretical maximum number of trees that can fit within an acre, based on the average size of the tree species of interest. In mixed forests, an average tree size of 25.4 cm diameter at breast height (DBH) is assumed. The United States Forest Service (USFS) defines low density as 0-24% of SDI_{max}, moderate density as 25-34% SDI_{max}, high density as 35-55% SDI_{max}, and extremely high density above 55% SDI_{max}. The upper range of high density marks the threshold for the onset of density-related tree mortality. SDI_{max} values for the most dominant tree species we observed exist (Table 3), however due to the lack of species being present at each plot within a transect for 50 transects (an assumption for the equation) we were unable to calculate density for each species, so we calculated density by functional group (Table 4). Due to the dominance of Gambel oak on the landscape, the shrub density value can be compared to the Gambel oak value, resulting in an observed stand density of approximately 51% of SDI_{max} for oak, which is high, but virtually all oak within the study area observed was < 7.6 cm DBH. High stand density is related to low understory forb and grass production. However, tree stand density is low at 1-2% SDI_{max} for any of the most common species encountered, which is associated with high understory production of forage beneficial to sheep (Tables 3, 4).

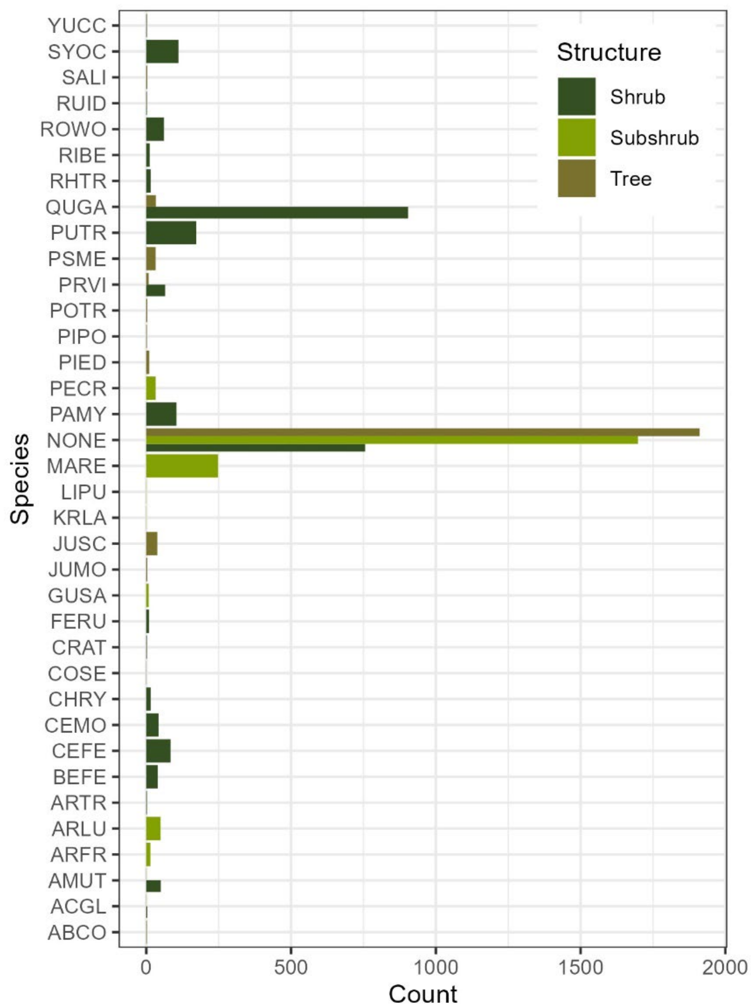


Figure 11. Frequency of species encountered in forage availability plots (*n* = 2,040). Species labeled with USDA 4-letter taxonomic code. Some species can be either a tree or shrub depending on growth form (e.g., QUGA).

The average mean horizontal visibility at transects was 38.6% ± 20.7% (SD) and the average median horizontal visibility at transects was 37.3 % ± 24.6% (SD; Fig. 13). When assessing horizontal visibility using the median of plot observations per transect, 66% of transects have an average horizontal visibility > 30% and 72% of transects have an average horizontal visibility > 30% when the mean across plot samples is assessed (Fig. 14). It was more common to have plots with no horizontal visual obstructions than those with obstruction ≥ 75%, but visibility varied widely across plots within a transect if shrubs were the dominant vegetation (Fig. 15).

Unfortunately, the models aimed at predicting forage quality, species occurrence, and horizontal visibility across the study area did not perform well enough to be used in creating rasters for habitat suitability models. However, top performing models still reveal associations with landscape characteristics and may be of interest to managers (Appendix B, Table B2). Model validation revealed R^2 values ranging from 0.052-0.559, where 0.5 is the minimum to indicate correlation between predictor variables and the response metric.

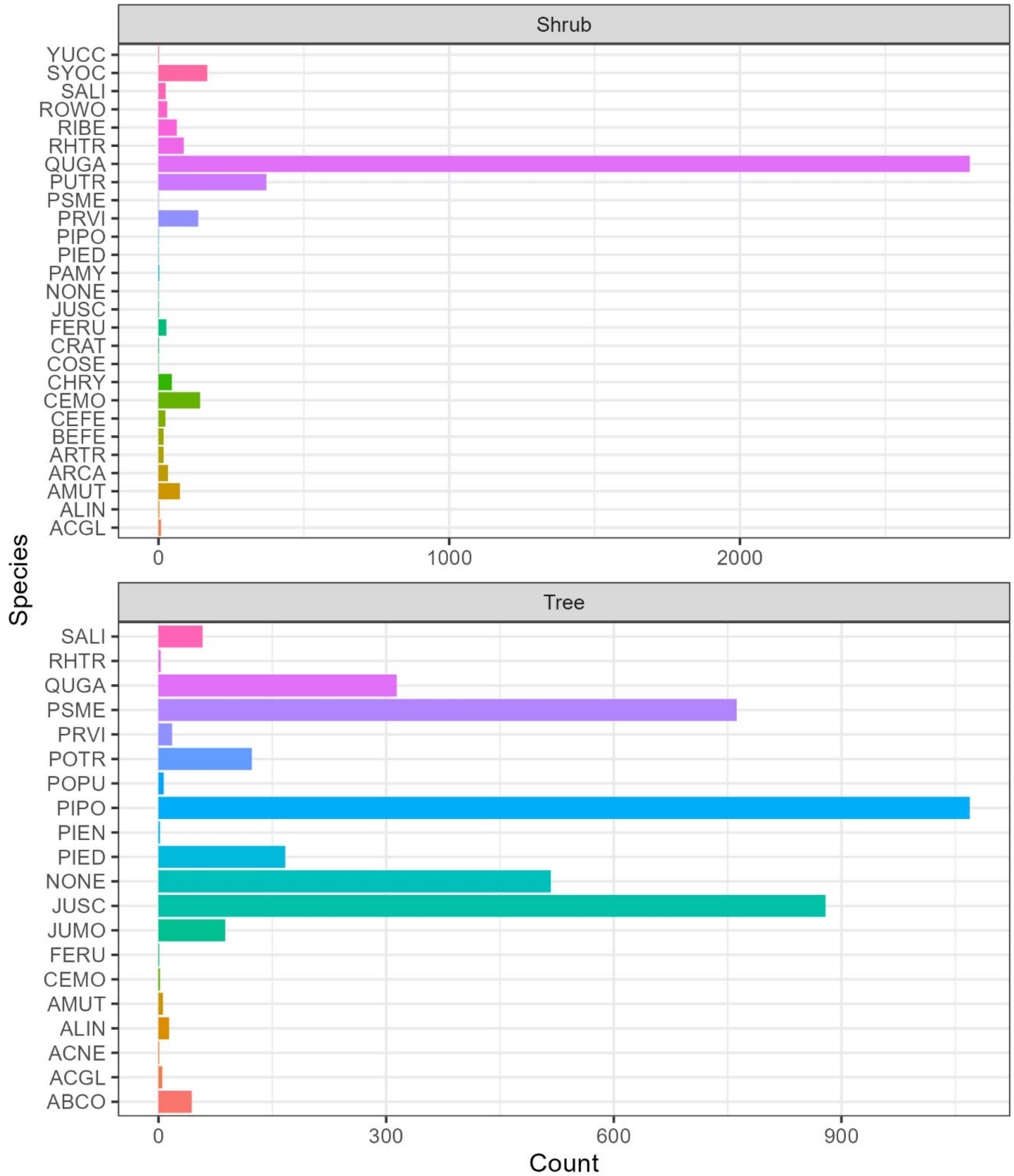


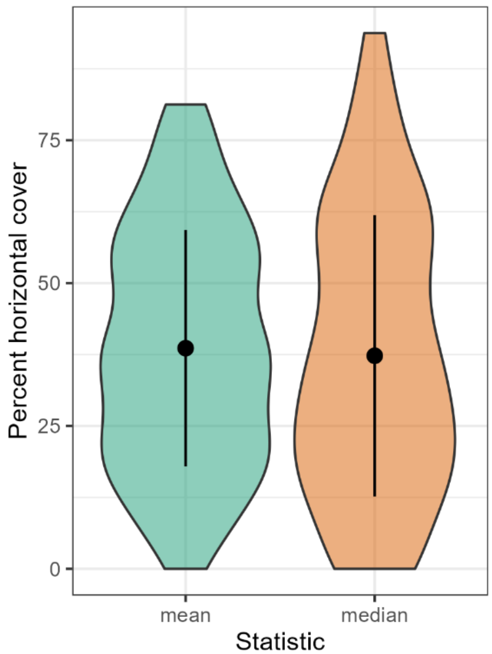
Figure 12. Frequency of species encountered in shrub and tree density quadrats (n = 4,080). Species labeled with USDA 4-letter taxonomic code (Table B1).

Table 3: Maximum stand density indices (SDI_{max}) from USFS used to reference to shrub and tree density indices estimated from field observations.

Species	**SDI_{max}**
Gambel oak	652
Ponderosa pine	446
Douglas fir	570
Two-needle pinyon	348
Rocky Mountain juniper	411

Table 4: Estimated shrub and tree density from field collection.

Structure	Density (plants/ha)	Density (plants/acre)
Shrub	825.50	334.07
Tree	18.80	7.61



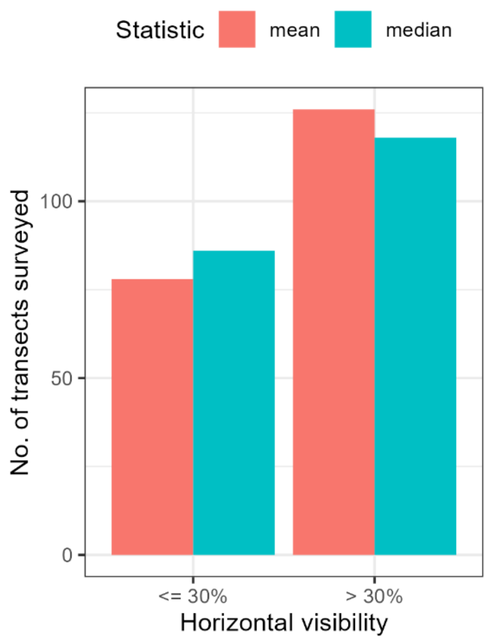


Figure 13. (above, left): Distribution of horizontal cover across transects with standard deviation.

Figure 14. (above, right): Proportion of transect with horizontal visibility ≤ 30% and >30%. Transect values determined by averaging horizontal visibility across plots are in pink, while those calculated using the median across plots are in blue.

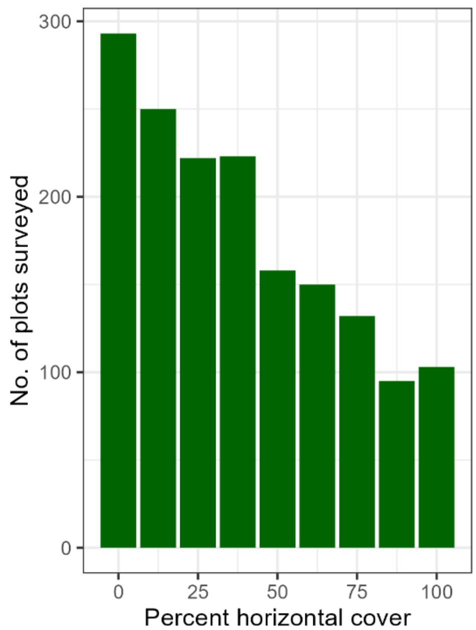


Figure 15. (left): Histogram depicting horizontal cover of plots sampled (*n* = 1,632).

Risk assessment of disease transmission

Relative to known domestic sheep and goat locations, the study area is within immediate proximity (≤ 3 km) to two active domestic grazing parcels—one just south of Dulce off highway 64 and the other on the River Road, on a private parcel bordering the eastern portion of the JAN. The next closest parcel is 11,848 ha of mixed ownership (50% Bureau of Land Management (BLM), 35% private, 15% state), approximately 30 km southwest of the study area, which is authorized for sheep and goat grazing but the BLM portion was not billed for grazing in 2023. Sheep and goat parcels become more common starting about 44 km out from the study area (Fig. 9). The RoCT estimates an annual herd contact rate with the closest (1 km) privately-owned parcel to be 0.3-100%, depending on core range size, foray behavior, and herd demographics and size, with 100% risk of contact occurring when the core range size is ≥ 32 km^2, regardless of other parameters (Table 6). Core home range size varies based on density of animals and resources available, but for reference, the size of the core range for the 12 Hells Canyon herds ranged from 86-2,395 km^2 and the size of the Jemez core home range was approximately 69 km^2 five years after reintroduction (Appendix C). With a risk of contact rate of 100%, estimated contact will occur within one year after introduction and an outbreak may occur within 0-4 years with a moderate transmission rate of 0.25 (Table 6). The herd rate of contact for the JAN parcel 3 km away from the potential core area ranges from 0.1-7.4%, with an expected time to contact to be at least 13.5 years (Table 7). Despite being near the potential core area, this parcel may be less likely to be used by bighorn sheep because it is far from escape terrain and not preferable habitat for bighorn sheep. Only one other parcel of mixed ownership falls within foray distances calculated for the RoCT, which was 32 km away from the potential core home range and had an estimated annual herd contact rate of 0.05-18.4% and minimum time to contact of 5.4 years (Table 8).

Table 6: Estimated maximum annual rate of contact with domestic sheep or goats at the private property parcel bordering the east side of the JAN, for various demographic and foray scenarios.

					Est. max annual contact rates via foray-closest (private)							
CHHR size (km^2)	Herd demographics	Herd Size	Density	Foray	Single Ram	Single Ewe	All Rams	All Ewes	Herd	Allotment Dist (km)	Time to contact (years)	Time to outbreak* (years)
20	35M:65F (default)	30	1.47	Default	0.0003	0.0000	0.0028	0.0005	0.0033	1	303	1212
20	35M:65F (default)	30	1.47	Jemez	0.0019	0.0016	0.0196	0.0308	0.0503	1	19.9	80
20	35M:65F (default)	77	3.85	Default	0.0003	0.0000	0.0071	0.0014	0.0085	1	118.1	472
20	35M:65F (default)	77	3.85	Jemez	0.0019	0.0016	0.0502	0.0790	0.1291	1	7.7	31
20	24M:76F (Jemez)	30	1.47	Default	0.0003	0.0000	0.0019	0.0006	0.0025	1	395.3	1581
20	24M:76F (Jemez)	30	1.47	Jemez	0.0019	0.0016	0.0134	0.0360	0.0494	1	20.3	81
20	24M:76F (Jemez)	77	3.85	Default	0.0003	0.0000	0.0049	0.0016	0.0065	1	154.3	617
20	24M:76F (Jemez)	77	3.85	Jemez	0.0019	0.0016	0.0344	0.0923	0.1267	1	8	32
32	35M:65F (default)	47	1.47	Default	1	1	1	1	1	0	0-1	0-4
32	35M:65F (default)	47	1.47	Jemez	1	1	1	1	1	0	0-1	0-4
32	35M:65F (default)	125	3.85	Default	1	1	1	1	1	0	0-1	0-4
32	35M:65F (default)	125	3.85	Jemez	1	1	1	1	1	0	0-1	0-4
32	24M:76F (Jemez)	47	1.47	Default	1	1	1	1	1	0	0-1	0-4
32	24M:76F (Jemez)	47	1.47	Jemez	1	1	1	1	1	0	0-1	0-4
32	24M:76F (Jemez)	125	3.85	Default	1	1	1	1	1	0	0-1	0-4
32	24M:76F (Jemez)	125	3.85	Jemez	1	1	1	1	1	0	0-1	0-4
85	35M:65F (default)	125	1.47	Default	1	1	1	1	1	0	0-1	0-4
85	35M:65F (default)	125	1.47	Jemez	1	1	1	1	1	0	0-1	0-4
85	24M:76F (Jemez)	125	1.47	Default	1	1	1	1	1	0	0-1	0-4
85	24M:76F (Jemez)	125	1.47	Jemez	1	1	1	1	1	0	0-1	0-4

* CHHR denotes potential sizes of core habitat home range based on herd size and density where 95% of use is likely to happen. Movement outside the CHHR is considered a foray, with the Jemez forays representing movement behavior of a translocated herd and the default representing behavior of established herds.

Table 7: Estimated maximum annual rate of contact with domestic sheep or goats at the Jicarilla parcel 3 km south on highway 64, for various demographic and foray scenarios.

					Est. max annual contact rates via foray-within Jicarilla							
CHHR size (km^2)	Herd demographics	Herd Size	Density	Foray	Single Ram	Single Ewe	All Rams	All Ewes	Herd	Allotment Dist (km)	Time to contact (years)	Time to outbreak* (years)
20	35M:65F (default)	30	1.47	Default	0.0001	0.0000	0.0011	0.0001	0.0012	3	840.3	3361
20	35M:65F (default)	30	1.47	Jemez	0.0008	0.0006	0.0083	0.0110	0.0192	3	52	208
20	35M:65F (default)	77	3.85	Default	0.0001	0.0000	0.0027	0.0004	0.0031	3	326.8	1307
20	35M:65F (default)	77	3.85	Jemez	0.0008	0.0006	0.0213	0.0281	0.0493	3	20	81
20	24M:76F (Jemez)	30	1.47	Default	0.0001	0.0000	0.0007	0.0002	0.0009	3	1136.4	4545
20	24M:76F (Jemez)	30	1.47	Jemez	0.0008	0.0006	0.0057	0.0128	0.0185	3	54.1	216
20	24M:76F (Jemez)	77	3.85	Default	0.0001	0.0000	0.0019	0.0004	0.0023	3	440.5	1762
20	24M:76F (Jemez)	77	3.85	Jemez	0.0008	0.0006	0.0146	0.0329	0.0474	3	21	84
32	35M:65F (default)	47	1.47	Default	0.0001	0.0000	0.0015	0.0002	0.0017	3	581.4	2326
32	35M:65F (default)	47	1.47	Jemez	0.0007	0.0005	0.0120	0.0158	0.0278	3	35.9	144
32	35M:65F (default)	125	3.85	Default	0.0001	0.0000	0.0041	0.0005	0.0046	3	217.9	871
32	35M:65F (default)	125	3.85	Jemez	0.0007	0.0005	0.0319	0.0421	0.0740	3	13.5	54
32	24M:76F (Jemez)	47	1.47	Default	0.0001	0.0000	0.0010	0.0002	0.0013	3	781.3	3125
32	24M:76F (Jemez)	47	1.47	Jemez	0.0007	0.0005	0.0082	0.0185	0.0267	3	37.4	150
32	24M:76F (Jemez)	125	3.85	Default	0.0001	0.0000	0.0028	0.0006	0.0034	3	294.1	1176
32	24M:76F (Jemez)	125	3.85	Jemez	0.0007	0.0005	0.0219	0.0493	0.0711	3	14.1	56
85	35M:65F (default)	125	1.47	Default	0.0001	0.0000	0.0032	0.0004	0.0036	3	276.2	1105
85	35M:65F (default)	125	1.47	Jemez	0.0006	0.0004	0.0251	0.0332	0.0584	3	17.1	69
85	24M:76F (Jemez)	125	1.47	Default	0.0001	0.0000	0.0022	0.0005	0.0027	3	373.1	1493
85	24M:76F (Jemez)	125	1.47	Jemez	0.0006	0.0004	0.0172	0.0389	0.0561	3	17.8	71

* CHHR denotes potential sizes of core habitat home range based on herd size and density where 95% of use is likely to happen. Movement outside the CHHR is considered a foray, with the Jemez forays representing movement behavior of a translocated herd and the default representing behavior of established herds.

Table 8: Estimated maximum annual rate of contact with domestic sheep or goats at the closest known allotment outside the JAN, for various demographic and foray scenarios.

					Est. max annual contact rates via foray-outside Jicarilla							
CHHR size (km^2)	Herd demographics	Herd Size	Density	Foray	Single Ram	Single Ewe	All Rams	All Ewes	Herd	Allotment Dist (km)	Time to contact (years)	Time to outbreak* (years)
20	35M:65F (default)	30	1.47	Default	0	0	0.0005	0.0001	0.0005	34	1923.1	7692
20	35M:65F (default)	30	1.47	Jemez	0	0.0018	0	0.0342	0.0342	35	29.3	117
20	35M:65F (default)	77	3.85	Default	0	0	0.0012	0.0001	0.0013	34	751.9	3008
20	35M:65F (default)	77	3.85	Jemez	0	0.0018	0	0.0877	0.0877	35	11.4	46
20	24M:76F (Jemez)	30	1.47	Default	0	0	0.0003	0.0001	0.0004	33	2631.6	10526
20	24M:76F (Jemez)	30	1.47	Jemez	0	0.0018	0	0.0399	0.0399	35	25	100
20	24M:76F (Jemez)	77	3.85	Default	0	0	0.0007	0.0002	0.0010	33	1010.1	4040
20	24M:76F (Jemez)	77	3.85	Jemez	0	0.0018	0	0.1025	0.1025	35	9.8	39
32	35M:65F (default)	47	1.47	Default	0	0	0.0007	0.0001	0.0008	34	1265.8	5063
32	35M:65F (default)	47	1.47	Jemez	0	0.0017	0	0.0525	0.0525	35	19.1	76
32	35M:65F (default)	125	3.85	Default	0	0	0.0019	0.0002	0.0021	34	473.9	1896
32	35M:65F (default)	125	3.85	Jemez	0	0.0017	0	0.1396	0.1396	35	7.2	29
32	24M:76F (Jemez)	47	1.47	Default	0	0	0.0005	0.0002	0.0006	33	1666.7	6667
32	24M:76F (Jemez)	47	1.47	Jemez	0	0.0017	0	0.0614	0.0614	35	16.3	65
32	24M:76F (Jemez)	125	3.85	Default	0	0	0.0012	0.0004	0.0016	33	628.9	2516
32	24M:76F (Jemez)	125	3.85	Jemez	0	0.0017	0	0.1632	0.1632	35	6.1	25
85	35M:65F (default)	125	1.47	Default	0.0001	0	0.0024	0.0006	0.0030	32	338	1351
85	35M:65F (default)	125	1.47	Jemez	0	0.0019	0	0.1571	0.1571	35	6.4	25
85	24M:76F (Jemez)	125	1.47	Default	0.0001	0	0.0016	0.0007	0.0023	32	432.9	1732
85	24M:76F (Jemez)	125	1.47	Jemez	0	0.0019	0	0.1837	0.1837	35	5.4	22

* CHHR denotes potential sizes of core habitat home range based on herd size and density where 95% of use is likely to happen. Movement outside the CHHR is considered a foray, with the Jemez forays representing movement behavior of a translocated herd and the default representing behavior of established herds.

The results from the RoCT demonstrate how rate of contact is highly dependent on herd size, density, demographics, and foray behavior. Foray behavior is the most influential in contact risk and animals who make more frequent and/or farther forays significantly increase the risk of contact, which is behavior more common in introduced or translocated individuals (Fig. 16). In the case of the Jemez herd, 100% of collared individuals conducted forays (n = 26; 2 males, 24 females) and with respect to animal-years, the foray probability was 100% for males (n = 6) and 84.7% for females (n = 59). The maximum distance an individual traveled beyond their home range was 39 km for females and 26 km for males. Comparatively, for the established Hells Canyon herds, the animal-year foray probability was 14.1% for males and 1.5% for females during the summer and 31.9% for males and 7.1% for females year-round (O'Brien et al. 2014, 2021; Appendix D). The analysis of the bighorn sheep in the Jemez revealed movements and home ranges of relocated bighorn sheep began to stabilize around 4 months post-translocation, but took 7-8 months to localize (Appendix C, Figs. C3 & C6). Aside from foray behavior, herd size is the second most influential factor in risk of contact and as herd size or density increases, the rate of contact increases, especially if the area the sheep occupy increases or the probability of making forays is high (Fig. 16).

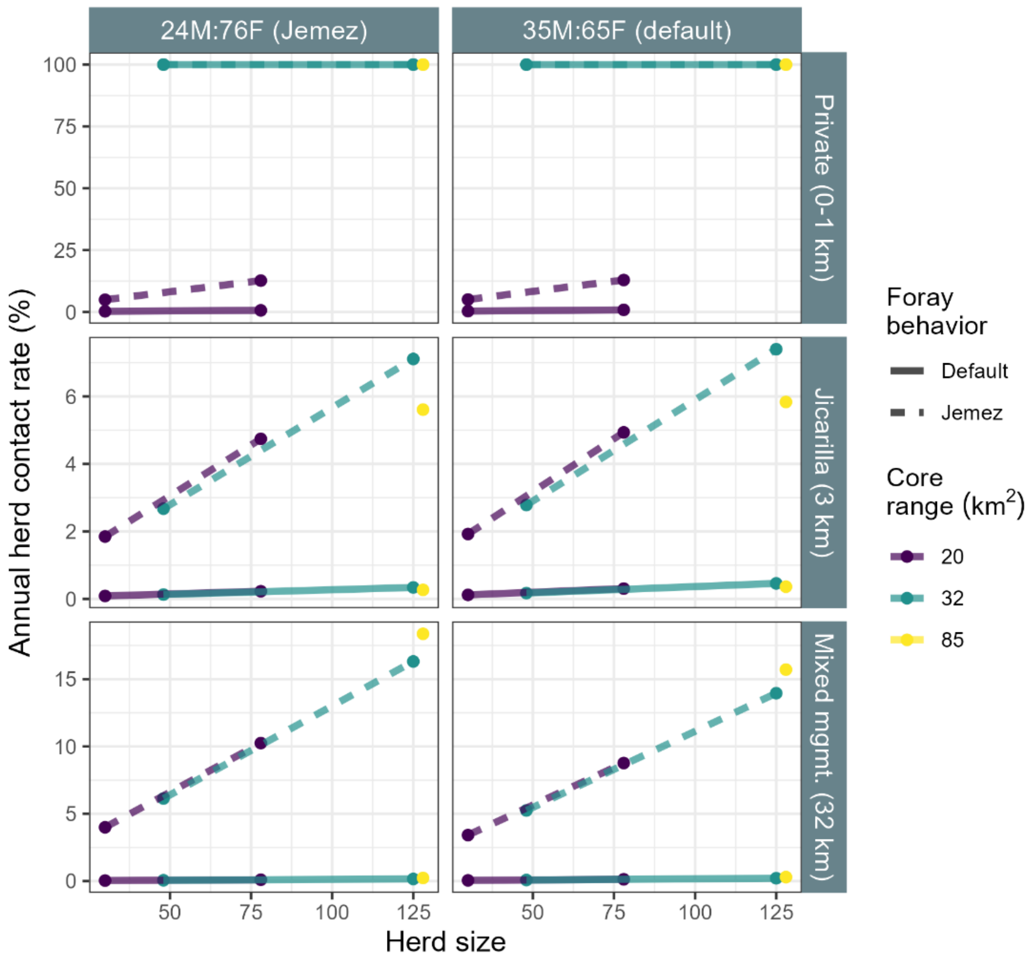


Figure 16. Estimated annual herd contact rate with domestic sheep or goat parcels in different demographic, spatial, and foray behavior scenarios, relative to each of the three closest known parcels with or approved for domestic sheep or goat grazing.

The cost-distance analysis conducted on the sheep in the Jemez revealed individuals used areas with habitat (cost) values as low as 50 during the first four months after introduction, but after four months, the sheep used better quality habitat with less cost, only using areas with a value of 81 or higher. Thus, we evaluated the number of domestic sheep and goat parcels within three different cost thresholds surrounding an 80 km expansion of the study area: 50, 81, and 91 (Anderson et al. 2022; Fig. 17). The cost threshold of 50 included 67.3% or 35 out of 52 domestic sheep and goat parcels, while only two or 3.8% of parcels fell within the cost threshold of 91 (and thus 81 as well; Fig. 17). Many of the parcels within the risk threshold of 50 are along the periphery of the 80 km buffer around the study area and thus, because the likelihood of a sheep travelling 80 km is a rare occurrence, the number of parcels within 40 km of the study area in the risk threshold of 50 is 4 (7.7%), but there are a handful of parcels just beyond 40 km from the study area boundary as well. The two parcels within 91 and 81 thresholds are the same hobby farms immediately adjacent to the study area, but the amount of risk for the parcel south of highway 64 varies between the two analyses—the RoCT identifies this parcel as having less of a risk than the parcel off River Road and the parcel 32 km away, but the cost-distance analysis identifies the risk value being equal and being within range of what actual bighorn sheep have used in both literature and in the Jemez analysis.

Discussion

The majority of the study area is within preferred proximity to escape terrain and water and contains sufficient terrain ruggedness for bighorn sheep. The most limiting landscape factor within the area of interest is horizontal visibility and cover, specifically shrub cover. The dominance of Gambel oak and other shrubs is likely a result of the relationship between fire severity and successional patterns. Relative to woody and herbaceous biomass, more frequent low to moderate severity burns increase herbaceous growth, while infrequent, high-severity burns typically result in initial herbaceous growth, followed by shrub dominated regeneration 5-20+ years post-burn (Hibbs and Jacobs 2011, Minor et al. 2017). The largest quantities of high-quality potential bighorn sheep habitat within the study area occur in unburned areas or those burnt by the predominantly low to moderate severity Amargo fire in 2021.

The area of interest has steep elevation gain and narrow valley bottoms which limit the quantity of snow-free areas in winter. These narrow valley bottoms also tend to be where the most heavily trafficked roads are within the study area, so if bighorn sheep are introduced, it should be anticipated they will be near vehicles and possibly residential areas in winter. The size of a potential bighorn sheep herd within the study area is likely to be limited by the amount of available winter habitat. When temperatures become milder with climate change, the amount of available winter habitat may slightly increase, but it is uncertain how long this would take. It is also of note, the scale of the SNODAS data available and used in this analysis is fairly large (1-km x 1-km) and does not match the smaller scale of most habitat patches, thus, the snow depth data may be too homogenous to capture micro-climates created by small changes in topography, aspect, tree cover, and shade. Currently, no finer scale remotely sensed resolution data exist. Because of the mismatch in scales, our estimates of snow-free areas (or areas with $\leq$ 16 or 25 cm of snow) are likely to be underestimates.

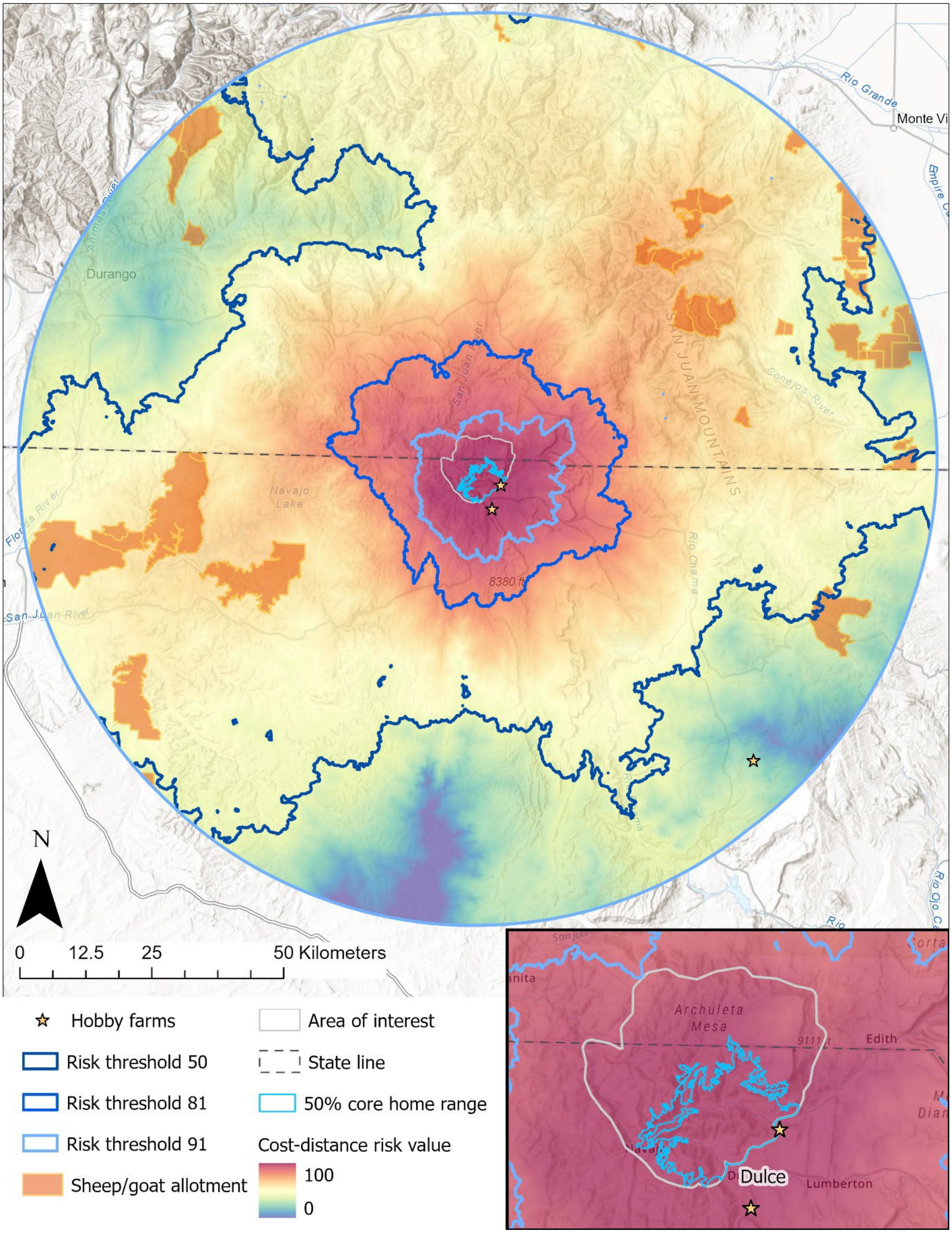


Figure 17. Cost-distance map depicting a transformed predicted habitat map relative to domestic sheep and goat locations and risk threshold based on values determined for sheep in the Jemez herd and the Sierra Nevada Mountains (Anderson et al. 2022).

While potential habitat exists with the study area, potential risk of contact with domestic sheep or goats is of critical importance when considering an introduction effort. If introduced, foray behaviors and sex ratios of bighorn sheep will likely be similar to those of the Jemez population. Thus, more frequent and farther forays are to be expected, as is the use of less preferred habitat upon initial release, as part of the process of sheep establishing themselves on the landscape. However, there are instances of relocation efforts where most (75%) of translocated individuals did not disperse within three years, although, no dispersal does not necessarily mean no extra-home range forays (Dwinnell et al. 2021). In literature and within our analysis of the Jemez population, it appears most large forays from relocated sheep occur within one-year post-release (DeCesare et al. 2006, Dwinnell et al. 2021, Werdel et al. 2021, Appendix C Fig. C2) and males, particularly older males, typically foray more frequently or make large dispersal movements (O'Brien et al. 2014, Appendix C).

To avoid potential transmission of respiratory disease, general recommendation is to be > 23 km from domestic sheep and goats, but values (with varying success) in literature range from 13.5 km to 35 km (Zeigenfuss et al. 2000, MTFWP 2010, WAFWA 2012). Only 2-3 parcels with domestic sheep or goats fall within this distance in study area, however, any contact with domestic sheep and goats is of serious concern as transmission and contraction of pneumonia would likely make costly introduction efforts futile. Of particular concern is the potential core home range of reintroduced sheep likely overlapping in space with the parcel containing domestic goats off the River Road. Both the RoCT and the cost-distance analysis assume domestics can come freely into contact with wild sheep either free range or with current fencing structures at parcels. However, some fencing configurations are considered effective at reducing contact between wild and domestic sheep, such as an outer and inner fence spaced at least 3 m apart to prevent physical contact and inhalation of respiratory droplets, in addition to the outer fence being tall enough wild sheep cannot jump over (> 2.5 m; MTFWP 2010). A minimum height of 2.5 m is also recommended by the Wild Sheep Foundation, but in personal communication with Dr. Paul Krausman (professor emeritus, University of Arizona and University of Montana), he witnessed yearlings clearing fences of this height when studying desert bighorn sheep in captivity. Additionally, routine testing for respiratory pathogens in domestics may be feasible with a limited number of small flocks or hobby farms prior and post-introduction efforts. Both efforts obviously require the cooperation of owners and additional expenses but given the high potential risk of transmission, are options to explore and are necessary if introduction of bighorn sheep is desired.

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Appendix A: Supplementary figures and tables for analyses of potential bighorn sheep habitat

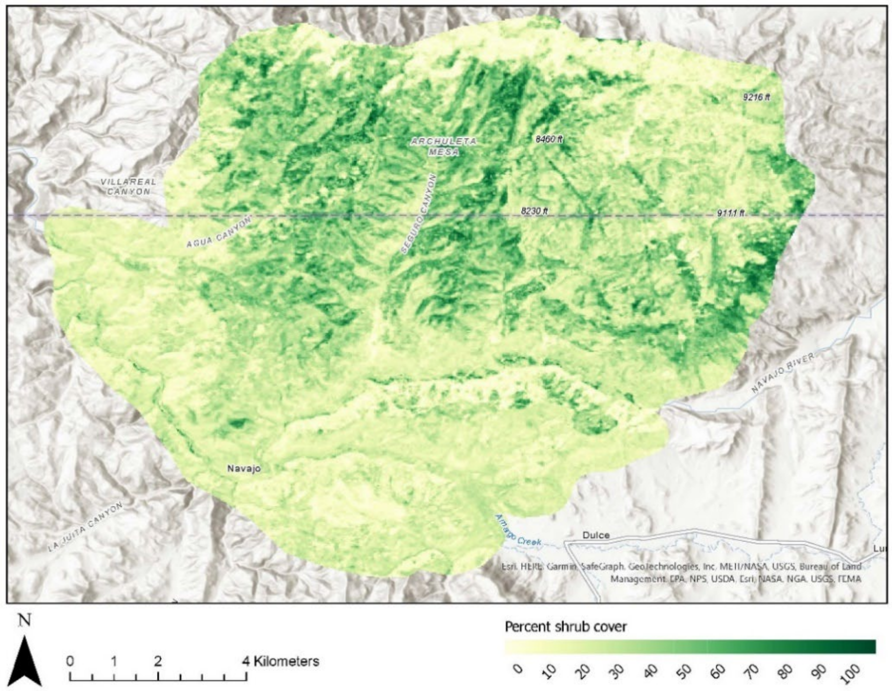

Figure A1. 30 m resolution percent shrub cover derived from 2022 Rangeland Analysis Platform continuous vegetation cover imagery.

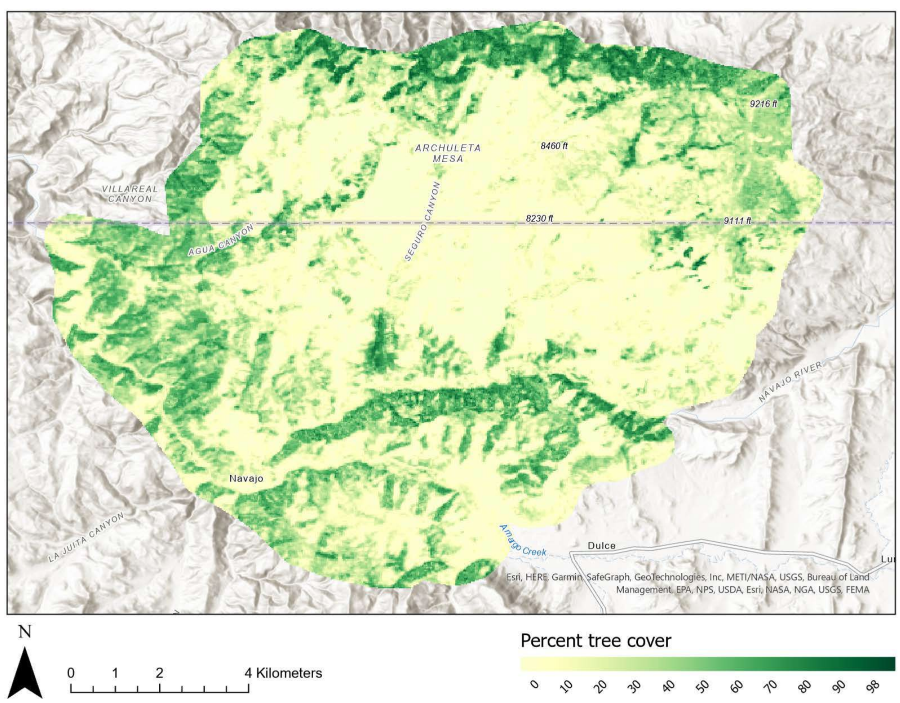

Figure A2. 30 m resolution percent tree cover derived from 2022 Rangeland Analysis Platform continuous vegetation cover imagery.

Figure A3. Input parameters within the transformation pane of the suitability modeler tool in ArcPro for distance to escape terrain ≥ 51% (top), Rangeland Analysis Platform maximum vegetation cover (second from top), distance from perennial water (third down), and the terrain ruggedness index (TRI; bottom).

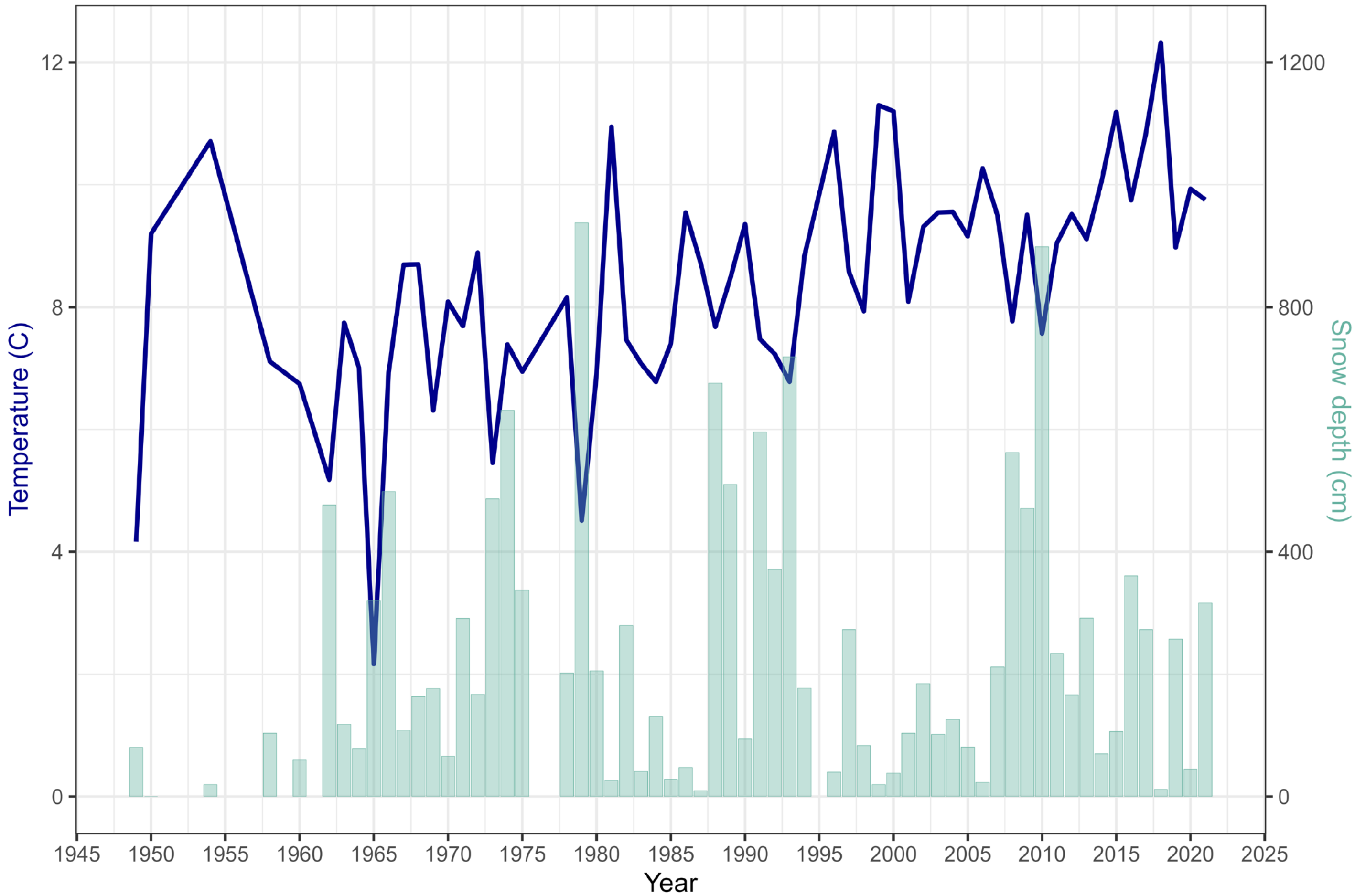

Figure A4. Mean total snow depth relative to average daily maximum temperature for winter (November-March 1948-2021).

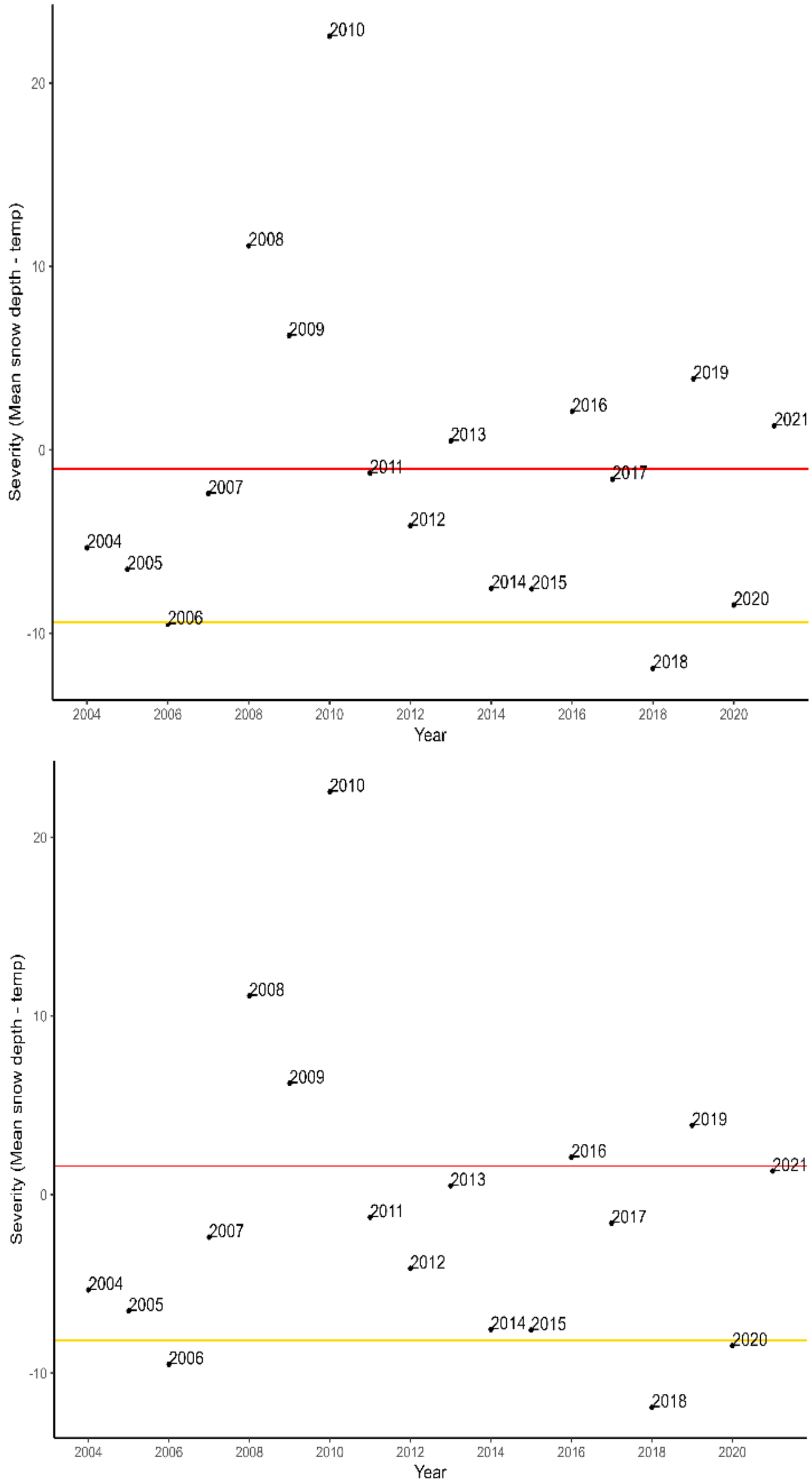

Figure A5. Classification of winter severity since 2003 relative to the recent (top) and historical (bottom) averages (red line) and one standard deviation below the average (yellow line).

Table A1. Area calculations for primary potential winter range (PPWR) and maximum potential winter range (MPWR) within the area of interest (AOI) and proportion of potential habitat (PH) for each escape terrain definition based off recent averages.

51% Slope																
Duration of winter	≥60%				≥75%				≥90%				100%			
	Area (km^2)	% of AOI	% of PH	% of PWR	Area (km^2)	% of AOI	% of PH	% of PWR	Area (km^2)	% of AOI	% of PH	% of PWR	Area (km^2)	% of AOI	% of PH	% of PWR
Mild																
< 25cm of snow in PPWR	17.49	14.29	56.07	100	17.49	14.29	56.07	100	17.49	14.29	56.07	100	17.49	14.29	56.07	100
< 25cm of snow in MPWR	19.63	16.04	55.73	100	19.63	16.04	55.73	100	19.63	16.04	55.73	100	19.63	16.04	55.73	100
< 16cm of snow in PPWR	17.49	14.29	56.07	100	17.49	14.29	56.07	100	17.49	14.29	56.07	100	17.31	14.15	55.51	99.00
< 16cm of snow in MPWR	19.63	16.04	55.73	100	19.63	16.04	55.73	100	19.63	16.04	55.73	100	19.40	15.85	55.09	98.84
Average																
< 25cm of snow in PPWR	17.19	14.04	55.10	98.27	17.12	13.99	54.89	97.90	17.04	13.93	54.64	97.44	16.12	13.18	51.69	92.20
< 25cm of snow in MPWR	19.13	15.63	54.31	97.45	18.91	15.45	53.68	96.32	18.85	15.41	53.53	96.06	17.43	14.24	49.49	88.79
< 16cm of snow in PPWR	16.22	13.26	52.01	92.76	15.32	12.52	49.13	87.63	14.93	12.20	47.88	85.40	14.63	11.95	46.90	83.64
< 16cm of snow in MPWR	17.56	14.35	49.85	89.45	16.54	13.51	46.95	84.24	16.12	13.17	45.76	82.11	15.42	12.60	43.77	78.53
Severe																
< 25cm of snow in PPWR	15.13	12.36	48.51	86.51	1.04	0.85	3.32	5.93	0	0	0	0	0	0	0	0
< 25cm of snow in MPWR	16.16	13.20	45.88	82.31	1.06	0.86	3.00	5.38	0	0	0	0	0	0	0	0
< 16cm of snow in PPWR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
< 16cm of snow in MPWR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55% Slope																
Duration of winter	≥60%				≥75%				≥90%				100%			
	Area (km^2)	% of AOI	% of PH	% of PWR	Area (km^2)	% of AOI	% of PH	% of PWR	Area (km^2)	% of AOI	% of PH	% of PWR	Area (km^2)	% of AOI	% of PH	% of PWR
Mild																
< 25cm of snow in PPWR	16.65	13.60	55.93	100	16.65	13.60	55.93	100	16.65	13.60	55.93	100	16.65	13.60	55.93	100
< 25cm of snow in MPWR	19.07	15.59	55.65	100	19.07	15.59	55.65	100	19.07	15.59	55.65	100	19.07	15.59	55.65	100
< 16cm of snow in PPWR	16.65	13.60	55.93	100	16.65	13.60	55.93	100	16.65	13.60	55.93	100	16.47	13.46	55.34	98.95
< 16cm of snow in MPWR	19.07	15.59	55.65	100	19.07	15.59	55.65	100	19.07	15.59	55.65	100	18.85	15.40	54.99	98.81
Average																
< 25cm of snow in PPWR	16.35	13.36	54.93	98.21	16.29	13.31	54.73	97.86	16.20	13.24	54.45	97.35	15.38	12.57	51.67	92.38
< 25cm of snow in MPWR	18.57	15.18	54.20	97.38	18.37	15.01	53.60	96.31	18.32	14.97	53.46	96.07	16.95	13.85	49.45	88.85
< 16cm of snow in PPWR	15.48	12.65	52.01	92.99	14.59	11.92	49.02	87.65	14.20	11.60	47.70	85.28	13.90	11.36	46.72	83.53
< 16cm of snow in MPWR	17.08	13.95	49.83	89.53	16.07	13.13	46.88	84.24	15.67	12.81	45.74	82.19	15.00	12.26	43.76	78.63

Severe																
< 25cm of snow in PPWR	14.41	11.77	48.40	86.54	0.99	0.81	3.33	5.95	0	0	0	0	0	0	0	0
< 25cm of snow in MPWR	15.78	12.89	46.03	82.72	1.05	0.86	3.06	5.49	0	0	0	0	0	0	0	0
< 16cm of snow in PPWR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
< 16cm of snow in MPWR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

60% slope

Duration of winter	≥60%				≥75%				≥90%				100%			
	Area (km^2)	% of AOI	% of PH	% of PWR	Area (km^2)	% of AOI	% of PH	% of PWR	Area (km^2)	% of AOI	% of PH	% of PWR	Area (km^2)	% of AOI	% of PH	% of PWR
Mild																
< 25cm of snow in PPWR	15.74	12.87	55.91	100	15.74	12.87	55.91	100	15.74	12.87	55.91	100	15.74	12.87	55.91	100
< 25cm of snow in MPWR	18.40	15.04	55.67	100	18.40	15.04	55.67	100	18.40	15.04	55.67	100	18.40	15.04	55.67	100
< 16cm of snow in PPWR	15.74	12.87	55.91	100	15.74	12.87	55.91	100	15.74	12.87	55.91	100	15.57	12.72	55.29	98.89
< 16cm of snow in MPWR	18.40	15.04	55.67	100	18.40	15.04	55.67	100	18.40	15.04	55.67	100	18.18	14.85	54.98	98.77
Average																
< 25cm of snow in PPWR	15.45	12.63	54.86	98.13	15.39	12.58	54.66	97.77	15.31	12.51	54.38	97.27	14.56	11.90	51.70	92.47
< 25cm of snow in MPWR	17.91	14.63	54.16	97.29	17.71	14.47	53.57	96.24	17.67	14.44	53.44	96.00	16.34	13.35	49.41	88.77
< 16cm of snow in PPWR	14.66	11.98	52.04	93.09	13.84	11.31	49.15	87.91	13.46	11.00	47.79	85.48	13.07	10.68	46.42	83.03
< 16cm of snow in MPWR	16.48	13.46	49.84	89.53	15.51	12.67	46.90	84.25	15.09	12.33	45.65	82.01	14.36	11.73	43.42	78.01
Severe																
< 25cm of snow in PPWR	13.64	11.15	48.43	86.63	0.89	0.72	3.15	5.63	0	0	0	0	0	0	0	0
< 25cm of snow in MPWR	15.30	12.50	46.28	83.14	0.94	0.76	2.83	5.09	0	0	0	0	0	0	0	0
< 16cm of snow in PPWR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
< 16cm of snow in MPWR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A2. Area calculations for primary potential winter range (PPWR) and maximum potential winter range (MPWR) within the area of interest (AOI) and proportion of potential habitat (PH) for each escape terrain definition based off historical averages.

51% Slope																
Duration of winter	≥60%				≥75%				≥90%				100%			
	Area (km^2)	% of AOI	% of PH	% of PWR	Area (km^2)	% of AOI	% of PH	% of PWR	Area (km^2)	% of AOI	% of PH	% of PWR	Area (km^2)	% of AOI	% of PH	% of PWR
Mild																
< 25cm of snow in PPWR	17.49	14.29	56.07	100	17.49	14.29	56.07	100	17.48	14.28	56.04	99.95	17.15	14.02	54.99	98.08
< 25cm of snow in MPWR	19.63	16.04	55.73	100	19.63	16.04	55.73	100	19.62	16.03	55.71	99.96	19.06	15.57	54.11	97.09
< 16cm of snow in PPWR	17.26	14.11	55.35	98.71	17.14	14.01	54.96	98.01	17.12	13.99	54.89	97.89	14.26	11.65	45.72	81.54
< 16cm of snow in MPWR	19.30	15.77	54.80	98.32	19.05	15.56	54.08	97.03	18.91	15.45	53.69	96.33	15.21	12.43	43.18	77.47
Average																
< 25cm of snow in PPWR	17.19	14.05	55.11	98.29	17.12	13.99	54.89	97.90	17.05	13.93	54.66	97.48	16.12	13.18	51.69	92.20
< 25cm of snow in MPWR	19.18	15.67	54.46	97.71	18.91	15.45	53.69	96.34	18.81	15.37	53.40	95.82	17.43	14.24	49.48	88.77
< 16cm of snow in PPWR	16.23	13.26	52.03	92.80	15.15	12.38	48.56	86.61	14.80	12.10	47.46	84.65	11.29	9.23	36.20	64.56
< 16cm of snow in MPWR	17.56	14.35	49.85	89.44	16.33	13.35	46.37	83.20	15.99	13.07	45.39	81.45	12.33	10.08	35.01	62.83
Severe																
< 25cm of snow in PPWR	14.27	11.66	45.74	81.58	0	0	0	0	0	0	0	0	0	0	0	0
< 25cm of snow in MPWR	15.26	12.47	43.33	77.75	0	0	0	0	0	0	0	0	0	0	0	0
< 16cm of snow in PPWR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
< 16cm of snow in MPWR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
55% Slope																
Duration of winter	≥60%				≥75%				≥90%				100%			
	Area (km^2)	% of AOI	% of PH	% of PWR	Area (km^2)	% of AOI	% of PH	% of PWR	Area (km^2)	% of AOI	% of PH	% of PWR	Area (km^2)	% of AOI	% of PH	% of PWR
Mild																
< 25cm of snow in PPWR	16.65	13.60	55.93	100	16.65	13.60	55.93	100	16.64	13.60	55.90	99.95	16.32	13.33	54.83	98.03
< 25cm of snow in MPWR	19.07	15.59	55.65	100	19.07	15.59	55.65	100	19.06	15.58	55.63	99.96	18.52	15.14	54.05	97.12
< 16cm of snow in PPWR	16.43	13.43	55.20	98.70	16.31	13.33	54.80	97.98	16.29	13.31	54.73	97.86	13.54	11.07	45.51	81.36

< 16cm of snow in MPWR	18.76	15.33	54.74	98.36	18.51	15.13	54.02	97.06	18.37	15.02	53.62	96.34	14.83	12.12	43.26	77.74
Average																
< 25cm of snow in PPWR	16.35	13.36	54.94	98.22	16.29	13.31	54.74	97.86	16.21	13.25	54.47	97.39	15.38	12.57	51.69	92.41
< 25cm of snow in MPWR	18.62	15.22	54.35	97.65	18.37	15.01	53.61	96.32	18.27	14.93	53.33	95.82	16.94	13.85	49.44	88.83
< 16cm of snow in PPWR	15.49	12.66	52.04	93.04	14.41	11.77	48.42	86.56	14.06	11.49	47.26	84.50	10.87	8.88	36.52	65.30
< 16cm of snow in MPWR	17.07	13.95	49.82	89.52	15.89	12.98	46.36	83.30	15.54	12.70	45.36	81.50	12.06	9.85	35.19	63.23
Severe																
< 25cm of snow in PPWR	13.56	11.08	45.55	81.44	0	0	0	0	0	0	0	0	0	0	0	0
< 25cm of snow in MPWR	14.89	12.17	43.44	78.06	0	0	0	0	0	0	0	0	0	0	0	0
< 16cm of snow in PPWR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
< 16cm of snow in MPWR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60% Slope																
Duration of winter	≥60%				≥75%				≥90%				100%			
	Area (km^2)	% of AOI	% of PH	% of PWR	Area (km^2)	% of AOI	% of PH	% of PWR	Area (km^2)	% of AOI	% of PH	% of PWR	Area (km^2)	% of AOI	% of PH	% of PWR
Mild																
< 25cm of snow in PPWR	15.74	12.87	55.91	100	15.74	12.87	55.91	100	15.74	12.86	55.88	99.95	15.42	12.60	54.76	97.94
< 25cm of snow in MPWR	18.40	15.04	55.67	100	18.40	15.04	55.67	100	18.40	15.03	55.64	99.95	17.86	14.60	54.03	97.06
< 16cm of snow in PPWR	15.53	12.69	55.15	98.63	15.41	12.60	54.74	97.90	15.39	12.58	54.66	97.77	12.82	10.48	45.53	81.44
< 16cm of snow in MPWR	18.10	14.79	54.74	98.33	17.85	14.59	53.99	97.00	17.72	14.48	53.60	96.29	14.36	11.74	43.45	78.05
Average																
< 25cm of snow in PPWR	15.45	12.63	54.87	98.14	15.39	12.58	54.66	97.77	15.32	12.52	54.41	97.31	14.56	11.90	51.71	92.48
< 25cm of snow in MPWR	17.96	14.67	54.32	97.57	17.71	14.48	53.58	96.26	17.62	14.40	53.30	95.75	16.35	13.36	49.44	88.82
< 16cm of snow in PPWR	14.66	11.98	52.07	93.13	13.67	11.17	48.53	86.81	13.33	10.89	47.33	84.65	10.30	8.42	36.58	65.43
< 16cm of snow in MPWR	16.47	13.46	49.83	89.52	15.31	12.51	46.30	83.17	14.96	12.23	45.26	81.31	11.68	9.55	35.34	63.48
Severe																
< 25cm of snow in PPWR	12.82	10.47	45.52	81.41	0	0	0	0	0	0	0	0	0	0	0	0

< 25cm of snow in MPWR	14.40	11.76	43.54	78.22	0	0	0	0	0	0	0	0	0	0	0	0
< 16cm of snow in PPWR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
< 16cm of snow in MPWR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A3. Comparison of woody vegetation cover within the study area from 2022 Rangeland Analysis Platform's continuous vegetation cover imagery. Maximum cover depicts the maximum cover value across tree and shrub layers.

Metric	**> 30% cover**	**> 35% cover**	**> 40% cover**
Maximum cover	46.7%	38.3%	30.2%
Shrub cover	26.3%	20.0%	15.1%
Tree cover	22.4%	18.7%	15.2%

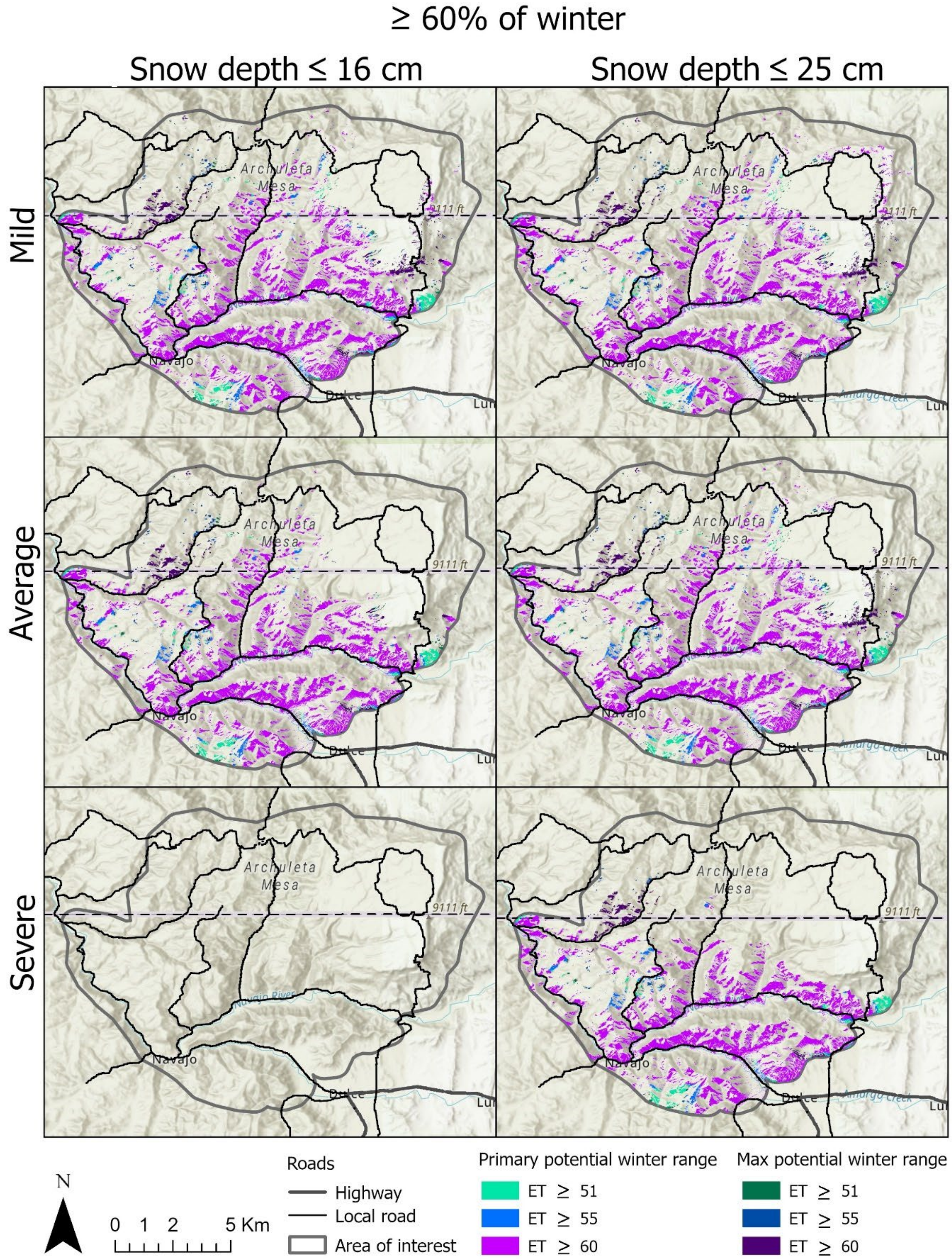

Figure A6. Primary potential and maximum potential winter range depicting areas of preferred habitat and snow depth for ≥ 60% of winter (Nov-March) based on historical normals (past 80 years) for each escape terrain (ET) definition.

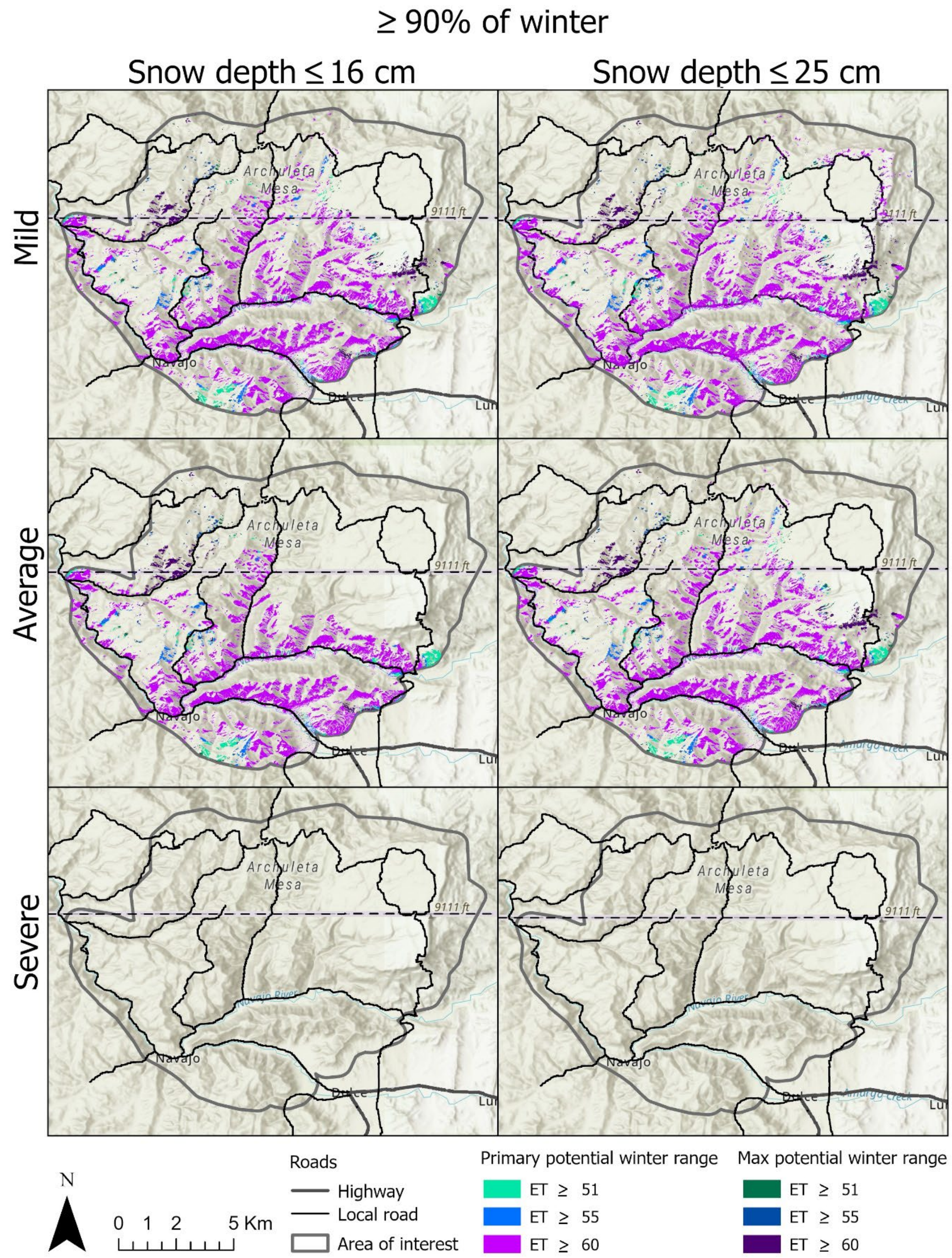

Figure A7. Primary potential and maximum potential winter range depicting areas of preferred habitat and snow depth for ≥ 90% of winter (Nov-March) based on historical normals (past 80 years) for each escape terrain (ET) definition.

Appendix B: Supplementary figures and tables for vegetation assessment

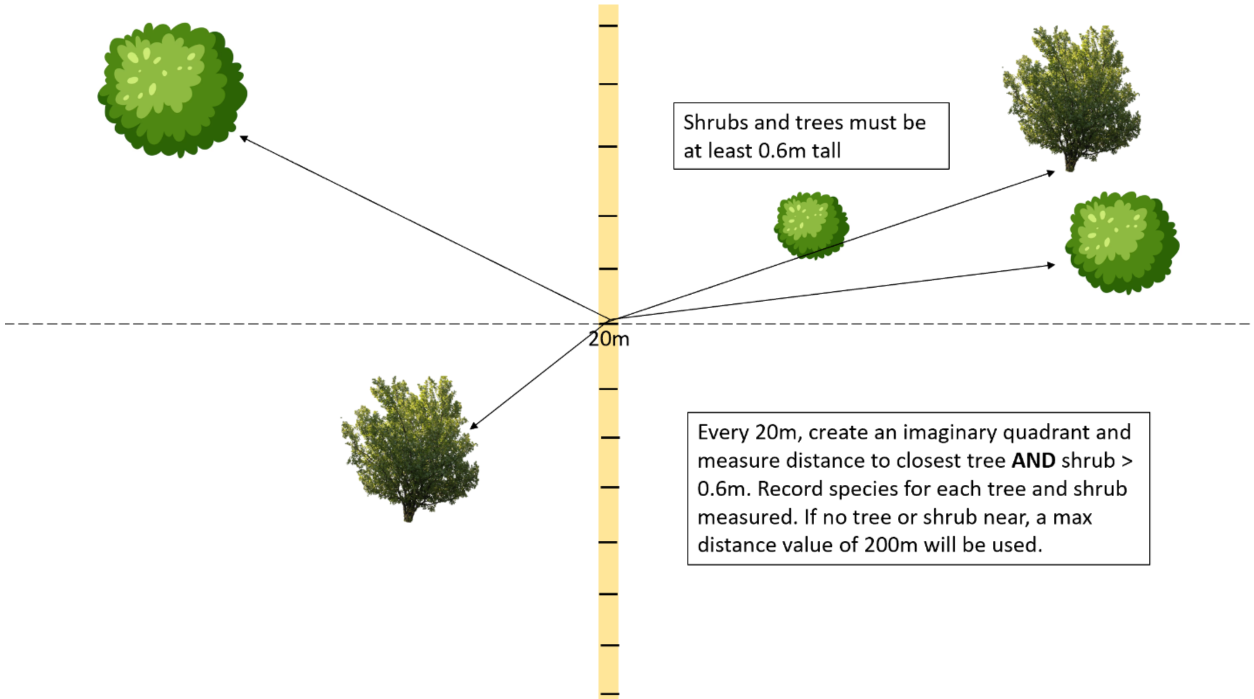

Figure B1. Diagram of point-center quarter method (Cottom and Curtis 1956, Khan et al. 2016) to estimate tree and shrub density.

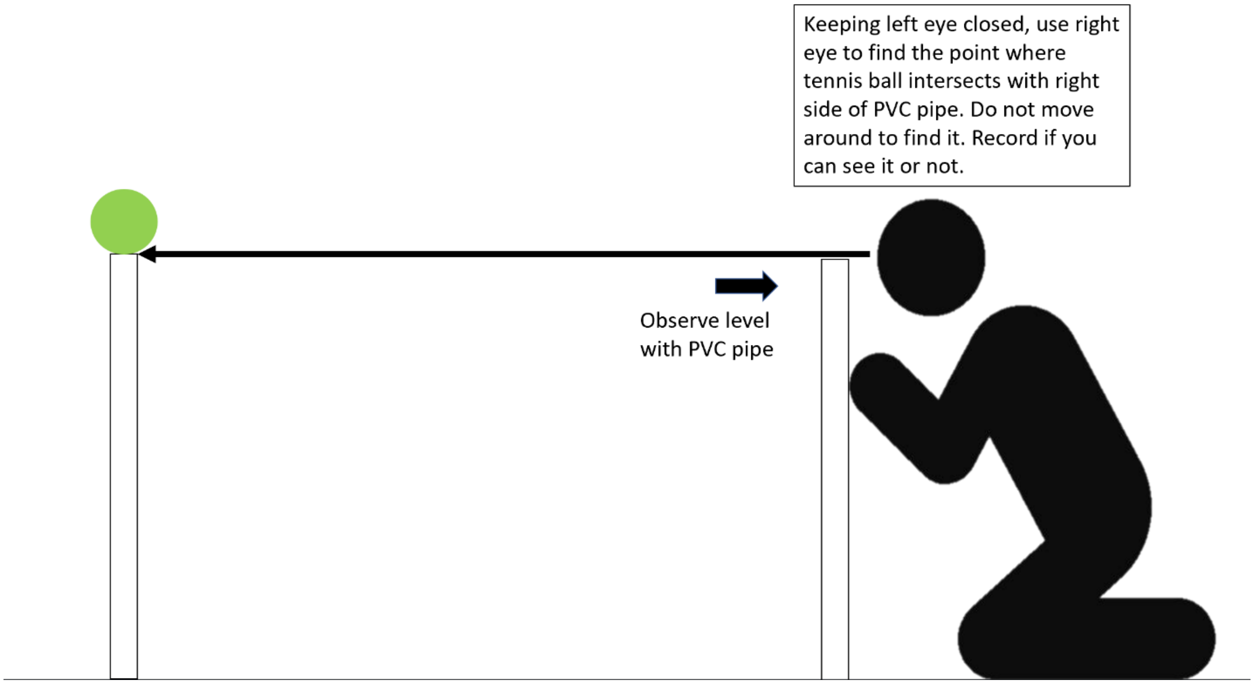

Figure B2. Diagram of ball and staff method (Collins and Becker 2001, Pop 2020) for assessing horizontal visibility.

Table B1. Species encountered and recorded in forage availability plots with corresponding quality designation based on palatability and nutritional value, source(s), and 4-letter USDA plant code. In-depth information on nutritional value and preference can be found for each species using the USFS Fire Effects Information System under "Management Considerations".

Plant code	Species	Quality	Domestic sheep used as proxy?	Source
ABCO	*Abies concolor*	Poor	N	Lamb 1971, Eyre 1980
ACGL	*Acer glabrum*	Moderate	Y	Orme and Ragain 1982, Dittberner and Olson 1983
ACNE	*Acer negundo*	Poor	Y	Dittberner and Olson 1983
ALIN	*Alnus incana*	Poor	N	Haeussler and Coates 1990, Hansen et al. 1995
AMUT	*Amelanchier utahensis*	Good	N	Gullion 1964
ARCA	*Artemisia cana*	Moderate	N	Fairaizl 1978, Hansen et al. 1988
ARFR	*Artemisia frigida*	Good	N	USDA 1937, Bayless 1971, Blower 1982
ARLU	*Artemisia ludoviciana*	Moderate	Y	Bezeau and Johnston 1962, Dittberner and Olson 1983
ARTR	*Artemisia tridentata*	Moderate	Y	Sheehy and Winward 1981, Welch et al. 1987
BEFE	*Berberis fendleri*	Moderate	N	Martin et al. 1951
CEFE	*Ceanothus fendleri*	Good	N	Elmore 1976
CEMO	*Cercocarpus montanus*	Good	N	Risenhoover and Bailey 1986, Rominger et al. 1988
CHRY	*Chrysothamnus spp.*	Moderate	Y	Dittberner and Olson 1983, McArthur and Meyer 1987
COSE	*Cornus sericea*	Good	N	Stelfox 1976, Hansen et al. 1995, Pardo et al. 2005
CRAT	*Crataegus* spp.	Moderate	Y	Dittberner and Olson 1983
FERU	*Fendlera rupicola*	Good	N	Kearney et al. 1960
GUSA	*Gutierrezia sarothrae*	Poor	N	Dittberner and Olson 1983, Keating et al. 1985
JUMO	*Juniperus monosperma*	Poor	N	Rushing 1977, Dittberner and Olson 1983
JUSC	*Juniperus scopulorum*	Poor	N	Randles 1949, Dittberner and Olson 1983
KRLA	*Krascheninnikovia lanata*	Good	N	Cook et al. 1954, Fairaizl 1978, Keating et al. 1985
LIPU	*Linanthus pungens*	Poor	N	Dayton 1931, Lauer and Peek 1976, Dittberner and Olson 1983
MARE	*Berberis aquifolium*	Moderate	N	Tilton and Willard 1981, Dittberner and Olson 1983, Hansen et al. 1995
OPUN	*Opuntia* spp.	Good	N	Hanselka 1989, Tarango et al. 2002, Sipango et al. 2022

PAMY	*Paxistima myrsinites*	Moderate	N	Vines 1960, Dittberner and Olson 1983
PECR	*Penstemon crandallii*	Moderate	N	Ogle 2002
PIED	*Pinus edulis*	Poor	Y	Dittberner and Olson 1983
PIEN	*Picea engelmannii*	Poor	N	Dittberner and Olson 1983, Alexander 1987
PIPO	*Pinus ponderosa*	Poor	N	Atzet and Wheeler 1984, Barrett 1985
POPU	*Populus* spp.	Moderate	N	Carey and Gill 1980, Dittberner and Olson 1983
POTR	*Populus tremuloides*	Good	N	USDA 1937, Tew 1970
PRVI	*Prunus virginiana*	Good	N	Tilton and Willard 1981, Dittberner and Olson 1983, Van Dyke et al. 1983
PSME	*Pseudotsuga menziesii*	Poor	Y	Wasser 1982, Dittberner and Olson 1983
PUTR	*Purshia tridentata*	Good	N	Gullion 1964, Tilton and Willard 1981, Shaw and Monsen 1983
QUGA	*Quercus gambelii*	Moderate	N	Smith 1957, Risenhoover and Bailey 1985, Rominger et al. 1988
RHTR	*Rhus trilobata*	Good	N	Schallenberger 1966, NAS 1971, Stubbendieck et al. 1989
RIBE	*Ribes* spp.	Moderate	Y	Dittberner and Olson 1983, Mozingo 1987
ROWO	*Rosa woodsii*	Good	N	Welch and Andrus 1977, Erickson et al. 1981, Hansen et al. 1995
RUID	*Rubus idaeus*	Poor	Y	Dittberner and Olson 1983
SALI	*Salix* spp.	Good	N	Dittberner and Olson 1983
SYOC	*Symphoricarpos occidentalis*	Good	N	Fairaizl 1978, Dittberner and Olson 1983
YUCC	*Yucca* spp.	Moderate	N	Todd 1975, Fairaizl 1978

Table B2: Summary tables of coefficient values and model R^2 values for top performing predictive models. Positive coefficient estimates indicate the value of the response variable increases as the independent variable increases, while negative values indicate the value of the response variable decreases as the independent variable increases. The larger the number, the more influence the variable has on the response. The reference category for dominant vegetation was grassland and the reference category for fire age was unburned. * denotes value is statistically significant at $p < 0.05$ and • denotes value is statistically significant at $p < 0.1$ (in both cases confidence intervals do not overlap zero). See Table B1 for 4-digit plant code definition.

Response metric	**R2**	**Intercept**	**Aspect**	**Slope**	**Fire age (continuous)**	**Fire age (continuous)^2**	**Shrub Cover**	**NDVI**
% horizontal cover (mean)	0.218	0.553*	-0.161*	0.342*	-0.247*	-1.062*		
% horizontal cover (median)	0.221	-0.640	-0.202*	0.394*			0.137•	0.258*

Response metric	**R2**	**Intercept**	**Slope**	**Slope^2**	**Fire age (continuous)**	**Tree Cover**	**Burn**	**NDVI**
% high quality forage	0.299	0.077	-0.395*	0.263*		-0.279*	-0.375*	
% moderate quality forage	0.253	-0.118	0.318*	-0.208*	-0.271*	0.246*		0.153*
% poor quality forage	0.258	-3.457*	0.171*		0.290*			-0.110

Response metric	**R2**	**Intercept**	**Slope**	**Slope^2**	**Fire age (cont.)**	**NDVI**	**NDVI^2**	**Tree Cover**	**Burn**	**Piñon Juniper**	**Spruce Fir**	**Pondo-rosa**	**Shrub land**	**Elev**	**Elev^2**
Frequency of QUGA (shrub)	0.271	0.366*	0.026	-0.342*				0.363*	1.598*						
Frequency of PUTR (shrub)	0.499	-3.632*			0.378*	-0.236*				0.979*	-0.279	0.369•	0.277	0.122	-0.134*
Frequency of SYOC (shrub)	0.499	-3.632*				0.183*								0.105	0.339*
Frequency of CEMO (shrub)	0.227	-2.826*	0.142•						-0.527*					0.265*	-0.124*
Frequency of QUGA (tree)	0.052	-2.364*				0.133•	-0.068							-0.031	0.048
Frequency of PIED (tree)	0.365	-2.673*				-0.327*			-0.607*					0.247*	-0.142*

Response metric	**R2**	**Intercept**	**Slope**	**NDVI**	**NDVI^2**	**Tree Cover**	**Tree Cover^2**	**Burn**	**Woody closed**	**Open canopy**	**Fire age = 27**	**Fire age = 8**	**Fire age = 2**	**Elev**	**Elev^2**
Frequency of PRVI (shrub)	0.325	-3.344*		0.082	0.121*				0.861*	-0.069	0.599*	0.282	0.309		
Frequency of PSME (tree)	0.559	-1.985*	0.433*			0.540*	0.251*								
Frequency of PIPO (tree)	0.242	-0.464*	-0.418*			0.466*	-0.283*				0.633*	-0.947*	-0.598*		
Frequency of JUSC (tree)	0.419	-0.640*		-0.358*				-1.196*	-0.926*	0.034				-0.07	-0.104•

Field-collected vegetation analysis—model structures

Key to Abbreviations Used in Model Structures*
TreeCov = % tree cover
FireAge.cont = fire age as a continuous variable
FireAge = fire age as categorical variable
NDVI = Normalized difference vegetation index
Elev = Elevation
Max_BS.cont = Maximum burn severity as a continuous variable
Max_BS = Maximum burn severity as a categorical variable
DomVeg = Dominant vegetation type (aspen/mixed conifer, piñon-juniper, Douglas fir, ponderosa, shrubland, grassland, and other)
ShrubCov = % shrub cover
VegStruct = Vegetation structure (semi-open woody, closed woods, grassland, open woods, and other/developed)

*Only model structures with an AIC weight > 0 are shown.

Forage Quality Models

Table B2: Model structures for predicting the proportion of high-quality forage**

Model structure	K	AICc	ΔAICc	Model Likelihood	AICc Weight	Log-Likelihood
TreeCov + Slope + $Slope^2$ + FireAge.cont	6	-131.37	0.00	1.00	0.33	71.90
TreeCov + Slope + FireAge.cont + NDVI + $Slope^2$	7	-130.28	1.09	0.58	0.19	72.43
TreeCov + ShrubCov + Slope + $Slope^2$ + FireAge.cont	7	-130.03	1.34	0.51	0.17	72.30
TreeCov + Slope + $Slope^2$ + Elev	6	-128.96	2.41	0.30	0.10	70.69
TreeCov + Slope + $Slope^2$ + Aspect + Elev	7	-128.68	2.69	0.26	0.09	71.63
TreeCov + Slope + $Slope^2$ + FireAge.cont + Max_BS.cont + FireAge.cont * Max_BS.cont	8	-127.47	3.91	0.14	0.05	72.10
DomVeg + TreeCov + Slope + $Slope^2$ + FireAge.cont	10	-126.28	5.10	0.08	0.03	73.71
ShrubCov + Slope + $Slope^2$ + TreeCov	6	-125.59	5.78	0.06	0.02	69.01
TreeCov + Slope + $Slope^2$ + NDVI	6	-125.14	6.23	0.04	0.01	68.78
TreeCov + Slope + $Slope^2$	5	-124.73	6.64	0.04	0.01	67.52
TreeCov + Slope + $Slope^2$ + Aspect	6	-123.53	7.84	0.02	0.01	67.98

** High-quality forage supplies valuable nutrients in sufficient to abundant quantity and does not contain high concentrations of tannins, silica, cellulose, or toxic compounds that interfere with digestibility.

Table B3: Model structures for predicting the proportion of moderate-quality forage**

Model structure	K	AICc	ΔAICc	Model Likelihood	AICc Weight	Log-Likelihood
TreeCov + Slope + FireAge.cont + NDVI + $Slope^2$	7	-104.33	0.00	1.00	0.58	59.45
TreeCov + ShrubCov + Slope + $Slope^2$ + FireAge.cont	7	-102.03	2.30	0.32	0.18	58.30
DomVeg + TreeCov + Slope + $Slope^2$ + FireAge.cont	10	-100.27	4.06	0.13	0.08	60.71
TreeCov + Slope + $Slope^2$ + FireAge.cont	6	-100.03	4.30	0.12	0.07	56.23
DomVeg + Slope + $Slope^2$ + FireAge.cont + NDVI	10	-99.66	4.67	0.10	0.06	60.40
DomVeg + FireAge.cont + Slope + $Slope^2$	9	-96.56	7.77	0.02	0.01	57.74
TreeCov + Slope + $Slope^2$ + FireAge.cont + Max_BS.cont + FireAge.cont * Max_BS.cont	8	-96.46	7.87	0.02	0.01	56.60

** Moderate-quality forage supplies nutrients in moderate to sufficient quantity and/or may contain tannins, silica, cellulose, or toxic compounds that are not ideal, but are tolerated when preferred forage is not available (such as in winter months).

Table B4: Model structures for predicting the proportion of poor-quality forage**

Model structure	K	AICc	ΔAICc	Model Likelihood	AICc Weight	Log-Likelihood
DomVeg + FireAge.cont	7	-1302.47	0.00	1.00	0.19	658.52
TreeCov + Slope + FireAge.cont + NDVI	6	-1301.76	0.72	0.70	0.13	657.09
Slope + FireAge.cont + NDVI	5	-1301.48	0.99	0.61	0.12	655.89
FireAge.cont + Slope	4	-1301.23	1.25	0.54	0.10	654.71
TreeCov + Slope + FireAge.cont	5	-1300.43	2.04	0.36	0.07	655.37
DomVeg + FireAge.cont + Slope + Slope^2	9	-1300.24	2.23	0.33	0.06	659.59
TreeCov + Slope + FireAge.cont + NDVI + Slope^2	7	-1299.66	2.82	0.24	0.05	657.12
TreeCov + ShrubCov + Slope + FireAge.cont + NDVI	7	-1299.65	2.82	0.24	0.05	657.11
FireAge.cont + Slope + Elev	5	-1299.16	3.32	0.19	0.04	654.73
TreeCov + Slope + Elev + Slope * Elev + FireAge.cont	7	-1298.96	3.52	0.17	0.03	656.76
DomVeg + Slope + Slope^2 + FireAge.cont + NDVI	10	-1298.90	3.58	0.17	0.03	660.02
TreeCov + Slope + Slope^2 + FireAge.cont	6	-1298.32	4.16	0.13	0.02	655.37
DomVeg + TreeCov + Slope + Slope^2 + FireAge.cont	10	-1298.13	4.34	0.11	0.02	659.64
FireAge.cont + NDVI	4	-1297.26	5.22	0.07	0.01	652.73
TreeCov + ShrubCov + Slope + Slope^2 + FireAge.cont	7	-1297.13	5.35	0.07	0.01	655.85
DomVeg + FireAge + Slope + Slope^2	11	-1296.67	5.81	0.05	0.01	660.02
FireAge.cont + NDVI + Elev	5	-1295.51	6.96	0.03	0.01	652.91
DomVeg + NDVI	7	-1295.27	7.20	0.03	0.01	654.92

** Poor-quality forage supplies little nutrients and/or contain tannins, silica, cellulose, or toxic compounds at a concentration rendering them unpalatable to bighorn sheep.

Horizontal Visibility Models

Table B5: Model structures for mean percent horizontal visibility

Model structure	K	AICc	ΔAICc	Model Likelihood	AICc Weight	Log-Likelihood
Aspect + Slope + FireAge.cont + $FireAge.cont^2$	6	-128.09	0.00	1.00	0.25	70.26
Aspect + Slope + FireAge.cont + Max_BS.cont + Max_BS.cont * FireAge.cont	7	-127.88	0.21	0.90	0.22	71.23
ShrubCov + Aspect + Slope + FireAge.cont + $FireAge.cont^2$	7	-127.71	0.38	0.83	0.21	71.14
ShrubCov + Aspect + Slope + FireAge.cont + Max_BS.cont + FireAge.cont * Max_BS.cont	8	-127.69	0.41	0.82	0.20	72.21
ShrubCov + Aspect + Slope + FireAge	8	-126.01	2.08	0.35	0.09	71.37
ShrubCov + Aspect + Slope + NDVI	6	-121.34	6.75	0.03	0.01	66.88
Aspect + Slope + Max_BS	7	-120.64	7.45	0.02	0.01	67.61
ShrubCov + Aspect + Slope	5	-120.46	7.63	0.02	0.01	65.38

Table B6: Model structures for median percent horizontal visibility

Model structure	K	AICc	ΔAICc	Model Likelihood	AICc Weight	Log-Likelihood
ShrubCov + Aspect + Slope + NDVI	6	-112.44	0.00	1.00	0.55	62.43
Aspect + Slope + NDVI	5	-111.41	1.03	0.60	0.33	60.85
ShrubCov + Aspect + Slope + FireAge.cont + $FireAge.cont^2$	7	-107.04	5.40	0.07	0.04	60.80
Aspect + Slope + FireAge.cont + $FireAge.cont^2$	6	-106.10	6.34	0.04	0.02	59.26
ShrubCov + Aspect + Slope + FireAge.cont + Max_BS.cont + FireAge.cont * Max_BS.cont	8	-105.80	6.64	0.04	0.02	61.27
ShrubCov + Aspect + Slope + FireAge	8	-105.54	6.90	0.03	0.02	61.14
Aspect + Slope + FireAge.cont + Max_BS.cont + Max_BS.cont * FireAge.cont	7	-104.71	7.73	0.02	0.01	59.64

Species Frequency Models—Shrubs

Table B7: Model structures depicting frequency of occurrence of mountain mahogany (*Cercocarpus montanus;* shrub)

Model structure	K	AICc	ΔAICc	Model Likelihood	AICc Weight	Log-Likelihood
Elev + Elev^2 + Slope + FireAge.cont	6	-1371.49	0.00	1.00	0.19	691.96
Elev + Elev^2 + FireAge.cont	5	-1370.30	1.19	0.55	0.10	690.30
Slope + Elev + Elev^2 + FireAge.cont + FireAge.cont^2	7	-1370.20	1.29	0.52	0.10	692.39
Elev + Elev^2 + FireAge.cont + NDVI	6	-1369.83	1.66	0.44	0.08	691.13
Elev + Elev^2 + Slope + Slope^2 + FireAge.cont	7	-1369.38	2.11	0.35	0.07	691.98
Elev + Elev^2 + FireAge.cont + FireAge.cont^2	6	-1368.75	2.74	0.25	0.05	690.59
Elev + Elev^2 + Aspect + FireAge.cont	6	-1368.54	2.95	0.23	0.04	690.49
Elev + Slope + FireAge.cont	5	-1368.13	3.36	0.19	0.03	689.22
Elev + Elev^2 + Aspect + FireAge.cont + NDVI	7	-1368.07	3.42	0.18	0.03	691.32
Burn	3	-1367.46	4.04	0.13	0.02	686.79
FireAge.cont	3	-1367.32	4.17	0.12	0.02	686.72
Elev + Elev^2 + Aspect + FireAge.cont + ShrubCov	7	-1366.79	4.70	0.10	0.02	690.68
ShrubCov + Elev + Elev^2 + FireAge.cont + FireAge.cont^2	7	-1366.69	4.80	0.09	0.02	690.63
Elev + Elev^2 + TreeCov + TreeCov^2 + FireAge.cont	7	-1366.65	4.84	0.09	0.02	690.61
Elev + Elev^2 + FireAge.cont + Max_BS.cont + FireAge.cont * Max_BS.cont	7	-1366.62	4.87	0.09	0.02	690.60
TreeCov + Elev + Elev^2 + FireAge.cont + FireAge.cont^2	7	-1366.60	4.89	0.09	0.02	690.59
VegStruct + NDVI + FireAge.cont + Elev + Elev^2	8	-1365.85	5.65	0.06	0.01	691.29
Elev + FireAge.cont	4	-1365.84	5.65	0.06	0.01	687.02
NDVI + FireAge.cont	4	-1365.78	5.71	0.06	0.01	686.99
ShrubCov + FireAge.cont	4	-1365.27	6.22	0.04	0.01	686.74
Slope + TreeCov + TreeCov^2 + FireAge.cont	6	-1364.97	6.52	0.04	0.01	688.70
Elev + Slope + Slope^2 + FireAge.cont + FireAge.cont^2	7	-1364.86	6.63	0.04	0.01	689.71
Elev + Elev^2 + Slope + ShrubCov	6	-1364.82	6.67	0.04	0.01	688.62
TreeCov + Slope + Slope^2 + FireAge.cont	6	-1364.69	6.80	0.03	0.01	688.56
Elev + Aspect + FireAge.cont	5	-1364.46	7.03	0.03	0.01	687.38
Elev + Slope + NDVI	5	-1364.36	7.13	0.03	0.01	687.33

Table B8: Model structures depicting frequency of occurrence of chokecherry (*Prunus virginiana;* shrub)

Model structure	**K**	**AICc**	**ΔAICc**	**Model Likelihood**	**AICc Weight**	**Log-Likelihood**
VegStruct + NDVI + FireAge + NDVI^2	9	-1420.27	0.00	1.00	0.25	719.60
VegStruct + FireAge	7	-1419.39	0.88	0.64	0.16	716.98
VegStruct + NDVI + FireAge + Elev + Elev^2	10	-1418.16	2.11	0.35	0.09	719.65
VegStruct + FireAge.cont + FireAge.cont^2	6	-1417.83	2.44	0.30	0.07	715.13
VegStruct + Slope + FireAge + ShrubCov + ShrubCov^2	10	-1417.68	2.59	0.27	0.07	719.41
VegStruct + Slope + FireAge + ShrubCov	9	-1417.63	2.64	0.27	0.07	718.28
VegStruct + FireAge + ShrubCov + ShrubCov^2	9	-1417.25	3.02	0.22	0.06	718.09
Slope + VegStruct + TreeCov + TreeCov^2 + FireAge	10	-1417.04	3.23	0.20	0.05	719.09
VegStruct + NDVI + FireAge + ShrubCov	9	-1416.33	3.94	0.14	0.04	717.63
VegStruct + NDVI + FireAge.cont + FireAge.cont^2	7	-1415.96	4.31	0.12	0.03	715.27
ShrubCov + NDVI + FireAge + NDVI^2	8	-1414.30	5.98	0.05	0.01	715.52
Slope + TreeCov + TreeCov^2 + FireAge	8	-1413.81	6.47	0.04	0.01	715.27
Elev + Elev^2 + FireAge + NDVI	8	-1413.17	7.10	0.03	0.01	714.96
ShrubCov + NDVI + NDVI^2 + FireAge + ShrubCov^2	9	-1413.05	7.22	0.03	0.01	715.99
DomVeg + NDVI + FireAge + NDVI^2	11	-1412.87	7.40	0.02	0.01	718.12
Elev + Slope + NDVI + NDVI^2	6	-1412.62	7.65	0.02	0.01	712.52

Table B9: Model structures depicting frequency of occurrence of antelope bitterbrush (*Purshia tridentata;* shrub)

Model structure	**K**	**AICc**	**ΔAICc**	**Model Likelihood**	**AICc Weight**	**Log-Likelihood**
DomVeg + NDVI + FireAge.cont + Elev + $Elev^2$	10	-965.59	0.00	1.00	0.40	493.37
VegStruct + NDVI + FireAge.cont + Elev + $Elev^2$	8	-964.35	1.24	0.54	0.22	490.54
DomVeg + NDVI + FireAge.cont	8	-964.09	1.50	0.47	0.19	490.42
DomVeg + NDVI + FireAge.cont + $NDVI^2$	9	-962.29	3.30	0.19	0.08	490.61
Elev + $Elev^2$ + FireAge.cont + NDVI	6	-960.73	4.86	0.09	0.04	486.58
Elev + $Elev^2$ + Aspect + FireAge.cont + NDVI	7	-958.60	6.99	0.03	0.01	486.59
VegStruct + NDVI + FireAge.cont + $NDVI^2$	7	-958.58	7.01	0.03	0.01	486.58
VegStruct + NDVI + FireAge.cont + ShrubCov	7	-958.57	7.02	0.03	0.01	486.57
VegStruct + NDVI + FireAge.cont + $FireAge.cont^2$	7	-958.54	7.05	0.03	0.01	486.55
DomVeg + FireAge.cont	7	-958.16	7.43	0.02	0.01	486.36
Slope + Elev + $Elev^2$ + FireAge.cont + DomVeg	10	-956.95	8.64	0.01	0.01	489.04

Table B10: Model structures depicting frequency of occurrence of Gambel oak (*Quercus gambelii;* shrub)

Model structure	**K**	**AICc**	**ΔAICc**	**Model Likelihood**	**AICc Weight**	**Log-Likelihood**
TreeCov + Slope + $Slope^2$ + FireAge.cont	6	-202.92	0.00	1.00	0.36	107.67
TreeCov + Slope + $Slope^2$ + FireAge.cont + $FireAge.cont^2$	7	-202.25	0.67	0.71	0.26	108.41
Slope + $Slope^2$ + TreeCov + $TreeCov^2$ + FireAge.cont	7	-201.35	1.57	0.46	0.17	107.96
Elev + $Elev^2$ + TreeCov + $TreeCov^2$ + FireAge.cont	7	-200.36	2.56	0.28	0.10	107.47
TreeCov + Elev + $Elev^2$ + FireAge.cont + $FireAge.cont^2$	7	-200.08	2.84	0.24	0.09	107.33
Elev + $Elev^2$ + Slope + $Slope^2$ + FireAge.cont	7	-196.49	6.44	0.04	0.01	105.53

Table B11: Model structures depicting frequency of occurrence of western snowberry (*Symphoricarpos occidentalis;* shrub)

Model structure	**K**	**AICc**	**ΔAICc**	**Model Likelihood**	**AICc Weight**	**Log-Likelihood**
Elev + Elev^2 + NDVI	5	-1419.10	0.00	1.00	0.24	714.70
Elev + Elev^2 + NDVI + NDVI^2	6	-1417.83	1.27	0.53	0.13	715.13
Elev + Elev^2 + Slope + Slope^2 + NDVI	7	-1417.33	1.77	0.41	0.10	715.95
Elev + Elev^2 + FireAge.cont + NDVI	6	-1417.23	1.87	0.39	0.10	714.83
Elev + Elev^2 + TreeCov + TreeCov^2 + NDVI	7	-1417.19	1.91	0.38	0.09	715.88
VegStruct + NDVI + FireAge.cont + Elev + Elev^2	8	-1415.87	3.23	0.20	0.05	716.30
Elev + Elev^2 + Aspect + FireAge.cont + NDVI	7	-1415.45	3.65	0.16	0.04	715.01
Elev + Elev^2 + FireAge.cont + Max_BS.cont + FireAge.cont * Max_BS.cont	7	-1414.24	4.86	0.09	0.02	714.41
Elev + Elev^2 + Slope + Slope^2	6	-1414.11	4.99	0.08	0.02	713.27
Elev + Elev^2 + Slope + Aspect	6	-1414.07	5.03	0.08	0.02	713.25
Elev + Elev^2 + Slope + Slope^2 + TreeCov	7	-1414.02	5.08	0.08	0.02	714.30
Elev + Elev^2 + Slope + FireAge.cont	6	-1413.85	5.25	0.07	0.02	713.14
Elev + Elev^2 + Slope + ShrubCov	6	-1413.72	5.39	0.07	0.02	713.07
Elev + Elev^2 + TreeCov + TreeCov^2 + Slope	7	-1413.48	5.62	0.06	0.01	714.03
Slope + Elev + Elev^2 + FireAge.cont + FireAge.cont^2	7	-1413.46	5.64	0.06	0.01	714.02
DomVeg + NDVI + FireAge.cont + Elev + Elev^2	10	-1413.24	5.87	0.05	0.01	717.19
Elev + Elev^2 + ShrubCov + ShrubCov^2	6	-1413.22	5.88	0.05	0.01	712.82
Elev + Elev^2 + FireAge.cont	5	-1413.05	6.06	0.05	0.01	711.67
TreeCov + Elev + Elev^2 + FireAge.cont + FireAge.cont^2	7	-1412.90	6.20	0.05	0.01	713.74
Elev + Elev^2 + FireAge.cont + FireAge.cont^2	6	-1412.61	6.50	0.04	0.01	712.52
Elev + Elev^2 + Slope + Slope^2 + Aspect	7	-1412.33	6.78	0.03	0.01	713.45
Elev + Elev^2 + Slope + Slope^2 + FireAge.cont	7	-1412.16	6.94	0.03	0.01	713.37
Elev + Elev^2 + Slope + Slope^2 + ShrubCov	7	-1411.99	7.11	0.03	0.01	713.28
Elev + Elev^2 + TreeCov + TreeCov^2 + FireAge.cont	7	-1411.77	7.34	0.03	0.01	713.17
Elev + Elev^2 + TreeCov + TreeCov^2 + Aspect	7	-1411.75	7.35	0.03	0.01	713.16

Species Frequency Models—Trees

Table B12: Model structures depicting frequency of occurrence of Rocky Mountain juniper (*Juniperus scopulorum;* tree)

Model structure	K	AICc	ΔAICc	Model Likelihood	AICc Weight	Log-Likelihood
VegStruct + NDVI + FireAge.cont + Elev + $Elev^2$	8	-590.18	0.00	1.00	0.61	303.46
DomVeg + NDVI + FireAge.cont + Elev + $Elev^2$	10	-587.50	2.69	0.26	0.16	304.32
VegStruct + NDVI + FireAge.cont + $FireAge.cont^2$	7	-587.00	3.18	0.20	0.12	300.79
Elev + $Elev^2$ + FireAge.cont + NDVI	6	-583.97	6.21	0.04	0.03	298.20
VegStruct + NDVI + FireAge.cont + $NDVI^2$	7	-583.04	7.15	0.03	0.02	298.80
DomVeg + NDVI + FireAge.cont	8	-582.91	7.28	0.03	0.02	299.82
VegStruct + NDVI + FireAge.cont + ShrubCov	7	-582.35	7.83	0.02	0.01	298.46
Elev + $Elev^2$ + Aspect + FireAge.cont + NDVI	7	-582.29	7.89	0.02	0.01	298.43
ShrubCov + NDVI + FireAge.cont + $FireAge.cont^2$	6	-582.02	8.16	0.02	0.01	297.22
DomVeg + NDVI + FireAge.cont + $NDVI^2$	9	-581.83	8.35	0.02	0.01	300.38

Table B13: Model structures depicting frequency of occurrence of piñon pine (*Pinus edulis;* tree)

Model structure	**K**	**AICc**	**ΔAICc**	**Model Likelihood**	**AICc Weight**	**Log-Likelihood**
Elev + Elev^2 + FireAge.cont + NDVI	6	-1315.88	0.00	1.00	0.36	664.15
DomVeg + NDVI + FireAge.cont + Elev + Elev^2	10	-1314.20	1.68	0.43	0.15	667.67
Elev + Elev^2 + Aspect + FireAge.cont + NDVI	7	-1313.92	1.96	0.37	0.13	664.25
NDVI + FireAge.cont	4	-1312.53	3.36	0.19	0.07	660.36
VegStruct + NDVI + FireAge.cont + Elev + Elev^2	8	-1312.25	3.64	0.16	0.06	664.49
DomVeg + NDVI + FireAge.cont + NDVI^2	9	-1311.31	4.57	0.10	0.04	665.12
DomVeg + NDVI + FireAge.cont	8	-1311.18	4.70	0.10	0.03	663.96
ShrubCov + NDVI + FireAge.cont	5	-1310.61	5.27	0.07	0.03	660.46
ShrubCov + NDVI + FireAge.cont + NDVI^2	6	-1310.45	5.43	0.07	0.02	661.44
Elev + Slope + NDVI	5	-1309.70	6.18	0.05	0.02	660.00
VegStruct + NDVI + FireAge.cont + NDVI^2	7	-1309.23	6.65	0.04	0.01	661.90
Elev + Aspect + FireAge.cont + NDVI	6	-1308.95	6.93	0.03	0.01	660.69
Elev + Elev^2 + TreeCov + TreeCov^2 + NDVI	7	-1308.92	6.97	0.03	0.01	661.74
ShrubCov + NDVI + FireAge.cont + FireAge.cont^2	6	-1308.68	7.20	0.03	0.01	660.55
ShrubCov + NDVI + NDVI^2 + FireAge.cont + ShrubCov^2	7	-1308.51	7.37	0.03	0.01	661.54
Elev + Slope + NDVI + NDVI^2	6	-1308.44	7.44	0.02	0.01	660.44
Elev + Elev^2 + Slope + Slope^2 + NDVI	7	-1308.40	7.48	0.02	0.01	661.49

Table B14: Model structures depicting frequency of occurrence of ponderosa pine (*Pinus ponderosa*; tree)

Model structure	**K**	**AICc**	**ΔAICc**	**Model Likelihood**	**AICc Weight**	**Log-Likelihood**
Slope + TreeCov + TreeCov^2 + FireAge.cont	6	-401.25	0.00	1.00	0.52	206.84
Slope + Slope^2 + TreeCov + TreeCov^2 + FireAge.cont	7	-399.91	1.34	0.51	0.27	207.24
Slope + VegStruct + TreeCov + TreeCov^2 + FireAge.cont	8	-399.14	2.11	0.35	0.18	207.94

Table B15: Model structures depicting frequency of occurrence of Douglas fir (*Pseudotsuga menziesii*; tree)

Model structure	**K**	**AICc**	**ΔAICc**	**Model Likelihood**	**AICc Weight**	**Log-Likelihood**
Slope + TreeCov + $TreeCov^2$	5	-759.44	0.00	1.00	0.36	384.87
Slope + TreeCov + $TreeCov^2$ + FireAge.cont	6	-759.09	0.35	0.84	0.30	385.76
Slope + $Slope^2$ + TreeCov + $TreeCov^2$ + FireAge.cont	7	-757.83	1.61	0.45	0.16	386.20
Slope + VegStruct + TreeCov + $TreeCov^2$ + FireAge.cont	8	-756.52	2.92	0.23	0.08	386.63
Elev + $Elev^2$ + TreeCov + $TreeCov^2$ + Slope	7	-755.51	3.93	0.14	0.05	385.04
TreeCov + Slope + $Slope^2$ + FireAge.cont + $FireAge.cont^2$	7	-754.18	5.25	0.07	0.03	384.38
TreeCov + Slope + $Slope^2$ + FireAge.cont	6	-752.75	6.69	0.04	0.01	382.59

Table B16: Model structures depicting frequency of occurrence of Gambel oak (*Quercus gambelii;* tree)

Model structure	**K**	**AICc**	**ΔAICc**	**Model Likelihood**	**AICc Weight**	**Log-Likelihood**
NDVI + FireAge.cont	4	-1074.47	0.00	1.00	0.08	541.34
Burn	3	-1074.13	0.34	0.84	0.07	540.12
FireAge.cont	3	-1074.00	0.48	0.79	0.07	540.06
Elev + $Elev^2$ + NDVI	5	-1073.24	1.23	0.54	0.04	541.77
ShrubCov + FireAge.cont + $FireAge.cont^2$	5	-1072.95	1.53	0.47	0.04	541.62
ShrubCov + FireAge.cont	4	-1072.80	1.67	0.43	0.04	540.50
ShrubCov + NDVI + FireAge.cont + $FireAge.cont^2$	6	-1072.58	1.90	0.39	0.03	542.50
Elev + Slope + NDVI	5	-1072.53	1.95	0.38	0.03	541.41
Elev + $Elev^2$ + NDVI + $NDVI^2$	6	-1072.52	1.96	0.38	0.03	542.47
ShrubCov + NDVI + FireAge.cont	5	-1072.48	1.99	0.37	0.03	541.39
Elev + FireAge.cont	4	-1072.41	2.07	0.36	0.03	540.30
VegStruct + FireAge.cont + $FireAge.cont^2$	6	-1072.33	2.14	0.34	0.03	542.38
Elev + Aspect + FireAge.cont + NDVI	6	-1072.27	2.20	0.33	0.03	542.35
Elev + Aspect + FireAge.cont	5	-1072.13	2.34	0.31	0.03	541.22
Elev + Slope + NDVI + $NDVI^2$	6	-1071.79	2.69	0.26	0.02	542.11
ShrubCov + NDVI + FireAge.cont + $NDVI^2$	6	-1071.65	2.82	0.24	0.02	542.04
Elev + $Elev^2$ + FireAge.cont + $FireAge.cont^2$	6	-1071.20	3.27	0.19	0.02	541.82
Slope + $Slope^2$ + FireAge.cont + $FireAge.cont^2$	6	-1071.19	3.29	0.19	0.02	541.81
Elev + $Elev^2$ + FireAge.cont + NDVI	6	-1071.13	3.34	0.19	0.02	541.78
Elev + $Elev^2$ + Aspect + FireAge.cont + NDVI	7	-1071.13	3.35	0.19	0.02	542.85
VegStruct + NDVI + FireAge.cont + $FireAge.cont^2$	7	-1071.11	3.37	0.19	0.02	542.84
Elev + FireAge.cont + Max_BS.cont + FireAge.cont * Max_BS.cont	6	-1070.79	3.68	0.16	0.01	541.61
Elev + $Elev^2$ + FireAge.cont	5	-1070.76	3.71	0.16	0.01	540.53
Elev + $Elev^2$ + Slope + Aspect	6	-1070.70	3.77	0.15	0.01	541.56
Elev + $Elev^2$ + Aspect + FireAge.cont	6	-1070.67	3.80	0.15	0.01	541.55
Slope + TreeCov + $TreeCov^2$	5	-1070.60	3.87	0.14	0.01	540.45
VegStruct + FireAge.cont	5	-1070.59	3.88	0.14	0.01	540.45
Elev + Slope + FireAge.cont	5	-1070.43	4.04	0.13	0.01	540.37
VegStruct + NDVI + FireAge.cont + $NDVI^2$	7	-1070.28	4.20	0.12	0.01	542.42
Elev + Slope + $Slope^2$ + Aspect	6	-1070.27	4.20	0.12	0.01	541.35
DomVeg	6	-1069.89	4.58	0.10	0.01	541.16
Elev + $Elev^2$ + Slope + ShrubCov	6	-1069.75	4.72	0.09	0.01	541.09

Elev + $Elev^2$ + ShrubCov + $ShrubCov^2$	6	-1069.56	4.91	0.09	0.01	541.00
ShrubCov + NDVI + $NDVI^2$ + FireAge.cont + $ShrubCov^2$	7	-1069.51	4.97	0.08	0.01	542.04
Elev + $Elev^2$ + Slope + $Slope^2$ + NDVI	7	-1069.37	5.11	0.08	0.01	541.97
Elev + $Elev^2$ + Aspect + FireAge.cont + ShrubCov	7	-1069.37	5.11	0.08	0.01	541.97
Slope + Elev + $Elev^2$ + FireAge.cont + $FireAge.cont^2$	7	-1069.35	5.13	0.08	0.01	541.96
Elev + $Elev^2$ + TreeCov + $TreeCov^2$ + Aspect	7	-1069.32	5.15	0.08	0.01	541.95
Elev + Slope + $Slope^2$ + ShrubCov	6	-1069.25	5.22	0.07	0.01	540.84
Elev + $Elev^2$ + TreeCov + $TreeCov^2$ + NDVI	7	-1069.23	5.25	0.07	0.01	541.90
ShrubCov + Elev + $Elev^2$ + FireAge.cont + $FireAge.cont^2$	7	-1069.21	5.26	0.07	0.01	541.89
TreeCov + Elev + $Elev^2$ + FireAge.cont + $FireAge.cont^2$	7	-1069.19	5.28	0.07	0.01	541.88
ShrubCov + Slope + $Slope^2$ + FireAge.cont	6	-1069.19	5.29	0.07	0.01	540.81
TreeCov + Slope + $Slope^2$ + FireAge.cont + $FireAge.cont^2$	7	-1069.17	5.30	0.07	0.01	541.87
ShrubCov + Slope + $Slope^2$ + FireAge.cont + $FireAge.cont^2$	7	-1069.12	5.35	0.07	0.01	541.85
Elev + Slope + $Slope^2$ + FireAge.cont + $FireAge.cont^2$	7	-1069.12	5.35	0.07	0.01	541.85
Elev + $Elev^2$ + Slope + $Slope^2$	6	-1069.12	5.36	0.07	0.01	540.77
Elev + $Elev^2$ + FireAge.cont + Max_BS.cont + FireAge.cont * Max_BS.cont	7	-1069.10	5.37	0.07	0.01	541.84
Slope + $Slope^2$ + ShrubCov + $ShrubCov^2$	6	-1069.10	5.38	0.07	0.01	540.76
DomVeg + FireAge.cont + $FireAge.cont^2$	8	-1069.06	5.41	0.07	0.01	542.90
Elev + TreeCov + $TreeCov^2$ + FireAge.cont	6	-1068.94	5.53	0.06	0.01	540.68
Elev + $Elev^2$ + Slope + FireAge.cont	6	-1068.87	5.60	0.06	0.01	540.65

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Appendix C: Jemez herd reintroduction analysis

Introduction

In 2011, the high intensity Las Conchas fire burnt more than 607 km^2 (150,000 acres) west of Los Alamos, New Mexico, clearing the forest that dominated the landscape. The loss of tree stands allowed for herbaceous regrowth and was the final impetus for reintroducing bighorn sheep to Cochiti Canyon. Cochiti Canyon is an approximately 10 km^2 area 88 miles southeast of Dulce, located within Santa Fe National Forest. The greater area surrounding Cochiti Canyon identified as potential habitat for bighorn sheep (135 km^2) is primarily in the Santa Fe National Forest, but also includes Bandelier National Monument as well as small portions of Cochiti Pueblo, Jemez Pueblo, state, private, and Department of Energy lands. As part of a multi-agency effort, Rocky Mountain bighorn sheep were reintroduced to Cochiti Canyon in 2014, after being extirpated from the canyon since the 1880s. Initially, 34 ewes, 10 rams, and one lamb were relocated from Wheeler Peak to Cochiti Canyon, 20 of which were GPS collared (18 females and 2 males). In 2016, three rams were translocated with at least one VHF collared and in 2017, 25 ewes and 8 rams were translocated from the Chevron Mine between Questa and Red River, 8 of which were GPS collared (all female). At the time of release, 8 of 28 GPS collared individuals were 3 years old, 9 were 4 years old, 4 were 6 years old, 5 were classified as "adult" and one of the males was 8 years old while the other was 10 years old. Of the GPS collared individuals, two died shortly after release; one was from capture myopathy and the other was euthanized after dispersing to a hobby farm with domestic sheep 19.3 km away 15 days post-release. The initial release location was at the north end of Cochiti Canyon, while the 2017 individuals were released about 6 km south of the initial release site, at the south end of the canyon.

The goal of analyzing the post-translocation GPS data from the Jemez herd was to provide a reference of patterns of settling, dispersal, and habitat use in a context similar to that of a potential relocation effort on the JAN. Additionally, metrics derived from these analyses were used in assessing risk of contact. It should be noted however, that every relocation effort and the individuals introduced are unique and thus, bighorn sheep behavior can vary dramatically between translocation efforts and behavior seen within the Jemez herd may not necessarily occur in other herds. Behavior can be strongly influenced by age, sex, experience, resources available, and connectivity to potential habitat or lack thereof.

Methods

Habitat use and movements

Using the GPS collar data from 2014-2021 and program R, we evaluated cumulative mean daily movement post-release from individuals with > 1 fix/day, daily displacement from the release site over time, and changes in movement relative to time since release. We evaluated maximum distances traveled from release site by sex, examined a timeline of dispersal events, and calculated foray behavior (methods described in main text). We also calculated the percentage of GPS locations within Cochiti Canyon and within the identified potential habitat polygon developed by NMDGF to assess the use of these pre-identified areas of potential high use habitat. Additionally, due to the importance of escape terrain, we calculated distance from escape terrain for each GPS point and escape terrain definition to compare and add to the distances found in literature.

Home range analysis

Using the GPS collar data from 2014-2021 and program R, we calculated 95%, 90%, and 50% home ranges for the population using a kernel density estimator, as well as average 95% and 90% home range sizes for individuals based on sex and source population. Due to the large amount of foray behavior after reintroduction, we used the 90% isopleth of all GPS points as the core habitat home range in the foray analysis to portray core habitat more realistically. The 50% isopleth was used as the source layer in a cost-distance analysis to determine risk thresholds for bighorn sheep use relative to domestic sheep and goats (methods described in main text). Additionally, for each individual we evaluated changes in monthly home range size post-release and spatial overlap in home ranges month to month.

Results

Habitat use and movements

All collared individuals conducted forays (n = 26; 2 males, 24 females) and with respect to animal-years, the foray probability was 100% for males (n = 6) and 84.7% for females (n = 59). Foray probabilities for ewes and rams are depicted in Table C1. The maximum distance an individual traveled beyond their home range was 39 km for females and 26 km for males. Relative to release location, the maximum furthest exploratory location was 42 km and the average furthest foray location was 19.9 km for an individual (n = 27; Fig. C1). Relative to release date, 42.3% of farthest exploratory movements occurred in the first month, while 69.2% of farthest forays occurred in the first four months post-translocation (Fig. C2). This leaves 30.7% of farthest forays to occur between 11 months and 2.5 years post-translocation. There appears to be a slight positive correlation between age and farthest distance traveled, but the exact age for approximately one-fifth of sheep in the Jemez is unknown and the two oldest sheep are males which although there were only two collared individuals, may bias this relationship as males tend to travel more and further than females. Mean daily cumulative movement stabilized between 3-4 months post-translocation and became even more localized after 7-8 months post-release (Fig. C3).

Generally, most GPS locations were within Cochiti Canyon (> 50%), for both males and females, however it appeared as time went on, females spent more time within the canyon, while males spent less time, eventually dramatically dropping to only spending 10% of their time in the canyon at 100 weeks post-release (Fig. C4). This is likely due to the fact both collared males made their longest forays in both time and duration around 100 weeks post-release (Fig. C2). We observe a similar behavior in the percentage of GPS points within pre-identified potential habitat and found that females increase their time spent in the potential habitat polygon from approximately 80% immediately after release to 90-95% after 20 weeks post-release (Fig. C5). Males were more variable in their time spent within the potential habitat polygon with 60-92% of locations occurring within the area on average, but generally spent less time in this pre-identified area compared to females (Fig. C5).

Relative to escape terrain (ET), we found the response to 51% and 55% ET definitions to be nearly identical. On average, a GPS point was 27.7 m from ET ≥ 51/55% slope and 29.1 m from ET ≥ 60% slope, with a median distance of 8.3 m ± 60.15 m (SD) for ET ≥ 51/55% slope and 9 m ± 81.47 m (SD) for ET ≥ 60% slope. The vast majority of GPS locations occurred within 25-50 m of ET (approximately 92.8-96.8% depending on definition). This is significantly closer to ET than most literature reports and may be a result of the surrounding habitat consisting of dramatic elevation changes characterized by a tall mountain surrounded by consecutive finger-like canyons draining into the Rio Grande.

Table C1: Calculated foray probabilities for each kilometer beyond the core home range for ewes and rams of the Jemez herd.

Distance (km)	Ewe foray probability	Ram foray probability
1	1	1
2	0.88	1
3	0.84	1
4	0.74	1
5	0.62	0.83
6	0.46	0.83
7	0.36	0.83
8	0.28	0.5
9	0.22	0.5
10	0.22	0.5
11	0.22	0.5
12	0.22	0.5
13	0.22	0.5
14	0.22	0.5
15	0.2	0.5
16	0.16	0.5
17	0.16	0.5
18	0.16	0.5
19	0.16	0.5
20	0.16	0.33

Distance (km)	Ewe foray probability	Ram foray probability
21	0.14	0.33
22	0.14	0.33
23	0.14	0.17
24	0.14	0.17
25	0.14	0.17
26	0.14	0.17
27	0.14	0
28	0.14	0
29	0.12	0
30	0.1	0
31	0.08	0
32	0.08	0
33	0.06	0
34	0.06	0
35	0.06	0
36	0.06	0
37	0.06	0
38	0.02	0
39	0.02	0

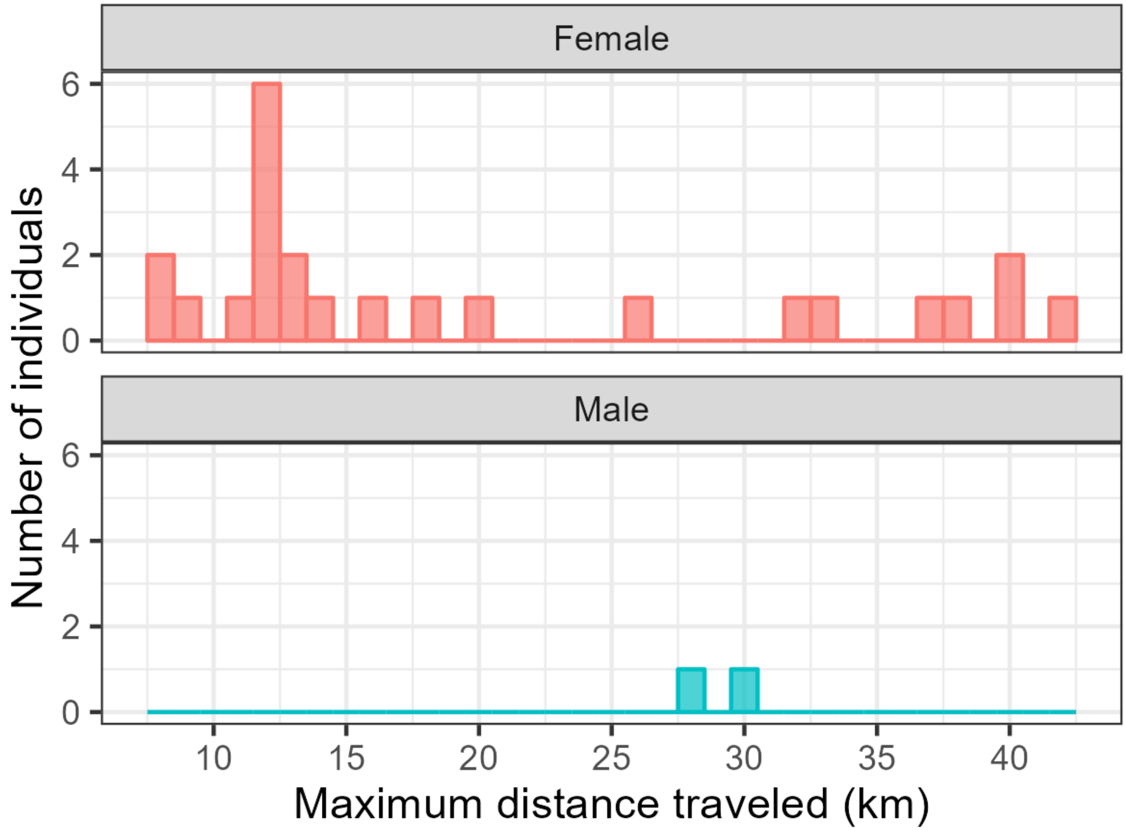


Figure C1. Frequency distribution of maximum distance traveled by a translocated, GPS collared individuals in the Jemez herd from their respective release site.

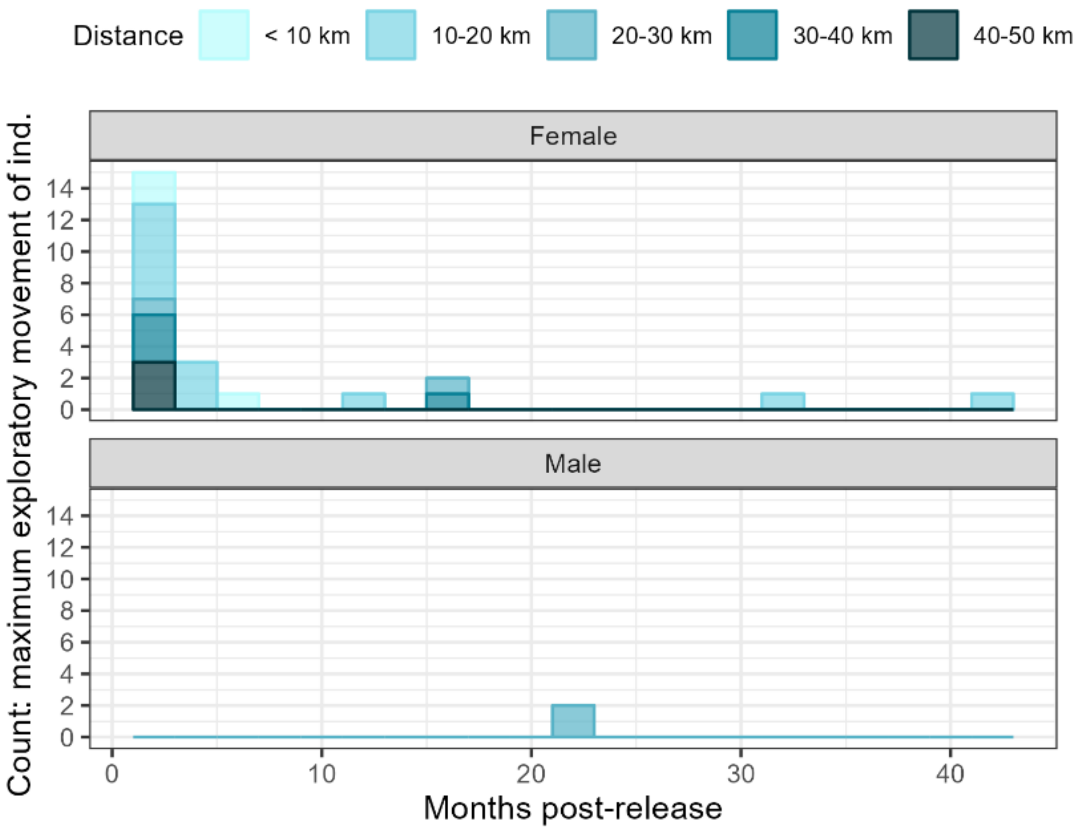


Figure C2. Time post-release of maximum foray from release site for translocated GPS collared Jemez individuals.

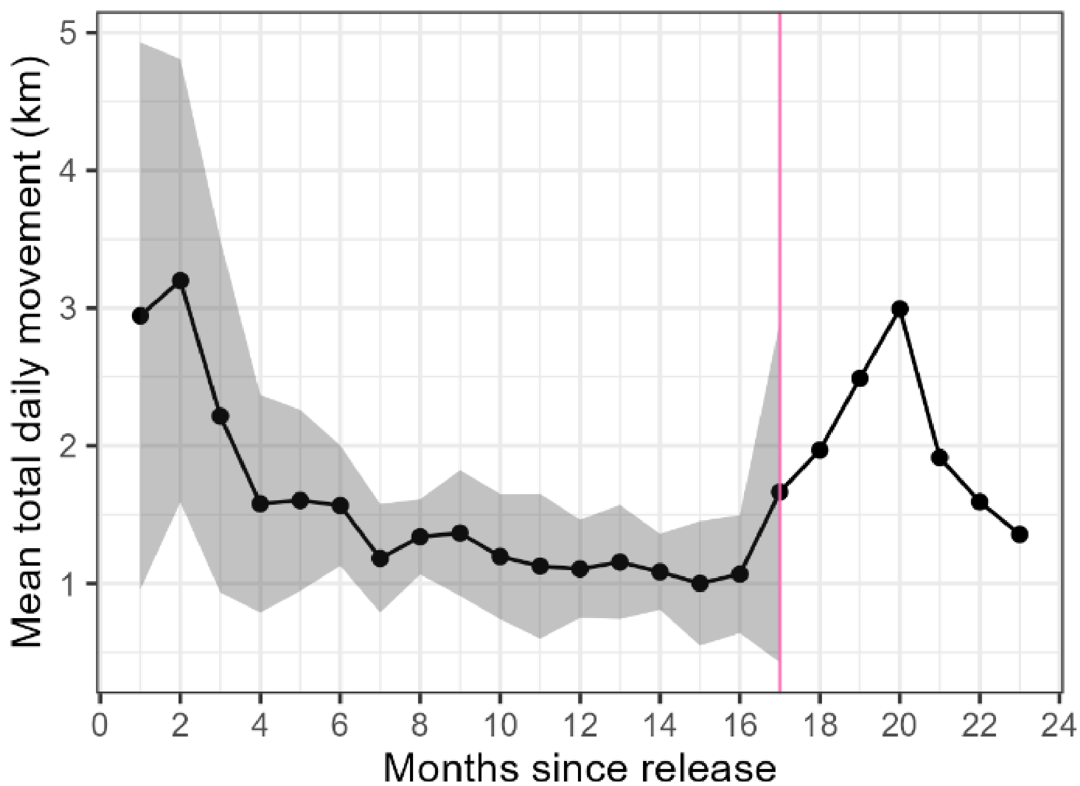
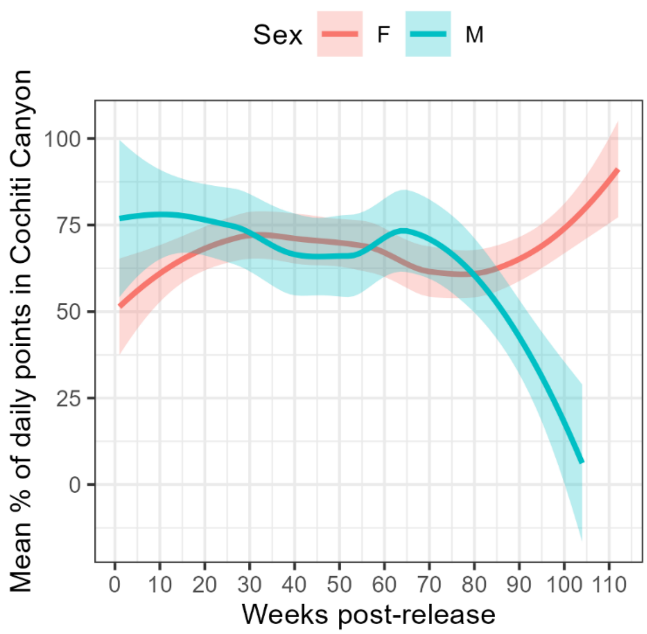
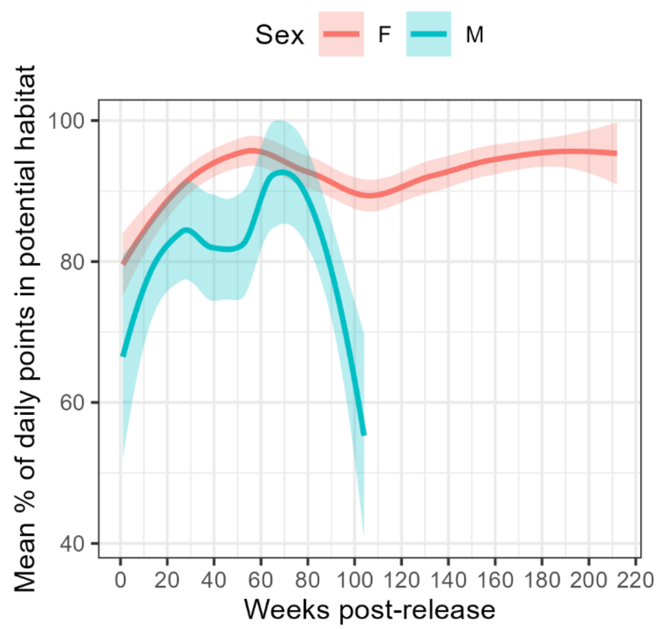


Figure C3. Mean cumulative daily movement of GPS collared sheep after translocation (n = 20). The pink line indicates when only one GPS collared individual remained with a fix rate greater than one per day (several sheep had fix intervals of 13 hours and thus were excluded from the daily movement analysis).





Figures C4 (left) and C5 (right): The mean percentage of daily points within Cochiti Canyon (left) and within pre-identified potential habitat (right) after translocation by sex. Both males were legally harvested around week 105 post-translocation.

Home range analysis

On an individual level, home range sizes and locations started to become relatively stable after three months post-release for both males and females, with variability in size greatly reducing after six months post-release (Fig. C6 & C7). Males appeared to establish home ranges slightly quicker than females (Fig. C6), however with the small sample size of collared males this may not be typical or representative of males within the population. The size of home ranges for males and females was similar across time after the first month post-release (Fig. C7). Not censoring for any forays, the average 95% home range size for males was 23.79 km^2 (n = 2), and 24.22 km^2 for females (n = 24). The 90% home range size for males was 18.64 km^2 and 19.38 km^2 for females. The 50% population home range used in the cost-distance analysis was 34.35 km^2. The 90% isopleth of all GPS locations from the Jemez population is 68.72 km^2. There was noticeable difference between in home range size and landscape use between the animals introduced in 2014 from Wheeler Peak and in 2017 from Red River. Individuals released into the north end of Cochiti Canyon in 2014 typically stayed in the vicinity of the canyon and had smaller home ranges than those released at the south end of Cochiti Canyon in 2017, which used the San Miguel Mountains and canyons east of Cochiti much more heavily (Table C2).

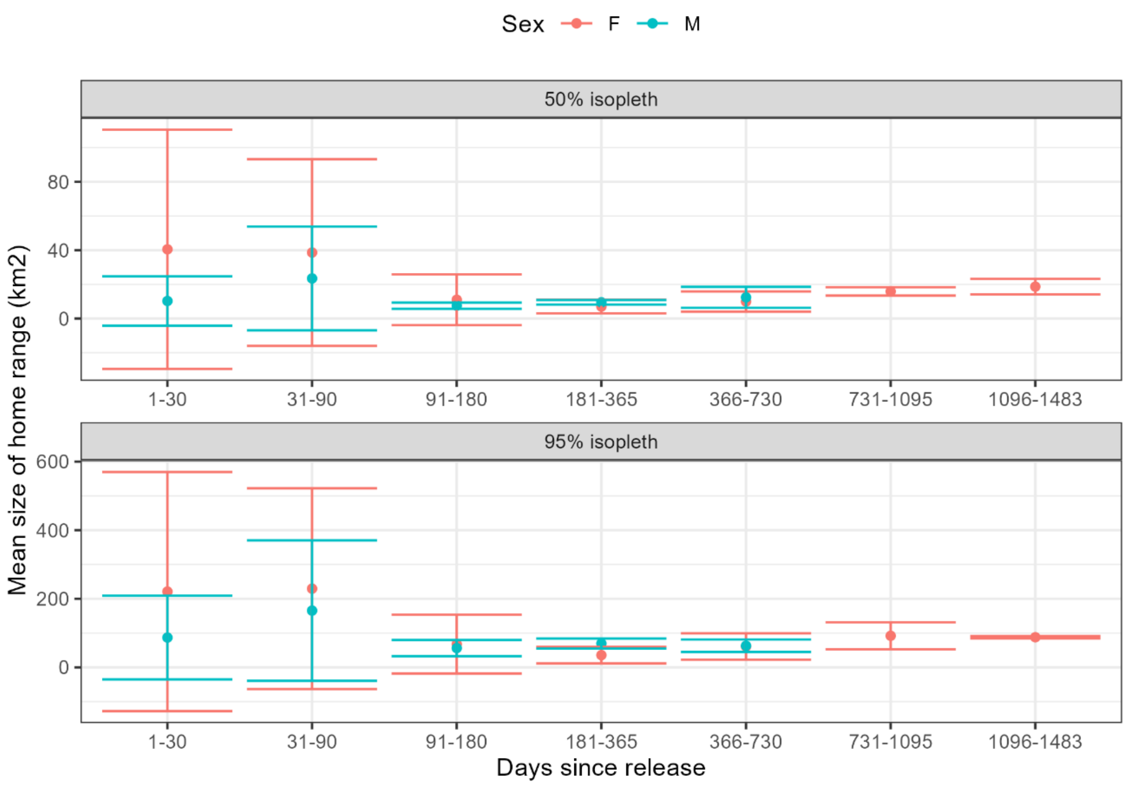


Figure C6: Mean home range size of male and female sheep from the Jemez herd after relocation. Both males with GPS collars were legally harvested two years after release.

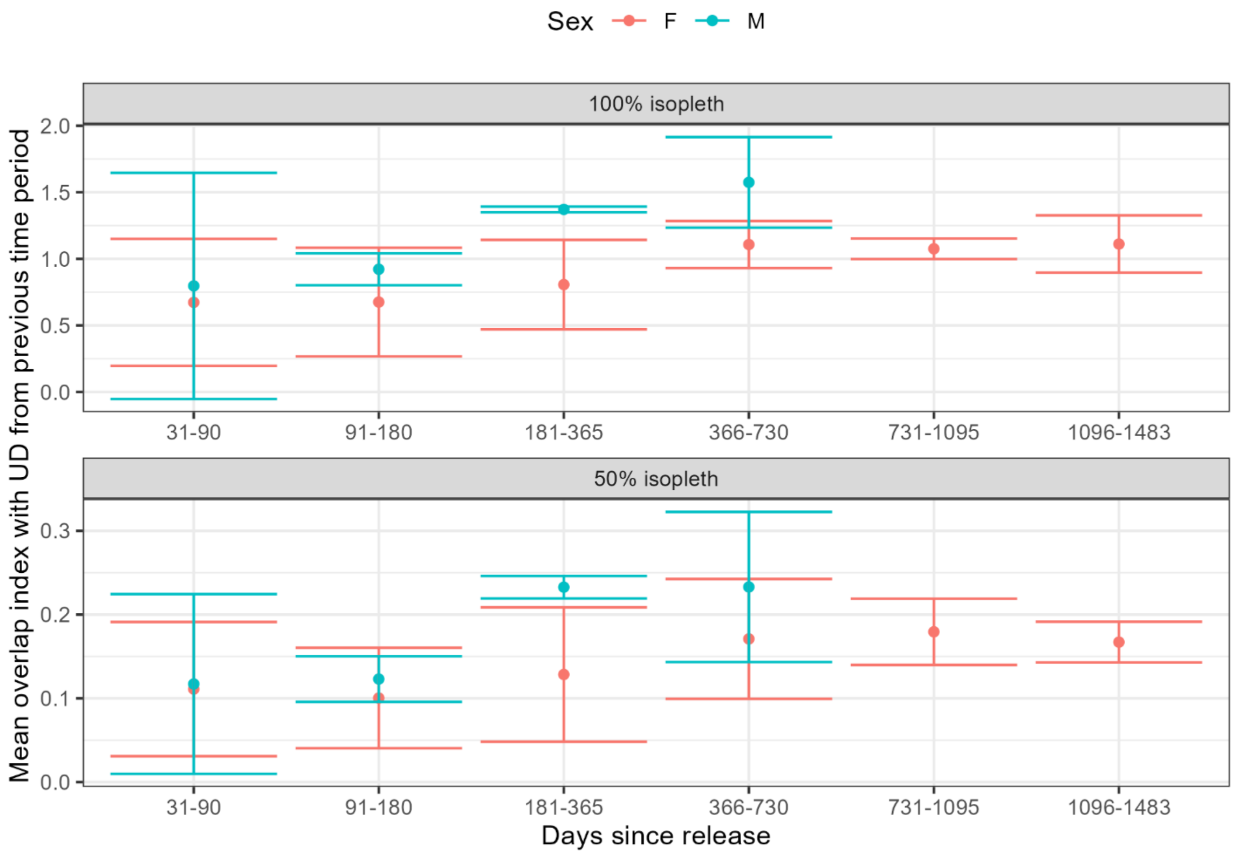


Figure C7: Mean spatial overlap of utilization distributions(UD)/home range isopleths from translocated male and female sheep in the Jemez herd. Both males with GPS collars were legally harvested two years after release.

Table C2: 90% and 95% home range sizes of Wheeler Peak and Red River sheep translocated to the Jemez herd. The source populations were released in different locations 6 km apart.

Source population	**90 % isopleth (km^2)**	**90 % isopleth (km^2)**	**95% isopleth (km^2)**	**90 % isopleth (km^2)**
	Individual	Population	Individual	Population
Wheeler Peak	16.46	40.03	20.73	50.19
Red River	27.08	47.19	33.56	55.32

Appendix D: Risk of Contact Tool sample data

Table D1. Summary of foray behavior by sex for Hells Canyon herds both in summer and winter (O'Brien et al. 2014, DOI 2021). CHHR, core habitat home range.

Summer (May–October)	Ewes		Rams	
	Percent of observations	Number out of total observations	Percent of observations	Number out of total observations
Animals leaving CHHR at least once	6.50%	14/215	28.80%	30/104
Animal-years with at least one foray	1.50%	15/985	14.10%	44/311
Telemetry points outside of CHHR	0.20%	29/17,258	4.40%	160/3,674
Winter (November–April)	**Ewes**		**Rams**	
Animals leaving CHHR at least once	12.9%	28/217	34.9%	38/109
Animal-years with at least one foray	5.6%	60/1,062	17.8%	68/380
Telemetry points outside of CHHR	0.8%	109/12,941	3.7%	156/4,200

Table D2. Calculated foray probabilities for each kilometer beyond the core home range for ewes and rams of the 12 Hells Canyon herds May-October.

Distance (km)	Ewe foray probability	Ram foray probability
1	1	1
2	0.779	0.951
3	0.603	0.902
4	0.492	0.852
5	0.425	0.801
6	0.358	0.750
7	0.268	0.698
8	0.180	0.646
9	0.126	0.596
10	0.107	0.548
11	0.103	0.503
12	0.102	0.462
13	0.102	0.425
14	0.102	0.391
15	0.102	0.361
16	0.102	0.334
17	0.102	0.309
18	0.098	0.284

Distance (km)	Ewe foray probability	Ram foray probability
19	0.087	0.260
20	0.068	0.235
21	0.049	0.210
22	0.038	0.185
23	0.035	0.160
24	0.034	0.136
25	0.034	0.113
26	0.034	0.092
27	0.034	0.074
28	0.034	0.059
29	0.034	0.046
30	0.034	0.036
31	0.032	0.027
32	0.025	0.021
33	0.015	0.015
34	0.006	0.011
35	0.001	0.008

Literature Cited

O'Brien, J. M., O'Brien, C. S., McCarthy, C. M., & Carpenter, T. E. 2014. Incorporating foray behavior into models estimating contact risk between bighorn sheep and areas occupied by domestic sheep. Wildlife Society Bulletin, 38:321–331.