Determination of critical habitat for the endangered Nelson's bighorn sheep in southern California

Jack C. Turner, Charles L. Douglas, Cecil R. Hallum, Paul R. Krausman, and Rob Roy Ramey

Abstract The United States Fish and Wildlife Service's (USFWS) designation of critical habitat for the endangered Nelson's bighorn sheep (*Ovis canadensis nelsoni*) in the Peninsular Ranges of southern California has been controversial because of an absence of a quantitative, repeatable scientific approach to the designation of critical habitat. We used 12,411 locations of Nelson's bighorn sheep collected from 1984–1998 to evaluate habitat use within 398 km^2 of the USFWS-designated critical habitat in the northern Santa Rosa Mountains, Riverside County, California. We developed a multiple logistic regression model to evaluate and predict the probability of bighorn use versus non-use of native landscapes. Habitat predictor variables included elevation, slope, ruggedness, slope aspect, proximity to water, and distance from minimum expanses of escape habitat. We used Earth Resources Data Analysis System Geographic Information System (ERDAS-GIS) software to view, retrieve, and format predictor values for input to the Statistical Analysis Systems (SAS) software. To adequately account for habitat landscape diversity, we carried out an unsupervised classification at the outset of data inquiry using a maximum-likelihood clustering scheme implemented in ERDAS. We used the strata resulting from the unsupervised classification in a stratified random sampling scheme to minimize data loads required for model development. Based on 5 predictor variables, the habitat model correctly classified >96% of observed bighorn sheep locations. Proximity to perennial water was the best predictor variable. Ninety-seven percent of the observations were within 3 km of perennial water. Exercising the model over the northern Santa Rosa Mountain study area provided probabilities of bighorn use at a 30 × 30-m^2 pixel level. Within the 398 km^2 of USFWS-designated critical habitat, only 34% had a graded probability of bighorn use to non-use ranging from ≥1:1 to 6,044:1. The remaining 66% of the study area had odds of having bighorn use <1:1 or it was more likely not to be used by bighorn sheep. The USFWS designation of critical habitat included areas (45 km^2) of importance (2.5 to ≥40 observations per km^2 per year) to Nelson's bighorn sheep and large landscapes (353 km^2) that do not appear to be used (<1 observation per km^2 per year).

Key words California, habitat, logistical regression, Nelson's bighorn sheep, *Ovis canadensis nelsoni,* Peninsular Ranges, Santa Rosa Mountains

Bighorn sheep (*Ovis canadensis*) populations have declined from being comparatively abundant in pristine times to among the rarest ungulate species in North America (Seton 1929, Buechner

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1960, Valdez 1988, Valdez and Krausman 1999). Bighorn sheep inhabiting deserts of the Southwest currently number <20,000 animals in the contiguous United States (Krausman 2000). The Peninsular Ranges of California, consisting of the San Jacinto, Santa Rosa, San Ysidro, Tierra Blanca, In-Ko-Pah, and Jacumba Mountains, extend 225 km in California and continue 1,200 km into Baja California, Mexico. At least 8 subpopulations (female groups) of Peninsular Ranges bighorn sheep in the United States inhabit the steep, xeric eastern slopes at elevations ranging from 91 m to nearly 1,400 m (Jorgensen and Turner 1975, Rubin et al. 1998, United States Fish and Wildlife Service [USFWS] 2001). These bighorn sheep were previously considered a unique subspecies (*O. c. cremnobates*) among the desert races (Cowan 1940, Manville 1980). Recent morphometric and genetic analyses have synonymized the Peninsular Ranges bighorn sheep with Nelson's bighorn sheep (*O. c. nelsoni*) (Ramey 1993, 1995; Wehausen and Ramey 1993).

Peninsular bighorn sheep were fully protected by the California Department of Fish and Game (CDFG) in 1873 (Bureau of Land Management [BLM] and CDFG 1980), listed as rare in 1971, and in 1984 their status was changed to threatened (USFWS 2000). A 25-year decline in this population further prompted the listing as a distinct vertebrate population segment under the federal Endangered Species Act (ESA) of 1973, as amended (USFWS 1998). A 13-member Peninsular Bighorn Sheep Recovery Team developed the recovery plan (USFWS 2000), and critical habitat was designated based on data provided in that recovery plan (USFWS 2001). The designation of critical habitat in the Peninsular Ranges, particularly in the northern portion of the Santa Rosa Mountains, has perplexed and evoked controversy between resource managers, the public, and the legal and scientific communities (Krausman et al. 2000).

The Santa Rosa mountains population of Peninsular Ranges bighorn sheep is unique in that the animals' range abuts the urban interface of cities along the western edge of the Coachella Valley. This subpopulation was estimated to be 350 animals in 1953; it remained stable through 1964 (Jones et al. 1954, Blong 1965) and increased to 500 animals in the late 1960s to mid 1970s, when it may have been the largest, densest, and most stable bighorn population in the state (Weaver and Mensch 1970, Weaver 1972, 1975; USFWS 2000). In April 1977, the ewe:lamb ratio was 61:100, which declined to 7:100 by September. The following year the October ewe:lamb ratio was 9:100 (Weaver 1982). Depressed lamb survival, low recruitment, and premature adult mortality attributed to anthropogenic influences in concert with natural events (e.g., predation, falls, poor nutrition, inadequate water, disease epizootics) decreased the 1960–1970 population >75% by 1995. Research on factors leading to the population decline in the Peninsular Ranges has focused on disease (DeForge et al. 1982, Turner and Payson 1982*a*,*b*; Mullens and Dada 1992), water and nutrition (Wehausen et al. 1987*a*,*b*), predation (Hayes et al. 2000), and anthropogenic-related causes (DeForge and Ostermann 1998, USFWS 2000). Although habitat loss and fragmentation were implicated as factors in the Peninsular Ranges sheep population decline (USFWS 2000), the indirect effects of these factors were vague and difficult to quantify (Wilcove et al. 1986, Gilpin 1987, Burgman et al. 1993). Empirical data documenting habitat loss and fragmentation in concert with the population decline in the Santa Rosa Mountains are absent.

A qualitative model to delineate essential Peninsular Ranges bighorn sheep habitat was developed (USFWS 2000). The lower eastern elevation limit of bighorn habitat was determined from modified algorithms defining a minimum ≥20% (≥9°) slope or the toe of the Santa Rosa Mountains as being important. All upslope terrain was designated high-quality habitat essential to the recovery and conservation of bighorns and possibly requiring special management considerations or protection (USFWS 1988, Murphy and Noon 1991, Hall et al. 1997). The maximum westernmost extent of bighorn habitat was determined at the interface with vegetation associations not typically used by bighorn sheep in the Peninsular Ranges. This was generally below 1,400 m. The chaparral species of Muller's oak (*Quercus cornelius-mulleri*), sugar bush (*Rhus ovata*), chamise (*Adenosoema fasciculatum*), and manzanita (*Arctostaphylos* spp.) provided that delineation. An 0.8-km buffer to the upper and lower habitat delineation was extended westerly and easterly and added to the USFWS bighorn sheep essential-habitat delineation. This habitat boundary was then subjectively modified to exclude or include parcels of land determined by Recovery Team consensus. The boundary was agreed upon by consensus of Recovery Team members using comparisons with previous modeling efforts (BLM and CDFG 1980, Hansen 1980*a*) that are generally considered to be of limited value in measuring habitat quality in the Santa Rosa Mountains (Andrew et al. 1997, USFWS 2000). Upper and lower habitat boundaries were recorded with GPS from helicopter flight paths and again determined by consensus of Recovery Team biologists (USFWS 2000). We were unsuccessful in reproducing the existing USFWS essential-habitat delineations with the data provided, because the procedural methodology for determining essential habitat as described in the Recovery Plan was qualitative (USFWS 2000). The essential habitat delineation in the Recovery Plan was virtually identical to the final critical-habitat designation. The absence of sufficient data in the Recovery Plan to independently reproduce the critical-habitat (essential-habitat) delineation is a serious shortcoming of the Recovery Plan and critical-habitat delineation documents because it violates a basic premise of the scientific method and the requirements under ESA to use the best scientific data available.

Habitat models can be useful to understanding the ecology of a species and pivotal to management decisions focused on the recovery of an endangered species. Desert bighorn sheep habitat can vary from population to population and readily lends itself to generalizations of habitat requirements, although subpopulation differences do exist (e.g., availability of water [Rubin et al. 1998, USFWS 2000]). No quantitative model currently exists for bighorn sheep in the Peninsular Ranges. Several habitat models have been developed to evaluate bighorn habitat in the desert Southwest (Armentrout and Brigham 1988, Cunningham 1989, McCarty and Bailey 1994, Andrew and Bleich 1999). A modified Hansen Model (Hansen 1980*a,b*) was used by state and federal resource agencies to classify bighorn habitat in the Santa Rosa and San Jacinto Mountains (BLM and CDFG 1980). The Hansen Model was designed to differentiate between parcels of good- and poor (deficient)-quality habitat. Its application is subject to some investigator bias because it was developed for evaluating habitat within a different life zone in Nevada. Use of the Hansen Model was discontinued by CDFG in the early 1990s as being of limited value in assessing habitat outside of the landscape for which it was devised (Andrew and Bleich 1999, S. Torres, California Department of Fish and Game, personal communication as cited in USFWS 2000). However, bighorn sheep habitat classifications in the Peninsular Ranges made prior to the Hansen Model's discontinuance continue to be used and cited by resource agencies (USFWS 2000).

Bighorn sheep populations will have increased chances of survival if those parcels of habitat with the greatest measure of importance to survival are identified and preserved. Recent court decisions have shown that repeal of critical-habitat designations potentially may be avoided if they are based on quantitative models developed from empirical data, instead of qualitative models or opinions (New Mexico Cattle Growers versus United States Fish and Wildlife Service, 248 Federal Supplement 3d, 1277 [10th Circuit, 2001], National Association of Home Builders versus Evans, Case No. 1:00-CV-02799 [District of D. C., 2002], Building Industry Legal Defense Foundation versus Norton, 231 Federal Supplement 2d, 100 [District of D. C., 2002], National Association of Home Builders versus Norton, D.C. No. CV 00-0903 SRB, [District of Arizona 2003]). Our objective was to quantify Nelson's bighorn sheep habitat in the northern Santa Rosa Mountains, identify those parcels of land having the greatest potential and probability for occupancy, and compare this to the USFWS (2001) critical-habitat designation. We analyzed bighorn sheep distribution and habitat utilization in the northern Santa Rosa Mountains employing data obtained under the Freedom of Information Act (FOIA) from the USFWS to determine whether habitat use could be predicted from observations and readily available GIS-based data and technologies.

Study area

The Santa Rosa Mountains in Riverside, San Diego, and Imperial counties were oriented northwest to southeast, and were in the northern portion of the Peninsular mountain chain. The range was bounded to the northwest by San Jacinto Mountains at Palm Canyon, to the north and east by the Coachella Valley, to the south by the San Ysidro Mountains at Coyote (Creek) Canyon and Collins and Borrego Valley, and to the west by the Anza Uplands. This range of mountains reached a northern elevation of 2,657 m at Toro Peak, with the range tapering to a narrow ridge 19 km to the southeast at the 2,022-m crest of Rabbit Peak. Four of the 9 Peninsular Ranges' bighorn sheep subpopulations dispersed within the Santa Rosa Mountains represent approximately one-third ($n = 129 \pm 37.9$) of the United States population (DeForge et al. 1995, Rubin et al. 1998, USFWS 2000).

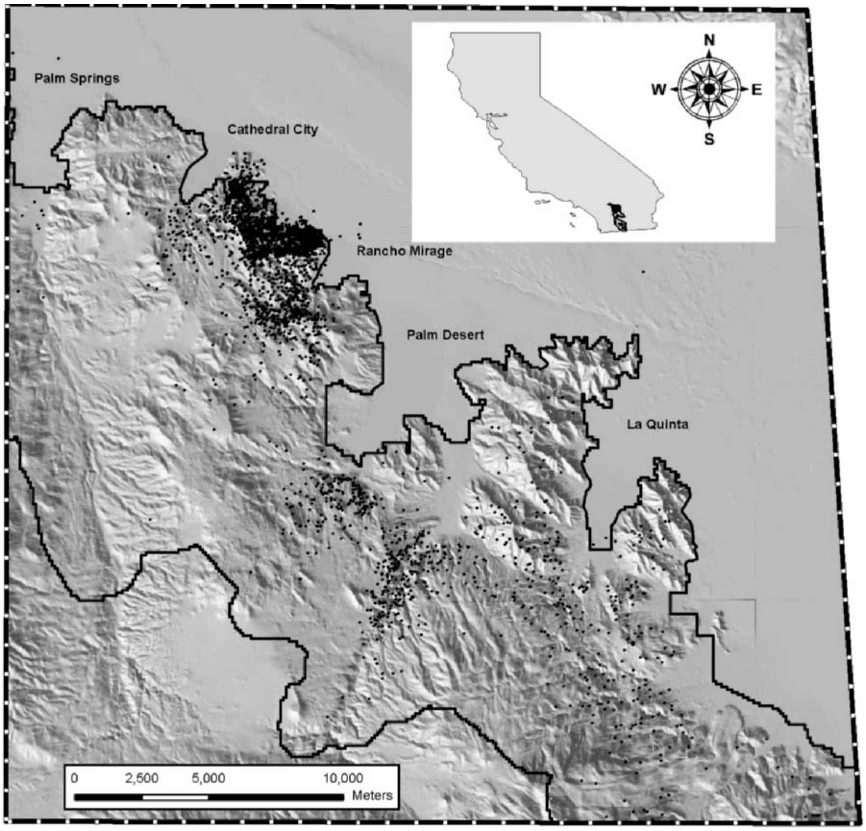

Figure 1. Distribution of 12,411 telemetry observations of Nelson's bighorn sheep made from 1984–1998 within the northern Santa Rosa Mountain study area, Riverside County, California. The solid black line circumscribes the 398-km^2 United States Fish and Wildlife Service critical-habitat designation (United States Fish and Wildlife Service 2001).

We based our habitat model on the observations of Nelson's bighorn sheep occupying the USFWS critical-habitat (USFWS 2001) delineation within the northern Santa Rosa Mountains (Figure 1). This study area was bounded by Palm Canyon on the north; the developed portions of the City of Palm Springs, the Coachella Valley, and State Highway 111 on the east; and Martinez Mountain on its southern limits, and contained approximately half of the Santa Rosa Mountains population of bighorns (USFWS 2000). The denser vegetation of the upper Santa Rosa Mountains elevations demarcated the western edge. The substrate was mostly soils of granitic origin, with intrusions of pre-Cretaceous metamorphic rock being common. Due to faulting, steep scarps and precipitously eroded canyons with narrow bottoms were common. The watershed was under the climatic influence of the Colorado (Sonoran) Desert (Jaeger 1957, Ryan 1968, Zabriskie 1979, USFWS 2000). The Santa Rosa Mountains had desert slopes on the northeastern interior side resulting from orographic effects. Here, native bighorns occurred on east-facing desert slopes, typically below 1,400 m (Jorgensen and Turner 1975, Rubin et al. 1998, USFWS 2000). Characteristically, rainfall was scant and erratic, but generally concentrated in November–March and August–September. The long-term (>70 years) annual average rainfall was <10 cm and was subject to considerable annual variation. Temperature patterns were more consistent seasonally. June, July, August, and September were the warmest months, with an average daytime high temperature in excess of 39°C and occasionally reaching >49°C. Low humidity and high vapor pressure deficits make the air very arid. July had the highest temperatures and the greatest evaporative demand. The summer months were coincident with the bighorn sheep's breeding season, with the rut peaking in August (Thompson and Turner 1982, Rubin et al. 1998).

Vegetation was characterized by a Sonoran Creosote Bush Scrub, but was inclusive of other distinct vegetation assemblages such as Desert Dry Wash Woodland and Desert Fan Palm Oasis Woodland (Sawyer and Keeler-Wolf 1995). Indicative of the Sonoran Creosote Bush Scrub were the perennial species of creosote bush (*Larrea tridentata*), burrobush (*Ambrosia dumosa*), brittlebush (*Encelia farinosa*), sweetbush (*Bebbia juncea*), cheesebush (*Hymenoclea salsola*), and indigo bush (*Psorothamnus schottii*). The upper elevations of this plant community included jojoba (*Simmondsia chinensis*) and ocotillo (*Fouquieria splendens*). The Dry Wash Woodland was characterized by the winter-deciduous species of palo verde (*Parkinsonia florida*), honey mesquite *(Prosopis glandulosa*), catclaw

(*Acacia greggii*), and desert willow (*Chilopsis linearis*). Consistently associated with the Dry Wash Woodland was chuparosa, (*Justicia californica*), desert lavender (*Hyptis emoryi*), and the desert fan palm (*Washingtonia filifera*), which defined its own unique vegetation association, the Desert Fan Palm Oasis. Pervasive ruderal elements could be found in virtually all assemblages. Differences of elevation, slope, substrate, anthropogenic impacts, and water availability affected the plant diversity, abundance, and endemism (Zabriskie and Zabriskie 1976, Zabriskie 1979).

Methods

Data acquisition and analysis

Observation locations of Nelson's bighorn sheep in the Santa Rosa Mountains were obtained in electronic format under a FOIA request to the Carlsbad Office of the USFWS, Carlsbad, California. We had to obtain these data under a FOIA request because they were not publicly available despite being part of a public document. The only amplification to these data were the accompanying Universal Transverse Meridian (UTM) coordinates for each observation, the year of observation, and the data source for 12,697 bighorn sheep observations within the 398-km^2 USFWS delineation of critical habitat in the northern Santa Rosa Mountains. This was the same data set previously used in the Recovery Plan (USFWS 2000), the critical-habitat designation (USFWS 2001), and Peninsular bighorn sheep Section 7 consultations with the USFWS as proof of bighorn sheep habitat use (Wagner and McKinney 2001). We used a homogeneous set of 12,411 data points from 14 consecutive years (1984–1998) of these observations, having a precision of ±250 m. Metadata files describing how the observations were made (telemetry collar, direct visual observation with GPS ground follow-up, manually determined UTM coordinate or triangulation), total numbers of animals represented by each observation, age of animals, gender, or the presence of lambs were excluded from these data under a proprietary information exclusion of FOIA. The remaining 286 observations were non-GPS historical data spanning 47 years. Almost 94% of these observations were extracted from field notes of observations and sign (i.e., tracks, bedding, and feces), that occurred from 1953–1985. The UTM coordinates for these observations were extrapolated from maps and field descriptions of locations. Fifty-six percent of these observation points were assigned a ±250-m precision of observation, and the remainder were consigned a precision of ±1 km by the USFWS using undescribed criteria. None of these historical data were used in our model development.

Cogent to the development of our predictive model was a consideration of the habitat predictor variables or primary constituent elements (USFWS 2000) important to the management and recovery of the Nelson's bighorn sheep in the Peninsular Mountain Ranges. We chose 6 quantitative factors or habitat predictor variables identified as important considerations (USFWS 2000) in evaluating bighorn sheep habitat upon which to base our logistic regression model: slope, elevation, ruggedness, proximity to a perennial water source, proximity to minimum expanses of escape habitat, and slope aspect (Smith et al. 1991, USFWS 2000). Values were scaled for each of these variables at a 30×30-m^2 pixel level for the 398 km^2 of the critical habitat designation in the northern Santa Rosa Mountains.

Slope

Topographic surface expression refers to the assemblage of slopes and the 3-dimensional pattern of forms. Slope reflects vertical relief and horizontal distance with the slope angle defined as:

$$\frac{\text{Relief}}{\text{Horizontal distance}} = \tan(\text{slope angle}).$$

An incline of 45° is a 100% slope (a 10% slope approximates a handicap ramp).

Elevation and slope aspect

We derived topographic information from 1:24,000 Digital Elevation Models (DEM). We used the ERDAS Imagine software to examine relationships of slope and slope aspect, 3-dimensional renderings, and draping of raster and vector data. We scored each pixel to its mean absolute elevation. Slope aspect was reported in degrees (e.g., 90° being due east).

Ruggedness

We determined acute changes in the slope of the terrain as a topographic ruggedness index (TRI). We calculated the TRI for each pixel by an image-processing technique that calculated the standard deviation of the difference in the mean elevation from a center pixel and the 8 pixels that immediately surrounded it (neighborhood analysis). Using a moving window, a standard deviation for each new pixel was calculated based on the values of the surrounding pixels (focal standard deviation). A histogram equalization transformation reassigned the data into 10 equal histogram sets; data set 1 contained pixel values with a low index of ruggedness, and data set 10 contained the pixels with values reflecting considerable ruggedness.

Proximity to minimal expanse of escape habitat

Escape terrain within the study area was defined by areas ≥2 ha exhibiting ≥80% (≥36°) slope (Smith and Flinders 1991, Smith et al. 1991, Singer et al. 2000*a*,*b*). These areas were distinguished from DEMs using ERDAS Imagine software. Each pixel within a 300-m radius of escape terrain was scored relative to its distance from escape terrain.

Proximity to a perennial water source

There were 4 perennial water sources within the northern Santa Rosa Mountains. We delineated an 8-km radial zone around each perennial water source to assure encompassing yearly home ranges of the bighorn sheep herds and to include all of the USFWS (2001) critical-habitat delineation. We scored each $30 \times 30\text{-m}^2$ pixel within the 8 km from its center to the nearest perennial water source. This created 267 classifications (8,000 m/30 m) or scoring groups within the 8 km.

Proximity to domestic and exotic animals

We reviewed land use adjacent to bighorn sheep habitat and documented potential sources of pathogens from domestic livestock and exotic wildlife. Although not specifically codified within our habitat model, the potential for exposure to pathogens emanating from contact with exotic or domestic animals can have a negating effect on recovery, irrespective of habitat availability or quality (Smith et al. 1991, Gross et al. 2000, Krausman 2000, Singer et al. 2000*a*,*c*).

Logistic regression model development

We developed a multiple logistic regression model (DeMaris 1992, Menard 1995, Estrella 1998, Johnson and Wichern 1998) to evaluate attributes of occupied and unoccupied habitat. Specifically, the model should predict the "active" or presence versus "inactive" or absence of bighorn sheep within the study area at a pixel-level resolution. Included within the database for each designated active or inactive pixel was the location, elevation, slope, a measure of ruggedness (TRI), distance from perennial water source(s), and distance from minimum expanses of escape habitat. Because the key response variable was binary in this situation (i.e., had a value of 1 if the pixel experienced bighorn sheep activity; otherwise its value was 0, indicating inactivity) a logistic statistical model was appropriate for prediction purposes. Moreover, because all variables were quantitative (e.g., elevation, slope, distance from water), we used a multiple regression logistic model.

To effectively account for the diversity of the habitat landscape, an unsupervised classification was carried out at the outset of the investigation using the maximum-likelihood clustering scheme implemented in ERDAS. This was applied to the aforementioned data in a multivariate mode (Wright 1995, Tabachnick and Fidell 1996), thereby incorporating potential intercorrelations that may exist between the variables. The unsupervised classification directly supported a more efficient approach to be conducted because each resulting cluster (i.e., stratum) possessed somewhat more homogeneous land characteristics. This also permitted a minimization of needed observations and improved accuracy of model inferences. The logistic model estimated the response variable in a minimum bias and maximal precision manner as could best be achieved by use of the maximum-likelihood approach for model fitting (i.e., the maximum-likelihood approach is utilized in the Statistical Analysis Systems Procedure Logistic module). We investigated the predictor variables in regard to their influence on the likelihood of bighorn activity versus non-activity at the pixel level; this was achieved through tests conducted as a part of a standard logistic regression analysis; specifically, the χ^2 Goodness of Fit Test. We used the Mallow's C_p Statistic in ranking the relative importance of the predictor variables used in the model. The development of a reliable model requires the inclusion of randomly selected inactive pixels along with the observed active pixels. In particular, model development required the use of more inactive sites than active sites because of the typical higher variability of the former (Gross et al. 2002). To assist in determining the appropriate ratio of active to inactive sites to use in model development, we tried several ratios such as 1:1, 1:5, and 1:10 to see which maximized the coefficient of determination (Nagelkerke 1991) and which, at the same time, minimized the Akaike's Information Criterion (Akaike 1973, Burnham and Anderson 1998) and the model mean square error (Cox and Snell 1989). To further ensure the development of a reliable model, checks for multicollinearity along with assessments regarding the optimum (i.e., significant) variables included in the model were determined. Because the model's primary function was to provide a probability assessment for habitat utilization, tests were conducted using cross-validation (Johnson and Wichern 1998). We used procedure LOGISTIC in the Statistical Analysis Systems (SAS) software in the development and testing of the bighorn sheep habitat predictability model (Statistical Analysis Systems 2000).

The equation form of the predictive model for the bighorn sheep habitat is given by the logistic regression:

$$P(A) = \frac{\exp(\beta_0 + \beta_1 x_1 + \ldots + \beta_k x_k)}{1 + \exp(\beta_0 + \beta_1 x_1 + \ldots + \beta_k x_k)},$$

where, *P(A)* is the probability of the use of an active site (i.e., pixel). The $x_1, x_2, \ldots, x_k$ are independent predictor variables (i.e., habitat predictor variables of location, elevation, slope, ruggedness, distance from water, distance from minimum expanses of escape habitat) and the $\beta_1, \beta_2, \ldots, \beta_k$ are the logistic coefficients (Hosmer and Lemeshow 1989). We also checked the model to see if it was more appropriate to be curvilinear (i.e., checked to see whether second-order [or higher] predictors were more appropriate for prediction of bighorn presence or absence). Statistical tests were conducted using cross-validation (employing holdout samples) to assess the effectiveness of model predictions.

The exercising of the model provided probabilities of the presence versus absence of bighorn sheep at the pixel level; in addition, it provided estimates of the odds ratios of the presence or absence status. For example, an odds ratio of 6.3:1 for a given pixel suggested that it was 6.3 times more likely that one would observe bighorn activity rather than non-activity in that pixel for the given values of the habitat predictor variables.

Results

We developed a logistic regression model for Nelson's bighorn sheep habitat that evaluated relative importance of selected variables essential for native wild sheep (Table 1). The model correctly classified >96% of the active pixels (12,148 observations) within 135 km^2 (34%) of the 398-km^2 USFWS-designated critical habitat in the northern Santa Rosa Mountains (USFWS 2001). The remaining 66% (263 km^2) of the designated critical habitat in the northern Santa Rosa Mountains contained 345 observations (4%) made during the 14-year period and showed a greater probability of inactivity than activity based upon occurrence of the selected variables (Table 2).

Slope

Multicollinearity occurs when ≥2 variables or covariates (habitat predictor variables) are highly correlated with each other. The correlated relationship makes it difficult to obtain reliable estimates of effects of the individual variable on the dependent variable (e.g., bighorn sheep activity versus non-activity within a given pixel). The variance inflation factors (VIF) were investigated to assess the extent of multicollinearity. A VIF ≥9 suggested a high level of variable relatedness. The VIF for topographic ruggedness index (TRI) was between 8 and 9 and was >9 for slope. This was primarily due to a high correlation between slope and the TRI (r=0.93). A consideration of slope as a habitat predictor variable in the model kept the estimates of the model coefficients from being stable. The VIF values for the remaining 5 variables after eliminating slope (i.e., distance from perennial water source, elevation, TRI, slope aspect, and distance from escape habitat) were <2.

Logistic regression model development

A matrix of 1,019 rows and 1,061 columns of pixels comprised the northern Santa Rosa Mountain study area and surrounding terrain. Model development required sampling both within and outside of the USFWS critical-habitat designation. The matrix was refined with the elimination of all but 826,748 pixels from the model development by excluding areas of urban developments (e.g., the city of Palm Springs, Cathedral City, Palm Desert). The grid matrix embraced the critical-habitat designation in the northern Santa Rosa Mountains. Before pixel sampling was conducted, 10 strata were created by clustering the vector-valued data comprised of distance from perennial water, distance from >2 ha of escape habitat, TRI, elevation, and slope aspect. These strata were used

Table 1. Odds ratios for bighorn sheep activity versus non-activity at the pixel (30 × 30-m^2) level within the 398-km^2 United States Fish and Wildlife Service-designated critical habitat (USFWS 2001) in northern Santa Rosa Mountains, Riverside County, California. Odds ratios are the probability of activity divided by the probability of non-activity. Pixel-level summary values for each of the habitat predictor variables provides for habitat characterization.

Landscape classification (odds of activity)	Habitat predictor variable[a]	No. of pixels	$\bar{x}$	SD	Min	Max
I	Odds of activity	609,781	0.15	0.19	0.00	1.00
(<1:1)	Probability of activity	609,781	0.11	0.11	0.00	0.50
	Distance to perennial water (m)	609,781	8,699.19	2,053.95	3,015.29	11,999.97
	Elevation (m)	609,781	558.31	543.70	–34.00	2,058.00
	Distance from >2 ha of escape habitat (m)	609,781	302.37	52.31	0.00	330.00
	TRI	609,781	3.39	3.38	0.00	10.00
	Slope aspect (degrees)	609,781	168.35	121.82	0.00	361.00
II	Odds of activity	88,975	2.39	1.12	1.00	5.00
(≥1:1 to <5:1)	Probability of activity	88,975	0.67	0.10	0.50	0.83
	Distance to perennial water (m)	88,975	4,588.97	964.28	2,108.42	1,1998.75
	Elevation (m)	88,975	464.37	363.09	0.00	1376.00
	Distance from >2 ha of escape habitat (m)	88,975	301.56	56.70	0.00	330.00
	TRI	88,975	3.66	3.39	0.00	10.00
	Slope aspect (degrees)	88,975	156.29	122.06	0.00	361.00
III	Odds of activity	33,301	7.21	1.43	5.00	10.00
(≥5:1 to <10:1)	Probability of activity	33,301	0.87	0.02	0.83	0.91
	Distance to perennial water (m)	33,301	3,589.77	752.07	1678.11	7,283.91
	Elevation (m)	33,301	428.33	326.92	0.00	1,227.00
	Distance from >2 ha of escape habitat (m)	33,301	309.93	38.17	0.00	330.00
	TRI	33,301	3.83	3.26	0.00	10.00
	Slope aspect (degrees)	33,301	154.11	118.57	0.00	361.61
IV	Odds of activity	28,611	14.19	2.81	10.00	20.00
(≥10:1 to 20:1)	Probability of activity	28,611	0.93	0.01	0.91	0.95
	Distance to perennial water (m)	28,611	2,949.87	650.80	1,131.02	5,356.43
	Elevation (m)	28,611	425.08	301.04	61.00	1,134.00
	Distance from >2 ha of escape habitat (m)	28,611	313.20	19.51	0.00	330.00
	TRI	28,611	3.53	3.10	0.00	10.00
	Slope aspect (degrees)	28,611	155.70	121.68	0.00	361.00
V	Odds of activity	28,396	32.33	8.63	20.00	50.00
(21:1 to 50:1)	Probability of activity	28,396	0.97	0.01	0.95	0.98
	Distance to perennial water (m)	28,396	2,260.89	652.10	546.91	3,822.70
	Elevation (m)	28,396	442.66	291.37	66.00	1,105.00
	Distance from >2 ha of escape habitat (m)	28,396	309.02	33.26	0.00	330.00
	TRI	28,396	4.27	3.12	0.00	10.00
	Slope aspect (degrees)	28,396	159.41	126.11	0.00	361.00
VI	Odds of activity	15,995	69.35	13.84	50.01	100.00
(51:1 to 100:1)	Probability of activity	15,995	0.99	0.00	0.98	0.99
	Distance to perennial water (m)	15,995	1,749.59	574.92	131.73	3,581.60
	Elevation (m)	15,995	416.90	265.58	0.00	945.00
	Distance from >2 ha of escape habitat (m)	15,995	295.07	60.06	0.00	330.00
	TRI	15,995	5.12	3.27	0.00	10.00
	Slope aspect (degrees)	15,995	165.26	122.84	0.00	361.00
VII	Odds of activity	21,689	332.98	350.34	100.00	6,044.09
(101:1 to 6,044:1)	Probability of activity	21,689	1.00	0.00	0.99	1.00
	Distance to perennial water (m)	21,689	1,092.43	474.69	15.13	3,548.23
	Elevation (m)	21,689	365.60	210.39	67.00	899.00
	Distance from >2 ha of escape habitat (m)	21,689	234.79	120.61	0.00	330.00
	TRI	21,689	6.81	3.21	0.00	10.00
	Slope aspect (degrees)	21,689	149.28	116.17	0.00	361.00

[a] Distance to perennial source of water is given as meters from water; elevation in feet above sea level; distance from ≥2 ha of escape habitat (maximum 11 pixel or 330 m); topographic ruggedness index (TRI) is non-dimensional, the greater the value (maximum of 10) the greater the ruggedness; slope aspect reflects 360º with 90º as due East.

Table 2. Landscape classification determined from the 5 habitat predictor variables and distinguished by probability odds of bighorn sheep activity as determined from the 12,411 observations of bighorn sheep from 1984–1998 within the 398-km^2 United States Fish and Wildlife Service-designated critical habitat (USFWS 2001) in the northern Santa Rosa Mountains, Riverside County, California. The largest area (263 km^2) was landscape classification I, which had <0.1 observations of bighorn sheep per km^2 × yr^{-1} from 1984–1998; landscape classification VII had the greatest frequency of observations 40.0 observations of bighorn sheep per km^2 × yr^{-1} during the same period.

Landscape classification	Odds of activity	Total area (km^2)	Total no. observations 1984–1998	% observations 1984–1998	No. observations per (km^2 × yr^{-1})
I	<1:1	263.0	345	2.8	0.1
II	≥1:1 to <5:1	55.5	216	1.7	0.3
III	≥5:1 to <10:1	18.1	103	0.8	0.4
IV	≥10:1 to 20:1	16.4	189	1.5	0.8
V	21:1 to 50:1	18.3	641	5.2	2.5
VI	51:1 to 100:1	10.2	1,736	14.0	12.1
VII	101:1 to 6044:1	16.4	9,181	74.0	40.0

to support the stratified random sampling effort. A sample size of 5,473 pixels was selected to carry the logistic model development resulting from a 1:10 ratio of the sampled active to non-active pixels. This rate of sampling provided the strongest model diagnostics and subset selection when compared to 1:1 and 1:5 sampling rates (Statistical Analysis Systems 1995, Allison 1999). All pixels with bighorn sheep observations were used in the model development along with 10 times that number of pixels lacking bighorn observations. The resulting model, based on the logistic regression of habitat values stemming from the 5 habitat predictor variables, ranked the study area into 7 landscape classifications based upon their respective odds ratios for activity versus non-activity at the pixel level (Table 1). The 7 habitat groupings ranged from a low (less than <1:1)-odds ratio of activity to regions of high (6,044:1)-odds ratio of activity. Those landscapes having the greatest odds of bighorn sheep activity in the northern Santa Rosa Mountains were described as occurring at a mean elevation of 366±210 m; 1,092±475 m from water; 234±121 m from≥2 ha of escape habitat on a slope aspect of 149±116° and a TRI of 7±3 (very rugged terrain).

The odds ratios as determined utilizing the occurrence of the 5 habitat predictor variables data subsets were processed through GIS (Figure 2A). The logistic regression model correctly accounted for >96% of the bighorn observations in the northern Santa Rosa Mountains. Less than 4% of the observations occurred in landscapes where the quality of habitat predictor variables failed to provide for the odds of activity to be >1:1.

Within the broad scope of the northern Santa Rosa Mountains, the USFWS designated 398 km^2 as critical habitat (USFWS 2001), of which 263 km^2 (66%) had a graded probability of bighorn activity to inactivity <1:1, or a greater probability of inactivity than activity (Figure 2B). There were 1.3 observations of bighorn sheep per km^2 in landscape classification I over the 14-year period represented in the data set. The remaining 135 km^2 of the USFWS-designated critical habitat indicated activity odds ratios >1:1 reflecting the availability and quality of the habitat predictor variables. Landscape classification II comprised nearly 56 km^2, averaged more than 4.5 km from a perennial water source, and had <2% percent of the bighorn sheep observations (3.9 observations per km^2 per 14 years). Landscape group III occupied 18.1 km^2 and had a range of odds probability ratio for activity ranging from ≥5:1 to <10:1. Less than 1% of the observations were distributed within this classification, although the frequency of observations was 5.7 per km^2. Landscape classification IV contained 1.5% of the observations at a frequency of 11.5 observations per km^2 over its entire 16.4 km^2. More than 5% of the observations were found in the 18.3 km^2 of landscape V habitat at frequency of 35.1 observations per km^2. Landscape class VI and VII collectively contained 88% of the observations at a frequency of 170 and 561 observations per km^2, respectively. Classifications VI (10.2 km^2) and VII (16.4 km^2) occurred with least frequency (Table 2).

The 5 habitat predictor variables were evaluated by the χ^2 Score statistic such that the better the model, the greater the χ^2 Score (Statistical Analysis Systems 1995). The single habitat predictor variable of perennial water availability was only slightly less effective in predicting activity (χ^2 Score = 4,170) than was a consideration of all 5 predictor variables ([χ^2 Score = 4,286] Table 3). A consideration of water availability and elevation was the best

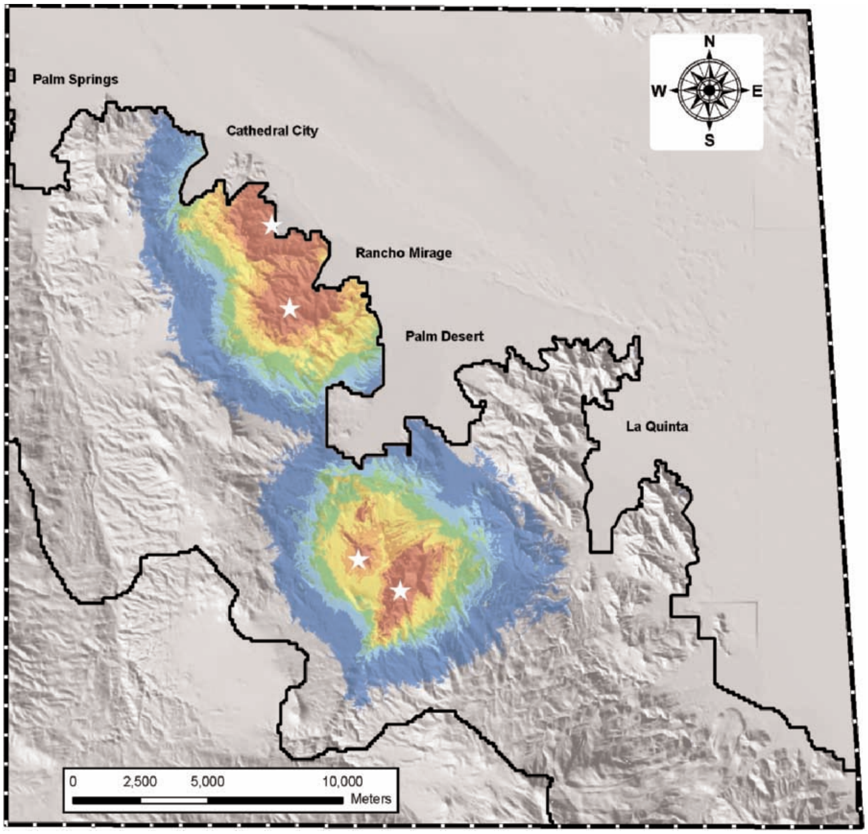

Figure 2A. Distribution of 7 landscape classifications resulting from the GIS-processed logistical regression model for the 398-km^2 United States Fish and Wildlife Service-designated critical habitat (black line) within the northern Santa Rosa Mountains, Riverside County, California. Landscape types were defined at a 30 × 30-m^2 pixel level of resolution by the 5 predictor variables: distance to a perennial source of water, distance to ≥2 ha of escape terrain, slope aspect, topographical ruggedness index, and elevation. The landscape classifications were collectively ranked on the basis of the observation data as to the probability or odds of bighorn sheep activity relative to non-activity within a given pixel. Landscape classification I (gray) occupies 66% (263 km^2) of the United States Fish and Wildlife Service's designated critical habitat (398 km^2); this terrain has a greater probability of being unoccupied by bighorn sheep than being occupied. Classification II (dark blue) embraces 55.5 km^2 with a probability ≥1:1 to <5:1 for bighorn sheep occupation. Light blue represents landscape classification III (18.1 km^2) with a probability ≥5:1 to <10:1 of bighorn activity. Landscape classification IV (green) occupies 16.4 km^2 with odds ≥10:1 to 20:1. The 18.3 km^2 of landscape classification V (yellow) has a probability of 21:1 to 50:1 for bighorn activity. Landscape classifications VI (orange) and VII (red) occupy 10.2 km^2 and 16.4 km^2 with probability of activity 51:1 to 100:1 and 51:1 to 6,044:1, respectively. Stars mark sites of perennial water sources.

choice of 2 predictor variables (χ^2 Score = 4,243). Without regard to season, 97% of all the northern Santa Rosa Mountain bighorn sheep observations occurred within 3 km of a perennial water source (Figure 3). Water availability from perennial sources was the most decisive variable in determining presence of bighorn sheep in the northern Santa Rosa Mountains.

The Conditional Odds Ratio Estimate provided estimation of how much each independent variable was incremented to produce the estimated odds ratio; it was analogous to a correlation of the predictor variable and probability of bighorn sheep activity (Table 4). A predicted increased distance from water or increased elevation resulted in a proportional decrease in the odds ratio for bighorn sheep activity at the pixel level. By contrast, an increase in TRI, proximity to ≥2 ha of escape habitat, or slope aspect served to increase the estimated odds ratio for bighorn sheep activity.

Proximity to domestic or exotic animals

Although our habitat model was developed for comparison to the USFWS-designated critical habitat, we identified 3 potential sources of disease from livestock, exotic wildlife, and rehabilitated wildlife in and near the study area (Figure 4). The first of these was located southeast of La Quinta. This 74-ha feed lot operation for domestic goats and domestic sheep had been in operation at its present location since at least 1965. Approximately 450 animals (combined) were farmed within 2–3 km of the toe of the Santa Rosa Mountains outside of Peninsular Ranges' bighorn sheep critical-habitat designation. Fencing consisted of a combination of cyclone wire, hog wire, and wooden loading pallets varying from 1.5–2 m in height. A double-fenced perimeter was absent, and the owner indicated that what few animals escaped were easily recaptured. There were some losses to predation. Overflow from the ad libitum availability of drinking water created large localized areas of mud and wet fecal duff (Figure 5).

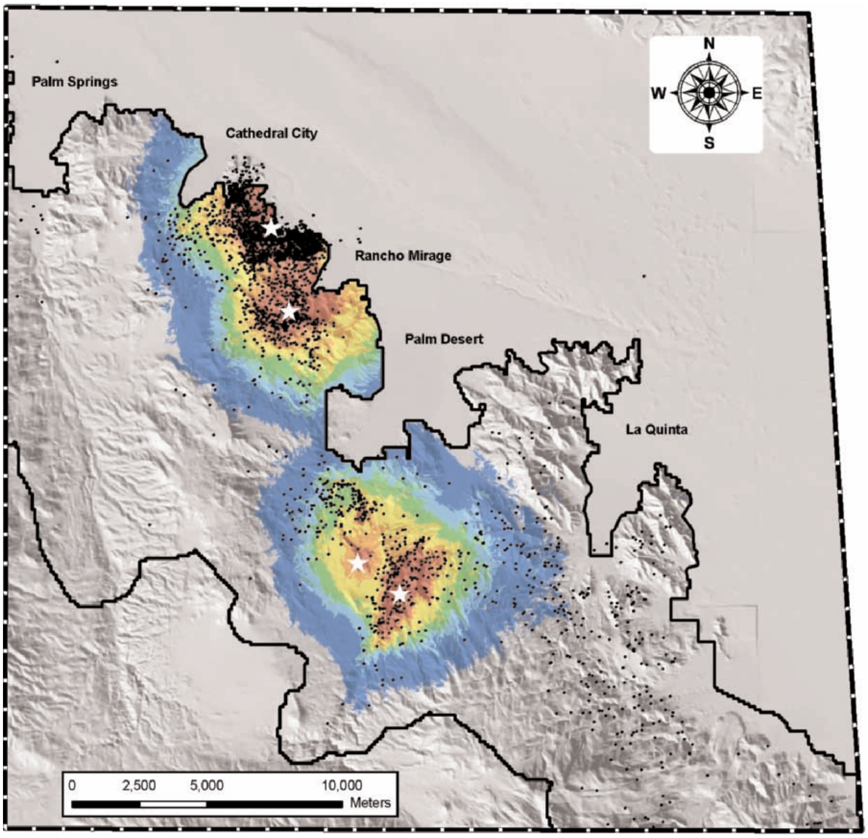

Figure 2B. Locations of 12,411 observations of Nelson's bighorn sheep relative to logistic regression landscape classifications within the northern Santa Rosa Mountains, Riverside County, California. Ninety-five percent of the observations of bighorn sheep fall within the 61.2 km^2 of landscapes IV–VII (green, yellow, orange, and red). Stars mark sites of perennial water sources.

The second site was an education–conservation center and accredited zoo facility situated on nearly 486 ha contained within a small cove against the toe of the slope and partially within the USFWS-designated Peninsular bighorn sheep critical habitat near Palm Desert. The facility maintained a small group of local native endangered desert bighorn sheep, which were restricted from breeding to prevent overcrowding of their pen facilities. Additionally, the zoo maintained small exhibit herds of Arabian oryx (*Oryx leucoryx*), Grevy's zebras (*Equus grevyi*), Mhorr gazelles (*Gazella dama mhorr*), Cuvier's gazelles (*G. cuvieri*), slender-horned gazelles (*G. leptoceros*), dromedary camels (*Camelus dromedarius*), and reticulated giraffes (*Giraffa camelpardalis reticulata*). Mountain lions (*Puma concolor*), leopards (*Panthera pardus*), and cheetahs (*Acinonyx jubatus*) also were exhibited, and sheep, goats, and exotic cattle were maintained at a petting zoo. The facility hosted more than 300,000 visitors each season. Fencing was primarily associated with the penned exhibits and varied in height, type, and style depending upon the type of wildlife contained. Perimeter fencing existed only to the extent that it controlled unauthorized human access to the immediate exhibit areas. Much of the southern access from the Santa Rosa Mountains was unfenced (Figure 5). The only double fencing was associated with some of the penned exhibit facilities. Nose-to-nose contact with free-ranging native bighorn sheep and penned exhibit animals was possible.

A private special-interest group focusing on native bighorn sheep operated the third facility. The BLM, through a cooperative memorandum of understanding in the late 1970s, provided 120 ha of public land for the operation of this wildlife facility. Its location in the confluence of Carrizo and Dead Indian Canyon washes was immediately adjacent to the USFWS-designated critical habitat. In cooperation with the USFWS and the CDFG, the facility maintained a breeding herd of approximately 30 endangered desert bighorn sheep to produce animals for translocation into the Peninsular Ranges. Additionally, the facility captured, treated, and rehabilitated diseased bighorns from the Peninsular Ranges for reintroduction into native habitat. Between 1982 and 1998, 39 lambs exhibiting clinical symptoms of disease were captured from the Peninsular Ranges and treated; 33 survived and 26 were reintroduced back to the wild. Seven of the animals became part of the captive breeding program. The wildlife facilities were adjacent to State Highway 74, and security was maintained by facility personnel and not through a fenced enclosure. Pen facilities consisted of a single barrier fence of 3-m cyclone-wire fencing. Nose-to-nose contact with native free-ranging bighorn sheep was possible.

Table 3. Best choice for habitat predictor variables in the logistic regression modeling effort to estimate the probability of Nelson's bighorn sheep activity within the northern Santa Rosa Mountains, Riverside County, California. The top 5 choices are shown for combinations of the habitat predictor variables based on the χ^2 statistic. The greater the χ^2 Score the greater the fit to the model's predictability.

No. habitat predictor variables	χ^2 Score	Habitat predictor variable
1	4,170	Distance from water
1	1,620	Elevation
1	450	Topographical ruggedness index (TRI)
1	277	Distance from escape habitat
1	157	Slope aspect
2	4,243	Distance from water; elevation -Best choice for 2 predictor variables
2	4,214	Distance from water; TRI
2	4,184	Distance from water; distance from escape habitat
2	4,170	Distance from water; slope aspect
2	1,863	Elevation; TRI
3	4,283	Distance from water; elevation; TRI -Best choice for 3 predictor variables
3	4,256	Distance from water; elevation; distance to escape habitat
3	4,243	Distance from water; elevation; slope aspect
3	4,216	Distance from water; TRI; slope aspect
3	4,215	Distance from water; TRI; distance from escape habitat
4	4,285	Distance from water; elevation; TRI; slope aspect -Best choice for 4 predictor variables
4	4,284	Distance from water; elevation; TRI; Distance from escape habitat
4	4,256	Distance from water; elevation; slope aspect; distance from escape habitat
4	4,217	Distance from water; TRI; slope aspect; distance from escape habitat
4	2,017	Elevation; TRI; slope aspect; distance from escape habitat
5	4,286	Distance from water; elevation; TRI; slope aspect; distance from escape habitat

Table 4. Wald confidence intervals for the β parameters (primary constituent elements) in the logistic regression model and profile likelihood intervals (Conditional Odds Ratio Estimates). The point estimate indicates how much each independent habitat predictor variable is incremented to produce the estimated odds ratio. The default is 1 unit. For each 1-point increase, it multiplies the odds by the point estimate. Point estimate values <1 serve to reduce the odds of activity as the parameter value (habitat predictor variable) increases. By converse, point estimate values >1 serve to increase the odds of activity as the parameter values increase.

	Conditional odds ratio estimates		
Habitat predictor variable	Point estimate	95% Wald confidence limits	
Elevation	0.998	0.997	0.998
Slope aspect	1.000	0.999	1.002
Distance to perennial water	0.965	0.963	0.967
Topographical ruggedness index	1.017	1.010	1.023
Distance from >2 ha of escape habitat	1.144	1.092	1.200

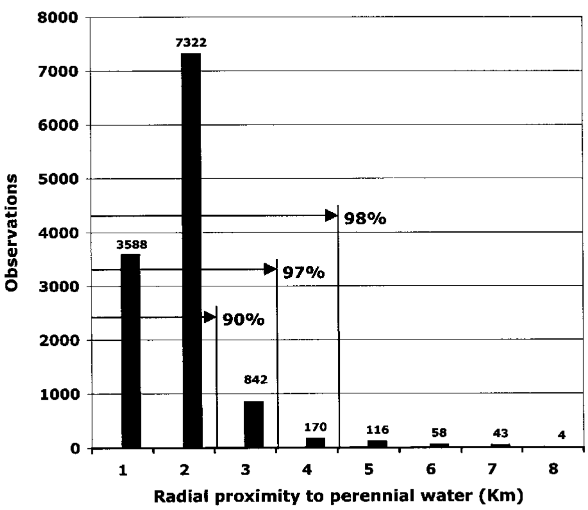

Figure 3. Bighorn sheep observations collected from 1984–1998 in the northern Santa Rosa Mountains, Riverside County, California in comparison with their distance from a perennial source of water. Ninety-seven percent of the observations were made within 3 km of water.

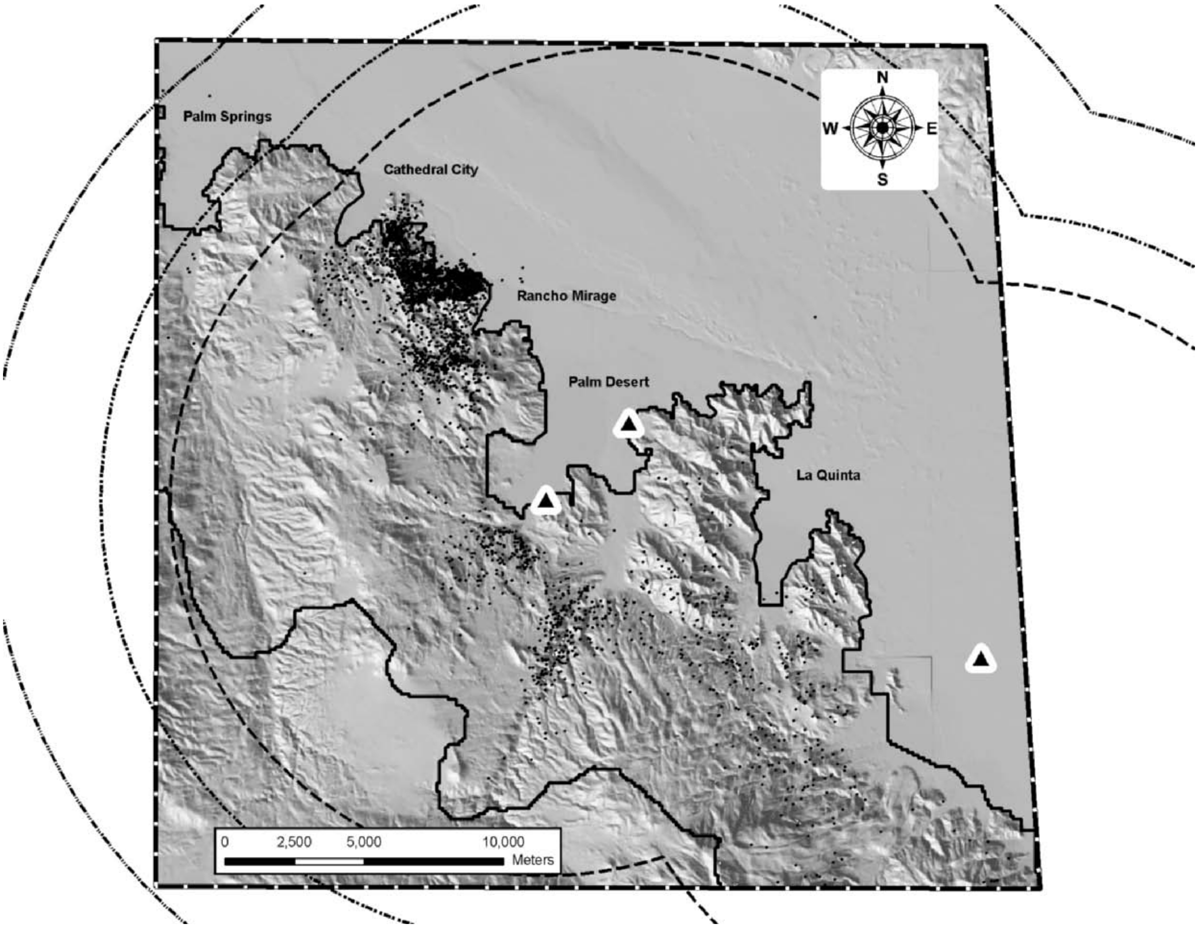

Figure 4. Locations of 3 potential sources of disease from livestock, exotic wildlife, and rehabilitated wildlife within the northern Santa Rosa Mountain study area, Riverside County, California. The solid line depicts the United States Fish and Wildlife Service 398-km^2 critical-habitat designation (United States Fish and Wildlife Service 2001). Broken lines of concentric circles depict recommended distances between bighorn sheep and livestock to preclude transmission of disease. The least restrictive distance is at a radius of 13.5 km (Desert Bighorn Council 1990) from potential pathogen source, followed by a radius of 16 km (Smith et al. 1991; Bureau of Land Management 1992). The most aggressive of these distances (20 km) is proffered by Singer et al. (2000*b*). Nearly the entire northern Santa Rosa Mountain portion of the 398-km^2 USFWS critical-habitat designation (United States Fish and Wildlife Service 2001) is embraced by the least restrictive (13.5 km) of these distances.

Discussion

Recently, several USFWS critical-habitat designations for western and desert southwestern spe-cies have succumbed to legal challenges. In multiple actions, the United States District Courts have ruled the USFWS's ap-proach to critical-habitat designations to be in violation of section 4(b)(2) of the federal Endangered Species Act (16 United States Code, §1531, et seq.) for failure to utilize the best scientific data available and adequately consider the economic impacts of critical-habitat designation. The courts remanded and vacated critical-habitat designations for 19 species of West Coast salmon (*Oncorhynchus* spp.) and steelhead (*O. mykiss*) (National Association of Home Builders versus Evans, Case No. 1:00-CV-02799 [District of D.C., 2002]), the ferruginous pygmy owl (*Glaucidium brasilianum cactorum*) (National Association of Home Builders versus Norton, Case No. CIV-00-0903-PHX-SRB [District of Arizona, 2001]), the arroyo southwestern toad (*Bufo californicus*) and Riverside fairy shrimp (*Streptocephalus woottoni*) (Building Industry Legal Defense Foundation versus Norton, 231 Federal Supplement 2d, 100 [District of D. C., 2002]), and the southwestern willow flycatcher (*Empidonax traillii extimus*) (New Mexico Cattle Growers versus United States Fish and Wildlife Service, 248 Federal Supplement 3d, 1277 [10th Circuit, 2001]). Similarly, the United States Court for the Central Dis-

Figure 5. Single-fence boundaries potentially allowing nose-to-nose contact between free-ranging native sheep and captive livestock, exotic wildlife, or rehabilitated wildlife at a 486-ha zoo–education–conservation center (A), at a 120-ha private special-interest wildlife facility (B), and at a family-operated (>30 years) 74-ha goat and sheep feedlot operation that maintains approximately 450 animals within 2–3 km of the United States Fish and Wildlife Service's critical-habitat designation (C), and untreated run-off from drinking water supplied ad libitum to the feedlot livestock which potentially promotes propagation of insect vectors to bighorn sheep pathogens (D).

trict of California remanded the final designation of critical habitat for the coastal California gnatcatcher (*Polioptila californica californica*) and San Diego fairy shrimp (*Branchinecta sandiegonensis*) (Building Industry of Southern California versus Norton, Civil No. 01-07028 SVW [Central District California, 2001]). In the face of legal challenge, the USFWS voluntarily rescinded nearly 2 million ha of the critical habitat designated for the red-legged frog (*Rana aurora draytonii*) (Home Builders Association of Northern California versus Norton, 01-1291 RJL, [District of D. C., 2002]). The United States Court of Appeals for the Ninth Circuit has found the USFWS's listing rule for the Arizona population of ferruginous pygmy owl to be arbitrary and capricious, and therefore substantively flawed (National Association of Home Builders versus Norton, D.C. No. CV 00-0903 SRB, [District of Arizona 2003]). The Court reversed and remanded the federal listing. The critical-habitat designations and federal listings for multiple western species are slated for preemptory legal challenges due to failure by the USFWS to base their determinations on the best scientific data available as required by section 4 of the Endangered Species Act.

The high correlation between the results of our logistical regression analysis and observed habitat use differs substantially from the habitat model presented in the Recovery Plan (USFWS 2000) or critical-habitat designation (USFWS 2001). The Recovery Plan presents observation data without specific analysis and only unreferenced subjective correlations. Further, there was no quantification of primary essential elements (habitat predictor variables) used in the critical-habitat designation. Similarly, the critical-habitat designation lacked an analysis of correlation with bighorn sheep distribution. Our landscape-classification error rate was better than that of other models employing similar or more involved statistics, technologies, and expense (Pereira and Itami 1991, Nadeau et al. 1995, Ozesmi and Mitsch 1997, Gross et al. 2002). Publicly available data in either the Recovery Plan or critical-habitat designation were insufficient to provide for an independent validation. This fails a basic premise of science.

We were not surprised by the importance (Table 3) of perennial water availability (Blong and Pollard 1968, Turner 1970, Leslie and Douglas 1979, Turner and Weaver 1980) in determining the probability of activity within the study area (Figure 3). Probability of activity decreased with increased distance from water and elevation (Table 4). However, in other desert ranges including sections of the Peninsular Ranges, free-standing water was more abundant and not as restrictive a parameter, even during summer (Smith and Krausman 1988).

Perennial water sources have increased value for bighorn sheep when located within 300 m of escape terrain (Hansen 1980*a*, Cunningham 1989, Andrew 1994). In the Santa Rosa Mountains, perennial free-standing water was a focus of bighorn activity during summer months (Turner 1973). For the remainder of the year, vegetative succulence adequately met the bighorn's water requirement (Blong and Pollard 1968, Turner 1973). During summer months Nelson's bighorn sheep dispersed only 2–3 km from free-standing perennial water sources (Jones et al. 1954, 1957; Blong and Pollard 1968; Turner 1973; Turner and Weaver 1980). Habitat in the near vicinity was greatly impacted by the social focus around watering sites. This was reflected in summer home-range movements of 0.7–3 km with perennial water sources as their focus. Winter home ranges of desert bighorn sheep have a radius of 1.5–7 km enveloping the summer home-range pattern (McQuivey 1978, Leslie and Douglas 1979, Turner 1981).

Bighorn sheep are considered to be habitat specialists (Geist 1971), with escape habitat being a primary focus of critical-habitat evaluation (Smith and Flinders 1991; Smith et al. 1991; Singer et al. 2000*a*,*b*). However, in the northern Santa Rosa Mountains, proximity to escape habitat was fourth in importance as a predictor variable for estimating probability of activity, behind considerations of distance to perennial water source, elevation, and ruggedness (Table 3).

The low priority of escape terrain in our habitat model may be the consequence of reduced predation pressures during the years most of the data were gathered or due to habituation of bighorn sheep to human habitats where predation pressures were reduced. Another contributing factor may be the inclusion of both rams and ewes used in the model, because rams venture farther from escape terrain than do ewes (Bleich et al. 1997, USFWS 2000). Historical data on predation in the Santa Rosa Mountains was anecdotal at best, but in general, predation, specifically mountain lion predation, was not considered to be a serious threat to bighorn sheep (Weaver and Mensch 1970). Lion predation, however, was the primary cause for mortality in the Santa Rosa Mountains from 1992–1998, accounting for 50–100% of bighorn sheep mortalities (Hayes et al. 2000, Ostermann et al. 2001).

Escape terrain allows bighorn sheep to escape to a position above a perceived threat. This escape terrain typically has a slope $\geq 36^{o}$ (80%) and may offer protection from above with rocky projections or overhangs (Hansen 1980*a*; Cunningham 1989; Smith and Flinders 1991; Andrew 1994; Singer et al. 2000*a*,*b*). Patches of escape terrain occur as islands within the larger landscape. These other areas of seemingly unused or unoccupied habitat may be of lower quality depending upon access to water, food resources, and distance to adequate escape habitat. Escape habitat in proximity (within 0.6 km) to watering sites has higher value than other escape habitat. In other populations, bighorn sheep spend nearly 95% of their time on or within 300 m of escape habitat; unbroken alluvial fans, open expanses of wash, and bajadas lacking topographic relief afford little escape from predation (Turner 1976; Smith and Flinders 1991; Singer et al. 2000*a*,*b*). Relevant to a consideration of escape terrain, but not considered in our model (because ancillary data on sex and age of animals with each location was not available), is lambing habitat (Geist 1971; Van Dyke et al. 1983; Ravey 1984; Etchberger and Krausman 1999). Typically, a consideration of lambing habitat parallels the requisites of escape terrain by affording protection from the weather and an adequacy of expanse ($\geq$2 ha) to provide escape from predation for the pre-parous female and the postpartum female and neonate within 1 km of perennial water (Smith et al. 1991; Johnson and Swift 2000; Singer et al. 2000*a*,*b;* Zeigenfuss et al. 2000).

Because our habitat model does not include information on seasonality of observations or vegetation, there are limitations to its interpretation. In the absence of separating observations on the basis of season (hot season versus cool season), water likely would be the most important predicting variable because of its strong influence during the summer months and during protracted drought (i.e., dry vegetation creates a need for water, and moisture strongly influences plant phenology). In the absence of specific data on vegetation, particularly those species that are most likely to be an important source of nutrition and moisture during periods of prolonged drought, some areas important to bighorns likely would be missed. However, data on the occurrence and use of those could be gathered in the field, on such key forage species such as catclaw acacia that are important sources of nutrition during drought. While our model cannot be used to predict all areas important to bighorns, it predicts the majority of the areas that are important to them in the northern Santa Rosa Mountains because of the number of observations (n=12,411) spanning 14 years (1984–1998). The resolution of the model may be improved by inclusion of data on the seasonality of observations, the occurrence of key forage species, and known lambing areas.

Each of the 7 habitat groups resulting from our logistical regression analysis were characterized by attributes of the habitat predictor variables. The correlation of frequency and density of bighorn sheep observations with habitat attributes further characterized these groupings (Table 5). Landscapes I–III comprised 337 km^2 and represented 85% of the USFWS critical-habitat delineation. It was generally lacking in ruggedness and escape habitat, was >3.5 km from a perennial source of water, and had <0.5 bighorn sheep observations (0.1–0.4) per km^2 per year. This portion of the USFWS critical-habitat designation was unoccupied. The landscape was a gradation between non-habitat in classification I–II to poor-quality and deficient habitat in classifications II to III. Classification IV landscape (16.4 km^2) occurred within 3 km of perennial water and received occasional bighorn activity (>1 observation per km^2 per year) and may function as a buffer between occupied and unoccupied habitat, although it lacks ruggedness and proximity to escape terrain. Landscape classifications V to VII comprised the remaining 45 km^2 (11%) of the USFWS-designated critical habitat. Although landscape classification V was high-quality habitat, it would not be if landscape classifications VI and VII possessed essential features of critical habitat (USFWS 1988, Murphy and Noon 1991, Hall et al. 1997).

Our multiple logistic regression analysis evaluates landscape characteristics in a predictive model for the presence or absence of bighorn sheep. Given the magnitude of uncertainty for the 12,411-observation data set (±250 m), the resulting probabilities of bighorn sheep activity within the designation of the specific landscape classifications would expectedly be reflected in the landscape boundaries in a similar magnitude. This would effectively result in a ±250-m "wobble" of the landscape classification over the study-area terrain. Indeed, this wobble would be random, increasing or decreasing the commitment of the total classification regimen by 250 m or some fraction thereof, depending upon the direction of movement. Since proximity of perennial water source was the most important predictor variable, the consequence of a 250-m shift in a landscape-classification boundary would have little influence in the overall landscape or habitat classifications.

The quality of bighorn sheep critical habitat in the Santa Rosa Mountains is compromised by the proximity to native bighorn herds of wildlife and domestic-husbandry operations. A strong relationship existed between the incidence of disease in wild bighorn populations and the spatial separation between domestic and wild sheep (Goodson 1982, Spraker and Adrian 1990). Disease has a greater influence on growth and recovery of bighorn populations than other parameters (Gross et al. 2000, Singer et al. 2000*c*). Epizootic pathogens have played devastating roles in the historic reduction of native bighorn herds in the United States (Spraker 1977, Monson 1980, Onderka and Wishart 1984, Onderka et al. 1988). Similarly, it has been hypothesized that disease may have impacted the bighorn population dynamics within the Santa Rosa Mountains during 1983–1998 (DeForge et al. 1982; DeForge and Scott 1982; Turner and Payson 1982*a*,*b*; Wehausen et al. 1987*a*,*b*). Although the causal relationship between disease and population decline in the Peninsular Mountain Ranges is circumstantial, its contention is supported by several studies (Clark et al. 1985; Wehausen et al. 1987*a*,*b*; Clark et al. 1993, Elliot et al. 1994). Bighorn sheep in the Peninsular Mountain Ranges were specifically identified as having higher ($P \leq 0.05$) levels of multiple exposures to pathogens (antibodies against >2 pathogens) and to higher prevalence values for 8 of 10 individual pathogens when compared to other California bighorn sheep herds (Elliott et al. 1994).

Bighorn sheep die in penned experiments with clinically normal domestic sheep, with no apparent ill effects to the domestic sheep, because bighorns are susceptible to domestic sheep strains of *Pasturella* pneumonia (Foreyt 1989, Callan et al. 1991). Free-ranging bighorns similarly do not fare well when exposed to domestic sheep. Twenty-eight groups of bighorn sheep experienced die-offs

Table 5. Landscape classification characteristics of the 398-km^2 United States Fish and Wildlife Service-delineated critical habitat (USFWS 2001) for the northern Santa Rosa Mountains, Riverside County, California. Classification was predicated upon a multiple logistic regression analysis of 5 predictor variables: distance to a perennial source of water, distance to ≥2 ha of escape terrain, slope aspect, topographical ruggedness index (TRI), and elevation. The landscape classifications were collectively ranked on the basis of the observation data as to the probability or odds of bighorn sheep activity relative to non-activity within a given 30 × 30-m^2 pixel.

Habitat[a] and classification	Logistic regression landscape classification	Characteristics
Non-habitat[b]	I	<1:1 odds of activity
		>4 km from perennial water source
		Mean TRI <4
		Mean elevation >500 m
		Mean distance from ≥2 ha of escape habitat is >300 m
		≤0.1 observations of bighorn sheep per km^2 × yr^{-1}
		1:1 to <5:1 odds of activity
		>4 km from perennial water source
Unoccupied habitat[c],	II	Mean TRI <4
low quality[d]		Mean elevation >450 m
		Mean distance from ≥2 ha of escape habitat is >300 m
		≤0.3 observations of bighorn sheep per km^2 × yr^{-1}
		≥5:1 to <10:1 odds of activity
		>3.5 km from perennial water source
Unoccupied habitat,	III	Mean TRI <4
low quality		Mean elevation >400 to <450 m
		Mean distance from ≥2 ha of escape habitat is >300 m
		≤0.4 observations of bighorn sheep per km^2 × yr^{-1}
		≥10:1 to 20:1 odds of activity
		<3.5 km from perennial water source
Unoccupied habitat	IV	Mean TRI <4
Infrequently used		Mean elevation >400 to ≤450 m
		Mean distance from ≥2 ha of escape habitat is >300 m
		>0.4 to <1.0 observations of bighorn sheep per km^2 × yr^{-1}
		21:1 to 50:1 odds of activity
		<2.3 km from perennial water source
Occupied habitat	V	Mean TRI >4
High quality		Mean elevation >400 to ≤450 m
		Mean distance from ≥2 ha of escape habitat is >300 m
		>1 to <10 observations of bighorn sheep per km^2 × yr^{-1}
		51:1 to 100:1 odds of activity
		<2 km from perennial water source
Occupied habitat	VI	Mean TRI >5
Critical habitat[e]		Mean elevation ≤450 m
		Mean distance from ≥2 ha of escape habitat is <300 m
		≥10 to <20 observations of bighorn sheep per km^2 × yr^{-1}
		101:1 to 6044:1 odds of activity
		<1.5 km from perennial water source
Occupied habitat	VII	Mean TRI >6
Critical habitat		Mean elevation ≤450 m
		Mean distance from ≥2 ha of escape habitat is >300 m
		>21 observations of bighorn sheep per km^2 × yr^{-1}

[a] Habitat is the sum of the biotic and abiotic resources and conditions present in an area that results in occupancy, including survival and reproduction, by a specific species population, or individual (Hall et al. 1997).

[b] Non-habitat has a quality or other biotic or abiotic defining parameter(s), which results in likelihood that it will not be used by a specific species, population, or individual.

[c] Unoccupied habitat is of sufficiently low availability or poor quality that it is unoccupied by a specific species, population, or individual.

[d] Habitat quality relates to the landscape's ability to provide the biotic and abiotic resources and conditions necessary for a specific species, population, or individual to persist.

[e] Critical habitat is of sufficient high quality that it is essential to the recovery and conservation of a species, which may require special management considerations or protection (USFWS 1988, Murphy and Noon 1991, Hall et al. 1997).

or declines after exposure to domestic sheep (Blaisdell 1982, Onderka and Wishart 1984, Clark et al. 1985, Jessup 1985, Sandoval 1988, McCarty and Bailey 1994). The avoidance of direct physical contact between bighorns and domestic or exotic livestock is of sufficient concern that the Desert Bighorn Council (1990), the BLM (1992), and Smith et al. (1991) have recommended that restrictive distances of 13.5–16 km be maintained between bighorn sheep and domestic or exotic livestock to preclude disease transmission. Singer et al. (2000*b*) recommended distances of 20 km. However, a clear causal relationship between bighorn sheep mortality and exposure to domestic livestock other than domestic sheep is equivocal (Onderka and Wishart 1984, Spraker et al. 1984, Festa-Bianchet 1988, Miller et al. 1991). For example, in November 2003 domestic goats escaped into desert bighorn habitat in the Silver Bell Mountains near Tucson, Arizona. Within 4 weeks bighorn sheep were blind due to infectious keratoconjunctivitis transmitted to them by the goats. By 10 February 2004 >33% of the bighorn population ($n \sim 100$) had been infected. Of the infected bighorns, 36% recovered their sight, 30% died from factors exacerbated by blindness, 6% were still blind, and the status of 28% was still unknown (B. D. Jansen, University of Arizona, unpublished data).

A domestic sheep and goat feedlot operation exists within 2 km of the USFWS-designated critical habitat, and a zoo facility with domestic sheep, goats, cattle, and numerous exotic ungulate (related) species operates within critical habitat. A third facility was adjacent to the USFWS-delineated critical habitat and maintained a breeding herd of approximately 30 bighorn sheep, some of which were captured from the wild after exhibiting clinical disease symptoms. Progeny from this facility's captive breeding and rearing program are used to augment the northern Santa Rosa ewe group through translocation of small numbers of individuals. From 1985–1998, 74 animals have been released into the northern Santa Rosa Mountains. Captive-reared bighorns numbered 26 in a total of 41 adult and yearling bighorn sheep in 1990. The northern Santa Rosa Mountains bighorn population declined nearly 50% to 22 adults by 1998, despite having been augmented by 70 translocated animals (Ostermann et al. 2001).

The 3 facilities lack double fencing in whole or in part and present the potential for nose-to-nose contact between their captive animals and free-ranging bighorns. The least restrictive distance (13.5 km) around each of the 3 facilities effectively included the entire northern Santa Rosa Mountains study area (Figure 4). The most aggressive of the restrictive distances of 20 km suggested by Singer et al. (2000*b*) embraces a major portion of the nearby San Jacinto Mountains bighorn distribution.

Translocation of native sheep into former habitat has been used to bolster and restore dwindling populations (Bailey 1990, Jessup et al. 1995, Singer et al. 2000*b*). Although 50% of all present-day bighorn populations stem from such translocations (Bailey 1990), most restoration programs have not been successful. Translocations in 6 western states from 1923–1997 had a success rate of only 41% (Singer et al. 2000*a*,*b*). The implication of disease, emanating from domestic or exotic animal sympatry, as a significant limiting factor to the restoration and recovery of native sheep is recurrent in this lack of success (Krausman 2000, Gross et al. 2000, Singer et al. 2000*a*,*b*). Conspicuous by its absence within the Recovery Plan was a consideration of domestic- or exotic-animal exposure to endemic, translocated, or captive-bred and released bighorn sheep (USFWS 2000). This has particular relevance given the potential role of disease in the catastrophic decline of native sheep in the Peninsular Ranges, and particularly the Santa Rosa Mountains (DeForge et al. 1982, Turner and Payson 1982*a*; Jessup 1985; Elliot et al. 1994).

Coachella Valley golf courses and their associated water hazards (impoundments) near bighorn habitat have generated concern for potentially promoting disease vectors and enhancing nematode parasitism. Golf courses are considered an "attractive nuisance" that, by virtue of their grasses, exotic landscape, and water availability, attract bighorn sheep from their native range to congregate, exacerbating the alleged potential of disease and passage of parasites through fecal contamination in addition to the potential for ingesting toxic ornamental plants (USFWS 2000). Quantitative data supporting this conjecture have not been established.

A consideration for the potential impacts of disease occupies a pivotal role in habitat evaluations for translocation and restoration consideration elsewhere (Gross et al. 2000; Singer et al. 2000*a*,*b*,*c*; Zeigenfuss et al. 2000; Smith et al. 1991). Indeed, such a consideration potentially obviates the inclusion of the Santa Rosa Mountains and portions of the San Jacinto Mountains for augmentation via translocation and potentially jeopardizes population recovery efforts (Figure 4). The Recovery Plan and critical-habitat designation for the Peninsular Ranges bighorn sheep (USFWS 2000, 2001) places low priority on management of these epizootic issues, instead emphasizing barrier perimeter fencing of urban areas, reducing human disturbance, and managing wildfire.

Pneumonia is frequently diagnosed as the cause of bighorn deaths (DeForge et al. 1982), but the etiology is often unclear (Hailey et al. 1972, Hibler et al. 1972, Parks et al. 1972, Spraker 1977, Spraker and Hibler 1977, Foreyt and Jessup 1982). Gnats (*Culicoides* spp.) and black flies (Simuliidae) vector viral pathogens such as bluetongue. Although these vectors frequent bighorn habitat, viral isolations have been negative for pathogens (DeForge et al. 1982).

The probability for long-term success in the recovery of the Peninsular Ranges bighorn sheep will depend upon rational decision-making in both the public and private sectors regarding allocation of conservation resources that will have the greatest effect for the long-term protection of the animals. Unsubstantiated inclusion of private and public lands and other mitigation exactions, without a scientific basis as critical habitat under the auspices of the federal ESA, does not serve the recovery of Peninsular bighorn sheep or the integrity of the ESA. Besides diverting important conservation resources away from a realistic recovery, such an approach to endangered-species conservation undermines confidence in resource management agencies and does not represent the best standard of science and commercial information as required by the USFWS, ESA, and the National Environmental Protection Act.

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