Stacey D. Ostermann for the degree of Master of Science in Wildlife Science presented on July 9, 2001.

Title: Conservation and Spatial Use Analyses for the Recovery of Bighorn Sheep in the Peninsular Ranges

Signature redacted for privacy.

Abstract approved: W. Daniel Edge

The status of wild sheep in North America typifies the plight of many wildlife species in modern times: wild sheep have declined to 10-40% of their numbers during pristine times and on a global scale approximately 31% of Caprine are considered threatened or critical. As human populations and the number of threatened and endangered wildlife species increase, research into the causes of wildlife population declines and tools to aid recovery are urgently needed.

We conducted two studies of endangered desert bighorn sheep (*Ovis canadensis nelsoni*) in the Peninsular Ranges of Southern California with the primary goal of furthering recovery efforts for this species. First, in order to evaluate a captive breeding program for Peninsular bighorn, we developed the following criteria to provide a standard means of evaluating ongoing captive breeding and reintroduction programs: (1) survival and recruitment rates in the captive population, (2) survival of released animals, (3) recruitment of released animals, (4) growth rate of the reintroduced or augmented population, and (5) establishment of a viable wild population. In assessing the Peninsular bighorn sheep program, we found that while reintroduction did not result in population growth or establishment of a viable population, it helped prevent extirpation of the reinforced deme, preserved metapopulation linkage, and aided habitat preservation. Chronic low recruitment and low adult survivorship precluded achievement of criteria 3-5. Environmental conditions in the

release area also appeared to hinder program success. We suggest that periodic evaluations are useful for improving the success of individual captive breeding and reintroduction programs, as well as for meta-analyses needed to refine reintroduction science as a recovery tool for threatened or endangered populations.

Wildlife habituated to the presence of humans have been recognized as a new dilemma facing wildlife managers. Our second study involved examining the habitat use, home range size, and nutritional levels of Peninsular desert bighorn sheep along an urban-wildland interface during two time periods (1981-82 and 1995-98). We found that bighorn sheep monitored during 1995-98 used habitat within ($P < 0.001$) and closer to ($P < 0.001$) urban environments than bighorn sheep monitored in 1981-82. Females monitored in the 1990s had smaller home ranges ($P = 0.03$), and selected habitat farther from escape terrain, natural water sources, and hiking trails ($P < 0.05$) than females monitored in the 1980s. Habitat selection patterns were similar among captive-reared and wild-reared bighorn, as well as males and females within the 1990s. Bighorn use of urban areas increased 5-fold between our study periods; however, this population has declined precipitously in recent times and urbanization appears to be contributing directly and indirectly to adult and juvenile mortality. We recommend excluding bighorn from urban areas in order to encourage more natural resource use patterns. Understanding the implications of wildlife-human interactions may require long-term studies because the results of these interactions are often not obvious or intuitive.

CONSERVATION AND SPATIAL USE ANALYSES FOR THE RECOVERY OF BIGHORN SHEEP IN THE PENINSULAR RANGES

By

Stacey D. Ostermann

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Stacey D. Ostermann, Author

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CONTRIBUTION OF AUTHORS

Chapters two and three are co-authored with several individuals. In chapter two, published in Conservation Biology (2001,15:749-760), Jim DeForge contributed data and assisted with study design, obtaining funding, data collection, data analyses, and writing. Dan Edge assisted with study design, data analyses, and writing.

In chapter three, Jim DeForge contributed data and assisted with study design, logistical support, obtaining funding, data collection, data analyses, and writing. Trent McDonald provided advice regarding statistical analyses. Dan Edge assisted with study design, data analyses, and writing.

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CONSERVATION AND SPATIAL USE ANALYSES FOR THE RECOVERY OF BIGHORN SHEEP IN THE PENINSULAR RANGES

CHAPTER 1
INTRODUCTION

Conservation biology is considered a crisis-oriented discipline (Soulé 1985); data, funding, and time are frequently limited and the risk of non-action can outweigh the risk of inappropriate action. In some situations, this leads to decision making in the absence of sufficient data. These characteristics of conservation biology make it more suitable to the method of case studies rather than classical experimental methods involving manipulation, controls, replicated observations, and randomization. Shrader-Frechette and McCoy (1993) advocated using case studies to promote the development of general principals in ecology. Inductive, heuristic, particularistic (i.e., focusing on a specific process or phenomenon), and quasi-experimental, case studies may also be the most promising path for advancing the science of conservation biology. Ecology, and more specifically conservation biology, are fields with relatively few deterministic processes and hence low predictive power. The most predictive power in ecology is achieved with simplified scenarios involving one or two taxa in particular situations (Schrader-Frechette and McCoy 1993). While it is important to examine specific cases to understand complex and unique processes, it is equally important to place results from focused studies into a broader context to recognize patterns and emergent properties. My thesis research focused on narrowly defined, applied conservation problems involving bighorn sheep (*Ovis canadensis nelsoni*) in the Peninsular Ranges of Southern California; however, results from these case studies may be applied to a broad range of species and may be used to test general models. Here I provide an introduction to the conservation issues confronting bighorn sheep that are addressed further in chapters 2 and 3 of my thesis.

Wild sheep in North America have declined from an estimated 0.5-2.0 million in pristine times (Seton 1929, Valdez 1988) to just under 200,000 presently (Valdez and Krausman 1999). Bighorn sheep numbers were reduced drastically during the last half of the 19^{th} century by a combination of disease, competition with livestock, and excessive hunting. Audubon's bighorn (*O.c. auduboni*) were extirpated by 1920 (Buechner 1960) and at various times bighorn sheep were eliminated from the states of North Dakota, South Dakota, Nebraska, Oregon (Buechner 1960), Washington (Johnson 1983), Texas (Monson 1980), and the Mexican states of Chihuahua and Coahuila (Valdez and Krausman 1999). Through aggressive management, which included captive breeding and translocation programs, localized bighorn sheep populations have been re-established in all American states where they once occurred (Buechner 1960, Valdez and Krausman 1999).

Despite many successes in the restoration of this species, overall population numbers remain low and some populations are critically small. Desert bighorn sheep inhabiting the Peninsular Ranges of California were state listed as threatened in 1972 and federally listed as endangered by the U.S. Fish and Wildlife Service (USFWS) in 1998 (USFWS 1998). Bighorn sheep inhabiting the Sierra Nevada Mountains of California have been state listed as threatened since 1984, were emergency listed as federally endangered in 1999, and formally listed as endangered later that year. Desert bighorn sheep in New Mexico have been state listed as endangered since 1980. In Mexico, few bighorn populations have been re-established in historical habitat and the lack of information on the status and distribution of free-ranging species may hamper conservation efforts. On a global scale, approximately 31% of Caprinae are considered critical or endangered according to the IUCN Red List categories of threat (Shackleton 1997). Consequently, research into the causes of population declines and methods to aid recovery of wild sheep populations is urgently needed.

Captive breeding and reintroduction is a commonly used management tool for threatened and endangered species. One objective of my thesis research was to evaluate a captive breeding and reintroduction program for Peninsular bighorn sheep; however, no standard criteria had been established for evaluating ongoing captive breeding programs. Chapter 2 of my thesis develops criteria for evaluating ongoing captive breeding and reintroduction programs, and uses the Peninsular bighorn sheep program as a case study. This analysis helped give perspective to the role of captive breeding in recovery planning efforts for bighorn sheep in the Peninsular Ranges and the Sierra Nevada Mountains. Captive breeding is typically a costly endeavor, and if not successful, it could be viewed as a significant misallocation of time and funds. Through the evaluation process, the successes of a program can be understood and the problems identified and potentially rectified. Furthermore, meta-analyses of captive breeding programs may identify common challenges for captive breeding programs and help refine the technique in general.

The third chapter of my thesis examines the spatial use patterns of bighorn sheep along an urban-wildland interface. Within the Peninsular Ranges, bighorn in the northern

Santa Rosa Mountains (NSRM) are among the most eminently threatened demes, and multiple factors appear to be contributing to the decline. The most outstanding features of this population are the pervasive urban encroachment into bighorn habitat and the population's use of urban environments. The NSRM bighorn population is also unique within the Peninsular Ranges because of its chronic low recruitment, frequent displays of respiratory disease symptoms, and rapid population decline despite augmentation with captive-reared animals.

In 1970, Peninsular bighorn sheep populations in the Santa Rosa Mountains (SRM) were stable or increasing, had high lamb survival, and were described as "excellent and among the densest in the state" (Weaver and Mensch 1970). At that time the SRM were estimated to support 500 bighorn. However, in the late 1970's, a disease epizootic caused a population decline throughout the San Jacinto Mountains and SRM (DeForge and Scott 1982; DeForge et al. 1982 1997; Wehausen et al. 1987). Population declines were also documented in some southern portions of the Peninsular Ranges (Rubin et al. 1998). Between 1981 and 1990, a total of 36 lambs showing clinical signs of illness were captured from throughout the Peninsular Ranges for treatment and study at Bighorn Institute (Ostermann et al. 2001). Additionally, multiple fresh lamb carcasses were recovered from the field for necropsy (Bighorn Institute, unpublished data). Serological evidence and virus isolation indicated that parainfluenza-3, bluetongue, epizootic hemorrhagic disease, and possibly contagious ecthyma viruses were probable initiating factors in a bacterial pneumonia that killed many lambs in the Peninsular Ranges during the early 1980's (DeForge et al. 1982; Bighorn Institute, unpublished data). Adult bighorn showed clinical signs of disease, but adult mortality rates were not abnormally high (DeForge and Scott 1982, DeForge et al. 1982). The apparent disease outbreak of the late 1970's contributed to at least 14 years of poor recruitment in the SRM (DeForge et al. 1995).

During the 1990's, recruitment in the central and southern SRM improved and overt signs of disease abated (DeForge et al. 1995). In recent years, disease was not considered a limiting factor for most bighorn in the Peninsular Ranges (USFWS 2000), although it may still exert some control on NSRM bighorn. Lambs showing signs of illness (e.g., coughing, nasal discharge, droopy ears, rough haircoat, weight loss, and lethargy) are still common in the NSRM (Bighorn Institute 1999, 2000).

Locally acting, population-specific limiting factors appear to be operating in the NSRM deme; this population has experienced chronic low recruitment, yet relatively high recruitment has been reported for adjacent bighorn demes in the San Jacinto Mountains (DeForge et al. 1997) and in the Deep Canyon area of the SRM (Rubin et al. 2000). Urbanization (automobile accidents, exotic plant poisoning, wire fence strangulation) was the leading cause of death for adult bighorn in the NSRM between 1991-1996, accounting for 34% of the documented mortalities (DeForge and Ostermann, unpublished data). In chapter 3 of my thesis, I compared the spatial use patterns of the NSRM bighorn population during 2 time periods (1981-82 and 1995-98). This allowed me to document the changes in habitat use patterns that occurred, and propose that spatial use patterns may be contributing to the chronic disease observed in this population. Chapter 3 also addresses a new dilemma facing wildlife managers: wildlife habituated to humans. Results from this study show that human-wildlife interactions deserve careful examination because the implications are often not obvious or intuitive.

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CHAPTER 2

CAPTIVE BREEDING AND REINTRODUCTION EVALUATION CRITERIA: A CASE STUDY OF PENINSULAR BIGHORN SHEEP

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ABSTRACT

Captive breeding and reintroduction programs are rarely evaluated, and assessment criteria vary widely. We used the following criteria to evaluate a bighorn sheep (*Ovis canadensis*) augmentation program: (1) survival and recruitment rates in the captive population, (2) survival of released animals, (3) recruitment of released animals, (4) growth rate of the reintroduced or augmented population, and (5) establishment of a viable wild population. Captive bighorn survival and recruitment was high, averaging 0.98 (SD = 0.05) and 71.0% (SD = 19.4), respectively. Annual survival of free-ranging captive-reared bighorn ($n = 73$, $\bar{x} = 0.80$, SD = 0.11) did not differ ($Z = -0.85$, $p = 0.40$; N = 14) from survival of wild-reared bighorn ($n = 43$, $\bar{x} = 0.81$, SD = 0.12). Recruitment was low for both captive-reared ($\bar{x} = 13.7\%$, SD = 0.24) and wild-reared ewes ($\bar{x} = 13.7\%$, SD = 0.20). Although reintroduction did not result in population growth or establishment of a viable population, it helped prevent extirpation of the reinforced deme, preserved metapopulation linkage, and aided habitat preservation. Chronic low recruitment and low adult survivorship precluded achievement of criteria 3-5. Environmental conditions in the release area also appeared to hinder program success. Standard evaluation criteria for ongoing reintroductions allow for informative assessments and facilitate comparisons needed to refine reintroduction science as a recovery tool for threatened or endangered populations.

INTRODUCTION

We use the term *reintroduction* to refer to the intentional movement of captive-reared animals into a species' historical range to augment or re-establish wild populations. Reintroduction is a widely used conservation tool, having been recommended in 64% of 314 recovery plans for endangered species within the United States (Tear et al. 1993) and included in recovery efforts for the American bison (*Bison bison*), Arabian oryx (*Oryx leucoyx*), black-footed ferret (*Mustela nigripes*), California Condor (*Gymnogyps californianus*), Mauritius Kestrel (*Falco punctatus*), European wisent (*Bison bonasus*), and red wolf (*Canis rufus*) (Campbell 1980; Conway 1980; Snyder & Snyder 1989; Stanley Price 1989; Phillips 1990; Jones et al. 1995; Myers & Miller 1992). Although guidelines for reintroductions (Griffith et al. 1989; Stanley Price 1991; Kleiman et al. 1994; IUCN 1995) suggest an assessment phase, in which the experiences and results of the program are regularly evaluated, published results of evaluations remain scarce. As recently as 1994, less than half of the projects known to have reintroduced animals had produced assessment information (Beck et al. 1994). Only 29% of 336 bird and mammal translocation programs used marked animals and 16% used radiotelemetry in post-release monitoring (Wolf et al. 1996). The paucity of information on reintroductions is attributed to a failure to monitor released animals, insufficient project duration (Beck et al. 1994), reluctance to report failures, and publications confined to obscure literature (Sarrazin & Barbault 1996). Because of difficulties with the evaluation and refinement of reintroduction programs, strong arguments exist for improved documentation and development of standard evaluation criteria (Scott & Carpenter 1987; Stanley Price 1991; Beck et al. 1994; Kleiman et al. 1994; Sarrazin & Barbault 1996).

Creating a viable population is the ultimate goal of most reintroductions (Griffith et al. 1989; Caughley & Gunn 1996), but measurable goals for evaluating the short-term progress of ongoing reintroductions have not been established. Most reintroduction evaluations (Griffith et al. 1989; Beck et al. 1994; Wolf et al. 1996) used criteria for long-term success to evaluate ongoing reintroductions in various phases. In a review of 145 reintroductions, Beck et al. (1994) concluded that only 16 programs (11%) were successful. Beck et al. (1994) defined success as establishment of a wild population of $\geq$500 individuals, free of human support, or population viability as determined by a formal genetic/demographic analysis. Releases were not necessarily the factor that contributed most to population growth; other factors may have been more important in population recovery. Because Beck et al. (1994) included programs in various phases, the reported success rate should increase with time and probably underestimates the value of reintroductions. Furthermore, Beck et al. (1994) did not necessarily assess the reintroduction programs themselves, and their criterion of 500 individuals may be considered arbitrary given the variance in autecology among species (Sarrazin & Barbault 1996). Standard criteria specifically for evaluating ongoing reintroductions would allow more informative program assessments, facilitate the comparisons needed to detect patterns and test general concepts (Stanley Price 1991; Beck et al. 1994; Wolf et al. 1996), and provide guidance for post-release monitoring and reporting. Additionally, evaluations often generate recommendations to improve program effectiveness (Akcakaya 1990; Beck et al. 1991; Black et al. 1997; Biggins et al. 1998).

We propose five criteria identifying the major accomplishments and challenges for most reintroduction programs: (1) survival and recruitment rates in the demographically and genetically managed captive population are high; (2) survival and (3) recruitment rates of captive-reared animals released into the wild are within the normal range of values for that or similar species; (4) the reintroduced or augmented population has a positive growth rate; and (5) one or more viable wild populations have been established as a result of the reintroduction. Criteria 1-3 are indices of the released animals' ability to contribute to the population. The fourth criterion may or may not be a direct result of population augmentation, but it is an indicator of conditions for the free-ranging population. The fifth criterion is a measure of long-term success that may require years to achieve and may be considered on spatial scales ranging from isolated populations to metapopulations, depending on the program goals. Because the fifth criterion is the ultimate goal of most reintroductions, in some cases, reduced progress toward criteria 1-3 (which may be sensitive to management intensity) may be acceptable in exchange for achieving longer-term measures of success.

We used a captive breeding and augmentation program for the endangered desert bighorn sheep (*Ovis canadensis*) population inhabiting the Peninsular Ranges of southern California as a case study for evaluating ongoing reintroductions. Our assessment included documentation of captive propagation and release methods and survival and reproduction rates of captive bighorn sheep. We compared survival and reproduction rates of post-release captive-reared and wild-reared bighorn and analyzed factors affecting post-release survival.

Peninsular Bighorn Sheep

Peninsular bighorn sheep inhabit the eastern slopes of the Peninsular Ranges from the San Jacinto Mountains in southern California, south to the Sierra San Borjas area of Baja California, Mexico (DeForge et al. 1999). As recently as 1974, there were an estimated 1,171 Peninsular bighorn within the United States (Weaver 1975). By 1988, they had declined to 570 (Weaver 1989) and by 1996 only 280 remained, distributed in a metapopulation of $\geq$8 demes (Rubin et al. 1998). Bighorn sheep are polygynous breeders, with females $\geq$2 years old typically producing one offspring per year. The life span is 10-12 years for males and 12-14 years for females, although in this study we documented a 16-year-old wild ewe with a lamb. Predators of Peninsular bighorn include mountain lions (*Puma concolor*), bobcats (*Felis rufus*), and coyotes (*Canis latrans*).

Bighorn sheep in the Peninsular Ranges were listed as threatened by the state of California in 1971 and endangered by the U.S. Fish and Wildlife Service (USFWS) in 1998 (USWFS 1998). Reasons for the endangered listing included population declines potentially caused by low recruitment, habitat loss and fragmentation, and high predation rates coinciding with low population numbers. Urban development of bighorn habitat and low adult survivorship are among the greatest threats to the metapopulation (USFWS 1999).

History of the Captive Breeding Program

In cooperation with the California Department of Fish and Game (CDFG), Bureau of Land Management (BLM), and USFWS, the Bighorn Institute has maintained a captive bighorn population since 1984 (Table 1). Originally, the captive breeding program was a by-product of disease research on causes of low lamb survival (DeForge et al. 1982; DeForge & Scott 1982). In 1995 the program was redirected as a formal captive breeding program with the primary goals of safeguarding a sample of the Peninsular bighorn gene pool and producing stock for augmenting and re-establishing wild populations.

Between 1982 and 1998, the Bighorn Institute captured 39 lambs with signs of illness from the Santa Rosa, Jacumba, and In-Ko-Pah mountains for treatment and study. Thirty-three lambs survived: 26 were returned to the wild (some after breeding several years in captivity), and 7 became founders in the captive breeding herd. Healthy wild lambs were captured for breedstock in 1996 (2 females, 1 male) and 1998 (2 females). Two of the four breeding rams were captured as lambs from the northern Santa Rosa Mountains (NSRM), the third ram was captive-born to stock from the NSRM, and the fourth was captured as a lamb from the San Jacinto Mountains. The 18 ewes in the captive breeding program came from several demes and varied in their reproductive success and longevity in the program (Table 2).

Between 1985 and 1998, 74 bighorn were released into the NSRM and three into the San Jacinto Mountains to augment two remnant bighorn demes. Our analysis concerns only bighorn released into the NSRM deme. In 1977 an estimated 90 adult bighorn inhabited the NSRM (Wehausen et al. 1987), by 1982 the population had declined to 60-70 adult bighorn (DeForge & Scott 1982), and in 1985 only 40 remained. Augmentation efforts focused on this subpopulation because of its declining size and its function in linking the small northernmost Peninsular bighorn deme (San Jacinto) to the remaining metapopulation.

STUDY AREA

The Santa Rosa Mountains of southern California are within the Colorado Desert division of the Sonoran Desert (Ryan 1968). Our study occurred in a 70-km^2 area of the Santa Rosa Mountains northwest of Highway 74. Elevations reach 1,160 m; however, bighorn are typically found between the valley floor (90 m) and 675 m. Mean annual temperatures for winter and summer range from 6-41° C. Annual rainfall during 1985-1998 varied from 3.4 to 28.5 cm and averaged 12.2 cm (Western Regional Climate Center; Reno, Nevada). Vegetation is dominated by brittlebush-white bursage series, creosote bush series, and creosote bush-white bursage series (Sawyer & Keeler-Wolf 1995). Urban development occurs within bighorn habitat in several locations and fringes the entire northern and eastern boundaries of the NSRM. Bighorn sheep have frequented residential communities along the base of the mountains in the study area since the late 1950s.

METHODS

Captive Rearing and Release

Between January and July of each year, ewes and their offspring were maintained in a 12-ha enclosure encompassing a rugged hilltop with elevations of 290-355 m. Adult rams were maintained in a similar 3-ha enclosure. In addition to the native vegetation in the enclosures, alfalfa, alfalfa pellets, salt and mineral blocks, and water were provided. A 3.1-m, chain-link fence that extended 0.8 m underground with 0.5 m of barbed wire on the top prevented mammalian predators from entering the enclosures and bighorn from escaping. The health and behavior of all bighorn were recorded twice daily. Captive animals were not available for public viewing and a standardized feeding and observation routine was used to limit exposure to humans. Hematology, serum chemistry, parasitology, serology, and virus isolation tests were performed annually on each captive bighorn. Bighorn captured from the wild were screened for common diseases and isolated $\geq$30 days before joining the captive population. Sick animals were tested and temporarily placed in isolation pens if necessary. Veterinary treatment was provided when deemed critical for survival. Necropsies were performed by Bighorn Institute biologists and veterinarians, or the California Veterinary Diagnostic Laboratory Service (San Bernardino, California).

Demographic management of the captive population consisted of maintaining the population within the estimated carrying capacity of the enclosures, with a high female: male ratio. Genetic management included controlling matings to avoid inbreeding and minimize mean kinship (Ballou & Lacy 1995), and obtaining healthy breedstock from demographically secure demes near the anticipated release sites. Captive bighorn were selectively combined for the breeding season during August-December. The parentage of all captive-born offspring was recorded in a SPARKS (Single Population Analysis Records Keeping System; International Species Information System) pedigree. Offspring typically were released as yearlings to avoid managing multiple generations in captivity and reduce captivity adaptation concerns. Before release, all bighorn were health-tested, eartagged, and fitted with mortality-sensing radiocollars. Bighorn were transported by truck 20-45 minutes and released directly into the wild. Within the NSRM, bighorn were released in Bradley Canyon (n = 59), east Magnesia Canyon (n = 6),and west Magnesia Canyon (n = 8). Release locations usually were based on the distribution of free-ranging sheep to encourage rapid integration with wild sheep. Water was provided at the release site for 3-20 days following release.

Sheep born at or captured and raised at the Bighorn Institute were considered captive-reared; all other bighorn were considered wild-reared. Of the 74 captive-reared bighorn released into the NSRM, 49 (22 males, 27 females) were captive-born and 25 (12 males, 13 females) were wild-born lambs brought into captivity for research and rehabilitation at 1-5 months of age. Most of these wild-born lambs were bottle-fed and regularly handled for treatment, so they generally were more habituated to humans than healthy captive-born animals. Most bighorn (n = 62: 33 males, 29 females) were released as yearlings; 12 (2 males, 10 females) were released as adults (2-6 years old). The 74 sheep were released in 33 groups of 1-6 sheep during all months of the year except March and

Table 2.1 Adult (≥ 2 years old) bighorn sheep in captivity at Bighorn Institute, sick lambs captured from the wild, and bighorn released into the northern Santa Rosa Mountains, California, 1982-1998.

Year	*Adult breeding rams*	*Adult breeding ewes*	*Wild sick lambs captured/survived*	*Captive-reared bighorn released (female, male)*
1982	0	0	1/1	0 (0, 0)
1983	0	0	3/3	0 (0, 0)
1984	1	2	4/4	0 (0, 0)
1985	2	5	10/9	1 (0, 1)
1986	3	7	14/12	6 (2, 4)
1987	2	8	3/3	12 (6, 6)
1888	2	9	0/0	5 (2, 3)
1989	2	9	0/0	6 (4, 2)
1990	2	7	1/0	10 (6, 4)
1991	2	6	0/0	6 (4, 2)
1992	2	6	0/0	4 (2, 2)
1993	2	6	0/0	4 (2, 2)
1994	2	6	1/1	6 (4, 2)
1995	2	6	0/0	5 (4, 1)
1996	2	5	1/0	5 (2, 3)
1997	3	6	1/0	3 (1, 2)
1998	3	6	0/0	1 (0, 1)
Total	4[a]	18[a]	39/33	74[b] (39, 35)

[a] *Number of different adult breeding bighorn.*

[b] *Includes a ewe released in 1994 that was excluded from further analysis*

Table 2.2 Reproductive history of female bighorn sheep bred in captivity at Bighorn Institute, 1985-1998.

ID	*Origin*	*Year* 1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	*Total productivity in captivity*[a]	*Total recruitment in captivity*[b]
AME	NSRM[c]	L[d]	L	R												2/2	2/2
EVE	NSRM	N	N	N	R											0/3	0/3
AND	NSRM		L	D	L	L	L	D	L	L	L	L	L	N	R	11/12	9/12
JUN	BI		N	R												0/1	0/1
SQU	NSRM		L	L	L	LL	R									5/4	5/4
CIM	SSRM			L	LL	L	L	L	L	L	L	L	L	L	L	13/12	13/12
MAG	NSRM			L	N	R										1/2	1/2
CAH	NSRM				L	L	N	L	N	L	L	N	L	D	N	7/11	8/11
ENC	NSRM				L	L	R									2/2	2/2
JAC	JUCM				D	R										1/1	0/1
CAR	JUCM				D	R										1/1	0/1
BOR	INKP					L	L	L	N	L	L	L	N	L	N	7/10	7/10

Table 2.2 Continued.

		Year														*Total productivity in*	*Total recruitment in*
ID	*Origin*	*1985*	*1986*	*1987*	*1988*	*1989*	*1990*	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*	*captivity*[a]	*captivity*[b]
INK	INKP					*L*	*L*	*L*	*L*	*L*	*D*	*L*	*L*	*D*	*L*	10/10	8/10
HIJ	BI						*L*	*D*	*R*							2/2	1/2
YAP	BI						*D*	*D*	*R*							2/2	0/2
ANZ	BI								*L*	*L*	*D*	*L*	*L*	*R*		5/5	4/5
AZU	CSRM														*L*	1/1	1/1
YSI	SYSI														*L*	1/1	1/1
Production (%)		*50*	*60*	*80*	*100*	*114*	*86*	*100*	*67*	*100*	*100*	*83*	*83*	*80*	*67*	84	na

Table 2.2 Continued.

ID	*Origin*	*1985*	*1986*	*1987*	*1988*	*1989*	*1990*	*1991*	*1992*	*1993*	*1994*	*1995*	*1996*	*1997*	*1998*	*Total productivity in captivity*[a]	*Total recruitment in captivity*[b]
Recruit-ment (%)		*50*	*60*	*60*	*75*	*114*	*71*	*57*	*67*	*100*	*67*	*83*	*83*	*40*	*67*	na	71

[a] Productivity is the number of lambs per 100 ewes produced per year.

[b] Recruitment is the number of lambs per 100 ewes that lived to December.

[c] NSRM,northern Santa Rosa Mountains; SSRM, southern Santa Rosa Mountains; JUCM, Jacumba Mountains; INKP, In-Ko-Pah Mountains; BI, captive born at Bighorn Institute; CSRM, central Santa Rosa Mountains; SYSI, San Ysidro Mountains.

[d] Symbols are defined as follows: L, lamb produced and survived; LL, twins produced and survived; R, ewe released into the wild; N, no lamb produced or stillborn lamb; D, lamb died before December of that year.

December. Three bighorn were recaptured after release because of health or integration problems: one ram with a neurological disease was euthanized after recapture and one ram and one ewe were housed in captivity a short time before being released again. The ram integrated with free-ranging bighorn, so only his second release was included in the dataset. The ewe did not integrate with resident bighorn and was eventually transferred to a zoo; she was excluded from our analysis.

When possible, we observed bighorn for several hours immediately following release to record their behavior and integration with free-ranging sheep. Post-release monitoring involved daily telemetry readings and observations at least twice weekly for 3-25 weeks. During all years, radio signals were monitored at least weekly and we attempted to observe collared bighorn at least once per month. Radiocollars were fitted on wild-reared sheep as well, and failed collars were replaced annually by capturing sheep in a drive net or by using a net gun fired from a helicopter. When mortality signals were detected, we located radiocollared animals as soon as possible to determine the cause of death. Population estimates were obtained by monitoring radiocollared sheep or recognition of individual sheep and by annual helicopter surveys.

Data Analysis

We defined lamb production as the number of lambs born per adult ewe ($\geq$2 years old) per year. Recruitment was defined as the percentage of lambs that survived to December (approximately 7-11 months old) per adult ewe per year (i.e., number of lambs per 100 ewes in December). Recruitment for captive-reared bighorn in the wild was reported beginning in 1987, the first year captive-reared ewes $\geq$2 years of age were free-ranging in the study area.

We calculated annual bighorn survival for 1985-1998 using the Kaplan-Meier method (Kaplan & Meier 1958) modified for a staggered entry design (Pollock et al. 1989). Bighorn were considered at risk from the month of collaring for wild-reared sheep and from the month of release for captive-reared sheep, until their death, censoring (removal from the dataset with their fate considered unknown), or the end of the study. Male bighorn have higher dispersal rates than females, and no females in this area were known to permanently emigrate in over 12 years of monitoring. Therefore, because of the small population size and our intensive monitoring, we considered ewes with failed radiocollars that disappeared ≥2 years after collaring or release dead as of their last sighting. Ewes who disappeared from the study area <2 years after collaring or release and all rams that disappeared from the study area were censored.

We compared survival and recruitment rates of captive-reared and wild-reared bighorn with a Wilcoxon signed-rank test ($\alpha = 0.05$) (Sokal & Rohlf 1995). First year post-release survival was compared to other values using a *t* test with a pooled estimate of the standard deviation (Sokal & Rohlf 1995). We used multiple linear regression ($\alpha = 0.05$) to determine the relationship between survival the first year post-release (number of weeks lived) and 11 variables (Wilkinson & Coward 1998). Categorical variables were gender, captive-born or wild-born, release site, release season (January-April, May-August, September-December), and release group size (1-6). Continuous variables were release age (in months), total rainfall 3 months before release, total rainfall 12 months before release, total rainfall 12 months post-release, annual survival of the NSRM population during the release year, and population size of the free-ranging herd at the time of release. The variables release age, survival of NSRM bighorn, and all three rainfall variables were log transformed to improve their distributions. To identify a subset of models for further investigation, we used backwards stepwise variable selection with $p = 0.15$. The final model was the most parsimonious that explained the highest amount of variation in first-year survival. All probability values (p) are two-sided.

RESULTS

Captive Bighorn

Survival for yearling and adult captive bighorn combined ranged from 0.89-1.0 and averaged 0.98 (SD = 0.054). No adult bighorn died from natural causes while in captivity; however, one terminally ill 14-year-old ewe was euthanized. Three yearlings died in captivity, two from disease and one during transport for release.

Captive ewes had high lamb production ($\bar{x}$ = 83.6%, SD = 18.1) and recruitment ($\bar{x}$ = 71.0%, SD = 19.4) during 1985-1998 (Table 2). Production and recruitment of individual ewes in captivity ranged from 0 to 108%; twins were produced twice (Table 2). Between

1985 and 1998, 71 lambs (30 males, 41 females) were born to ewes $\geq$2 years of age, resulting in a sex ratio at birth of 0.73:1. Eleven of 71 lambs (15.5%) born in captivity and 6 of 39 lambs (15.4%) captured from the wild died in captivity. Lamb mortalities were attributed to disease (65.0%), trauma or peritonitis (17.5%), or undetermined causes (17.5%).

Reintroduced Bighorn

Age and gender influenced the survival of captive-reared bighorn during their first year in the wild. Survival for released yearling and adult bighorn (n = 73) 12 months after release was 0.61 (SD = 0.06). First year survival for females (0.64, SD = 0.08, n = 38) was higher (t = 4.4, df = 71, p < 0.005) than for males (0.55, SD = 0.09, n = 35). First year survival for bighorn released as adults (0.75, SD = 0.13, n = 12) was higher (t = 7.3, df = 71, p <0.01) than for bighorn released as yearlings (0.57, SD = 0.06, n = 61).
After the first year in the wild, survival for captive-reared sheep improved substantially. Average annual survival for captive-reared bighorn excluding the first year after release (0.88, SD = 0.09) was significantly higher than survival during the first year after release (Z = -3.04, p < 0.01, n = 13) and survival for wild-reared bighorn during the same time period (Z = 1.92, p = 0.05, n = 14) (Table 3). Overall, survival of captive-reared and wild-reared sheep was similar. Average annual survival for yearling and adult captive-reared bighorn combined during 1985-1998 (0.80, SD = 0.10) did not differ (Z = -0.8475, p = 0.40; n = 14) from survival for wild-reared bighorn (0.81, SD = 0.12) (95% CI for the difference between means = -0.07 - 0.10) (Table 3).

Recruitment also was similar between wild-reared and captive-reared animals. From 1987 to 1998 recruitment for the two groups did not differ (Z=- 0.18, p = 0.86, n = 12), averaging 13.7 lambs per 100 ewes (SD = 0.24) for captive-reared ewes and 13.7 lambs per 100 ewes (SD = 0.20) for wild-reared ewes (Table 4). The release program did not result in growth of the augmented population.

Between 1985 and 1998 the NSRM bighorn population declined significantly (t = -6.3, p < 0.01) from an estimated 40 bighorn to 22 bighorn (Table 3), despite augmentation with 73 bighorn.

Of the 43 wild-reared bighorn monitored during 1985-1998, 21 died, 12 were considered dead, 5 were censored, and 5 were alive at the end of the study period. Cause of death for wild-reared sheep will be reported in a separate publication. Of 73 released bighorn, 51 died during the study, 7 were censored, and 15 were alive at the end of the study. Twenty-three (45%) released bighorn mortalities occurred $\leq$6 months after release. Mountain lion predation was the primary cause of death for released bighorn, followed by urbanization (Table 5). Mortalities attributed to urbanization included ingestion of toxic, exotic plants (*Oleander* spp. and *Prunus* spp.) ($n = 5$) and automobile collisions ($n = 4$). All 4 bighorn that died from urban-related causes $\leq$ 6 months after release had been released in Bradley Canyon (Table 5). Survival during the first year after release was associated (F = 3.4, df = 2, $p = 0.01$, $R^2 = 0.17$) with release site and season of release. Releases in Bradley Canyon and east Magnesia Canyon resulted in higher first-year survival than releases in west Magnesia Canyon. Bighorn released in January-April survived better during the first year than those released at other times of the year. We found a weak association ($p = 0.08$) between release group size and post-release survival, with a group size of 1 resulting in the highest survival.

DISCUSSION

Peninsular Bighorn Reintroduction

The Peninsular bighorn sheep reintroduction program met 2 of the 5 criteria we proposed for assessing ongoing reintroduction programs. High survival and recruitment for captive bighorn compared to free-ranging populations (Wehausen 1992; DeForge et al. 1995, 1997; Hayes et al. 2000) indicated the program attained the first criterion of success. Similar recruitment rates have been reported for other captive bighorn populations (Calkins 1993; Rominger & Fisher 1997). Because survivorship for captive-reared released sheep was within the lower range of reported values for other desert bighorn populations, the second criterion for program success was also met. Annual survival for desert bighorn sheep is typically $\geq$0.80 (Cunningham & deVos 1992; Wehausen 1992); however, in recent years, survivorship of bighorn sheep in other portions of the Peninsular ranges has been low relative to other bighorn populations primarily due to high predation rates (DeForge et al. 1997; Hayes et al. 2000). Our data show that urbanization is an additional factor contributing to adult mortality in the NSRM, and is therefore hindering program success.

Table 2.3 Population estimates, number of captive-reared bighorn sheep, and annual survival[a] of yearling and adult bighorn sheep in the northern Santa Rosa Mountains, California, 1985-1998.

Year	*Fall population estimate of yearling and adult bighorn (ewes)*	*Number of captive-reared bighorn in the population*	*Survival of all yearling and adult bighorn (95% CI)*	n *(animal months)*	*Survival of wild-reared bighorn (95% CI)*	n *(animal months)*	*Survival of captive-reared bighorn (95% CI)*	n *(animal months)*	*Survival of released bighorn > 12 months after release (95% CI)*	n *(animal months)*
1985	40 (22)	1	0.70	313	0.70	305	1.0	8	---	---
			(0.54-0.86)		(0.54-0.86)		(1.0-1.0)			
1986	46 (25)	5	0.87	335	0.88	282	0.83	53	1.0	12
			(0.76-0.99)		(0.76-1.0)		(0.56-1.0)		(1.0-1.0)	
1987	52 (30)	16	0.90	439	0.91	264	0.86	175	1.0	44
			(0.80-0.99)		(0.80-1.0)		(0.70-1.0)		(1.0-1.0)	
1988	52 (33)	19	0.90	451	0.90	234	0.90	217	0.93	145
			(0.81-1.0)		(0.77-1.0)		(0.76-1.0)		(0.80-1.0)	
1989	50 (32)	20	0.72	406	0.78	203	0.67	203	0.87	152
			(0.58-0.86)		(0.59-0.97)		(0.47-0.87)		(0.69-1.0)	

Table 2.3 Continued.

Year	*Fall population estimate of yearling and adult bighorn (ewes)*	*Number of captive-reared bighorn in the population*	*Survival of all yearling and adult bighorn (95% CI)*	n *(animal months)*	*Survival of wild-reared bighorn (95% CI)*	n *(animal months)*	*Survival of captive-reared bighorn (95% CI)*	n *(animal months)*	*Survival of released bighorn >12 months after release (95% CI)*	n *(animal months)*
1990	41 (24)	26	0.77 (0.63-0.90)	357	0.79 (0.57-1.0)	145	0.76 (0.58-0.94)	212	0.92 (0.78-1.0)	152
1991	30 (21)	17	0.75 (0.61-0.90)	296	0.80 (0.55-1.0)	105	0.73 (0.55-0.91)	191	0.86 (0.68-1.0)	154
1992	35 (24)	20	0.89 (0.78-1.0)	309	0.88 (0.65-1.0)	86	0.90 (0.78-1.0)	223	1.0 (1.0-1.0	165
1993	27 (17)	16	0.64 (0.47-0.81)	270	0.86 (0.60-1.0)	73	0.57 (0.37-0.77)	197	0.70 (0.49-0.91)	165

Table 2.3 Continued.

Year	Fall population estimate of yearling and adult bighorn (ewes)	Number of captive-reared bighorn in the population	Survival of all yearling and adult bighorn (95% CI)	n (animal months)	Survival of wild-reared bighorn (95% CI)	n (animal months)	Survival of captive-reared bighorn (95% CI)	n (animal months)	Survival of released bighorn >12 months after release (95% CI)	n (animal months)
1994	23 (11)	16	0.64 (0.45-0.82)	218	0.50 (0.10-0.90)	45	0.71 (0.51-0.91)	173	0.70 (0.46-0.94)	134
1995	24 (10)	16	0.82 (0.67-0.97)	238	0.83 (0.54-1.0)	61	0.81 (0.63-0.98)	177	0.90 (0.74-1.0)	127
1996	21 (10)	16	0.75 (0.58-0.91)	248	0.80 (0.45-1.0)	52	0.74 (0.55-0.92)	196	0.77 (0.58-0.97)	148
1997	22 (11)	16	0.78 (0.59-0.97)	237	0.75 (0.33-1.0)	42	0.82 (0.66-0.99)	195	0.85 (0.67-1.0)	156

Table 2.3 Continued.

Year	*Fall population estimate of yearling and adult bighorn (ewes)*	*Number of captive-reared bighorn in the population*	*Survival of all yearling and adult bighorn (95% CI)*	n *(animal months)*	*Survival of wild-reared bighorn (95% CI)*	n *(animal months)*	*Survival of captive-reared bighorn (95% CI)*	n *(animal months)*	*Survival of released bighorn >12 months after release (95% CI)*	n *(animal months)*
1998	22 (10)	15	0.89 (0.76-1.0)	222	1.0 (1.0-1.0)	42	0.88 (0.72-1.0)	180	0.93 (0.80-1.0)	166
Mean	--	--	0.79		0.81		0.80		0.88	

[a] Survival was calculated using the Kaplan-Meier method modified for a staggered entry design (Pollock et al. 1989).

Other reintroduction studies have also found substantial human related mortality for released animals; the primary cause of mortality for reintroduced red wolves (Phillips 1990) and golden lion tamarins (*Leontopithecus rosalia*) (Beck et al. 1991) was human activity (i.e., automobile collisions, accidental trapping, or theft).

The third criterion of reintroduction success, high recruitment, was not achieved. Perhaps the most striking result from this assessment was the chronic low recruitment of both captive-reared and wild-reared bighorn sheep in the NSRM. Our data on lamb production by free-ranging ewes corroborate other studies of bighorn sheep (DeForge & Scott 1982; Borjesson et al. 1996) that suggest low recruitment is caused by neonatal mortality rather than low production. Although in the 1980s disease was common among lambs (DeForge et al. 1982), signs of disease abated during the early 1990s and currently the direct and indirect effects of urbanization on bighorn appear to be more important. Predator populations along the urban interface, high and prolonged concentrations of bighorn feeding on lawns (which may facilitate disease transmission), altered maternal behavior of ewes browsing in urban areas, and other urban-related factors appeared to contribute to high lamb mortality. The NSRM is the only location in the Peninsular Ranges where bighorn frequent urban areas, and recruitment data from neighboring demes (DeForge et al. 1995, 1997; Rubin et al. 2000) suggest that local factors are reducing lamb survival in the NSRM. Achieving the next criteria for reintroduction program success will require minimizing the effects of urbanization on bighorn and reducing both juvenile and adult bighorn mortality rates.

The reintroduction program did not meet our last three criteria for success because the original cause for decline had not been alleviated and/or an additional limiting factor (urbanization) was operating. Understanding or eliminating the original or existing causes of population decline is imperative for successful reintroductions. As Caughley (1994) discussed, the Hawaiian Goose (*Nesochen sandvicensis*) reintroduction was unsuccessful because it lacked the diagnostic steps to determine why the population declined originally. Successful conservation entails merging the "declining population paradigm" that involves the cause of population reduction and its cure, with the "small population paradigm" that deals with the effect of smallness on population persistence. Reintroduction is a small population paradigm tool that can only help restore populations if the limiting factors have been addressed. Another benefit of reintroduction program assessments is the development of specific recommendations for program revisions. For example, survival patterns for released bighorn suggest that first year survival could be improved. Higher survival of

Table 2.4 Population estimates and recruitment (lambs per 100 ewes in December) for captive-reared and wild-reared female bighorn sheep in the northern Santa Rosa Mountains, California.

	No. of ewes ≥2 years old			*Lambs recruited n (percent recruitment)*		
Year	*Wild-reared*	*Captive-reared*	*Total*	*Wild-reared ewes*	*Captive-reared ewes*	*Total*
1985	22	0	22	---	---	---
1986	25	0	25	---	---	---
1987	25	5	30	0 (0)	0 (0)	0 (0)
1988	24	9	33	2 (8)	0 (0)	2 (6)
1989	21	11	32	0 (0)	1 (9)	1 (3)
1990	12	12	24	0 (0)	0 (0)	0 (0)
1991	11	10	21	0 (0)	1 (10)	1 (5)
1992	11	13	24	1 (9)	1 (8)	2 (8)
1993	7	10	17	1 (14)	0 (0)	1 (6)
1994	3	8	11	1 (33)	2 (25)	3 (27)
1995	3	7	10	0 (0)	0 (0)	0 (0)
1996	3	7	10	0 (0)	2 (29)	2 (20)
1997	2	7	9	1 (50)	0 (0)	1 (11)
1998	4	6	10	2 (50)	5 (83)	7 (70)
Mean				0.7 (13.7)	1.0 (13.7)	1.7 (13.0)

Table 2.5 Causes of mortality for captive-reared bighorn sheep released into the northern Santa Rosa Mountains, California, 1985-98.

Source of mortality	*All released bighorn mortalities (%)*	*Mortalities occurring ≤ 6 months after release (%)*	Causes of mortality during the first 6 months after release, by release site: *Bradley*	*East Magnesia*	*West Magnesia*
Mountain lion predation	29.4	30.4	3	0	4
Other predation	7.8	8.7	2	0	0
Urbanization	17.6	17.4	4	0	0
Possibly urbanization	7.8	17.4	4	0	0
Disease	3.9	4.3	1	0	0
Unknown	33.3	21.7	3	2	0
Mortalities ≤ 6 mos. after release	Na	Na	17	2	4
Total number of bighorn released	Na	Na	59	6	8

animals released in January-April probably reflects the better forage quality and water availability in the winter and spring seasons. The significance of the release site to first year survival may be a function of several factors, including the amount of escape terrain near the release site and proximity to free-ranging sheep. Our observations and the gregarious nature of bighorn sheep suggest that integration is key to survival for released animals. The importance of knowledge transfer from experienced to naïve animals has been recognized (May 1991; Tear et al. 1997); other studies found that releases to augment populations were more successful than releases into vacant habitat (Black et al. 1997; Maxwell & Jamieson 1997; Sanz & Grajal 1998). Bradley Canyon had the most escape terrain near the release site and almost always contained free-ranging sheep; however, it was also within 200 m of the urban/mountain interface where at least four sheep later died from urban-related causes. Releases were least successful in west Magnesia Canyon, an area that provided high quality forage, but little escape terrain, and was infrequently used by free-ranging sheep in recent years. Our results suggest that releasing bighorn near the urban interface may increase their vulnerability to urban-related mortality factors, and releasing bighorn in habitat with little escape terrain or few conspecifics may increase their risk of predation (Table 5).

Predation strongly influenced survival of released animals; however, during 1992-1998 predation was also the most frequent cause of death for six other bighorn demes in the Peninsular Ranges (Hayes et al. 2000). While in captivity bighorn reacted to coyotes near the enclosure, but they had no known experience with mountain lions, and translocated animals probably have less knowledge of escape terrain. Wolf et al. (1996) found that predation on released animals was not significantly greater for captive-reared animals compared to wild-reared, translocated animals. This perhaps indicates that habitat familiarity is more important than experience with predators. High predation on translocated bighorn (Rowland & Schmidt 1981) further supports this hypothesis. For captive-reared bighorn, the occurrence of most (82%) first-year mortalities within 6 months after release and the high survival of released animals beginning the second year after release implies that animals gain critical survival knowledge during the first year in the wild. Accordingly, even temporary predator control before and during the first year of a release may improve post-release survival.

Although survival of bighorn released as adults was significantly higher than for those released as yearlings, release age was not a significant factor in our regression analysis of first year survival. Releasing captive-reared bighorn at $\geq$2 years of age would likely increase first year survival; however, release age may influence whether released bighorn establish their own home range, as found by Roy and Irby (1994), or adopt that of the existing population. We suggest that releasing yearling bighorn promotes the transfer of traditional home range use knowledge, which presumably aids population persistence.

When evaluating reintroductions, indirect benefits of the project also warrant discussion (Kleiman 1989). By 1996, >70% of the NSRM population was captive-reared (Table 3), so we assume the population would have been extirpated without augmentation. Maintaining bighorn in the NSRM has provided a stepping-stone for ram movements through the metapopulation (DeForge et al. 1997), time to research the cause of decline, and opportunities for public education. Because NSRM bighorn are often visible to the public and have been frequently featured in the media, they have served as an important flagship species for habitat conservation.

Assessing Ongoing Reintroduction Programs

We presented five criteria for evaluating ongoing reintroduction programs, which also provide a guide for post-release monitoring and reporting results. Although few reintroductions have established viable populations (Beck et al. 1994), in most cases, why the programs fail is unknown: are captive animals not reproducing, are released animals not surviving, or is the original cause for decline still suppressing the population? The criteria we present allow assessment of ongoing programs, identification of the causes of reintroduction failures, and they promote adaptive management. Case studies and reviews thus far suggest that local community involvement and public education are associated with successful projects (Beck et al. 1994) and successful reintroductions often require many years (Griffith et al. 1989, Beck et al. 1994). Further comparative analyses will allow additional generalizations regarding successes and failures of reintroductions, resulting in a more refined and useful tool for preserving biodiversity.

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CHAPTER 3

SPATIAL USE PATTERNS OF DESERT BIGHORN SHEEP NEAR AN URBAN INTERFACE

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ABSTRACT

We examined the spatial use patterns and nutritional levels of an endangered population of desert bighorn sheep (*Ovis canadensis nelsoni*) during 2 time periods (1981-82 and 1995-98). Urban encroachment within the study area began >40 years ago and resulted in changes in resource availability between study periods. We found that female bighorn monitored in 1995-98 ($n = 17$) had smaller home ranges ($P = 0.03$) and used habitat within ($P < 0.01$) and in closer proximity ($P < 0.01$) to urban environments more frequently than bighorn monitored during 1981-82 ($n = 11$). During 1995-98 bighorn also selected habitat farther from natural water sources ($P < 0.001$), escape terrain ($P < 0.001$), and hiking trails ($P = 0.04$) than 1981-82 bighorn. Habitat selection patterns were similar between captive-reared ($n = 20$) and wild-reared ($n = 7$) bighorn during 1995-98, but varied among individuals, spatial scales, and study periods. When individuals were grouped for analysis, all bighorn selected habitat near urbanization ($P < 0.03$) at both the home range and study area levels. At the study area level, all bighorn selected habitat near escape terrain ($P < 0.001$) and water sources ($P < 0.001$), and avoided hiking trails ($P < 0.001$). Bighorn use of urban areas increased 5-fold between our study periods. This bighorn population has declined precipitously in the last 20 years and urbanization appears to be contributing directly and indirectly to adult and juvenile mortality. We recommend excluding bighorn from urban areas in order to encourage more natural resource use patterns.

INTRODUCTION

As urbanization continues to encroach on wildlands, understanding the response of wildlife to humans along the urban/rural interface is becoming increasingly important. Wildlife responses to human-induced stimuli can be broadly classified as attraction, habituation, or avoidance (Knight and Cole 1991). Managing wildlife that are habituated or attracted to human activity has been recognized as a new dilemma facing wildlife managers (Southwick et al. 1990, Thompson and Henderson 1998, Whittaker and Knight 1998). Habituation or attraction behaviors in response to human activity or urban areas have been documented in brown bears (*Ursus arctos*; Abert and Bowyer 1991), mule deer (*Odocoieus hemionus*; Southwick et al. 1990), elk (*Cervus elaphus*), white-tailed deer (*O. virginianus*), and Canada geese (*Branta candensis*) (Whittaker and Knight 1998). Key to managing these situations is an understanding of the cause and consequences of habituation or attraction. Several factors have been identified that influence how animals respond to human disturbance including the type, frequency, predictability, and the position of the disturbance relative to the animal (Knight and Cole 1995). However, few long-term studies have examined the process or consequences of wildlife habituation.

Typically, concerns with wildlife habituation or attraction focus on human and animal safety or the immediate and obvious changes in an animal's diet. However, it is also necessary to consider how changes in feeding or behavior may affect subtle aspects of the species' ecology and ultimately its demography or persistence. Such studies are complicated because the implications of behavioral changes may not be easily detected, causation is difficult to establish in field studies, and the behavior of wildlife may continue changing in response to a changing environment. Nevertheless, long-term habitat selection or behavioral studies may provide insight into the habituation/attraction phenomenon, and can be used to develop and test models predicting the risk of habituation to human presence (e.g., Thompson and Henderson 1998).

The northern portion of the Peninsular Ranges (the San Jacinto and Santa Rosa mountains) in southern California border the rapidly developing Palm Springs metropolitan area. Urban encroachment into alluvial fans, bajadas, and canyons within desert bighorn sheep (*Ovis canadensis nelsoni*) habitat in the northern Santa Rosa Mountains (NSRM) began in the 1950s and continues today. Bighorn sheep in the NSRM were documented using urban areas during hot summer months in the mid-1950s, shortly after homes were first built within bighorn habitat (DeForge and Scott 1982). At that time, the NSRM bighorn were described as a thriving population, ideal for studying the effects of humans on bighorn (Tevis 1959). Urban encroachment into historical bighorn habitat in the NSRM has created substantial changes in the resources available to bighorn sheep, coincident with a precipitous population decline.

In 1977, the NSRM bighorn population was estimated at 90 adults (Wehausen et al. 1987). By 1982 the population had declined to 60-70 adults (DeForge and Scott 1982), and in 1985 only 40 remained (Ostermann et al. 2001). A captive breeding and release program was initiated in 1984 to aid research on bighorn diseases and to provide stock for release into the wild. Although the NSRM deme was augmented with 74 captive-reared bighorn between 1985-98, by 1998 the population numbered only 22 adults. Between 1985-98, adult bighorn survival in the NSRM was low relative to most other desert bighorn populations, and lamb mortality was high (Ostermann et al. 2001). Urbanization was the leading source of mortality (i.e., automobile collisions, strangulation in fencing, and poisoning from exotic vegetation) for adult bighorn in the NSRM during 1991-96 (DeForge and Ostermann, unpublished data) and has caused 3 lamb deaths since 1998 (Bighorn Institute 1999). In recent years, disease has not been a limiting factor for bighorn in the Peninsular Ranges outside of the NSRM (U.S. Fish and Wildlife Service [USFWS] 2000), and recruitment in other portions of the Santa Rosa Mountains has been relatively high (Rubin et al. 2000). In the NSRM, however, signs of illness are still common among lambs and some mortality has been attributed to disease (Bighorn Institute 1998, 2000).

Unlike most mountain sheep, bighorn sheep in the Peninsular Ranges (Peninsular bighorn) inhabit the lower elevations of desert mountain slopes and canyons, generally from the valley floor up to approximately 1,400 m (Jorgensen and Turner 1975; USFWS 2000). This use of low elevation habitat makes them particularly vulnerable to habitat loss and human disturbance. Peninsular bighorn within the U.S. were listed as threatened by the state of California in 1971 and endangered by the USFWS in 1998 (USWFS 1998) because of population declines potentially caused by low recruitment, habitat loss and fragmentation, and high predation rates. Urban development of bighorn habitat and low adult survivorship are among the greatest threats to the metapopulation (USFWS 2000).

In this study, we examined spatial use patterns of desert bighorn sheep in the NSRM confronted with encroaching urbanization. Because habitat selection occurs in a hierarchical fashion and selection may vary at each scale (Johnson 1980), Manly et al. (1993) suggested studying selection at multiple scales. We compared home range sizes, habitat selection on multiple scales, group size, and diet quality of NSRM bighorn monitored during 1981-82 with those monitored in 1995-98. Bighorn sheep monitored during 1981-82 and 1995-98 are referred to as 1980s and 1990s bighorn, respectively. Our objectives were to determine if: (1) spatial use patterns, particularly use of urban areas, changed between the 2 time periods; (2) spatial use patterns differed between male and female bighorn monitored during the 1990s; and (3) nutritional levels (fecal nitrogen) differed between time periods. Between 1995 and 1998, 67-76% of the NSRM bighorn population was comprised of animals that were captive-reared and released (Ostermann et al. 2001). Therefore, in comparing spatial use patterns between study periods, it was necessary to identify differences that may have been attributed to rearing. We tested for differences in habitat selection attributed to study period, rearing status (captive or wild), or gender by developing logistic regression models for habitat use.

STUDY AREA

The Santa Rosa Mountains of southern California are within the Colorado Desert division of the Sonoran Desert (Ryan 1968). Bighorn generally inhabit the eastern side of this range, which contains steep scarps, eroded canyons, and much faulting. Our study occurred in an approximately 70 km^2 area of the Santa Rosa Mountains northwest of State Highway 74. Elevations in the study area reach 1,160 m, however bighorn in our study area are typically found between the valley floor (90 m) and 675 m. Mean annual temperatures range from 6 to 41° C. Annual rainfall during 1981 and 1982 was 3.1 and 6.6 cm, respectively. Annual rainfall during 1995-98 varied from 3.4 to 28.5 cm and averaged 12.2 cm (Western Regional Climate Center; Reno, Nevada). Vegetation is dominated by brittlebush (*Encelia farinosa*)-white bursage (*Ambrosia dumosa*), creosote bush (*Larrea tridentata*), and creosote bush-white bursage vegetation series (Sawyer and Keeler-Wolf 1995). Land ownership is shared among the Bureau of Land Management (BLM), the state of California, and numerous private landowners. Urban development occurs within bighorn habitat in several locations and borders the entire northern and eastern boundaries of the NSRM. The human population in the vicinity of the study area increased notably between study periods. The three cities bordering the NSRM (Palm Desert, Rancho Mirage, and Cathedral City) grew by 97%, 56%, and 239%, respectively between 1980 and 1990 (www.scag.ca.gov/census/). Additionally, in 1989, jeep eco-tours began on an unpaved road (the Dunn Road) that transverses the southern third of the study area (BLM Environmental Assessment CA-066-99-08, 5 August 1999, Special Recreation Permit, Desert Adventures Jeep Eco-Tours, Dunn Road). The Dunn Road received negligible human use prior to 1989.

METHODS

Radiotelemetry Monitoring

Eighteen free-ranging bighorn sheep (n = 11 in 1980s, n = 7 in 1990s) were captured via drivenet or a netgun fired from a helicopter and radiocollared. During the 1990s, captive-reared bighorn ($n = 20$) were radiocollared prior to their release into the wild and failed collars were replaced during captures with a netgun fired from a helicopter. All collars contained Telonics model 400, 500, or 505 transmitters with mortality sensors (Telonics, Inc., Mesa, AZ, USA). Information regarding rearing and release methods for captive-reared bighorn is provided by Ostermann et al. (2001). In 1981-82, bighorn were located visually at approximately monthly intervals. In 1995-98, bighorn were located visually between the hours of 0600-2000, 1-16 times monthly during pre-specified time periods. During both study periods, bighorn were located occasionally via telemetry from airplanes using LORAN-C or a geographic position system (GPS) to determine locations. On the ground, we used radio-telemetry, 8-10X binoculars, and 15-45X spotting scopes to detect bighorn sheep from distances that would not disturb or displace them. We plotted all locations on 1:24,000 topographic maps with an estimated 100-m accuracy. For each observation, we recorded the location (Universal Transverse Mercator coordinates), animal identification, date, time, group size and composition, and whether the observation was scheduled or incidental. Incidental sightings, which primarily occurred along the urban interface, were deleted from our analyses. This sampling design helped compensate for visibility biases within the study area, because bighorn sheep adjacent to urban areas were generally more visible than sheep elsewhere. As part of a separate study, some ewes were located every 48 hours during 1998, but to achieve home ranges more representative of year-round use, we deleted locations so that each ewe had ≤ 6 locations/month spaced approximately 5-7 days apart. All bighorn sheep locations in our analyses were >48 hours apart. This was sufficient time for a bighorn to traverse the diameter of its home range; therefore, we considered these locations independent (White and Garrott 1990).

Home Range and Group Size Estimation

Annual home ranges were estimated by 95% utilization distributions using the fixed-kernel estimator in KERNELHR 4.28 (Seaman et al. 1998). Seasonal home ranges were estimated using the same method for animals having ≥ 20 locations/season. We define seasons as spring (February-April), summer (May-July), fall (August-October), and winter (November-January). While least squares cross validation generally is recommended for choosing the smoothing parameter (h) of the kernel estimator (Worton 1989, Seaman and Powell 1996), this method works poorly with clustered locations (Seaman et al. 1998).

Because locations for many bighorn in our analysis were clustered, we set h at 45% of the reference value and set grid spacing at 100 m for all animals because these settings resulted in the best diagnostic scores. Annual home range sizes were compared between groups using Mann-Whitney U Tests (U_s) (Sokal and Rohlf 1995). We determined average monthly group size using visual locations of bighorn collected in 1981-82 and 1995-98, with incidental and extra sightings deleted as described above. Monthly average group sizes were compared between study periods using two sample t-tests (Sokal and Rohlf 1995).

Habitat Selection

We defined habitat to be the resources and conditions present in an area that produce occupancy by a given organism (Hall et al. 1997). Available habitat was measured by analyzing a sample of random locations that were generated using ArcView 3.2 GIS (Environmental Systems Research Institute, Redlands, CA, USA). We used ArcView GIS 3.2 with the Spatial Analyst 2 extension (Environmental Systems Research Institute, Redlands, CA, USA) to derive geographic parameters of bighorn locations and random locations. For these geographic information system (GIS) analyses, we used a single 1:24,000 digital elevational model (DEM) with 30-m cells and several Digital Ortho Photo Quads (DOQQ) with 8 bits per pixel resolution. We obtained GIS coverages containing trails, the Dunn Road, and landcover classifications from the Coachella Valley Association of Governments as used for the Coachella Valley Multi-Species Habitat Conservation Plan (CVMSHCP) (Palm Desert, CA, USA). The trails and Dunn Road coverages were digitized from the 1:42,240 Santa Rosa Wilderness Map. Landcover classifications were based on the California Gap Analysis Vegetation Layer for the Sonoran Desert Region, which uses the Holland (1986) classification system. The landcover classification coverage was refined for the CVMSHCP using 1992 Landsat imagery, and 1996 and 1998 1:1,000 scale aerial photos. To reflect changes in water availability and newly developed urban areas between study periods, we created separate GIS coverages for 1980s and 1990s landcover classifications and natural or artificial water sources located outside of urban areas. We used 1:24,000 black and white aerial photographs and 1996 DOQQs to record changes in the urban interface line and adjacent landcover classifications between study periods. Water sources were mapped or recorded using a GPS during ground field work and annual helicopter surveys.

We used logistic regression for our habitat analysis, in which bighorn use (i.e., bighorn or random location) was the response variable and explanatory variables were elevation (ELEV), slope (SLOPE), aspect (ASPECT), landcover classification (described below), distance to natural water sources (D-WATER), distance to urbanization (D-URBAN), distance to trails (D-TRAILS), distance to escape terrain ($\geq$ 20% slope; D-ESCAPE), and distance to the Dunn Road (D-DUNNRD). Elevation, slope, and aspect values were assigned to each cell using the DEM and the Spatial Analyst extension within ArcView. Arcview determined aspect by identifying the steepest down-slope direction from each cell to its neighbor and assigning a value to the cell representing the compass direction of the aspect. Slope was identified as the maximum rate of change from each cell to its neighboring cells, with values representing the degree of slope. All distance measurements were the shortest distance in km from a point to the object of analysis. Because bighorn sheep probably choose habitat based on patches of habitat or mosaics of patches, and to account for mapping error (Rettie and McLoughlin 1999), we buffered all points by 100-m to create 200-m diameter circular error polygons (CEP) for the landcover classification analysis. We then determined the amount of each landcover classification within a CEP.

We conducted habitat selection analyses at 3 scales: within the animals' home range, within a group of animals' home ranges, and at the study area level. This involved using designs I and III as described by Thomas and Taylor (1990), with sampling protocol A as described by Manly et al. (1993). Following Manly et al. (1993), we used logistic regression to develop resource selection probability functions using samples consisting of used (bighorn locations) and available (random) points or CEPs. In the first stage of analysis, we examined resource selection for each individual with the objective of identifying patterns in selection that would facilitate pooling data from multiple individuals for subsequent analyses. Available habitat for this scale of analysis was based on 300 randomly generated points within each sheep's 95% minimum convex polygon (MCP) (White and Garrott 1990) plus a 100-m buffer. The study area was defined as the combined 95% minimum convex polygon for all 38 bighorn sheep plus a 100-m buffer. Minimum convex polygons were generated using the program CALHOME (Kie et al. 1996).

We used SYSTAT 8.02 (SPSS, Inc. Chicago, IL, USA) for all statistical analyses. Preliminary analyses included univariate logistic regression and backwards stepwise logistic regression ($\alpha = 0.15$ to enter or remove) on all main effects and all possible two-way interactions to screen variables for inclusion in later analyses. Based on preliminary analyses, we excluded ELEV because it was correlated with D-URBAN ($r = 0.87$), and ASPECT because it was unimportant in most models. Although the study area contained land cover classifications Peninsular Juniper Woodland and Scrub, Sonoran Creosote Bush Scrub, Desert Dry Wash Woodland, and Desert Fan Palm Oasis Woodland, Sonoran Mixed Woody and Succulent Scrub (SONMIX), and Urban (URBAN), we included only the later two classes to eliminate collinearity among these variables. We developed habitat selection models for each sheep, using SLOPE, URBAN, SONMIX, D-WATER, D-URBAN, D-ESCAPE, D-TRAILS, D-DUNN RD, and the interactions D-ESCAPE x URBAN, D-ESCAPE x D-DUNNRD, and D-DUNNRD x SONMIX in the starting model with forward stepwise logistic regression (α-to-enter = 0.01 and α-to-remove = 0.05).

Bighorn were grouped according to the similarity of coefficient values of significant variables within individual regression models. This process grouped bighorn that selected habitat similarly. Next, we used backwards stepwise selection ($\alpha = 0.01$ to enter or remove) to develop common models for each bighorn group. At this stage of analysis, all random points and bighorn locations for a group were combined so that selection was measured at the group home range level. Once common models were obtained for each group, we tested the significance of coefficients for gender (GENDER), study period (YEARS), and whether bighorn were captive-reared or wild-reared (CRWR). We also tested for interactions between GENDER x D-URBAN, YEARS x D-URBAN, and CRWR x D-URBAN. Grouping animals according to habitat selection characteristics before testing the significance of independent variables (e.g., YEARS, CRWR) accounted for variation among individuals, and thereby provided a more sensitive test of these variables than direct comparisons among groups. Differences in habitat selection patterns among groups were quantified by comparing the average distances from each location to the urban interface, trails, water, escape terrain, and the Dunn Road using a Mann-Whitney U test. To examine habitat selection at the study area level, we developed logistic regression models for each group of sheep using 1,000 random points from within the polygon formed by the combined home ranges of all 38 bighorn plus a 100-m buffer as available habitat.

Dietary Quality

Fecal samples were collected from female bighorn monthly during 1995-98 to determine fecal nitrogen levels as an index of dietary quality. Fecal nitrogen is positively correlated with dietary intake, digestibility, protein, and weight changes in wild and domestic animals (Leslie and Starkey 1985). Composite samples were created separately for captive-reared and wild-reared ewes for 4 seasons/year by combining an equal number of fecal pellets from each animal in the sampling group. Samples were analyzed for fecal nitrogen at the Washington State University Wildlife Habitat Laboratory (Pullman, WA, USA) using the standard macro-Kjeldahl technique (Horwitz 1980). Seasonal values were compared between captive-reared and wild-reared ewes using a 2-way analysis of variance (Sokal and Rohlf 1995).

RESULTS

We collected 407 visual locations of 11 collared female bighorn between May 1981 and November 1982. Excluding incidental sightings, we recorded 3,032 visual observations of 27 collared bighorn (7 wild-reared females, 10 captive-reared females, 10 captive-reared males) and recorded 120 locations from airplanes between January 1995 and December 1998.

Home Range Size and Average Group Size

Annual home range size did not differ ($U_s = 22.0$, $P = 0.20$) between captive-reared ewes and wild-reared ewes monitored in 1995-98 (Table 1, Appendix A). Annual home range sizes of captive-reared males and captive-reared females were also similar ($U_s = 28.0$, $P = 0.10$). However, annual home ranges of 1980s ewes were significantly larger than 1990s ewes (1990's captive-reared and wild-reared ewes combined; $U_s = 47.5$, $P = 0.03$). Annual home range size was not related to the number of locations per animal ($r = -0.11$, $P = 0.50$). Seasonal home range sizes varied from 6.7 – 32.7 km^2 and were generally largest during spring months and smallest during summer months (Table 2).

For 9 months of the year, there were no significant differences in group size between 1980s and 1990s bighorn (Figure 1). In March, group size was significantly larger in 1981-82 than in 1995-98 ($t = 2.34$, $P = 0.03$, 16 df). Conversely, group size was significantly larger in 1995-98 than in 1981-82 during May ($t = 2.34$, $P = 0.03$, 16 df) and November ($t = -3.08$, $P = 0.003$, 56 df). During 1995-98, average group size for males and females combined in urban areas ($\bar{x}$ = 7.0, SD = 5.4) was significantly larger ($t = 4.8$, $P < 0.001$, 1,069 df) than group size in nonurban areas ($\bar{x}$ = 5.5, SD = 4.9).

Habitat Selection

Resource selection functions for individual sheep were grouped according to common variables and regression coefficients, resulting in 3 groups (Appendix B). Bighorn sheep in group 1 ($n = 9$) had negative coefficients for D-WATER, D-TRAILS, and/or D-DUNNRD, and their models did not contain interactions. Bighorn with positive or insignificant coefficients for D-WATER, D-DUNNRD, and D-TRAILS with no interactions in their models, formed group 2 ($n = 19$). Group 3 ($n = 10$) contained all bighorn with interactions in their models. Group 1 consisted of 7 1980s female bighorn, plus a 1990s female that was born prior to 1980, and a 1990s captive-reared male. Group 2 contained 1980s ($n = 4$) bighorn and captive-reared ($n = 12$) and wild-reared ($n = 3$) bighorn from the 1990s. Group 3 contained only 1990s bighorn, including captive-reared ($n = 7$) and wild-reared ($n = 3$) individuals. We retained these groups for subsequent analyses.

Logistic regression models for each of the 3 groups suggested that D-ESCAPE, D-URBAN, D-WATER, D-TRAILS, and D-DUNNRD were important variables explaining habitat selection (Table 3); however, regression coefficients varied among groups. Group 1 had negative coefficients for D-WATER and D-TRAILS, indicating bighorn in this group selected habitat in proximity to water sources and trails, while groups 2 and 3 had positive coefficients for these variables. Groups 1 and 2 selected for habitat near escape terrain, and all groups selected habitat significantly closer to urbanization than random points (Table 3). Although habitat selection differed for males and females in group 2 ($P = 0.005$), interpretation of this variable is confounded by the interaction between GENDER and D-URBAN for this group. The variable GENDER was not significant for groups 1 or 3 ($P = 0.08$ and 0.07, respectively). The variable YEAR was significant in models for both group 1 ($P < 0.001$) and 2 ($P = 0.03$), indicating that habitat selection differed between the 1980s and 1990s.

Table 1. Annual home range size for bighorn sheep in the northern Santa Rosa Mountains, California, monitored 1981-82 or 1995-98. Home ranges were the estimated 95% utilization distributions determined by the fixed-kernel method.

		Home range size (km^2)		
Group [a]	No. animals	Mean	SD	Range
1981-85 WR females	11	13.5	2.4	9.0 – 16.4
1995-98 WR females	7	11.9	2.9	5.3 – 13.4
1995-98 CR females	10	11.4	5.0	4.9 – 23.5
1995-98 CR males	10	13.3	3.0	10.1 – 18.3

[a] WR = wild-reared, CR = captive-reared.

Table 2. Seasonal home range size for bighorn sheep in the northern Santa Rosa Mountains, California, monitored 1995-98. Seasonal ranges were determined only for bighorn that had $\geq$20 locations/season. Home ranges were the estimated 95% utilization distributions determined by the fixed-kernel method.

		Home range size (km^2)		Number of	Number of
Bighorn Group[a]	Season	Mean	SE	locations	animals
WR Females	Feb - Apr	17.3	0.73	90	3
	May - Jul	11.4	2.02	190	5
	Aug - Oct	5.2	1.07	210	6
	Nov - Jan	8.5	0.98	136	4
CR Females	Feb - Apr	11.5	1.12	234	8
	May - Jul	7.1	1.20	351	7
	Aug - Oct	7.7	2.08	377	8
	Nov - Jan	6.7	0.58	290	7
CR Males	Feb - Apr	12.4	0.71	65	8
	May - Jul	8.8	1.67	219	8
	Aug - Oct	9.4	0.56	337	8
	Nov - Jan	9.3	0.47	223	7

[a] WR = wild-reared, CR = captive-reared.

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[a] WR = wild-reared, CR = captive-reared.

Table 3.2 Seasonal home range size for bighorn sheep in the northern Santa Rosa Mountains, California, monitored 1995-98. Seasonal ranges were determined only for bighorn that had ≥20 locations/season. Home ranges were the estimated 95% utilization distributions determined by the fixed-kernel method.

		Home range size (km^2)		Number of	Number of
Bighorn Group[a]	Season	Mean	SE	locations	animals
WR Females	Feb - Apr	17.3	0.73	90	3
	May - Jul	11.4	2.02	190	5
	Aug - Oct	5.2	1.07	210	6
	Nov - Jan	8.5	0.98	136	4
CR Females	Feb - Apr	11.5	1.12	234	8
	May - Jul	7.1	1.20	351	7
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[a] WR = wild-reared, CR = captive-reared.

DISCUSSION

Spatial use patterns differed significantly between our 2 study periods, but not between captive-reared and wild-reared bighorn or males and females within the 1990s. Use of urban areas and habitat adjacent to urban areas increased substantially between the 1980s and 1990s. Compared to 1980s bighorn, 1990s bighorn had smaller home ranges, used urban areas significantly more often, selected habitat closer to urbanization and farther from water, escape terrain, and trails. Additionally, average monthly group size during the 1990s study period was stable year-round, a pattern not typical of other bighorn populations. Considering that urban encroachment into bighorn habitat began in the 1950s, the difference in spatial use patterns between our study periods suggests that bighorn exhibited strong home range fidelity and habituated slowly to human-induced stimuli.

We found that spatial use patterns varied among individuals, spatial scales, and study periods. For example, within their group home range, only group 1 bighorn (comprised primarily of 1980s ewes) showed attraction to natural water sources (Table 3), but at the study area level all bighorn selected habitat near water (Table 4). Bighorn in groups 2 and 3 appeared to be less constrained by natural water availability within their home ranges and may have relied on urban water sources or undocumented ephemeral water sources. We frequently observed 1990s bighorn drinking from swimming pools, water fountains, and sprinklers within urban areas. Differential response to trails was another important difference among groups at the combined home range level. Group 1 bighorn selected habitat near trails, while groups 2 and 3 selected habitat away from trails. This result could be interpreted in at least 3 ways: (1) human use of trails in bighorn habitat was minimal in the 1980s, but by the 1990s trail use increased and bighorn were avoiding trails; (2) bighorn were attracted to urbanization in the 1990s and therefore were attracted away from trails; or (3) habitat quality declined and bighorn became increasingly attracted to forage in urban areas. It is unlikely that changes in habitat quality between study periods promoted the use of urban areas. Rainfall during 1981-82 was relatively low, in which case we would expect use of urban areas to increase. Data on human trail use is not available for our study area; however, nonconsumptive recreational activities in the U.S. grew in popularity by 64% between 1980 and 1990 (Duffus and Dearden 1990, Flather and Cordell 1995). In Riverside County, the resident population nearly doubled between 1980 and 1995

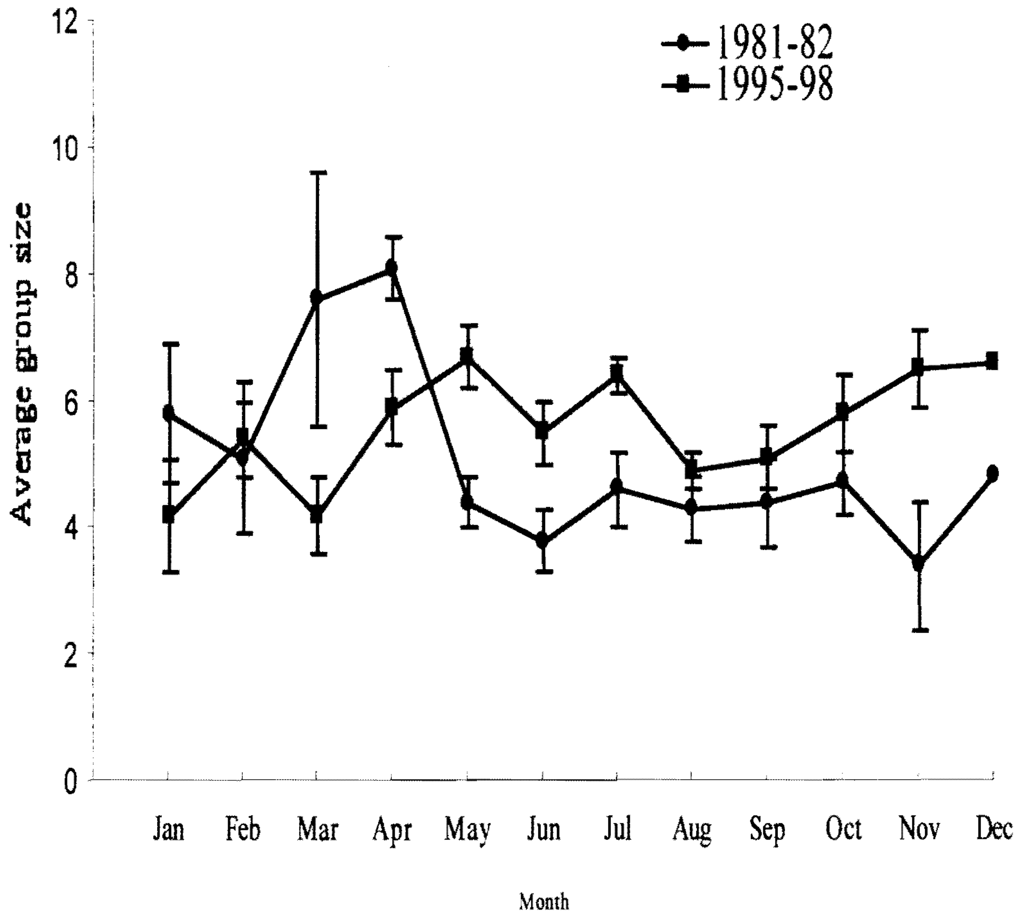

Figure 1. Monthly average group size (± SE) for female bighorn sheep monitored in 1981-82 and 1995-98 in the northern Santa Rosa Mountains, California.

Table 3.3 Logistic regression models of bighorn sheep habitat selection and tests for differences in selection attributed to gender, rearing status (captive or wild), or years monitored (1980-81 or 1995-98). The response variable was use (0 = random points, 1 = bighorn sheep location). Available habitat was examined at the group home range level (95% minimum convex polygon for all sheep in the group plus a 100-m buffer).

Group and variables	Estimate	SE	t-ratio	p-value	odds ratio	95% CI odds ratio
Group 1						
Constant	-0.454	0.250	-1.817	0.069	–	–
D-WATER	-0.416	0.135	-3.073	0.002	0.660	0.506 – 0.860
D-URBAN	-0.798	0.081	-9.894	<0.001	0.450	0.385 – 0.528
D-ESCAPE	-2.644	0.929	-2.848	0.004	0.071	0.011 – 0.439
D-DUNNRD	0.221	0.056	3.934	<0.001	1.248	1.117 – 1.393
D-TRAILS	-0.497	0.105	-4.717	<0.001	0.608	0.495 – 0.748
GENDER	-0.271	0.157	-1.727	0.080	0.762	0.560 – 1.037
CRWR	-0.271	0.157	-1.727	0.080	0.762	0.560 – 1.037
YEAR	1.616	0.119	4.041	<0.001	1.616	1.280 – 2.039
Group 2						
Constant	-3.178	0.192	-16.520	<0.001	–	–
SLOPE	0.031	0.004	7.878	<0.001	1.031	1.023 – 1.039
D-WATER	0.969	0.056	17.218	<0.001	2.634	2.359 – 2.941
D-URBAN	-1.285	0.088	-14.524	<0.001	0.277	0.233 – 0.329
D-ESCAPE	-3.641	0.584	-6.232	<0.001	0.026	0.008 – 0.082
D-DUNNRD	0.203	0.032	6.361	<0.001	1.225	1.151 – 1.304
D-TRAILS	0.396	0.065	6.096	<0.001	1.485	1.308 – 1.686
SONMIX	<0.001	<0.001	2.592	0.010	1.000	1.000 – 1.000

Table 3.3 Continued.

Group and variables	Estimate	SE	t-ratio	p-value	odds ratio	95% CI odds ratio
URBAN	<0.001	<0.001	8.945	<0.001	1.000	1.000 – 1.000
GENDER	0.453	0.157	2.884	0.0039	1.573	1.156 – 2.139
*DURBAN						
GENDER	0.174	0.063	2.771	0.006	1.190	1.052 – 1.346
CRWR	-0.057	0.065	-0.887	0.380	0.944	0.832 – 1.072
YEAR	0.226	0.105	2.156	0.030	1.253	1.021 - 1.538
Group 3						
Constant	-2.732	0.264	-10.358	<0.001	–	–
SLOPE	0.033	0.005	6.899	<0.001	1.033	1.024 – 1.043
D-WATER	0.573	0.080	7.179	<0.001	1.773	1.517 – 2.073
D-URBAN	-1.487	0.116	-12.797	<0.001	0.226	0.180 – 0.284
D-ESCAPE	1.805	2.058	0.877	0.381	–	–
D-DUNNRD	0.195	0.048	4.103	<0.001	–	–
D-TRAILS	0.534	0.082	6.485	<0.001	1.215	1.107 – 1.333
SONMIX	<0.001	<0.001	3.274	0.001	1.000	1.000 – 1.000
URBAN	<0.001	<0.001	7.571	<0.001	1.000	1.000 – 1.000
DESCAPE*						
D-DUNNRD	-1.470	0.474	-3.104	0.002	0.230	0.091 – 0.581
GENDER	-0.089	0.098	-0.915	0.360	0.915	0.755 – 1.107
CRWR	-0.167	0.092	-1.809	0.070	0.846	0.706 – 1.014
YEAR	N/A	N/A	N/A	N/A	N/A	N/A

Table 3.4 Logistic regression models of bighorn sheep habitat selection at the study area level. The study area was defined as the combined 95% minimum convex polygon for all 38 bighorn sheep plus a 100-m buffer. The response variable was use (0 = random points, 1 = bighorn sheep locations).

Group and variable	Estimate	SE	t-ratio	P-value	Odds ratio	95% CI odds ratio
Group 1						
Constant	1.298	0.271	4.792	<0.001	–	–
D-WATER	-1.314	0.122	-10.793	<0.001	0.269	0.212 – 0.341
D-URBAN	-0.167	0.077	-2.151	0.031	0.847	0.727 – 0.985
D-ESCAPE	-19.856	2.23	-8.916	<0.001	<0.001	<0.001 – 0.001
D-DUNNRD	-0.320	0.057	-5.587	<0.001	0.726	0.649 – 0.812
D-TRAILS	0.561	0.111	5.030	<0.001	1.752	1.408 – 2.181
SONMIX	<-0.001	<0.001	-5.716	<0.001	1.000	1.000 – 1.000
URBAN	<0.001	<0.001	5.986	<0.001	1.000	1.000 – 1.000
Group 2						
Constant	0.068	0.181	0.374	0.708	–	–
SLOPE	0.042	0.006	7.475	<0.001	1.043	1.031 – 1.054
D-WATER	-0.182	0.053	-3.416	0.001	0.833	0.750 – 0.925
D-URBAN	-1.037	0.083	-12.455	<0.001	0.354	0.301 – 0.417
D-ESCAPE	-8.127	0.777	-10.459	<0.001	<0.001	<0.001 – 0.001
D-TRAILS	0.728	0.085	8.595	<0.001	2.073	1.755 – 2.448
SONMIX	<-0.001	0.001	-9.276	<0.001	1.000	1.000 – 1.000
URBAN	<0.001	<0.001	9.085	<0.001	1.000	1.000 – 1.000
Group 3						
Constant	-0.247	0.212	-1.167	0.243	–	–
SLOPE	0.046	0.006	7.232	<0.001	1.047	1.034 – 1.060
D-WATER	-0.457	0.078	-5.918	<0.001	0.633	0.544 – 0.737
D-URBAN	-1.483	0.118	-12.571	<0.001	0.227	0.180 – 0.286
D-ESCAPE	-7.502	0.862	-8.706	<0.001	0.001	<0.001 – 0.003
D-TRAILS	0.985	0.100	9.845	<0.001	2.679	2.202 – 3.260
SONMIX	<-0.001	<0.001	-5.793	<0.001	1.000	1.000 – 1.000
URBAN	<0.001	<0.001	8.107	<0.001	1.000	1.000 – 1.000

Table 3.5 Percent of monthly locations of female bighorn sheep in urban areas and average distance from locations to the urban interface in the northern Santa Rosa Mountains, California.

Month	Percent of monthly locations in urban areas		Average distance (m) from all locations to the urban interface ± SD			
	1981-82	1995-98	1981-82	No. locations	1995-98	No. locations
January	0	22	2,001 ± 612	16	404 ± 490	127
February	0	25	1,283 ± 806	14	689 ± 638	137
March	0	10	785 ± 275	18	930 ± 552	136
April	0	16	1,441 ± 588	2	779 ± 587	135
May	9	25	1,040 ± 624	5	586 ± 563	174
June	9	39	678 ± 646	9	342 ± 437	206
July	7	45	1,196 ± 831	238	372 ± 530	214
August	14	37	552 ± 552	37	341 ± 442	206
September	14	38	809 ± 646	21	278 ± 289	224
October	3	27	1,641 ± 642	35	412 ± 447	199
November	0	34	1,921 ± 947	18	344 ± 422	204
December	0	37	1,683 ± 1,339	5	411 ± 506	178
Mean	4.7	29.6	1,252.5	N/A	490.7	N/A

Table 3.6 Average distance (m) from locations of female bighorn sheep in the northern Santa Rosa Mountains, California to the nearest resources and areas of disturbance. In all cases, distances for 1981-82 bighorn were significantly different than values for 1995-98 bighorn ($P < 0.05$).

	Water		Escape terrain		Urbanization		Hiking trails		Dunn road	
	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD	$\bar{x}$	SD
1981-82	653	601	0	0	1,122	857	1,041	77	2,945	1,101
1995-98	1,212	630	31	70	461	520	1,148	523	3,742	1,072

Table 3.7 Percent fecal crude protein in composite fecal samples from female bighorn sheep in the northern Santa Rosa Mountains, California.

Group and year	Winter	Spring	Summer	Fall
Captive-reared bighorn				
1995	--	--	2.77	2.36
1996	2.14	1.94	2.56	2.21
1997	1.53	1.95	2.04	2.12
1998	2.22	2.25	2.15	2.06
1999	1.90	--	--	--
Wild-reared bighorn				
1995	--	--	2.76	2.36
1996	1.78	1.75	2.49	2.31
1997	1.70	1.96	2.20	2.08
1998	--	--	2.12	2.08
1999	1.75	--	--	--
Wild-reared bighorn[a]				
1981	--	--	2.4	2.3
1982	1.5	1.7	--	--

[a] From Scott 1986

(www.scag.ca.gov/census/). When habitat availability was considered at the study area level, all bighorn avoided trails (Table 4). Concordance among spatial scales, such as groups 2 and 3 avoidance of trails at the group home range and study area levels, indicates strong selection for a variable.

Resource selection at the study area level was consistent across groups, except for group 1's selection for habitat near the Dunn Road (Table 4). Groups 2 and 3 did not select habitat near the Dunn Road. The average distance from each location to the Dunn Road was significantly greater in 1995-98 than in 1981-82. Jeep eco-tours on the Dunn Road began in 1989 (BLM Environmental Assessment CA-066-99-08, 5 August 1999, Special Recreation Permit, Desert Adventures Jeep Eco-Tours, Dunn Road) and the estimated traffic during operational months (September – June) in 1995-98 ranged from 43-366 vehicles/month (BLM case file CA-066-SRP-99-02, Special Recreation Permit, Section 7 Consultation for Desert Adventures Jeep Eco-Tours, Dunn Road). The increased human use of the Dunn Road coincided with a decrease in bighorn sheep use of this area, and corroborates other studies that indicate traffic on unpaved roads may interfere with bighorn resource use (DeForge 1972, Jorgensen and Turner 1973, Jorgensen 1974). However, as with apparent avoidance of trails, attraction to urban areas or changes in habitat quality are alternative explanations for avoidance by bighorn of the Dunn Road during 1990s.

Distance to escape terrain and distance to urbanization were the only variables included in resource selection models for all groups at both the group home range and study area scales (Tables 3 and 4). Definitions of escape terrain vary widely and include qualitative to quantitative descriptions (McCarty and Bailey 1994). While no single definition of escape terrain for bighorn sheep is widely accepted (McCarty and Bailey 1994), several authors (Cunningham 1989, Ebert and Douglas 1993, Andrew et al. 1999) have defined escape terrain as >60% slope. However, our study area contained only small amounts of slope $\geq$60%. Observations of NSRM bighorn during lambing season and when sheep reacted to disturbances (e.g., humans, predators, aircraft) revealed that small patches of broken terrain, considerably <60% slope, frequently provided cover for bighorn. Our results support the concept of using patches of habitat $\geq$20% slope as the basis for modeling Peninsular bighorn (USFWS 2000).

Bighorn in all 3 groups used habitat near urbanization (Tables 3 and 4). At both spatial scales, the strength of selection for habitat near urbanization increased in groups 1 to 3. Group 1 was least attracted to urbanization (Tables 3 and 4) and all but 1 of these bighorn were born in or prior to the 1980s. Group 2, comprised of bighorn from the 1980s and 1990s, represented an intermediate group. Group 3, consisting of only 1990s bighorn, showed strong selection for urban areas. While we were unable to quantify the effects of encroaching urbanization versus increasing attraction of bighorn to urban areas, both phenomena occurred. Urban encroachment increased substantially between study periods, and the percentage of female bighorn locations in urban areas increased 5-fold between study periods. Additionally, a higher percentage of the NSRM population used urban areas in the 1990s than in the 1980s. Similar situations of wildlife becoming increasingly attracted to urban or agricultural areas over time have been documented with mule deer (Southwick et al. 1990) and elk (Burcham et al. 1999).

Abundant resources in urban areas may have influenced bighorn group size. Group size is positively associated with foraging efficiency (Berger 1978, Risenhoover and Bailey 1985) and is thought to be primarily limited by forage availability (Jarman 1974). During 1981-82, mean monthly group size fluctuated near 7% of the population size, while in the 1990s group size was typically near 20% of the population size and was less variable among seasons. Most desert bighorn populations obtain maximum group sizes during periods of greater forage and water availability, often during spring and winter months (Leslie and Douglas 1979, Chilelli and Krausman 1981, Elenowitz 1984). The stability in mean monthly group size for 1990s bighorn (Figure 1) compared to other populations, and the larger group sizes in urban compared to nonurban areas suggests that forage availability in urban areas may have allowed NSRM bighorn to maintain large group sizes throughout the year.

Home range size is thought to be highly dependent on forage availability; as resource availability increases, home range size decreases (McNab 1983). Ungulates in higher quality habitat maintain smaller home ranges than those in less desirable habitat (Krausman et al. 1989, Longshore and Douglas 1995). Home ranges of NSRM bighorn were smaller than those of bighorn in the neighboring San Jacinto Mountains (DeForge et al. 1997). Although home ranges generated by different estimators and/or software programs are not directly comparable (Gallerani-Lawson and Rodgers 1997), annual home ranges of desert bighorn sheep are generally on the order of 17-25 km^2 for females and 15–275 km^2 for males (McCarty and Bailey 1994). Bighorn in the NSRM had small annual home ranges relative to estimates available for other desert bighorn populations, and female bighorn in the 1990s used significantly smaller areas than females in the 1980s. These results are consistent with the idea that NSRM bighorn minimized their energy expenditure by using abundant resources available within urban areas.

We expected the availability of lush forage in urban areas to affect the nutritional levels of NSRM bighorn. Fecal nitrogen levels for NSRM bighorn during the 1990s were among the highest reported values for desert bighorn sheep (Hebert 1986, Wehausen 1992, Andrew 1994, Rubin et al. 2000). Rubin et al. (2000) examined fecal nitrogen levels in the Peninsular bighorn subpopulation in Deep Canyon of the Santa Rosa Mountains (immediately south of the NSRM) during 1994-95 and reported peak levels during summer similar to those we found for NSRM bighorn. The main difference between results for neighboring bighorn in the NSRM and Deep Canyon (Rubin et al. 2000) was the lower range of values for Deep Canyon bighorn. Both captive-reared and wild-reared NSRM females maintained percent fecal nitrogen levels >1.50 and 1.70 year-round, respectively, while Deep Canyon bighorn had values ≤1.50 for 5 months of the year. When native forage quality declined, NSRM bighorn may have sustained a high quality diet by foraging in urban areas. Small samples sizes in Scott (1986) prohibited a statistical comparison of values from 1980s bighorn in that study to values for 1990s sheep in our study.

An animal's response to humans is determined by the its lifetime experiences (Knight and Temple 1995), although the philopatric and gregarious behaviors of bighorn sheep also foster cultural learning. Positive reinforcement (e.g., food and water) can also hasten habituation responses or lead to attraction (Whittaker and Knight 1998). Urban areas regularly used by NSRM bighorn included a golf course and several gated, residential communities with manicured lawns, little traffic, and few dogs. Watered lawns and urban water sources, in stark contrast to the dry native vegetation within the study area, therefore provided positive reinforcement along the urban interface. Furthermore, human activity in this desert environment was minimal during summer months when bighorn use of urban areas was highest. Both the predictability of human activity in urban areas, and the lower elevation of urban areas relative to bighorn habitat may have also contributed to bighorn habituation to human disturbance in urban areas. These observations are consistent with 2 factors thought to increase elk habituation to human disturbance (Thompson and Henderson 1998): human disturbance within the animal's normal range, and consistent and predictable human activities. Whittaker and Knight (1998) cautioned against labeling individuals or populations by their responses, rather than distinguishing responses to specific stimuli. We do not consider the NSRM bighorn population to be habituated to all forms of human disturbance. While bighorn often appeared habituated to human disturbance in urban areas, they used urban areas and habitat adjacent to urban areas less during the sensitive spring lambing season (Table 5), and they avoided trails and the Dunn Road, presumably due to human disturbance associated with these areas. Selective habitation to predictable disturbance (e.g., highway traffic), while avoiding other types of human disturbance (e.g., trails or roads with unpredictable traffic) has been observed in other ungulates (Geist 1978, Geist et al. 1985, Yarmoloy et al. 1988).

Bighorn sheep in the NSRM had been exposed to human disturbance at the urban-mountain interface within bighorn habitat for $\geq$25 years before this study was initiated in 1981. Our results suggest that over a period of 2 decades, NSRM bighorn modified their spatial use patterns and increased their use of urban environments. Female bighorn in the 1990s maintained smaller home ranges, and selected habitat closer to and within urban areas more frequently than female bighorn in the 1980s. Female bighorn in the 1990s also selected habitat farther from escape terrain, water sources, and trails than 1980s females. Habitat selection patterns were similar among captive-reared and wild-reared bighorn, as well as males and females within the 1990s.

MANAGEMENT IMPLICATIONS

Bighorn sheep use of urban areas does not occur without negative consequences. Between 1991-96, urbanization was the primary cause of death (i.e., automobile collisions, poisoning from non-native plants, and strangulation in a wire fence) for adult bighorn in this population, accounting for 34% of the documented mortalities. Additionally, a large percentage of the adult bighorn population during 1991-96 was infected with nematode parasites, with some animals showing clinical signs of infection (DeForge and Ostermann unpublished data). While these parasites are generally not lethal, they may compromise the host's body condition and behavior (Scott 1988). Because these parasites require a moist environment (e.g., watered lawns) to complete their life cycle, restricting bighorn access to urban areas would likely eliminate the parasite infestation. These parasites were not found elsewhere within the Peninsular Ranges (DeForge et al. 1997, Rubin et al. In review).

The NSRM bighorn population experienced poor lamb recruitment and a rapid population decline, despite augmentation with 74 captive-reared bighorn since 1984. Lamb recruitment in the NSRM appears to be suppressed by locally acting, population-specific factors, which may include disease and urbanization. Recruitment in this subpopulation has been low since a purported disease epidemic occurred in the late 1970s (DeForge and Scott 1982, Wehausen et al. 1987, Ostermann et al. 2001) and disease appeared to contribute to at least 14 years (1977-90) of poor recruitment throughout the Santa Rosa Mountains (DeForge et al. 1995). However, in recent years, disease has not been a limiting factor for bighorn in the Peninsular Ranges outside of the NSRM (USFWS 2000), and recruitment in other portions of the Santa Rosa Mountains has been relatively high (Rubin et al. 2000). In the NSRM, signs of illness are still common among lambs and some mortality has been attributed to disease (Bighorn Institute 1998, 2000).

Density-dependent mechanisms (Anderson and May 1979, May and Anderson 1979) may be contributing to the disease observed in this population. Bighorn density may be increased locally by the year-round large group sizes and small home ranges of NSRM bighorn. Because host density influences disease transmission rates (Anderson and May 1979, May and Anderson 1979, Scott 1988), use of urban areas may be contributing to lamb mortality in 2 ways: directly through accidents such as automobile collisions (Bighorn Institute 1999), and indirectly, by contributing to density-dependent disease processes.

Ultimately, through direct and indirect effects on both lambs and adult bighorn, bighorn use of urban areas may be the primary factor limiting the growth and recovery of the NSRM population. We suggest management actions to encourage natural ranging patterns in these bighorn; in particular, excluding bighorn from urban areas. Our results support the idea of constructing a bighorn-proof fence along the urban interface to exclude bighorn, as recommended in the USFWS Recovery Plan for Peninsular bighorn (USFWS 2000). We also recommend development or rehabilitation (i.e., removal of exotic vegetation) of water sources in historic habitat to ensure bighorn have adequate resources.

Because habituation or attraction responses are not intrinsically good or bad, and the consequences of an animal's behavior are not always immediate or direct (Whittaker and Knight 1998), long-term studies may be needed to understand the implications of some human-wildlife interactions. Our study is an example of a wildlife-human interaction that initially appeared to be beneficial to wildlife by providing abundant food and water sources. However, the dangers to bighorn in urban areas and the spatial use patterns associated with urban areas suggest that current resource selection habits of NSRM bighorn may be the primary factor limiting this population.

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CHAPTER 4
CONCLUSIONS

This thesis assessed conservation efforts to recover an endangered population of desert bighorn sheep, and spatial use patterns of bighorn sheep near an urban interface. Implications from both studies apply to bighorn sheep conservation and to wildlife management in a broader context. The first study, *Captive Breeding and Reintroduction Evaluation Criteria: a Case Study of Peninsular Bighorn Sheep* highlighted the paucity of data on past captive breeding programs, and provided criteria that may be used to evaluate ongoing captive breeding programs. While reintroduction programs are recognized as being costly and prone to failure, in some cases they may be the only hope for population recovery. Accumulating experience and knowledge from a variety of species through regular program evaluations will promote the refinement of reintroduction science as a recovery tool. For example, evaluations of reintroduction programs for the Hawaiian Goose (*Nesochen sandvicensis*; Caughley 1994) and our evaluation of the bighorn sheep program showed the importance of eliminating the cause of decline in the release area before releasing new animals. More specifically, results from my study showed the need to eliminate excessive mortality, particularly mortality attributed to urbanization. High lamb and adult mortality, caused primarily by urbanization and predation, prohibited the captive breeding program from attaining all 5 criteria of success. The key management recommendations resulting from Chapter 2 of my thesis are (1) the need to regularly assess captive breeding and release programs, and (2) the need to curb urban-related mortality and potentially implement predator control until the bighorn population in the northern Santa Rosa Mountains (NSRM) recovers.

Chapter 3 of my thesis compared the home range, habitat selection, and nutrition of NSRM bighorn monitored during 1981-82 with those monitored in 1995-98. Urban development within bighorn habitat changed resource availability between the 2 study periods. Overall, there were significant differences in resource selection patterns between 1980s and 1990's females, but not between captive-reared and wild-reared bighorn in the 1990s. One of the most significant findings from Chapter 3 is documentation of a 5-fold increase in bighorn use of urban areas between study periods. Although urban areas are a source of forage and water, bighorn use of urban areas has been linked to parasitism, adult and juvenile mortality (Bighorn Institute 1999, 2000), and it appears to influence spatial use patterns. These changes in habitat use may facilitate the disease observed in the NSRM bighorn population. Because the negative effects of urbanization on bighorn sheep in this area outweigh the benefits from water and forage in urban areas, we recommend excluding bighorn from these areas. Monitoring herd health, lamb recruitment, and spatial use patterns once bighorn are excluded from urban areas may provide insights into the mechanisms currently maintaining disease in this population.

The NSRM bighorn population provides an example of a wildlife-human interaction that initially appeared to be beneficial to wildlife by providing abundant food and water sources. However, the dangers to bighorn in urban areas and the spatial use patterns associated with urban areas suggest that current resource selection habits of NSRM bighorn may be the primary factor limiting this population. Human-wildlife interactions should be examined carefully and preferably through long-term studies before conclusions are drawn regarding the consequences of the interaction.

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APPENDICES

APPENDICES

Appendix A. Annual home range size for bighorn sheep in the northern Santa Rosa Mountains, California monitored 1981-82 and 1995-98. Home ranges were estimated as the 95% fixed-kernel utilization distributions.

ID	Gender	Years monitored	Captive (C) or wild (W) reared	Number of locations	Home range size (km^2) 95% FK estimate
1	F	81-85	W	36	16.3
2	F	81-85	W	37	13.8
3	F	81-85	W	48	10.8
4	F	81-85	W	37	9.0
5	F	81-85	W	37	13.9
6	F	81-85	W	37	16.4
7	F	81-85	W	30	13.0
8	F	81-85	W	32	14.4
9	F	81-85	W	40	13.8
10	F	81-85	W	49	11.2
11	F	81-85	W	24	16.4
12	F	95-98	W	194	13.4
13	F	95-98	W	176	13.4
14	F	95-98	W	104	12.4
15	F	95-98	W	102	13.3
16	F	95-98	W	82	12.9
17	F	95-98	W	27	12.7
18	F	95-98	W	58	5.3
19	F	95-98	C	164	10.4
20	F	95-98	C	114	11.1
21	F	95-98	C	181	23.5
22	F	95-98	C	176	9.0
23	F	95-98	C	220	12.6
24	F	95-98	C	76	10.4
25	F	95-98	C	174	8.6
26	F	95-98	C	182	8.9

Appendix A continued.

ID	Gender	Years monitored	Captive (C) or wild (W) reared	Number of locations	Home range size (km^2) 95% FK estimate
27	F	95-98	C	48	14.5
28	F	95-98	C	62	4.9
29	M	95-98	C	42	15.5
30	M	95-98	C	138	10.1
31	M	95-98	C	131	12.2
32	M	95-98	C	116	14.6
33	M	95-98	C	40	18.3
34	M	95-98	C	157	10.8
35	M	95-98	C	114	11.6
36	M	95-98	C	94	10.4
37	M	95-98	C	81	12.3
38	M	95-98	C	99	17.7

Appendix B. Logistic regression coefficients for significant variables ($P \leq 0.05$) in habitat selection models of individual bighorn. Bighorn sheep locations were compared to 300 random points within each sheep's home range (95% minimum convex polygon plus a buffer). The response variable was use, with bighorn locations coded 1 and random locations coded 0.

Animal ID	Rear-ing [a]	Sex	Years monitored [b]	SLOPE [c]	D-WATER	D-URBAN	D-DUNN	D-ESCAPE	D-TRAILS	URBAN	SON-MIX	D-ESCAPE X URBAN	D-ESCAPE X DDUNN	D-DUNN X SONMIX
Group 1														
315	W	F	80		-1.31									
329	W	F	80		-1.18	-1.05								
361	W	F	80		-2.38									
NAV	W	F	90		-1.62									
435	W	F	80		-1.22									
B-Y	W	F	80		-1.53									
391	W	F	80			-1.40			-1.42	-0.0001				
420	W	F	80			-1.01	1.16		-1.54					
WIL	C	M	90			-1.36	-0.54							
Group 2														
STO	C	M	90			-1.64								
ERN	C	M	90			-1.57								

Appendix B. Continued.

Animal ID	Rearing [a]	Sex	Years monitored [b]	SLOPE [c]	D-WATER	D-URBAN	D-DUNN	D-ESCAPE	D-TRAILS	URBAN	SON-MIX	D-ESCAPE X URBAN	D-ESCAPE X DDUNN	D-DUNN X SONMIX
BAJ	C	M	90		0.61	-2.10			0.91					
BET	C	F	90	0.07	3.54	-3.06								
BLU	W	F	90	0.03	0.90	-1.16								
COE	C	F	90		1.01	-1.51		-7.00		0.0000				
MES	W	F	90		1.50	-1.05								
SAG	C	F	90		1.22	-2.55	0.45	-4.56	1.41		0.0001			
SER	C	F	90	0.04	1.43	-1.44	0.40		0.69					
TRE	C	M	90		1.40	-2.50			1.08					
ZIN	C	M	90		0.65	-1.43								
SHA	C	F	90		1.02									
AAR	C	M	90		1.63									
FEL	C	F	90		1.63		0.42							
MCK	W	F	90		1.37		0.55		0.67					
HOP	C	M	90				0.64		0.78					
RBB	W	F	80	0.08										
345	W	F	80								-0.0001			

Appendix B. Continued.

Animal ID	Rearing [a]	Sex	Years monitored [b]	SLOPE [c]	D-WATER	D-URBAN	D-DUNN	D-ESCAPE	D-TRAILS	URBAN	SON-MIX	D-ESCAPE X URBAN	D-ESCAPE X DDUNN	D-DUNN X SONMIX
375	W	F	80											
406	W	F	80											
<u>Group 3</u>														
ALE	C	F	90			-1.15			1.23	0.0001			-9.1200	
ELL	W	F	90			-1.61			1.28	0.0001			-6.8100	
GAM	C	M	90			-1.16							-4.8800	
Y-O	W	F	90									0.0010		
YRUF	W	F	90		-2.62				1.97			0.0007		0.0001
POC	C	F	90	0.02	1.01							0.0020		-0.0001
JP	C	M	90			-3.32		-4.24						0.0001
PAH	C	F	90	0.05		-2.21			0.98					0.0000
SQU	C	F	90			-2.38								-0.0001

[a] Rearing = (C) captive-reared or (W) wild-reared.

[b] Bighorn were monitored via radiotelemetry during 1981-82 (80) or 1995-98 (90).

[c] SLOPE = Percent slope; D-WATER = Distance to water; D-URBAN = Distance to urbanization; D-DUNN = Distance to the Dunn Road D-ESCAPE = Distance to escape terrain; D-TRAILS = Distance to trails; URBAN = Urban land cover classification; SONMIX = Sonoran Mix land cover classification.