CAUSE SPECIFIC MORTALITY OF

DESERT BIGHORN SHEEP LAMBS IN THE

FRA CRISTOBAL MOUNTAINS, NEW MEXICO, USA

By

Zachary David Parsons

Bachelor of Science, University of New Mexico, 1997

Thesis

presented in partial fulfillment of the requirements
for the degree of

Master of Science
in Wildlife Biology

The University of Montana
Missoula, MT

Autumn 2007

Approved by:

Dr. David A. Strobel, Dean
Graduate School

Dr. Daniel H. Pletscher, Chair
Wildlife Biology Program

Dr. Jack Ward Thomas
Professor Emeritus

Dr. Kerry R. Foresman
Biological Sciences

Dr. Kyran Kunkel
Faculty Affiliate

Parsons, Zachary, M.S., Autumn 2007 Wildlife Biology

Cause Specific Mortality of Desert Bighorn Sheep Lambs in the Fra Cristobal Mountains, New Mexico, USA

Chairperson: Dr. Daniel H. Pletscher

Desert bighorn sheep (*Ovis canadensis mexicana*) are an endangered species in New Mexico. Many of the small, isolated populations of desert bighorn are declining, and factors affecting their growth rates include low lamb recruitment and high mortality of adults due to cougar predation. No one has previously reported cause-specific mortality rates for desert bighorn lambs. My objectives were to determine the causes, extent, and timing of lamb mortality in the Fra Cristobal Mountains, New Mexico, USA. I tested 3 capture techniques during 2001 and 2002: approaching lambs on foot and restraining them by hand; jumping from a helicopter and restraining them by hand; and firing a net-gun from a helicopter. I captured 6 lambs by hand on the ground, 4 lambs by hand from the helicopter, and 11 lambs from the helicopter with a shoulder-mounted and skid-mounted net-gun. No injuries occurred to lambs or capture personnel. The hand capture technique allowed me to capture very young lambs. I then monitored lambs for mortality, and examined carcass and site characteristics to determine cause. I found that the primary proximate cause of lamb mortality was cougar predation, followed by golden eagle predation. Coyotes and bobcats did not kill lambs. Although 1 lamb died from pneumonia, disease was not a critical factor affecting lamb recruitment. I measured habitat characteristics at sites where adults and lambs were killed by cougars and paired control sites, and derived habitat characteristics at predation sites, relocation sites representing used areas, and random sites representing available areas. Visibility was lower at predation than control sites, while slope, elevation, and ruggedness were lower at predation than relocation sites, and predation sites were closer to water and roads than random sites. I suggest selective cougar control of habitual sheep killers over the short term may be an appropriate management strategy to enhance the recovery of desert bighorn populations, while recognizing the importance of carnivore populations to ecosystem health. Wildlife managers may consider prescribed burning to reduce vegetation encroachment and increase visibility and forage quantity and quality. Additionally, assessment of desert bighorn and cougar use of artificial water developments would be beneficial.

Table of Contents

List of Tables and Figures

15 December 2007
Zachary D. Parsons
Wildlife Biology Program
Department of Ecosystem and Conservation Sciences
University of Montana
Missoula, MT 59812
406/243-5272; Fax: 406/243-4557
zachary.parsons@umontana.edu

RH: Desert Bighorn Lamb Capture Techniques • Parsons et al.

Capture Techniques for Desert Bighorn Sheep Lambs

Zachary D. Parsons,[1] Wildlife Biology Program, Department of Ecosystem and Conservation Sciences, University of Montana, Missoula, MT 59812, USA

Daniel H. Pletscher, Wildlife Biology Program, Department of Ecosystem and Conservation Sciences University of Montana, Missoula, MT 59812, USA

Kyran E. Kunkel,[2] Turner Endangered Species Fund, 1123 Research Drive, Bozeman, MT 59718, USA

Peter D. Bangs,[3] Wildlife Sciences, School of Natural Resources, University of Arizona, Tucson, AZ 85721, USA

Anthony L. Wright,[4] Hornocker Wildlife Institute / Wildlife Conservation Society, 2023 Stadium Drive, Suite 1A, Bozeman, MT 59715, USA

---

[1] E-mail: zachary.parsons@umontana.edu

[2] Present address: World Wildlife Fund, 1875 Gateway S., Gallatin Gateway, MT 59730, USA

[3] Present address: Division of Sport Fish, Alaska Department of Fish and Game, PO Box 110024, Juneau AK 99811, USA

[4] Present address: Utah Division of Wildlife Resources, 475 W. Price River Drive, Suite C, Price, Utah 84501, USA

ABSTRACT Bighorn sheep (*Ovis canadensis*) herds have suffered recent declines across their previous range, and desert bighorn sheep (*O. c. mexicana*) are listed as an endangered species in New Mexico. One factor affecting growth rates of these populations is low and variable lamb recruitment. Capturing and radio-collaring lambs can provide opportunities for collecting valuable information on factors potentially affecting long term population persistence. Little information is available on cause-specific lamb mortality or on methods for obtaining such data. We tested 3 different capture techniques on desert bighorn sheep lambs. We captured lambs during the spring lambing seasons of 2001 and 2002 by approaching lambs on foot and restraining them by hand, jumping from a helicopter and restraining them by hand, and firing a net-gun from a helicopter. We captured 6 lambs by hand on the ground, 4 lambs by hand from a helicopter, and 11 lambs from a helicopter with a shoulder-mounted or skid-mounted net-gun. The best capture technique depended on the specific circumstances of each different situation. Since we were concerned with sample size considerations, our success depended on the implementation of all 3 techniques. However, the hand-capture technique allowed us to capture very young lambs that we would not have attempted to capture with either helicopter technique due to stress, risk of injury, and cost. This technique may be applicable to other ungulate populations.

KEY WORDS capture, desert bighorn sheep, lamb, New Mexico, *Ovis canadensis mexicana*, technique.

Bighorn sheep (*Ovis canadensis*) were widely distributed over western North America in the early 19^{th} century (Buechner 1960), however, present geographic distributions as well as population numbers are considerably reduced (Krausman and Shackleton 2000). By the early 1900s, most populations were extirpated due to a combination of factors including excessive hunting and competition with and diseases introduced by domestic livestock as well as other anthropogenic factors (Krausman 2000). Use of isolated precipitous mountain terrain by bighorn sheep results in naturally fragmented habitat (Krausman et al. 1999). Desert bighorn sheep (*O. c. mexicana*) likely inhabited most of the mountain ranges in central and southern New Mexico, and their historic occurrence was documented in 14 of these arid ranges (New Mexico Department of Game and Fish [NMDGF] 1995). Only 2 populations remained in New Mexico by 1955, and desert bighorn sheep were listed as an endangered species in 1980. The NMDGF established a captive breeding population at the Red Rock Wildlife Area (RRWA) in 1972. Between 1979 and 1999, desert bighorn sheep were translocated from the RRWA to augment existing populations, reestablish locally extinct populations, and establish new populations, resulting in 8 mountain ranges with desert bighorn sheep populations. Translocations have become a common approach in bighorn sheep conservation and restoration efforts (Singer et al. 2000). Removal of desert bighorn sheep from the state endangered species list requires a minimum of 500 free-ranging desert bighorn sheep in at least 3 geographically distinct populations or metapopulations, each containing at least 100 bighorn (NMDGF 2003). Threats to bighorn include habitat degradation from extensive livestock overgrazing and fire suppression, cougar (*Puma concolor*) predation, competing public interests and increasing human pressure, which may exacerbate inherently low rates of increase, difficulty in colonizing new habitats, and sensitivity to diseases and human disturbances. Desert bighorn sheep populations have been slow to increase or are declining in all of these mountain ranges, most populations have suffered significant increases in mortality due to cougar predation, and no animals have been observed during autumn helicopter surveys in 2 of these ranges since 2000 (NMDGF 2003).

Small populations of bighorn sheep are more vulnerable to extinction than large populations (Berger 1990, 1993, 1999; Krausman et al. 1993; Wehausen 1999). Demographic sensitivity analysis of desert bighorn sheep populations in New Mexico revealed that the model was sensitive to mortality rates among female lambs (Fisher et al. 1999). Mortality of bighorn sheep lambs is typically high and variable (Bradley and Baker 1967, Hansen 1980, DeForge et al. 1982, Douglas and Leslie 1986, Krausman et al. 1989).

Knowledge of the causes of mortality of bighorn sheep lambs may improve predictive ability of models and suggest management strategies for improving the recovery of small populations of bighorn sheep. However, causes of mortality of bighorn sheep lambs are rarely investigated due to the extreme difficulty in locating carcasses of un-collared lambs, and the lack of technology until recent years for safely and successfully radio-collaring lambs (DeForge and Scott 1982, Nette et al. 1984, Festa-Bianchet 1988, Hass 1989, Etchberger and Krausman 1999). Scotton (1998) examined causes of Dall sheep (*O. dalli*) lamb mortality in Alaska, and Hass (1989) and Goldstein (2001) investigated causes of Rocky Mountain bighorn sheep (*O. c. canadensis*) lamb mortality in Montana and South Dakota, respectively. However, with the exception of Etchberger and Krausman (1999; $n = 2$), nobody has reported on the causes of desert bighorn sheep lamb mortality. Capturing and radio-collaring bighorn sheep lambs is essential to accurately determine cause-specific mortality. Appropriate techniques for capturing desert bighorn sheep lambs may differ from those used for capturing adults, as well as Dall sheep and Rocky Mountain bighorn sheep lambs.

The most appropriate capture technique for bighorn sheep adults depends on specific situations and purposes for capture (Jessup 1992). Firing a net gun from a helicopter was compared to use of drop-net, drive-net, and chemical immobilization via dart-gun for capturing adult bighorn sheep (Kock et al. 1987a, b, c). Drop-nets involve habituating bighorn to bait, and are used to simultaneously capture large groups of bighorn sheep. Drive-nets are also used to capture large groups of bighorn sheep, and involve placing several standing linear nets across strategic areas and then herding individual or groups of bighorn sheep towards the capture site by ground crews or a helicopter or both. Chemical immobilization involves approaching individual animals by helicopter or on the ground and firing a dart projectile that injects the animal with immobilizing drugs. The net-gun technique involves pursuing individual or groups of bighorn sheep on the ground or from a helicopter and shooting a net from a skid-mounted or hand-held four barreled net-gun delivering a large weighted nylon or cotton blend net over the animal (Barrett et al. 1982, Krausman et al. 1985). Kock et al. (1987a) found the net-gun to be the safest of these 4 methods for capturing adult bighorn sheep.

Alternate or modified capture techniques are necessary when capturing bighorn sheep lambs. The use of drop-nets and drive-nets requires extensive planning and long handling times as many sheep are caught at once, and the presence of adults in the captured group increase the risk of physical trauma to lambs. Chemical immobilizers pose high risks to bighorn sheep due to their susceptibility to capture myopathy (Jorgenson et al. 1990, 1991; Kock 1991; Jessup 1992). Andryk et al. (1983) speculated that net-gunning from a helicopter would be better than darting from a helicopter for capturing bighorn sheep lambs due to the potential for overdosing and injury from poor dart placement. Scotton and Pletscher (1998) successfully captured Dall sheep lambs by hand capture after stepping or jumping from a helicopter. Neonates of various ungulate species such as white-tailed deer (*Odocoileus virginianus*; Kunkel and Mech 1994), guanaco (*Lama guanicoe*; Franklin and Johnson 1994), and Mongolian gazelles (*Procapra gutturosa*; Olson et al. 2005) have been hand captured from a ground approach after radio-telemetric or observational monitoring of mothers' behavioral and/or physical characteristics indicative of parturition.

Unlike populations of bighorn sheep at more northern latitudes where lambing seasons begin later and are shorter, desert bighorn sheep lambing seasons typically extend from late winter to early summer (Thompson and Turner 1982, Rubin et al. 2000). Desert bighorn sheep ewes typically seek isolation for lambing (Bangs et al. 2005a, b). After parturition, the ewe and lamb will rejoin other groups of sheep, forming so-called "nursery bands". Desert bighorn sheep lambs are classic followers who are precocial in nature, and soon after birth are able to follow their mothers (Pitzman 1970, Lent 1974).

Our objectives were to develop and evaluate a safe and efficient technique for hand-capturing desert bighorn sheep lambs from a ground approach, and then to compare that technique to hand capture facilitated by jumping from a helicopter, and net-gun capture from a helicopter. We predicted that pursuit time, handling time, the distance of the ewe from the lamb after capture, and the time until reunification of the ewe and lamb following capture would be greater for both helicopter methods than for the ground approach method. We also compared number of lambs caught, and any cases of injury, abandonment, or mortality between techniques.

STUDY AREA

The Fra Cristobal Mountains (FCM) are located in south-central New Mexico in Sierra and Socorro Counties approximately 32 km northeast of Truth or Consequences; they lie entirely within the privately-owned Armendaris Ranch (Krausman et al. 2001). The range is bounded on the west by the Rio Grande Valley and Elephant Butte Reservoir, and on the east by the Jornada del Muerto Basin. The FCM are an east-tilted horst block characterized by massive granite cliffs and horizontally layered limestone cliff steps (Nelson 1986). The range is approximately 5 km wide by 24 km long (105 km^2), and elevations range from 1,400 - 2,109 m. Near the northernmost extent of the Chihuahaun Desert, vegetation associations consisted of a mosaic of desert scrub and desert grassland at lower elevations, patchy montane scrub at higher elevations typically between 1,850 and 1,950 m, and a limited amount of open coniferous woodland near the summit above 1,950 m (Miller 1999). Three perennial springs were located on the range, and 5 apron water catchment units capable of storing ~19,000 L were developed in 1995 (Dunn 1991). Precipitation at Elephant Butte Dam averaged 23.6 cm annually (Bangs et al. 2005a), and approximately 68% occurred during May through September (Brown 1982). The FCM contain approximately 65 km^2 of suitable desert bighorn sheep habitat, with 22.7 km^2 of escape terrain (Dunn 1994), and carrying capacity of the range for bighorn was estimated at 100 individuals. Evidence of 2 relatively recent wildfires suggested that a frequent fire regime has existed on the FCM. Little evidence of domestic livestock herbivory was observed, and no known domestic sheep herds occurred within 50 km of the range. No evidence existed that desert bighorn sheep occupied the FCM, though their proximity to the San Andres Mountains (55 km east of the FCM) with an extant population and the habitat quality of the FCM made their occurrence probable. Also, 1 desert bighorn sheep ram was observed in the Caballo Mountains (25 km south of the FCM) in 1907 (Sandoval 1979). A translocation of 37 desert bighorn sheep (13 rams and 24 ewes) to the FCM was conducted from the RRWA in autumn 1995, with an augmentation of 7 additional rams in autumn 1997. A helicopter and net-gun capture of 16 adult ewes was conducted in autumn 1999 to re-instrument ewes and maintain radio-telemetric contact with the herd. Potential bighorn predators on the FCM include cougars, bobcats (*Lynx rufus*), coyotes (*Canis latrans*), and golden eagles (*Aquila chrysaetos*; Frey 1999, Truett et al. 1999).

METHODS

Monitoring Natality

Our helicopter and net-gun capture and re-instrumentation of adult desert bighorn sheep during the autumn of 1999 provided 14 VHF radio-collared (Model 500, Telonics, Mesa, Arizona, USA) ewes in the FCM herd in 2001 and 13 radio-collared ewes in 2002. We monitored radio-collared ewes for movement patterns indicative of parturition, and for the presence of new born lambs via radio-telemetry and direct observation on a near daily basis during the spring lambing periods of 2001 (January through May) and 2002 (December through May). We estimated 27 mature adult ewes capable of reproducing in 2001, and 29 in 2002. Un-collared ewes were observed when with collared individuals or when otherwise visually detected. However, un-collared individuals were difficult to monitor, especially when they left groups for parturition.

Capture Techniques

Hand-capture from the ground.— When we detected the presence of a newborn lamb, we assessed its degree of mobility according to visual observations of any ambulatory movements or the lack thereof. Often, the lamb's age was known to within 1 to 2 days due to prior observations of the dam. Otherwise, age was determined during capture on the basis of new hoof growth measurements and texture, umbilicus condition, behavioral characteristics such as mobility, the presence of afterbirth, and wet hair. We attempted a hand-capture from the ground if we believed that we could capture the lamb due to its mobility and approximate age of ≤ 3 days, and the lamb and dam were in terrain where we could attempt an approach. Prior to a capture attempt, we waited until the animals bedded down. Solitary ewe-lamb pairs were preferred. However, we also attempted captures of lambs associated with small groups of ewes. Once the animals bedded down, we noted the location of the animals in relation to topography and notable landmarks. Two handlers then stalked the animals to as close as possible without detection; e. g. by climbing up the opposite side of a ridge, ideally ending up above the animals. When there was no more available cover we rapidly approached the animals by running directly toward them. The ewe would flee this perceived threat, and the lamb would hide or attempt to flee. After a short search or chase the lambs were manually restrained.

Hand-capture from a helicopter.— When we observed a sufficient number of newborn lambs that were too old and mobile for hand capture, we assembled a helicopter and capture crew. A Hughes 500 helicopter was used for all hand captures from a helicopter in 2001. In addition to the pilot, 2 handlers were aboard the helicopter. Helicopter personnel wore nomax suits and helmets. The doors were removed from the Hughes 500 to enhance visibility and facilitate exit of the capture crew from the aircraft. Radio contact was maintained between pilots and capture crews on the ground. Ground crews attempted to locate ewe and lamb groups prior to capture. The helicopter was equipped with antennas and a receiver to locate radio-collared ewes known to have lambs. We hazed sheep in dangerous terrain for <2 minutes into terrain where an attempt at capture could be made with reasonable safety for the crew and helicopter. Haze and chase time was limited to ≤ 5 minutes.

When a lamb became separated from a group and subsequently tried to hide against a sheer rock face or boulder, two handlers, one at a time, released their harnesses, stepped onto the skid, and jumped or stepped to the ground. Handlers departed the helicopter when they felt they could land safely and not incur self injury; jumps seldom exceeded 1 m. The handlers then approached the lamb from 5 to 10 m in front of the cliff from different angles. When the lamb tried to flee, handlers attempted to manually restrain it. The helicopter then moved >500 m away to minimize stress to the captured lamb.

Net-gun capture from a helicopter.— Alternately, if a fleeing lamb became separated from the group, a net-gun capture was attempted. A Hughes 500 helicopter was used in 2001 and a Bell 206 JetRanger was used in 2002. Both hand-held and skid-mounted net-guns were used (CODA Enterprises, Inc., Mesa, Arizona, USA), which discharged a blank 0.308 caliber cartridge to propel 4 254-g cylindrical weights attached to the corners of a 4- X 4-m nylon net with 10-cm mesh. Only 1 lamb was targeted, and ewes and lambs were not captured together. The net was fired forward and downward over the target, and any misses were followed rapidly by another shot when appropriate. Once the net was successfully deployed over a lamb, the helicopter landed and the handlers exited the helicopter and approached the entangled lamb. The helicopter then moved >500 m away and landed.

Handling

Processing gear including radio collar, nut driver and extra hardware, scale, GPS, sling, extra rubber gloves, measuring tape, blindfold, ear swab, fecal and hair sample tins, and a data sheet was stored in a small backpack to leave the catcher's hands free. All handlers wore latex gloves throughout processing and tagging. Captured lambs were blindfolded. We radio-collared (recording frequency, serial number, lamb #, and dam frequency and #), sexed, and weighed the lamb with a sling and spring scale. Transmitters (MOD-305) with a two-hour mortality delay were attached to stretchable nylon beige-colored collars (CB-6) with expansion loops and breakaway tabs, and weighed approximately 0.175 kg (Telonics, Mesa, Arizona, USA). Measurements of chest girth, neck girth, shoulder height, and hind foot length were taken, as well as an ear swab, hair, and fecal samples. We recorded the date, capture method, general location, Universal Transverse Mercator (UTM) coordinates, ambient temperature, capture crew, pursuit time (start and finish), and handling time (start and finish) to the nearest minute. We described lamb reaction upon release (e.g., the lamb jumped up and ran bleating; the lamb remained quiet and motionless in the bedded position) and the reaction of the dam during the capture (e.g., ewe fled initially, but remained in the immediate vicinity, and was seen upon leaving the capture site) when possible. The distance of the lamb from the dam upon release was visually estimated and recorded when possible, and the maximum time until the lamb reunited with the dam (i.e., when researchers first visually observed them together following capture) was noted when possible. We strived to keep handling time to <5 minutes.

Data Analysis

We used SPSS version 13.0 (Chicago, Illinois, USA) for statistical analyses. We used Student's *t*-test for independent samples to compare differences in means. We examined the assumption of equality of variances using Levene's test, and when F values were insignificant, we used t values for which equal variances were not assumed. We set significance levels at $P < 0.05$ for all statistical tests.

RESULTS

We captured desert bighorn sheep lambs during 2001 and 2002 using each of the 3 different capture techniques (Table 1). Hand capture from the ground resulted in 29% of total successful captures, while hand capture from a helicopter accounted for 19% of captures, and 52% were attributed to net-gun capture from both types of helicopter. We captured 8 males and 13 females; thus sex ratio of lambs at capture was skewed in favor of females (62%). Estimated ages of captured lambs ranged from < 1 to 71 days. Average estimated age of lambs captured by hand from the ground was significantly younger than average estimated age of lambs captured with all helicopter methods (t = -12.281, df = 19, $P \leq 0.001$); mean estimated age at capture was 1.8 days (SE = 0.40, n = 6) for hand captures from the ground, and mean estimated age at capture for all helicopter methods was 57.8 days (SE = 2.83, n = 15). Average pursuit time and average handling time were similar among all 3 capture techniques (Table 2); we found no statistically significant differences in pursuit or handling time between hand and net-gun capture from the Hughes 500, net-gun capture from the Hughes 500 and the Bell 206 JetRanger, or hand capture from the ground and the Hughes 500. No lambs suffered any physical injuries during any of the capture events by any of the 3 techniques. Mean estimated distance of the ewe from the lamb at release for hand captures from the ground was 391.7 m (SE = 135.66, n = 6); however, ewe distance from the lamb at release was not obtainable for any of the helicopter captures. Mean maximum time to reunification of the lamb and dam was 15.3 hrs (SE = 4.16, n = 6) for hand captures on the ground, and 32.9 hrs (SE = 3.91, n = 8) for all captures from the helicopters; average maximum time to reunification of the lamb and dam following capture and release was significantly shorter for hand capture from the ground compared to captures from helicopters (t = -3.033, df = 12, P = 0.010). Ambient temperature averaged 10.9° C (SE = 0.80, n = 14) for all captures, and although wind conditions varied during hand captures on the ground, wind speeds where low to negligible during helicopter captures. No dams attempted to defend their lambs with protective behaviors such as aggression towards the handlers during processing.

No lambs died immediately as a result of our capture and handling. One lamb was not visually confirmed to have reunited with its mother after capture. In this case, the lamb was hand captured from a ground approach in the late afternoon; by evening, telemetry triangulation indicated the ewe and lamb were in the same location, as well as on the next several days. A visual observation was not attempted due to their location and concern of further disturbing them. The lamb's radio collar remained in the active mode for 3 days. When a mortality signal was received on the fourth day following capture, the ewe was located on the same slope that the lamb carcass was eventually found, and the lamb had been killed by a golden eagle.

DISCUSSION

No one has previously reported capture methods for desert bighorn sheep lambs. A primary concern in all capture operations is animal welfare and safety of involved personnel. We successfully captured and handled desert bighorn sheep lambs safely and effectively with all 3 of the techniques described without physical injury or immediate mortality to lambs or endangering researcher's safety. While 1 lamb was not confirmed to have reunited with its mother, we do not believe this was a case of capture induced abandonment due to triangulation placing the ewe and lamb in the same location, and the duration the lamb's radio collar remained in the active mode.

Time to reunification of the lamb and dam were maximums since they represented the time from release at the end of capture to the first time observed together; ewe and lamb may have rejoined earlier than first seen back together, and in some cases lambs captured in the afternoon or evening were first seen together the following morning but likely reunited the previous day. Monitoring frequency was the same throughout the study. Contrary to our predictions, we did not find any differences in pursuit and handling times between methods. Ewe distance from lamb upon release could not be estimated for helicopter captures due to the flight response of ewes to the helicopter. During previous annual autumn helicopter surveys, we observed movement responses of desert bighorn sheep before the helicopter became visible. For ground captures, the identity of the dam was known, and the dam always stayed at least within telemetric contact if not visual contact. During helicopter captures, the identity of the dam of captured lambs was rarely known immediately, and in some cases even after groups of sheep reunited, pairs could not be confirmed until observed nursing. In one instance, in the afternoon following a helicopter capture, we observed a solitary ewe with two lambs; when she was subsequently observed with other sheep on the following day, the temporarily adopted lamb had rejoined with its mother.

Relatively quick reunification with the mother after the capture event is critical for lamb survival (Byers 1997). Handlers wore latex gloves to minimize scent transfer to lambs, and pursuit and handling times were kept as short as possible in order to minimize the duration and the intensity of the disturbance, and thus minimize capture related stress and the potential for capture induced abandonment, and to facilitate reunification (Livezey 1990) Garrott et al. (1985) found no difference in mortality rates between ear-tagged and radio-collared fawns, indicating radio-collars did not make fawns more conspicuous to predators as compared to ear-tags. Byers (1997) also found no evidence of increased mortality risk to neonatal ungulates due to handling in his study of young pronghorns.

Lambs caught from helicopters were significantly older than lambs captured by hand. This was partly an artifact of the methods themselves, as we were unwilling to risk stress and physical trauma in helicopter and net-gun captures to very young lambs. The potential for stress and physical trauma inherent in net-gunning was minimized by waiting until the lambs were several weeks old before capture. Also, due to the extended lambing periods of desert bighorn sheep as compared to the shorter periods of more northern populations (Bunnell 1982), logistic and cost constraints dictated that we wait until several lambs were present in the population before performing a helicopter capture. Consequently, helicopter captures took place in a single day each year. However, if the purpose of capture is to examine mortality of lambs, early causes will be missed.

In terms of the number of lambs captured, our success in capturing lambs depended on the implementation of all 3 of the capture techniques. Since sample size considerations were important to the ultimate research objectives and purposes for capture, helicopter captures were instrumental in achieving our goals. Besides applying the helicopter net-gun technique, we also applied the hand capture technique from the helicopter that had been used previously on Dall sheep lambs (Scotton and Pletscher 1998) but not on desert bighorn sheep lambs. However, the Bell 206 JetRanger helicopter used in 2002 was slower and much less maneuverable, so no lambs were captured using this method during this year. The net-gun capture method was successful from both helicopters. However, the repeated overflights during the helicopter captures disturbed the entire herd of sheep for a prolonged period and not just the target animals.

Bighorn sheep are susceptible to disturbance from aircraft, especially helicopters (Krausman and Hervert 1983, Miller and Smith 1985). Stockwell et al. (1991) found that helicopters modified bighorn sheep behavior by reducing foraging efficiency. Bleich et al. (1990, 1994) found that helicopter disturbance caused dramatic response in bighorn sheep, reporting movements 2.5 times farther following a helicopter survey, and concluded that the negative influence of the helicopter was extreme. Indeed, when comparing capture methods for bighorn sheep, Kock (1991) stated the contribution of the helicopter to the degree of stress experienced would be impossible to evaluate. Jessup (1992) followed by saying helicopter pursuit of bighorn sheep adds significantly to capture stress, and the use of helicopters to capture bighorn sheep should be avoided, if possible.

We applied a hand capture technique that had been used on white-tailed deer fawns (Kunkel and Mech 1994) and South American guanaco neonates (Franklin and Johnson 1994) but had never been used on desert bighorn sheep. The precocial nature of desert bighorn lambs is well documented (Hansen and Deming 1980). We found that for a short time after birth, desert bighorn lambs (≤ 3 days) tended to hide rather than flee with the dam when faced with a perceived threat, and this has never been described in the scientific literature. This behavior is common in other ungulates such as white-tailed deer; however, the length of time lambs display this behavior is much shorter than fawns (approximately 3 days versus 2 weeks; Carl and Robbins 1988, Kunkel and Mech 1994). By monitoring and observing radio-collared adult ewes, we identified newborn lambs for hand capture attempts from the ground. Through trial and error, we determined when to attempt a hand capture on the ground based on group size, microhabitat characteristics, and estimated lamb age, and were successful in implementing this technique. The technique of hand-capturing lambs from the ground proved successful for capturing lambs within a few days after birth. This technique reduced and delayed the need for helicopter capture operations and minimized the risk of stress and physical trauma to lambs.

MANAGEMENT IMPLICATIONS

Wildlife biologists must continually evaluate techniques we use to capture, handle, and monitor wildlife populations. Wildlife managers can safely capture desert bighorn sheep lambs by helicopter and net-gun, a technique that has also been applied to Rocky Mountain bighorn lambs, as well as proven effective for adult bighorn sheep and many other ungulate species. Researchers should attempt to hand capture young neonates from helicopters over net-gunning whenever possible to eliminate the potential risk of physical injury inherent in net-gunning. Both of these techniques may be more efficient when applied to neonate populations with more strongly synchronized birthing seasons. However, the effects of aerial harassment of wildlife should be critically evaluated and minimized by wildlife professionals. Through observation of maternal behavior and movements, wildlife biologists can take advantage of a common neonate ungulate predator evasion strategy, hiding versus fleeing, to hand capture desert bighorn sheep lambs on the ground. Given the extremely precocial nature of desert bighorn sheep lambs, the lack of a synchronized birthing season, low population density, ruggedness of terrain, lack of parturition site fidelity, and lack of habituation to people, we believe this technique for capturing and handling neonates has broad applicability to a wide variety of other ungulate species, especially for small populations where knowledge of the causes of neonate mortality may contribute to better understanding population dynamics and could give valuable insights for population viability and ultimately population persistence.

ACKNOWLEDGMENTS

We thank J. Anderson, G. Brennan, K. Eulinger, K. Foresman, E. Goldstein, R. Guty, K. Honness, D. Hunter, D. Klinka, P. Krausman, J. Mabe, M. Phillips, H. Provencio, E. Rominger, J. Thomas, R. B. Turner, R. E. Turner, D. Verhelst, T. Waddell, D. Wayne, D. Weybright, A. Whitelaw, and H. Whitlow. We also thank J. Olson and R. Small, in memoriam. Contributing organizations included the Boone and Crockett Wildlife Conservation Program, Foundation for North American Wild Sheep, National Fish and Wildlife Foundation, New Mexico Department of Game and Fish, New Mexico Ranch Properties Incorporated, Turner Endangered Species Fund, and the University of Montana.

LITERATURE CITED

Andryk, T. A., L. R. Irby, D. L. Hook, J. J. McCarthy, and G. Olson. 1983. Comparison of mountain sheep capture techniques: helicopter darting versus net-gunning. Wildlife Society Bulletin 11:184-187.

Bangs, P. D., P. R. Krausman, K. E. Kunkel, and Z. D. Parsons. 2005. Habitat use by desert bighorn sheep during lambing. European Journal of Wildlife Research 51:178-184.

Bangs, P. D., P. R. Krausman, K. E. Kunkel, and Z. D. Parsons. 2005. Habitat use by female desert bighorn sheep in the Fra Cristobal Mountains, New Mexico, USA. European Journal of Wildlife Research 51:77-83.

Barrett, M. W., J. W. Nolan, and L. D. Roy. 1982. Evaluation of a hand-held net-gun to capture large mammals. Wildlife Society Bulletin 10:108-114.

Berger, J. 1990. Persistence of different-sized populations: an empirical assessment of rapid extinctions in bighorn sheep. Conservation Biology 4:91-98.

Berger, J. 1993. Persistence of mountain sheep: methods and statistics. Conservation Biology 7:219-220.

Berger, J. 1999. Intervention and persistence in small populations of bighorn sheep. Conservation Biology 13:432-435.

Bleich, V. C., R. T. Bowyer, A. M. Pauli, M. C. Nicholson, and R. W. Anthes. 1994. Mountain sheep Ovis canadensis and helicopter surveys: ramifications for the conservation of large mammals. Biological Conservation 70:1-7.

Bleich, V. C., R. T. Bowyer, A. M. Pauli, R. L. Vernoy, and R. W. Anthes. 1990. Responses of mountain sheep to helicopter surveys. California Fish and Game 76:197-204.

Bradley, W. G., and D. P. Baker. 1967. Life tables for nelson bighorn sheep on the desert game refuge. Desert Bighorn Council Transactions 3:142-170.

Brown, D. E. 1982. Chihuahuan desertscrub. Desert Plants 4:169-179.

Buechner, H. K. 1960. The bighorn sheep in the United States, its past, present, and future. Wildlife Monographs 4:1-174.

Bunnell, F. L. 1982. The lambing period of mountain sheep: synthesis, hypotheses, and tests. Canadian Journal of Zoology 60:1-14.

Byers, J. A. 1997. Mortality risk to young pronghorns from handling. Journal of Mammalogy 78:894-899.

Carl, G. C., and C. T. Robbins. 1988. The energetic cost of predator avoidance in neonatal ungulates: hiding versus following. Canadian Journal of Zoology 66:239-246.

DeForge, J. R., D. A. Jessup, and C. W. Jenner. 1982. Disease investigations into high lamb mortality of desert bighorn in the Santa Rosa Mountains, California. Desert Bighorn Council Transactions 26:76-81.

DeForge, J. R., and J. E. Scott. 1982. Ecological investigations into high lamb mortality. Desert Bighorn Council Transactions 26:65-76.

Douglas, C. L., and D. M. Leslie, JR. 1986. Influence of weather and density on lamb survival of desert mountain sheep. Journal of Wildlife Management 50:153-156.

Dunn, W. C. 1991. Evaluation of desert bighorn sheep habitat in New Mexico: final report. New Mexico Department of Game and Fish, Santa Fe, New Mexico, USA.

Dunn, W. C. 1994. Evaluation of desert bighorn sheep habitat in New Mexico: a revision of the final report. New Mexico Department of Game and Fish, Santa Fe, New Mexico, USA.

Etchberger, R. C., and P. R. Krausman. 1999. Frequency of birth and lambing sites of a small population of mountain sheep. Southwetern Naturalist 44:354-360.

Festa-Bianchet, M. 1988. Birthdate and survival in bighorn lambs (Ovis canadensis). Journal of Zoology 214:653-661.

Firchow, K. M., M. R. Vaughan, and W. R. Mytton. 1986. Evaluation of the hand-held net gun for capturing pronghorns. Journal of Wildlife Management 50:320-322.

Fisher, A., E. Rominger, P. Miller, and O. Byers. 1999. Population and habitat viability assessment workshop for the desert bighorn sheep of New Mexico (Ovis canadensis): final report. IUCN/SSC Conservation Breeding Specialist Group, Apple Valley, Minnesota, USA.

Franklin, W. L., and W. E. Johnson. 1994. Hand capture of newborn open-habitat ungulates: the south american guanaco. Wildlife Society Bulletin 22:253-259.

Frey, J. K. 1999. Native mammals of the Fra Cristobal Mountains, Sierra County, New Mexico. Turner Biodiversity Division, Truth or Consequences, New Mexico, USA.

Garrott, R. A., R. M. Bartmann, and G. C. White. 1985. Comparison of radio-transmitter Packages relative to deer fawn mortality. Journal of Wildlife Management 49:758-759

Goldstein, E. 2001. Proximate and ultimate causes of rocky mountain bighorn lamb mortality in Custer State Park, South Dakota. Thesis, University of Washington, Seattle, Washington, USA.

Hansen, C. G. 1980. Population dynamics. Pages 217-235 *in* G. Monson and L. Sumner, editors. The Desert Bighorn. University of Arizona Press, Tucson, Arizona, USA.

Hansen, C. G., and O. V. Deming. 1980. Growth and development. Pages 152-171 *in* G. Monson and L. Sumner, editors. The Desert Bighorn. University of Arizona Press, Tucson, Arizona, USA.

Hass, C. C. 1989. Bighorn lamb mortality: predation, inbreeding, and population effects. Canadian Journal of Zoology 67:699-705.

Jessup, D. A. 1992. On capturing bighorn sheep. Journal of Wildlife Diseases 28:512-513.

Jorgenson, J. T., J. Samson, & M. Festa-Bianchet. 1990. Field immobilization of bighorn sheep with xylazine hydrochloride and antagonism with idazoxan. Journal of Wildlife Diseases 26:522-527.

Jorgenson, J. T., J. Samson, & M. Festa-Bianchet. 1991. Capturing and tagging free-ranging bighorn sheep. Journal of Wildlife Diseases 27:733-734.

Kock, M. D. 1991. On the use of xylazine for field immobilization of bighorn sheep. Journal of Wildlife Diseases 27:731-732.

Kock, M. D., R. K. Clark, C. E. Franti, D. A. Jessup, & J. D. Wehausen. 1987. Effects of capture on biological parameters in free-ranging bighorn sheep (Ovis canadensis): evaluation of normal, stressed, and mortality outcomes and documentation of postcapture survival. Journal of Wildlife Diseases 23:652-662.

Kock, M. D., D. A. Jessup, R. K. Clark, & C. E. Franti. 1987. Effects of capture on biological parameters in free-ranging bighorn sheep (Ovis canadensis): evaluation of drop-net, drive-net, chemical immobilization and the net-gun. Journal of Wildlife Diseases 23:641-651.

Kock, M. D., D. A. Jessup, R. K. Clark, C. E. Franti, and R. A. Weaver. 1987. Capture methods in five subspecies of free-ranging bighorn sheep: an evaluation of drop-net, drive-net, chemical immobilization and the net-gun. Journal of Wildlife Diseases 23:634-640.

Krausman, P. R. 2000. An introduction to the restoration of bighorn sheep. Restoration Ecology 8:3-4.

Krausman, P. R., P. D. Bangs, K. E. Kunkel, M. K. Phillips, Z. D. Parsons, and E. M. Rominger. 2001. Mountain sheep restoration through private/public partnership. Pages 231-242 *in*

D. S. Maehr et al., editors. Large mammal restoration: ecological and sociological challenges in the 21st century. Island Press, Washington, D.C., USA.

Krausman, P. R., R. C. Etchberger, and R. M. Lee. 1993. Persistence of mountain sheep. Conservation Biology 7:219.

Krausman, P. R., and J. J. Hervert. 1983. Mountain sheep responses to aerial surveys. Wildlife Society Bulletin 11:372-375.

Krausman, P. R., J. J. Hervert, and L. L. Ordway. 1985. Capturing deer and mountain sheep with a net-gun. Wildlife Society Bulletin 13:71-73.

Krausman, P. R., B. D. Leopold, R. F. Seegmiller, and S. G. Torres. 1989. Relationships between desert bighorn sheep and habitat in western Arizona. Wildlife Monographs 102:1-66.

Krausman, P. R., A. V. Sandoval, and R. C. Etchberger. 1999. Natural history of desert bighorn sheep. Pages 139-191 *in* R. Valdez and P. R. Krausman, editors. Mountain sheep of North America. University of Arizona Press, Tucson, Arizona, USA.

Krausman, P. R. and D. M. Shackleton. 2000. Bighorn sheep. Pages 517-544 *in* S. Demarais and P. R. Krausman, editors. Ecology and Management of Large Mammals in North America. Prentice Hall, Upper Saddle River, New Jersey, USA.

Kunkel, K. E., and L. D. Mech. 1994. Wolf and bear predation on white-tailed deer fawns in northeastern Minnesota. Canadian Journal of Zoology 72:1557-1565.

Lent, P. C. 1974. Mother-infant relationships in ungulates. Pages 14-55 *in* V. Geist et al., editors. The behavior of ungulates and its relation to management. IUCN Publications, Calgary, Alberta, Canada.

Livezey, K. B. 1990. Toward the reduction of marking-induced abandonment of newborn ungulates. Wildlife Society Bulletin 18:193-203.

Miller, M. E. 1999. Vegetation of the Fra Cristobal Range, Southern New Mexico. Turner Biodiversity Division, Truth or Consequences, New Mexico, USA.

Miller, G. & E. L. Smith. 1985. Human activity in desert bighorn habitat: what disturbs sheep? Desert Bighorn Council Transactions 29:4-7.

Nelson, E. P. 1986. Geology of the Fra Cristobal Range, south-central New Mexico. New Mexico Geology Society Guide 37:83-91.

Nette, T., D. Burles, and M. Hoefs. 1984. Observations of golden eagle, Aquila chrysaetos, predation on dall sheep, Ovis dalli dalli, lambs. Canadian Field-Naturalist 98:252-254.

New Mexico Department of Game and Fish. 1995. New Mexico’s long-range plan for desert bighorn sheep management, 1995-2000. New Mexico Department of Game and Fish, Santa Fe, New Mexico, USA.

New Mexico Department of Game and Fish. 2003. Plan for the recovery of desert bighorn sheep in New Mexico, 2003-2013. New Mexico Department of Game and Fish, Santa Fe, New Mexico, USA.

Olson, K. A., T. K. Fuller, G. B. Schaller, B. Lhagvasuren, and D. Odonkhuu. 2005. Reproduction, neonatal weights, and first-year survival of Mongolian gazelles (*Procapra gutturosa*). Journal of Zoology, London 265:227-233.

Pitzman, M. S. 1970. Birth behavior and lamb survival in mountain sheep in Alaska. Thesis, University Of Alaska, Fairbanks, Alaska, USA.

Rubin, E. S., W. M. Boyce, and V. C. Bleich. 2000. Reproductive strategies of desert bighorn sheep. Journal of Mammalogy 81:769-786.

Sandoval, A. V. 1979. Preferred habitat of desert bighorn sheep in the San Andreas Mountains, New Mexico. Thesis, Colorado State University, Fort Collins, Colorado, USA.

Scotton, B. D. 1998. Timing and causes of neonatal dall sheep mortality in the central Alaska range. Thesis, University of Montana, Missoula, Montana, USA.

Scotton, B. D., and D. H. Pletscher. 1998. Evaluation of a capture technique for neonatal Dall sheep. Wildlife Society Bulletin 26:578-583.

Singer, F. J., C. M. Papouchis, and K. K. Symonds. 2000. Translocations as a tool for restoring populations of bighorn sheep. Resoration Ecology 8:6-13.

Stockwell, C. A., G. C. Bateman, and J. Berger. 1991. Conflicts in National Parks: a case study of helicopters and bighorn sheep time budgets at the Grand Canyon. Biological Conservation 56:317-328.

Thompson, R. W., and J. C. Turner. 1982. Temporal geographic variation in the lambing season of bighorn sheep. Canadian Journal of Zoology 60:1781-1793.

Truett, J. C., T. Savage, and L. Vance. 1999. Breeding season birds of the Fra Cristobal Mountains, New Mexico. Turner Biodiversity Division, Truth or Consequences, New Mexico, USA.

Wehausen, J. D. 1999. Rapid extinction of mountain sheep populations revisited. Conservation Biology 13:378-384.

Associate editor:

Table 1. Results of number of desert bighorn sheep lambs captured by different techniques on the Fra Cristobal Mountains, New Mexico, USA during 2001 and 2002.

Year	Capture technique	*n*
2001	Ground by hand	6
	Helicopter (Hughes 500) by hand	4
	Helicopter (Hughes 500) by net-gun	4
2002	Helicopter (Bell 206 JetRanger) by net-gun	7
Total		21

Table 2. Results of pursuit and handling times (min) of desert bighorn sheep lambs captured by different techniques on the Fra Cristobal Mountains, New Mexico, USA during 2001 and 2002.

	Pursuit time			Handling time		
Capture technique	$\overline{X}$	SE	*n*	$\overline{X}$	SE	*n*
Ground by hand	5.0	2.10	6	5.8	0.75	6
Helicopter (Hughes 500) by hand	4.8	0.85	4	5.0	0.00	4
Helicopter (Hughes 500) by net-gun	5.0	0.82	4	5.0	0.58	4
Helicopter (Bell 206 JetRanger) by net-gun	3.4	1.25	5	6.4	0.75	5

15 December 2007
Zachary D. Parsons
Wildlife Biology Program
Department of Ecosystem and Conservation Sciences
University of Montana
Missoula, MT 59812
406/243-5272; Fax: 406/243-4557
zachary.parsons@umontana.edu

RH: Desert Bighorn Lamb Mortality • Parsons et al.

Cause Specific Mortality of Desert Bighorn Sheep Lambs

Zachary D. Parsons,[5] Wildlife Biology Program, Department of Ecosystem and Conservation Sciences, University of Montana, Missoula, MT 59812, USA

Daniel H. Pletscher, Wildlife Biology Program, Department of Ecosystem and Conservation Sciences, University of Montana, Missoula, MT 59812, USA

Kyran E. Kunkel,[6] Turner Endangered Species Fund, 1123 Research Drive, Bozeman, MT 59718, USA

Peter D. Bangs,[7] Wildlife Sciences, School of Natural Resources, University of Arizona, Tucson, AZ 85721, USA

Anthony L. Wright,[8] Hornocker Wildlife Institute/Wildlife Conservation Society, 2023 Stadium Drive, Suite 1A, Bozeman, MT 59715, USA

[5] E-mail: zachary.parsons@umontana.edu

[6] Present address: World Wildlife Fund, 1875 Gateway S., Gallatin Gateway, MT 59730, USA

[7] Present address: Division of Sport Fish, Alaska Department of Fish and Game, PO Box 110024, Juneau AK 99811, USA

[8] Present address: Utah Division of Wildlife Resources, 475 W. Price River Drive, Suite C, Price, Utah 84501, USA

ABSTRACT Anthropogenic factors such as hunting and diseases brought by domestic livestock caused declines in bighorn sheep (*Ovis canadensis*) distribution and abundance by the early 1900s. In New Mexico, all of the small, isolated populations of desert bighorn sheep (*Ovis canadensis mexicana*), a state endangered species, have been slow to increase or are declining. Low and variable lamb recruitment is one of the factors negatively affecting these population growth rates. No one has previously reported cause-specific mortality rates for desert bighorn lambs. We captured and radio-collared lambs during the spring lambing seasons of 2001 and 2002 to determine the causes, extent, and timing of desert bighorn sheep lamb mortality on the Fra Cristobal Mountains in south central New Mexico. We then monitored the lambs for mortality daily via radio telemetry, as well as visually monitoring ewe behavior indicative of lamb mortality. We examined carcass and site characteristics to determine cause of mortality. We found that the primary mortality agent of desert bighorn lambs was cougar (*Puma concolor*) predation, followed by golden eagle (*Aquila chrysaetos*) predation. Although 1 lamb died from pneumonia (*Pasturella multocida multocida b*), disease did not appear to be a critical factor affecting lamb recruitment. We suggest selective removal of cougars that become habitual sheep killers over the short term may be an appropriate management strategy to enhance the recovery of desert bighorn populations. Maintaining cougars that pose no apparent significant threat to sheep populations is also important.

KEY WORDS *Aquila chrysaetos*, cougar, desert bighorn sheep, eagle, lamb, mortality, New Mexico, *Ovis canadensis mexicana*, *Puma concolor*.

Present geographic distributions and abundance of bighorn sheep (*Ovis canadensis*) are considerably reduced (Krausman and Shackleton 2000) as compared to their wide distribution over western North America in the early 19th century (Buechner 1960). By the early 1900s, excessive hunting and competition with and diseases introduced by domestic livestock, combined with other anthropogenic factors, resulted in the extirpation of most populations (Krausman 2000). Bighorn sheep use remote mountainous habitat that occurs in a naturally fragmented distribution (Krausman et al. 1999).

Desert bighorn sheep (*Ovis canadensis mexicana*) likely inhabited most of the arid mountain ranges in central and southern New Mexico prior to the 1800s (New Mexico Department of Game and Fish [NMDGF] 1995). Documentation of their historic occurrence exists for 14 of these ranges. The reduction to 2 populations in the state by 1955 resulted in desert bighorn sheep being listed as a state endangered species in 1980. Restoration efforts by NMDGF included establishing a captive breeding population at the Red Rock Wildlife Area (RRWA) in southwestern New Mexico in 1972. This population has served as the source for translocations of desert bighorn sheep since 1979 to establish new populations, reestablish locally extinct populations, and augment existing populations. These efforts resulted in 8 desert bighorn sheep populations. Populations have declined (5 populations) or slowly increased (1 population) in all of these mountain ranges, and no animals have been observed in 2 of these ranges since 2000 during autumn helicopter surveys (NMDGF 2003). Management strategies that can improve performance of these populations are greatly needed.

Desert bighorn sheep must reach a threshold of 500 animals in 3 populations, each containing at least 100 individuals, to be removed from the state endangered species list. Restoration challenges include sensitivity to diseases and human disturbance, difficulty in colonizing new habitats, and inherently low rates of increase (Singer et al. 2000). Current threats to bighorn sheep populations are mortality due to cougar (*Puma concolor*) predation, increasing human development, competing public interests for land use, and habitat degradation from fire suppression and livestock overgrazing.

While population size and extinction probability has generated some debate, wildlife biologists agree that large populations of bighorn sheep are less vulnerable to extinction than small populations (Berger 1990, 1993, 1999; Krausman et al. 1993; Wehausen 1999). Small populations may require significant management intervention to persist. Fisher et al. (1999), using demographic sensitivity analysis on desert bighorn sheep populations in New Mexico, found that mortality rates among female lambs was the second most important factor influencing sheep population dynamics. Populations were most sensitive to ewe mortality. Small populations may therefore significantly benefit from factors that influence survival of ewes and lambs. Populations of bighorn sheep are typically subjected to high and variable lamb mortality (Bradley and Baker 1967, Hansen 1980, DeForge and Scott 1982, Douglas and Leslie 1986, Krausman et al. 1989). Information on the causes and extent of desert bighorn sheep lamb mortality may improve the accuracy and predictive ability of models, and guide conservation efforts for enhancing the restoration of the small populations of desert bighorn sheep in New Mexico.

Few radio telemetry studies have been conducted on bighorn sheep lambs (DeForge and Scott 1982, Nette et al. 1984, Festa-Bianchet 1988, Hass 1989, Etchberger and Krausman 1999). Most investigations into bighorn (*O. c.* spp.) lamb survival rely on annual aerial helicopter or aircraft flights, or ground observations (Woodard et al. 1974, Spraker and Hibler 1977, Berger 1982, Douglas and Leslie 1986, Douglas 2001). Scotton (1998) attributed most of the mortality of Dall sheep (*Ovis dalli*) lambs to predation by coyotes (*Canis latrans*), golden eagles (*Aquila chrysaetos)*, and wolves (*Canis lupus*). Hass (1989) found that coyotes likely accounted for most of the mortality of Rocky Mountain bighorn lambs (*O. c. canadensis*). Goldstein (2001) found that Rocky Mountain bighorn lambs died from cougar predation, disease (contagious ecthyma), accidental falls, and predation possibly by a bobcat (*Lynx rufus*). The only study that addressed desert bighorn sheep lambs (*O. c. mexicana*) was that of Etchberger and Krausman (1999) in Arizona. They captured and radio-collared 2 lambs and reported 2 lamb mortalities, 1 from a fall and the other from being stepped on by other bighorn. No studies on causes of desert bighorn sheep lamb mortality have been conducted in New Mexico.

Significant recent attention has been given to the issue of cougar predation of bighorn sheep. Recent increases in cougar predation may be responsible for bighorn sheep population declines in California, Arizona, and New Mexico (Wehausen 1996, Hayes et al. 2000, Kamler et al. 2002, Holl et al. 2004, Rominger et al. 2004). Population declines of the primary prey of cougars, mule deer (*Odocoileus hemionus*), may lead to increased predation on bighorn sheep (Hayes et al. 2000, Kamler et al. 2002, Holl et al. 2004). Cougars also kill domestic calves as alternate prey, and Rominger et al. (2004) hypothesized that this supports higher cougar populations during periods of mule deer decline. However, Polisar et al. (2003) found that cougars hunted selectively rather than opportunistically and preyed on livestock despite adequate natural prey. Cougar predation on bighorn as alternative prey may increase in areas where bighorn sheep and mule deer are sympatric (Schaefer et al. 2000, Hayes et al. 2000). The primary management strategy for sheep in New Mexico is cougar population reduction (NMDGF 2003). Whether such a strategy also enhances populations via lamb recruitment is unknown. The benefits of such a strategy may be even greater if cougars are a significant and additive predator on lambs. Benefits of cougar control then may further outweigh costs of this controversial strategy (Reiter et al. 1999).

Our objectives were to: 1) capture and radio-collar desert bighorn sheep lambs during the spring lambing seasons of 2001 and 2002; 2) determine the causes, extent, and timing of lamb mortality; and 3) determine whether characteristics of the lamb or dam affected lamb survival. We predicted that, similar to our findings for adult sheep (Kunkel et al. 2007a, b), cougars would be the primary source of mortality.

STUDY AREA

The Fra Cristobal Mountains (FCM) lie entirely within the privately-owned Armendaris Ranch, located approximately 32 km northeast of Truth or Consequences, Sierra County, New Mexico, USA (Krausman et al. 2001). The Jornada del Muerto basin lies to the east of the range, and the Rio Grande valley and Elephant Butte Reservoir lie to the west. The FCM are an east-tilted fault block characterized by horizontally layered limestone cliff steps and massive granite cliffs (Nelson 1986). Elevations range from 1,400 - 2,109 m. The range is approximately 5 km wide by 24 km long (105 km^2). The FCM are located near the Chihuahaun Desert's northernmost extent (Hunt 1974). Vegetation associations consist of desert scrub and desert grassland at lower elevations, montane scrub at higher elevations, and coniferous woodland near the summit (Miller 1999). Three perennial springs are located in the middle of the range < 0.75 km apart (Dunn 1991). Five water catchments capable of storing approximately 19,000 L were developed throughout the range in 1995 (Dunn 1994). Annual precipitation at Elephant Butte Dam averaged 23.6 cm (Bangs et al. 2005a, b). Approximately 68% of precipitation occurred during May through September (Brown 1982). Desert bighorn sheep carrying capacity of the range was estimated at 100 to 150 (NMDGF 2003). The FCM contain 22.7 km^2 of escape terrain and approximately 65 km^2 of suitable desert bighorn sheep habitat (Dunn 1994). Evidence of 2 recent wildfires suggested that a relatively frequent fire regime has existed on the FCM. Little evidence of domestic livestock herbivory was observed on the range, and no domestic sheep grazed within 50 km of the range. No historical evidence exists that desert bighorn sheep occupied the FCM. However, in 1907, 1 desert bighorn sheep ram was observed in the Caballo Mountains (25 km south of the FCM; Sandoval 1979), the FCM are in close proximity to the San Andres Mountains (55 km east of the FCM) with an extant population, and the FCM have good habitat quality, all of which suggest that their occurrence was probable. Potential predators of desert bighorn sheep which occur within the study area included cougars, bobcats, coyotes, and golden eagles (Frey 1999, Truett et al. 1999).

METHODS

NMDGF translocated 37 desert bighorn sheep from the RRWA to the FCM in October 1995. All sheep (24 females, 13 males) were fitted with VHF telemetry collars with mortality sensors (Model 500, Telonics, Mesa, Arizona, USA). The herd was augmented with an additional translocation of 7 radio-collared rams from the RRWA in 1997. We used a helicopter and net-gun technique described by Krausman et al. (1985) to capture and radio-collar 16 females in November 1999; 9 of these females were radio-collared previously. We monitored radio-collared ewes via radio-telemetry and direct observation on a near daily basis for movement patterns indicative of parturition, and for the presence of newborn lambs during the spring lambing periods of 2001 (January through May) and 2002 (December through May). We believe 27 ewes in 2001 and 26 in 2002 were capable of reproducing. Fourteen radio-collared ewes were present in the FCM herd in 2001 and 13 in 2002. Un-collared ewes were difficult to monitor, especially when they left groups for parturition; however, we observed un-collared individuals when with groups containing collared individuals or when otherwise incidentally visually detected.

We attempted to capture newborn lambs by hand on the ground if the lamb was ≤3 days old, and the lamb and dam were in an area where we could attempt an approach. Handlers stalked the ewe and lamb, and when the ewe fled this perceived threat, lambs would either hide or attempt to flee. After a short search or chase, lambs were manually restrained by hand. We assembled a helicopter and capture crew once a sufficient number of newborn lambs were observed that were too old and mobile for hand capture, but old enough to minimize risk of physical trauma. A Hughes 500 helicopter was used in 2001 and a Bell 206 JetRanger was used in 2002. If a lamb became separated from a group and subsequently tried to hide against a sheer rock face or boulder, handlers exited the helicopter and attempted to restrain it by hand. Alternately, if a fleeing lamb became separated from the group, a capture using a hand-held or skid-mounted net-gun fired from the helicopter was attempted.

We blindfolded captured lambs while we handled them, minimized scent transfer from handlers to lambs by wearing latex gloves during handling, and minimized the amount and duration of contact (to generally < 5 minutes). We radio-collared, sexed, and weighed the lamb and recorded the date, capture method, and location for each lamb. We collected ear swabs and fecal samples for disease monitoring. Fecal samples were examined by veterinary laboratory technicians through direct smear or fecal flotation. Ear swabs were also examined directly through a dissecting microscope or from direct smear. We determined dam identity and age when possible. We compared lamb birth date and capture date to determine age at capture.

All radio-collar signals were monitored for mortality on a near daily basis from January through August, and less frequently from September through December of 2001 and 2002. We also attempted to find any carcasses of un-collared lambs by visual observation of ewes and their behaviors. When a mortality signal was received or a ewe exhibited behavior indicative of a lamb mortality, we located and examined the carcass and mortality site. We recorded the date, location, estimated time since death, and the identity of the lamb and its dam. We described the site, general appearance of carcass, carcass characteristics, probable cause of death, signs of struggle or chase at the site, the condition of lamb prior to death, and evidence of prior injuries or disease. Lambs were necropsied by a veterinarian and tested for disease when we were unsure of the cause of death. Predation was considered the cause of death when there was sign of a struggle at the site, subcutaneous hemorrhaging at wound sites, blood on the ground or vegetation, and/or track evidence on the ground. Evidence such as hair, feathers, tracks, scats, vomit, bedsites, toilets, scrapes, whether the carcass was buried, wounds on the carcass, and the parts of the carcass consumed were examined to determine the species of predator likely responsible for death (O'Gara 1978, Wade and Bowns 1982, Hatter 1984). These data were incorporated into a key to aid in evaluating and categorizing the type of predator involvement. We determined the number of radio days for radio-collared lambs by comparing capture dates and mortality or collar drop off dates.

We used program MICROMORT for estimating survival and cause specific mortality rates (Heisey and Fuller 1985). We used SPSS software version 13.0 for windows (Chicago, Illinois, USA) for statistical analysis. To compare differences in means, we used Student's *t*-test for independent samples, and when the assumption of equality of variances was violated, we used t values for which equal variances were not assumed. We performed a linear regression on capture age and mass by sex to estimate birth masses (males: y = 0.176x + 4.317, R^2 = 0.894, $P \leq$

0.001; females: y = 0.148x + 5.267, R^2 = 0.826, $P \leq 0.001$). For all statistical tests, significance levels were set at $P < 0.05$.

RESULTS

We visually detected lambs born (n = 47) from late December through late May during this study, with 64% of lambs born within the first 3 weeks of the lambing period in late December and early January (Figure 1). Lamb production was high during both years (Table 1). All radio-collared ewes were observed to have lambs, and only 3 un-collared mature adult ewes (11%) were observed without lambs in each of the years 2001 and 2002. We captured and radio-collared 14 lambs in 2001 and 7 in 2002. Mean capture age for all methods was 42 days (SE = 6.03, n = 21). Mean age for lambs captured on the ground was 1.5 days (SE = 0.34, n = 6), while mean age for lambs captured from helicopters was 58 days (SE = 2.83, n = 15).

We examined 11 lamb mortalities (Table 2). In 2001, of 14 radio-collared lambs, 7 died; we also discovered the carcass of an additional lamb by monitoring ewe behavior. None of the 7 lambs collared in 2002 died. We discovered 3 lamb carcasses due to ewe mortalities (n=2) and behavior (n=1) in which ewes that were previously seen with lambs would stand and/or search a small area over the course of a day or two, which we interpreted as indicative of having lost the lamb. Cougars killed 5 lambs (45% of mortalities) over both years, while eagles killed 3 (27%). One lamb was killed by an unknown predator, thus predation accounted for 82% of all known mortalities. One lamb died due to disease; the pneumonia strain involved was isolated and identified as *P. multocida multocida b.* One lamb died due to trauma; we believe it was butted by a ram. The fecal sample for this lamb collected at capture tested positive for the intestinal parasite coccidia (*Eimeria* sp.). We did not observe any ova in the other intestinal parasite examinations, and we found no indications of parasites or infectious diseases during the other lamb necropsies or ear swab examinations.

The annual survival rate was 0.37 for radio-collared lambs in 2001 (Table 3) and 1.00 for radio-collared lambs in 2002; the cougar caused mortality rate was 0.18. Surviving lambs were similar in birth mass to lambs that died (t = -1.08, df = 18, P = 0.294; Table 4). The age of dams of surviving lambs was also similar to those of dying lambs (t = 0.19, df = 17, P = 0.856). However, surviving lambs were born significantly earlier than dying lambs (t = -2.63, df = 23, P = 0.015). We did not find an interaction between lamb birth date and the estimated mass of lambs at birth (Figure 2).

Age of lambs at death ranged from 2 days to almost 6 months; however 36% occurred within the first week of life (Figure 3). Two un-collared lambs disappeared during 2001, and 1 disappeared in 2002; the causes of these mortalities were unknown. Recruitment was higher in 2002 than in 2001. In 2001, 50% of collared lambs and 70% of un-collared were recruited, while in 2002, 100% of collared and 75% of un-collard were recruited.

DISCUSSION

We captured and radio-collared 58% of the 2001 lamb population and 30% of the 2002 population and believe our results are representative of this population. While lamb production was high, our estimates should be viewed as minimum values because lambs may have been born and died before being seen by observers. However, only 3 un-collared ewes were not observed with lambs each year; we don’t know if these ewes did not produce lambs, or if the lambs were killed before detection. Thus, there was a maximum of 3 mortalities of young lambs each year for which the cause may have been unknown. Similarly, we observed 3 lambs (2001: n = 2, 2002: n = 1) that we were unable to capture that subsequently went missing; these were the only lambs that we know died for which we could not attempt to determine the cause. While radio-collaring lambs was instrumental in finding lamb mortalities, by closely observing ewes and their behaviors we increased lamb mortalities examined by 36%. Lamb recruitment to 1 year on the FCM for the past 5 years since release has ranged from 13 – 81%, and averaged 45.6% (Kunkel et al. 2007b); thus since 58 and 83% of lambs were recruited in 2001 and 2002 respectively, lamb recruitment was above average during our study. While bighorn lamb survival is extremely variable, typical or average survival is roughly 50% (Hass 1989).

Cougars were the largest cause of lamb mortality in the FCM in 2001 and 2002, and cougar predation was the primary proximate factor limiting lamb recruitment. Because this is similar to our findings for adults, management directed at cougars will likely benefit both survival and recruitment rates in sheep. Goldstein (2001) also found cougars were the largest cause of Rocky Mountain bighorn sheep lambs in South Dakota. Most cougars do not prey on bighorn sheep, however, some individuals develop a learned behavior for successful predation on bighorn (Ross et al. 1997, Kamler et al. 2002, Mooring et al. 2004). Selective removal of offending cougars that have killed bighorn sheep is more efficient than prophylactic measures such as indiscriminate cougar control which results in killing cougars that don't necessarily prey on sheep (Ernest et al. 2002, Mooring et al. 2004). Festa-Bianchet et al. (2006) found that each of 3 bighorn populations experienced cougar predation leading to declines, and that population extinction can be caused cougars that specialize on bighorn. They believed that predator-prey equilibria are unlikely given habitat fragmentation and may only occur at large geographic and temporal scales. However, others have suggested that the time lag may be short term (< 10 years) for cougar populations to decline following mule deer population declines (Kamler et al. 2002). Thus, for small populations of bighorn sheep in immediate danger of extirpation due to cougar predation, short-term cougar removal may be needed to prevent declines (Ernest et al. 2002, Kamler et al. 2002).

Golden eagles were the second largest lamb mortality agent during our study. Scotton (1998) found that eagles also killed Dall sheep lambs in Alaska. DeForge and Scott (1982) observed eagles in peninsular bighorn range in California but did not observe eagle caused lamb deaths. Also, 1 anecdotal account described a golden eagle killing a desert bighorn sheep lamb (*O. c. mexicana*) in New Mexico (Kennedy 1948). While we did not observe any coyote predation on lambs, coyotes were the primary mortality agent of Dall (Scotton 1998) and Rocky Mountain bighorn (Hass 1989) lambs. Hass (1989) reported that her study area in Montana was probably not historic sheep habitat and may have lacked sufficient precipitous escape terrain for coyote avoidance. Bobcats did not kill desert bighorn sheep lambs on the FCM during our study. Although deaths from falls have been documented (Brundige 1987, Etchberger and Krausman 1999) we did not find any lambs that died from falls.

While some researchers have suggested density may affect lamb survival (Douglas and Leslie 1986, Portier et al. 1998), density is likely not a factor limiting the population we studied because the number of individual bighorn was estimated at approximately 60 to 70 during the time of the study and NMDGF (2003) suggested this mountain range was capable of supporting 100 to 150 individuals. Dunn (1994), however, estimated carrying capacity to be 30-50 sheep on the FCM. None of the lambs killed by predators appeared to be in poor nutritional condition. Therefore, cougar predation appeared to be additive rather than compensatory to other causes of mortality.

Goldstein (2001) identified lambs that died from disease, namely contagious ecthyma. Deforge et al. (1982) stated contagious ecthyma may have been an initiating factor to the pneumonia killing lambs. The pneumonia strain we isolated from the lamb mortality attributed to disease has been isolated from other apparently healthy bighorn populations, but has also been isolated from Rocky Mountain bighorn in 2 all-age die-offs, one of which was followed by high lamb mortality during the next 3 years (Spraker et al. 1984). Monello et al. (2001) reported dramatic reductions in abundance of lambs following a pneumonia outbreak, but that density dependent factors contributed to vulnerability of bighorn sheep herds. Singer et al. (2000) postulated that pneumonia outbreaks are the single greatest obstacle to bighorn sheep restoration, and modeling simulations of population dynamics showed the highest priority for improving bighorn sheep population restoration success was reducing frequency or severity of disease (Gross et al. 2000). One lamb tested positive for coccidians; no signs of coccidiosis were observed prior to death and the necropsy of the carcass showed good nutritional condition as evidenced by adequate body fat. However, coccidiosis is not uncommon and can cause diarrhea, malabsorption of nutrients, thin animals, and sometimes death in most species; generally it affects young animals.

The primary factor related to lamb mortality was date of birth. We speculate that the reason surviving lambs were found to have been born earlier than dying lambs on average was that the majority of lambs were born early in the lambing season during this study. Testa (2002) speculated that predators may alter searching behaviors in response to the presence of newborn offspring as vulnerable prey, and that early born individuals would have an advantage by being first to develop mobility necessary for predator evasion. Rubin (2000) and Festa-Bianchet (1988) also found that bighorn lambs born earlier had greater survival than those born later.

While there was a significant range in the ages of lambs at death, observational data for this herd showed lambs dying from 1 to 12 weeks of age and averaging 4.9 weeks at death during the 2 years prior to this study, 1999 and 2000; 4 lambs went missing within their first week in 2000 (Kunkel et al. 2007b). Other studies have similarly shown young lambs have the highest mortality rates. Harper (1984) reported 60% of lamb mortality occurred within the first 3 weeks postpartum. Lambing periods of bighorn sheep at more southern latitudes begin earlier and last longer than those at higher latitudes (Bunnell 1982, Thompson and Turner 1980, Hass 1997). This may be in response to unpredictable vegetation growth patterns in desert habitats due to erratic precipitation.

Large carnivores are important to ecosystem health by contributing to species diversity and influencing ecosystem structure and function (Miller et al. 2001). Top predators such as cougars probably reduce the number of mesopredators such as coyotes, which may reduce this potential cause of lamb mortality. Indeed, predator removal can lead to decreased species richness and diversity and increased microherbivore density and mesopredator abundance, demonstrating faunal community structure influenced by a keystone predator (Henke and Bryant 1999). Predation can serve an important role in reducing disease among prey populations. Through trophic cascades, cougar declines can affect vegetation structure and terrestrial and aquatic species abundance (Ripple and Beschta 2006). Appropriate cougar management should be implemented on a regional scale (Sweanor et al. 2000). Ernest et al. (2002) strongly recommended assessment of effects of predator control in removal of cougars to restore bighorn populations in danger of extinction so that conservation of 1 species does not imperil another.

The role of precipitation as a possible ultimate limiting factor of desert bighorn sheep mortality should be investigated. In xeric desert environments, erratic precipitation and its influence on available forage and thus dam nutritional status and fitness, and lamb health and vulnerability to predation should not be overlooked, especially with changing future climatic conditions. Several studies have examined the effect of weather on survival of bighorn sheep lambs and correlated survival with precipitation during various periods of the year (Douglas and Leslie 1986, Portier et al. 1998, Douglas 2001). Enk et al. (2001) demonstrated a correlation between summer climatic conditions and lamb production and survival, and that forage nutritional quality influenced susceptibility to disease as well as herd productivity. Rubin et al. (2000) found that the ultimate factors affecting the breeding season of bighorn sheep were climate patterns. Some have found an affect of precipitation on bighorn lamb survival independent of population density (Portier et al. 1998). However, precipitation, through forage quality and quantity, limited a population of desert bighorn sheep in New Mexico by affecting production or survival of lambs in a density dependent manner (Bender and Weisenberger 2005).

MANAGEMENT IMPLICATIONS

Although bobcats and coyotes have been observed within bighorn habitat, they were not major predators of desert bighorn sheep lambs on the FCM during our study and controlling these predators on other bighorn ranges in New Mexico may not help increase bighorn populations. Lethal control of coyotes is a widespread technique used for reducing depredations on domestic sheep, and Blejwas et al. (2002) showed selectively removing breeding coyotes reduced or eliminated domestic lamb losses. Managers should be aware of the potential for coccidia and pneumonia in populations of bighorn sheep in New Mexico, however, as ewe vaccinations following pneumonia epidemics did not increase neonatal survival and population recovery in Rocky Mountain bighorn in the northwest (Cassirer et al. 2001), current veterinary methods may not be effective in treating this potential problem. Cougars were the primary mortality cause in adults and lambs on the FCM in 2001 and 2002; therefore selective control of cougars that specialize on bighorn sheep may be an effective management tool for increasing growth rates of the small populations of desert bighorn sheep in New Mexico. Such evidence is important given the controversial nature of cougar control and the social and ecological costs.

ACKNOWLEDGMENTS

We thank J. Anderson, G. Brennan, K. Eulinger, K. Foresman, E. Goldstein, R. Guty, K. Honness, D. Hunter, D. Klinka, P. Krausman, J. Mabe, M. Phillips, H. Provencio, E. Rominger, J. Thomas, R. B. Turner, R. E. Turner, D. Verhelst, T. Waddell, D. Wayne, D. Weybright, A. Whitelaw, and H. Whitlow. We also thank J. Olson and R. Small, in memoriam. Contributing organizations included the Boone and Crockett Wildlife Conservation Program, Foundation for North American Wild Sheep, National Fish and Wildlife Foundation, New Mexico Department of Game and Fish, New Mexico Ranch Properties Incorporated, Turner Endangered Species Fund, and the University of Montana.

LITERATURE CITED

Bangs, P. D., P. R. Krausman, K. E. Kunkel, and Z. D. Parsons. 2005. Habitat use by female desert bighorn sheep in the Fra Cristobal Mountains, New Mexico, USA. European Journal of Wildlife Research 51:77-83.

Bangs, P. D., P. R. Krausman, K. E. Kunkel, and Z. D. Parsons. 2005. Habitat use by desert bighorn sheep during lambing. European Journal of Wildlife Research 51:178-184.

Bender, L. C., and M. E. Weisenberger. 2005. Precipitation, density, and population dynamics of desert bighorn sheep on San Andres National Wildlife Refuge, New Mexico. Wildlife Society Bulletin 33:956-964.

Berger, J. 1982. Female breeding age and lamb survival in desert bighorn sheep (Ovis Canadensis). Mammalia 46:183-190.

Berger, J. 1990. Persistence of different-sized populations: an empirical assessment of rapid extinctions in bighorn sheep. Conservation Biology 4:91-98.

Berger, J. 1993. Persistence of mountain sheep: methods and statistics. Conservation Biology 7:219-220.

Berger, J. 1999. Intervention and persistence in small populations of bighorn sheep. Conservation Biology 13:432-435.

Blejwas, K. M., B. N. Sacks, M. M. Jaeger, and D. R. McCullough. 2002. The effectiveness of selective removal of breeding coyotes in reducing sheep predation. Journal of Wildlife Management 66:451-462.

Bradley, W. G., and D. P. Baker. 1967. Life tables for nelson bighorn sheep on the desert game refuge. Desert Bighorn Council Transactions 3:142-170.

Brown, D. E. 1982. Chihuahuan desertscrub. Desert Plants 4:169-179.

Brundige, G. 1987. Fatal fall by bighorn lamb. Journal of Mammalogy 68:423-425.

Buechner, H. K. 1960. The bighorn sheep in the United States, its past, present, and future. Wildlife Monographs 4:1-174.

Bunnell, F. L. 1982. The lambing period of mountain sheep: synthesis, hypotheses, and tests. Canadian Journal of Zoology 60:1-14.

Cassirer, E. F., K. M. Rudolph, P. Fowler, V. L. Coggins, D. L. Hunter, and M. W. Miller. 2001. Evaluation of ewe vaccination as a tool for increasing bighorn lamb survival following pasteurellosis epizootics. Journal of Wildlife Diseases 37(1):49-57.

DeForge, J. R., and J. E. Scott. 1982. Ecological investigations into high lamb mortality. Desert Bighorn Council Transactions 26:65-76.

DeForge, J. R., D. A. Jessup, and C. W. Jenner. 1982. Disease investigations into high lamb mortality of desert bighorn in the Santa Rosa Mountains, California. Desert Bighorn

Council Transactions 26:76-81.

Douglas, C. L. 2001. Weather, disease, and bighorn lamb survival during 23 years in Canyonlands National Park. Wildlife Society Bulletin 29:297-305.

Douglas, C. L., and D. M. Leslie, JR. 1986. Influence of weather and density on lamb survival of desert mountain sheep. Journal of Wildlife Management 50:153-156.

Dunn, W. C. 1991. Evaluation of desert bighorn sheep habitat in New Mexico: final report. New Mexico Department of Game and Fish, Santa Fe, New Mexico, USA.

Dunn, W. C. 1994. Evaluation of desert bighorn sheep habitat in New Mexico: a revision of the final report. New Mexico Department of Game and Fish, Santa Fe, New Mexico, USA.

Enk, T. A., H. D. Picton, and J. S. Williams. 2001. Factors limiting a bighorn sheep population in Montana following a dieoff. Northwest Science 75:280-291.

Ernest, H. B., E. S. Rubin, and W. M. Boyce. 2002. Fecal DNA analysis and risk assessment of mountain lion predation of bighorn sheep. Journal of Wildlife Management 66:75-85.

Etchberger, R. C., and P. R. Krausman. 1999. Frequency of birth and lambing sites of a small population of mountain sheep. Southwetern Naturalist 44:354-360.

Festa-Bianchet, M. 1988. Birthdate and survival in bighorn lambs (Ovis canadensis). Journal of Zoology 214:653-661.

Festa-Bianchet, M., T. Coulson, J. Gaillard, J. T. Hogg, and F. Pelletier. 2006. Stochastic predation events and population persistence in bighorn sheep. Proceedings of the Royal Society B 273:1537-1543.

Fisher, A., E. Rominger, P. Miller, and O. Byers. 1999. Population and habitat viability assessment workshop for the desert bighorn sheep of New Mexico (Ovis canadensis): final report. IUCN/SSC Conservation Breeding Specialist Group, Apple Valley, Minnesota, USA.

Frey, J. K. 1999. Native mammals of the Fra Cristobal Mountains, Sierra County, New Mexico. Turner Biodiversity Division, Truth or Consequences, New Mexico, USA.

Goldstein, E. 2001. Proximate and ultimate causes of rocky mountain bighorn lamb mortality in Custer State Park, South Dakota. Thesis, University of Washington, Seattle, Washington, USA.

Gross, J. E., F. J. Singer, and M. E. Ross. 2000. Effects of disease, dispersal, and area on bighorn sheep restoration. Restoration Ecology 8:25-37.

Hansen, C. G. 1980. Population dynamics. Pages 217-235 *in* G. Monson and L. Sumner, editors. The Desert Bighorn. University of Arizona Press, Tucson, Arizona, USA.

Harper, W. L. 1984. Pregnancy rate and the timing of lamb losses in California bighorn sheep in the Ashnola, B. C. Symposium of the Northern Wild Sheep and Goat Council 4:35-50.

Hass, C. C. 1989. Bighorn lamb mortality: predation, inbreeding, and population effects. Canadian Journal of Zoology 67:699-705.

Hass, C. C. 1997. Seasonality of births in bighorn sheep. Journal of Mammalogy 78:1251-1260.

Hatter, I. W. 1984. Effects of wolf predation on recruitment of black-tailed deer on Northeastern Vancouver Island. Thesis, University of Idaho, Moscow, Idaho, USA.

Hayes, C. L., E. S. Rubin, M. C. Jorgensen, R. A. Botta, and W. M. Boyce. 2000. Mountain lion predation of bighorn sheep in the Peninsular Ranges, California. Journal of Wildlife Management 64:954-959.

Heisey, D. M., and T. K. Fuller. 1985. Evaluation of survival and cause-specific mortality rates using telemetry data. Journal of Wildlife Management 49:668-674.

Henke, S. E., and F. C. Bryant. 1999. Effects of coyote removal on the faunal community in western Texas. Journal of Wildlife Management 63:1066-1081.

Holl, S. A., V. C. Bleich, and S. G. Torres. 2004. Population dynamics of bighorn sheep in the San Gabriel Mountains, California, 1967-2002. Wildlife Society Bulletin 32:412-426.

Hunt, C. B. 1974. Natural regions of the United States and Canada. W. H. Freeman, San Francisco, California, USA.

Kamler, J. F., R. M. Lee, J. C. deVos Jr., W. B. Ballard, and H. A. Whitlaw. 2002. Survival and cougar predation of translocated bighorn sheep in Arizona. Journal of Wildlife Management 66:1267-1272.

Kennedy, C. A. 1948. Goden eagle kills a bighorn lamb. Journal of Mammalogy 29:68-69.

Krausman, P. R. 2000. An introduction to the restoration of bighorn sheep. Restoration Ecology 8:3-4.

Krausman, P. R., P. D. Bangs, K. E. Kunkel, M. K. Phillips, Z. D. Parsons, and E. M. Rominger. 2001. Mountain sheep restoration through private/public partnership. Pages 231-242 *in* D. S. Maehr et al., editors. Large mammal restoration: ecological and sociological challenges in the 21st century. Island Press, Washington, D.C., USA.

Krausman, P. R., R. C. Etchberger, and R. M. Lee. 1993. Persistence of mountain sheep.

Conservation Biology 7:219.

Krausman, P. R., B. D. Leopold, R. F. Seegmiller, and S. G. Torres. 1989. Relationships between desert bighorn sheep and habitat in western Arizona. Wildlife Monographs 102:1-66.

Krausman, P. R., A. V. Sandoval, and R. C. Etchberger. 1999. Natural history of desert bighorn sheep. Pages 139-191 *in* R. Valdez and P. R. Krausman, editors. Mountain sheep of North America. University of Arizona Press, Tucson, Arizona, USA.

Krausman, P. R. and D. M. Shackleton. 2000. Bighorn sheep. Pages 517-544 *in* S. Demarais and P. R. Krausman, editors. Ecology and Management of Large Mammals in North America. Prentice Hall, Upper Saddle River, New Jersey, USA.

Kunkel, K. E., A. L. Wright, Z. D. Parsons, T. E. Waddell, H. X. Quigley, M. G. Hornocker, M. K. Phillips, R. X. Thompson, and P. D. Bangs. 2007. Cougars and desert bighorn sheep in the Fra Cristobal Range: adaptive management of predation. Journal of Wildlife Management in preparation.

Kunkel, K. E., Z. D. Parsons, P. D. Bangs, M. K. Phillips, R. X. Thompson, E. M. Rominger, and E. J. Goldstein. 2007. Dynamics of a reintroduced population of desert bighorn sheep in southern New Mexico. Journal of Wildlife Management in preparation.

Miller, M. E. 1999. Vegetation of the Fra Cristobal Range, Southern New Mexico. Turner Biodiversity Division, Truth or Consequences, New Mexico, USA.

Miller, B., B. Dugelby, D. Foreman, C. Martinez del Rio, R. Noss, M. Phillips, R. Reading, M. E. Soule, J. Terborgh, and L. Willcox. 2001. The importance of large carnivores to Healthy ecosystems. Endangered Species Update 18:202-210.

Monello, R. J., D. L. Murray, and E. F. Cassirer. 2001. Ecological correlates of pneumonia epizootics in bighorn sheep herds. Canadian Journal of Zoology 79:1423-1432.

Mooring, M. S., T. A. Fitzpatrick, T. T. Nishihira, and D. D. Reisig. 2004. Vigilance, predation risk, and the allee effect in desert bighorn sheep. Journal of Wildlife Management 68:519-532.

Nelson, E. P. 1986. Geology of the Fra Cristobal Range, south-central New Mexico. New Mexico Geology Society Guide 37:83-91.

Nette, T., D. Burles, and M. Hoefs. 1984. Observations of golden eagle, Aquila chrysaetos, predation on dall sheep, Ovis dalli dalli, lambs. Canadian Field-Naturalist 98:252-254.

New Mexico Department of Game and Fish. 1995. New Mexico’s long-range plan for desert bighorn sheep management, 1995-2000. New Mexico Department of Game and Fish, Santa Fe, New Mexico, USA.

New Mexico Department of Game and Fish. 2003. Plan for the recovery of desert bighorn sheep in New Mexico, 2003-2013. New Mexico Department of Game and Fish, Santa Fe, New Mexico, USA.

O’Gara, B. W. 1978. Differential characteristics of predator kills. Pages 380-393 *in* Proceedings of the 8th Biennial Pronghorn Antelope Workshop, Jasper, Alberta, Canada.

Polisar, J., I. Maxit, D. Scognamillo, L. Farrell, M. E. Sunquist, and J. F. Eisenberg. 2003. Jaguars, pumas, their prey base, and cattle ranching: ecological interpretations of a management problem. Biological Conservation 109:297-310.

Portier, C., M. Festa-Bianchet, J. M. Gaillard, J. T. Jorgenson, and N. G. Yoccoz. 1998. Effects of density and weather on survival of bighorn sheep lambs (*Ovis canadensis*). Journal of Zoology 245:271-278.

Ripple, W. J., and R. L. Beschta. 2006. Linking a cougar decline, trophic cascade, and catastrophic regime shift in Zion National Park. Biological Conservation 133:397-408.

Rominger, E. M., H. A. Whitlaw, D. L. Weybright, W. C. Dunn, and W. B. Ballard. 2004. The influence of mountain lion predation on bighorn sheep translocations. Journal of Wildlife Management 68:993-999.

Ross, P. I., M. G. Jalkotzy, and M. Festa-Bianchet. 1997. Cougar predation on bighorn sheep in southwestern Alberta during winter. Canadian Journal of Zoology 74:771-775.

Rubin, E. S., W. M. Boyce, and V. C. Bleich. 2000. Reproductive strategies of desert bighorn sheep. Journal of Mammalogy 81:769-786.

Sandoval, A. V. 1979. Preferred habitat of desert bighorn sheep in the San Andreas Mountains, New Mexico. Thesis, Colorado State University, Fort Collins, Colorado, USA.

Schaefer, R. L., S. G. Torres, and V. C. Bleich. 2000. Survivorship and cause-specific mortality in sympatric populations of mountain sheep and mule deer. California Game and Fish 86:127-135.

Scotton, B. D. 1998. Timing and causes of neonatal dall sheep mortality in the central Alaska range. Thesis, University of Montana, Missoula, Montana, USA.

Singer, F. J., C. M. Papouchis, and K. K. Symonds. 2000. Translocations as a tool for restoring populations of bighorn sheep. Resoration Ecology 8:6-13.

Singer, F. J., L. C. Zeigenfuss, and L. Spicer. 2001. Role of patch size, disease, and movement in rapid extinction of bighorn sheep. Conservation Biology 15:1347-1354.

Spraker, T. R. and C. P. Hibler. 1977. Summer lamb mortality of Rocky Mountain bighorn sheep. Desert Bighorn Council Transactions 21:11-12.

Spraker, T. R., C. P. Hibler, G. G. Schoonveld, and W. S. Adney. 1984. Pathologic changes and microorganisms found in bighorn sheep during a stress-related die-off. Journal of Wildlife Diseases 20:319-327.

Sweanor, L. L., K. A. Logan, and M. G. Hornocker. 2000. Cougar dispersal patterns, metapopulation dynamics, and conservation. Conservation Biology 14:798-808.

Testa, J. W. 2002. Does predation on neonates inherently select for earlier births? Journal of Mammalogy 83:699-706.

Thompson, R. W., and J. C. Turner. 1982. Temporal geographic variation in the lambing season of bighorn sheep. Canadian Journal of Zoology 60:1781-1793.

Truett, J. C., T. Savage, and L. Vance. 1999. Breeding season birds of the Fra Cristobal Mountains, New Mexico. Turner Biodiversity Division, Truth or Consequences, New Mexico, USA.

Wade, D. A., and J. E. Bowns. 1985. Procedures for evaluating predation on livestock and wildlife. Texas A&M University, San Angelo, Texas, USA.

Wehausen, J. D. 1996. Effects of mountain lion predation on bighorn sheep in the Sierra Nevada and Granite Mountains of California. Wildlife Society Bulletin 24:471-479.

Wehausen, J. D. 1999. Rapid extinction of mountain sheep populations revisited. Conservation Biology 13:378-384.

Woodard, T. N., R. J. Gutierrez, and W. H. Rutherford. 1974. Bighorn lamb production, survival, and mortality in south-central Colorado. Journal of Wildlife Management 38:771-774.

Associate editor:

Figure 1. Date of birth for desert bighorn sheep lambs on the Fra Cristobal Mountains, New Mexico, USA during 2001 and 2002.

Figure 2. Estimated birth date (x) and birth mass (y) for dying (●) and surviving (○) radio-collared desert bighorn sheep lambs in the Fra Cristobal Mountains, New Mexico, USA during 2001 and 2002 ($y = 2.356x + 10.397$, $R^2 = 0.026$, $P = 0.499$).

Figure 3. Age at death for desert bighorn sheep lambs on the Fra Cristobal Mountains, New Mexico, USA during 2001 and 2002.

Table 1. Visually observed production and recruitment to 1 year of desert bighorn sheep lambs on the Fra Cristobal Mountains, New Mexico, USA during 2001 and 2002.

Year	Ewes	Natality	Production	Mortality	Recruitment	Lambs : 100 Ewes
2001	27	24	89%	10	58%	52
2002	26	23	88%	4	83%	73

Table 2. Known causes of mortality for desert bighorn sheep lambs on the Fra Cristobal Mountains, New Mexico, USA during 2001 and 2002.

	Year		
Cause of death	2001	2002	Total
Cougar	3	2	5
Eagle	2	1	3
Unknown Predator	1	0	1
Disease	1	0	1
Trauma	1	0	1
Total	8	3	11

Table 3. Survival to 1 year and cause-specific mortality rate estimates of 7 radio-collared desert bighorn sheep lambs in the Fra Cristobal Mountains, New Mexico, USA for 2001.

			95% Confidence Limits	
Parameter	Estimate	Variance	Lower	Upper
Survival	0.367	0.019	0.175	0.771
Mortality				
Cougar	0.181	0.013	0.000	0.407
Eagle	0.181	0.013	0.000	0.407
Disease	0.090	0.007	0.000	0.259
Predator	0.090	0.007	0.000	0.259
Trauma	0.090	0.007	0.000	0.259

Table 4. Estimated birth mass (kg), dam age (yr), and birth date (Julian) of dying and surviving desert bighorn sheep lambs on the Fra Cristobal Mountains, New Mexico, USA during 2001 and 2002.

	Dying			Surviving				
	X	SE	n	X	SE	n	t	p
Birth mass	5.54	0.50	6	4.60	0.65	14	-1.08	0.294
Dam age	7.94	0.92	8	8.14	0.63	11	0.19	0.856
Birth date	33.09	8.86	11	9.57	3.84	14	-2.63	0.015

Figure 1

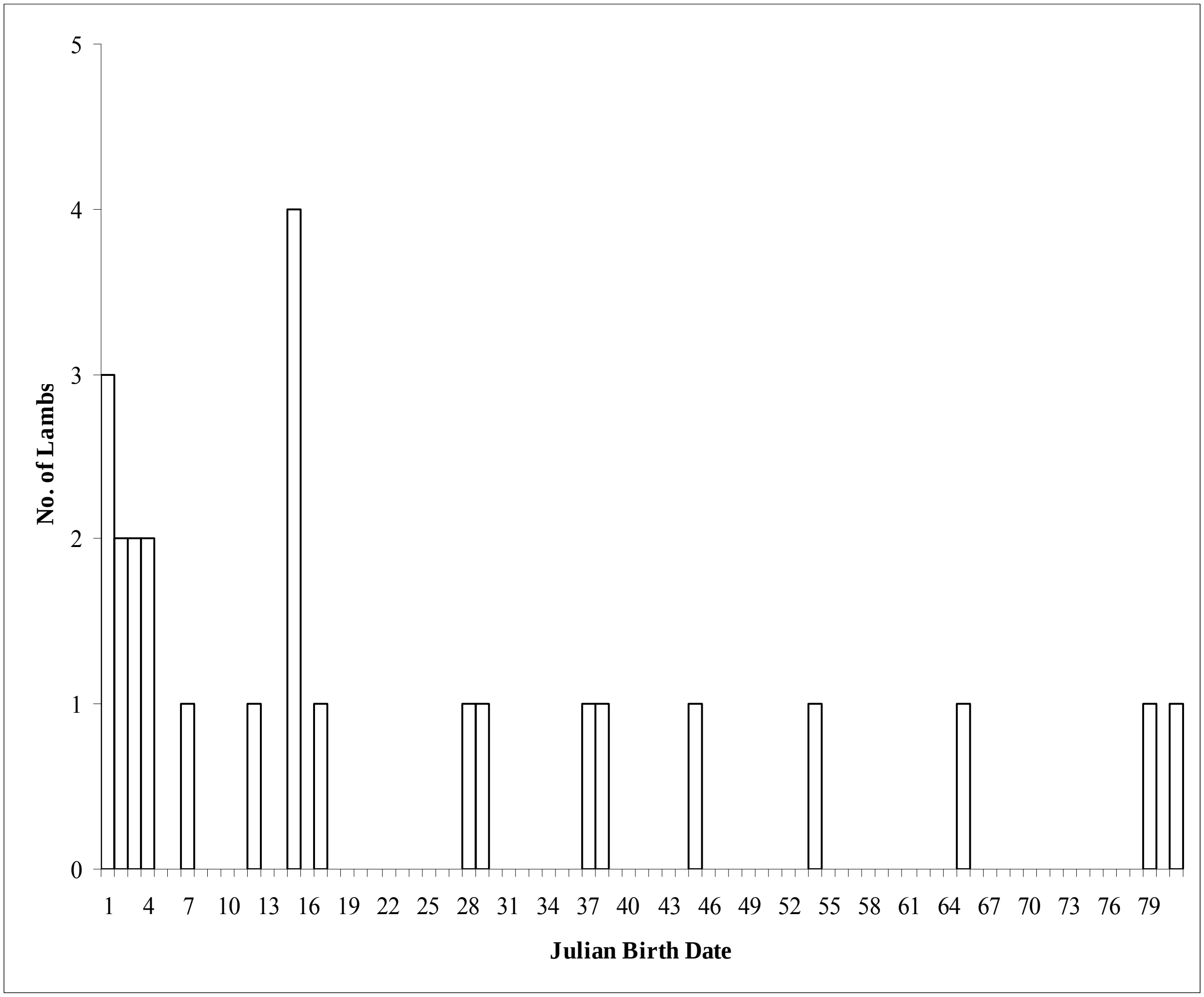

No. of Lambs
0
1
2
3
4
5
1 4 7 10 13 16 19 22 25 28 31 34 37 40 43 46 49 52 55 58 61 64 67 70 73 76 79
Julian Birth Date

Figure 2

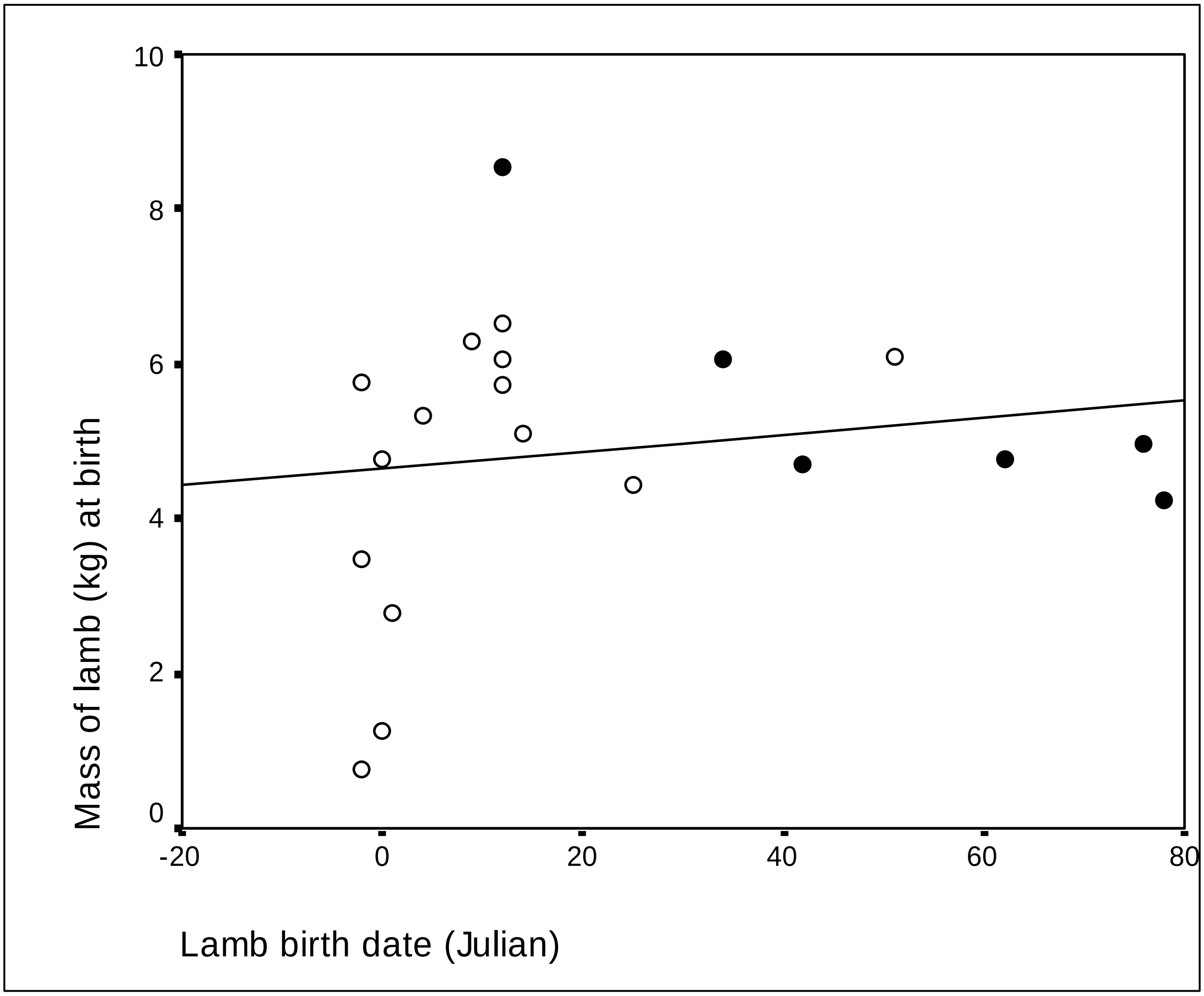
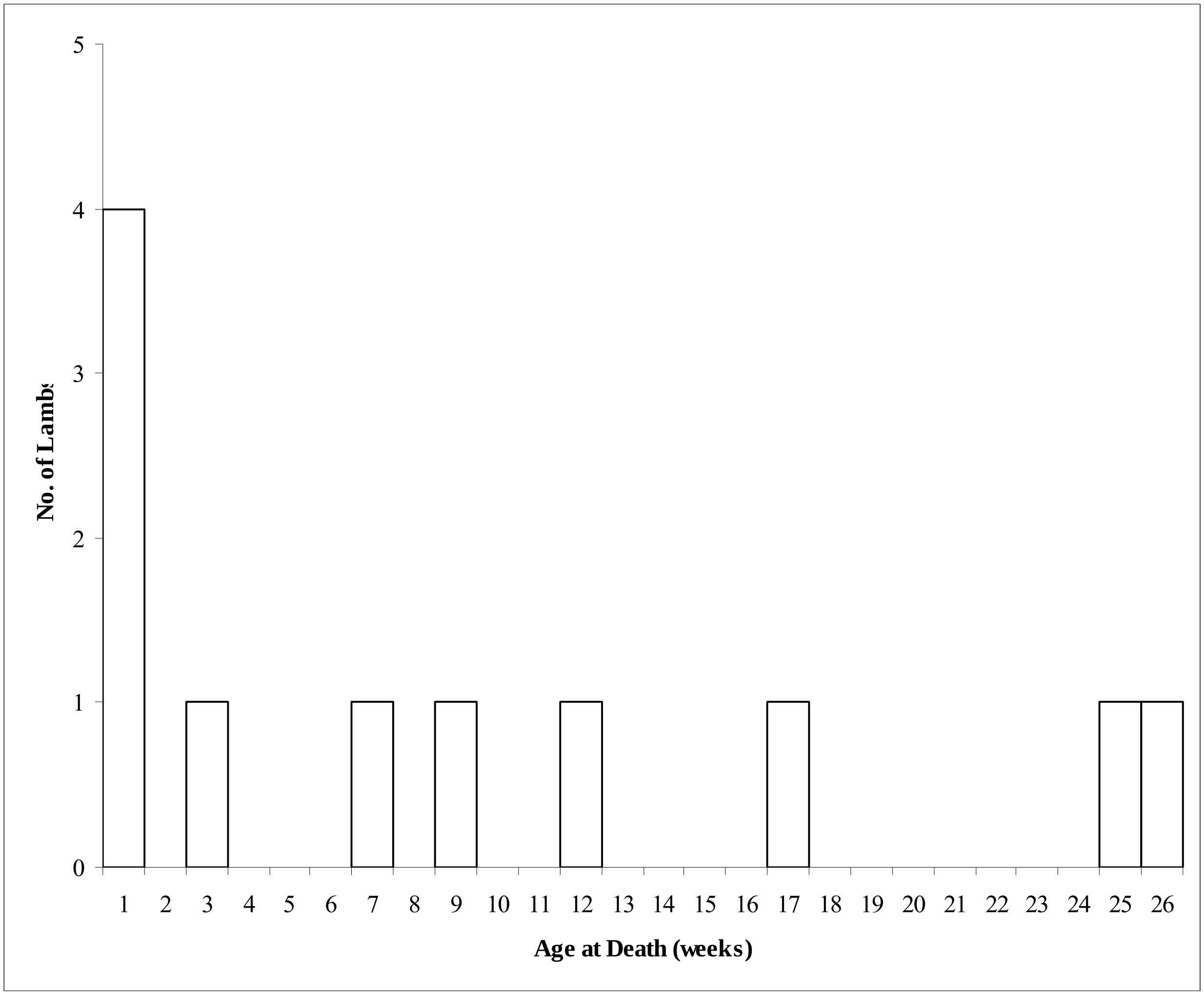

10
8
6
4
2
0
Mass of lamb (kg) at birth
-20
0
20
40
60
80
Lamb birth date (Julian)

Figure 3


5
4
3
2
1
0
No. of Lambs
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26
Age at Death (weeks)

15 December 2007
Zachary D. Parsons
Wildlife Biology Program
Department of Ecosystem and Conservation Sciences
University of Montana
Missoula, MT 59812
406/243-5272; Fax: 406/243-4557
zachary.parsons@umontana.edu

RH: Habitat at Cougar Predation Sites of Bighorn • Parsons et al.

Habitat Characteristics of Cougar Predation Sites on Desert Bighorn Sheep

Zachary D. Parsons,[9] Wildlife Biology Program, Department of Ecosystem and Conservation Sciences, University of Montana, Missoula, MT 59812, USA

Kyran E. Kunkel,[10] Turner Endangered Species Fund, 1123 Research Drive, Bozeman, MT 59718, USA

Daniel H. Pletscher, Wildlife Biology Program, Department of Ecosystem and Conservation Sciences, University of Montana, Missoula, MT 59812, USA

Peter D. Bangs,[11] Wildlife Sciences, School of Natural Resources, University of Arizona, Tucson, AZ 85721, USA

Anthony L. Wright,[12] Hornocker Wildlife Institute/Wildlife Conservation Society, 2023 Stadium Drive, Suite 1A, Bozeman, MT 59715, USA

---

[9] E-mail address: zachary.parsons@umontana.edu

[10] Present address: World Wildlife Fund, 1875 Gateway S., Gallatin Gateway, MT 59730, USA

[11] Present address: Division of Sport Fish, Alaska Department of Fish and Game, PO Box 110024, Juneau AK 99811, USA

[12] Present address: Utah Division of Wildlife Resources, 475 W. Price River Drive, Suite C, Price, Utah 84501, USA

ABSTRACT Bighorn sheep (*Ovis canadensis*) populations suffered declines in distribution and abundance by the early 1900s. Desert bighorn sheep (*Ovis canadensis mexicana*) were listed as an endangered species in New Mexico in 1980, and significant resources have been invested in captive breeding and translocations to restore populations. However, many of the small, isolated populations of desert bighorn have been slow to increase or are declining, and 1 of the factors affecting their population growth rates is high mortality due to cougar (*Puma concolor*) predation. Our objectives were to characterize habitat factors at all known desert bighorn sheep mortality sites due to cougar predation on the Fra Cristobal Mountains, New Mexico, USA. We monitored all translocated, radio-collared desert bighorn sheep, as well as additional augmented radio-collared rams, subsequently re-instrumented ewes, and radio-collared lambs for mortality signals, and examined carcass and site characteristics to determine the cause of mortality. We measured habitat characteristics at sites where bighorn where killed by cougars and the same characteristics at paired control sites. At a broader scale, we developed a geographic information system to derive habitat characteristics at predation sites, relocation sites representing used areas, and random sites representing available areas. Visibility was lower at predation sites than nearby control sites. Slope, elevation, and ruggedness were lower at predation sites than relocation sites, and predation sites were closer to water and roads than random sites. Wildlife managers should consider prescribed burning to reduce the encroachment of woody vegetation and increase visibility, and potentially increase available forage quantity and quality. Managers should also assess bighorn and cougar use of artificial water developments.

KEY WORDS cougar, desert bighorn sheep, habitat, mortality, New Mexico, *Ovis canadensis mexicana*, predation, *Puma concolor*.

In the early 19th century, bighorn sheep (*Ovis canadensis*) were widely distributed over western North America (Buechner 1960). Present distributions and abundances have been significantly reduced (Krausman and Shackleton 2000). A combination of anthropogenic factors including excessive hunting, and competition with and diseases introduced by domestic livestock, resulted in the extirpation of most populations by the early 1900s (Krausman 2000). Bighorn sheep habitat is naturally fragmented due to their use of isolated, precipitous mountain terrain (Krausman et al. 1999). The historic occurrence of desert bighorn sheep (*O. c. mexicana*) was documented in 14 ranges in central and southern New Mexico (New Mexico Department of Game and Fish [NMDGF] 1995). By 1955, only 2 populations remained and, in 1980, desert bighorn sheep were listed as an endangered species in New Mexico. In 1972, a captive breeding population was established at the Red Rock Wildlife Area (RRWA) north of Lordsburg, New Mexico. Between 1979 and 1999, translocations from the RRWA augmented existing desert bighorn sheep populations, re-established locally extinct populations, and established new populations. Translocations as a conservation and restoration tool have become widespread (Singer et al. 2000). These efforts resulted in 8 mountain ranges with desert bighorn sheep populations. The requirement for removal from the state endangered species list for desert bighorn sheep is a minimum of 500 free-ranging animals in at least 3 geographically distinct populations, each containing at least 100 individuals (NMDGF 2003). Challenges to desert bighorn sheep restoration include their inherently low rates of increase, difficulty in colonizing new habitats, and sensitivity to diseases and human disturbances. Threats to bighorn include predation, habitat degradation from livestock overgrazing and fire suppression, and competing public interests and increasing human pressure. Desert bighorn sheep populations have been slow to increase or are declining in all of these mountain ranges. Most populations have suffered significant mortality due to cougar predation (*Puma concolor*). No animals have been observed during autumn helicopter surveys in 2 of these ranges since 2000 (NMDGF 2003). While there has been debate over predicting extinction probabilities for populations of various sizes, researchers agree that small populations of bighorn sheep are more vulnerable to extinction than large populations (Berger 1990, 1993; Krausman et al. 1993; Goodson 1994; Wehausen 1999). Inverse density dependence may contribute to increased predation risk to small groups of bighorn sheep (Mooring et al. 2004).

Bighorn sheep and cougars have coexisted in the southwest for the past 10,000 years (Kelly 1980), along with other potential bighorn predators including bobcats (*Lynx rufus*), coyotes (*Canis latrans*), and golden eagles (*Aquila chrysaetos*). While the primary prey for cougars is mule deer (*Odocoileus hemionus*), cougars are known to prey on bighorn sheep, especially in areas where bighorn and deer are sympatric (Anderson 1983, Hayes et al. 2000, Schaefer et al. 2000). The decline of mule deer populations may contribute to more frequent bighorn predation by cougars (Kamler et al. 2002, Holl et al. 2004), and Rominger et al. (2004) speculated that domestic cattle predation subsidized cougar populations, preventing declines in cougar populations following declines in naturally occurring prey populations. Cougars have been the primary proximate cause of recent bighorn population declines from California to Arizona and New Mexico (Hayes et al. 2000, Kamler et al. 2002, Holl et al. 2004, Rominger et al. 2004, McKinney et al. 2006).

Many studies have been conducted on desert bighorn sheep habitat, however, no studies have examined the correlation between habitat and sheep mortality. In the absence of a naturally occurring fire regime, encroachment of trees and shrubs has reduced visibility in bighorn sheep habitat (Wakelyn 1987). This reduction of habitat visibility may increase predation risk to cougars, which are ambush predators (Rominger et al. 2004). Bighorn sheep increase their use of habitat in burned areas likely due to a combination of factors including increased forage as well as increased visibility (Bentz and Woodard 1988, Smith et al. 1999), and Smith et al. (1999) suggested that range burning may be an effective management tool to increase bighorn sheep populations.

Brown et al. (1999) and Laundre and Hernandez (2003) proposed that because cougars are an ambush predator adept at traveling and killing in rugged terrain, there may be very few places sheep are not vulnerable to cougars. Predation of desert bighorn sheep by cougars in New Mexico involved primarily desert bighorn sheep near escape terrain (Creeden and Graham 1997), consistent with the idea that escape terrain may provide limited benefit for avoidance of cougar predation (Sawyer and Lindzey 2002, Mooring et al. 2004). Cougars use steep, rugged topography in many ways similar to the same habitats used by sheep (Logan and Irwin 1985, Riley and Malecki 2001). Knowledge of habitat characteristics that may affect predation risk of bighorn sheep to cougars could improve habitat models, lead to specific range management strategies to improve desert bighorn sheep habitat quality, and enhance recovery of the small populations of desert bighorn sheep in New Mexico.

Our objective was to determine the role of habitat in desert bighorn sheep mortality by cougars. We predicted that habitat characteristics at sites where bighorn sheep were killed by cougars would differ from nearby control sites, relocation sites of bighorn sheep, and random sites within the home range of bighorn. We predicted that predation sites would be less steep, lower in elevation, less rugged, and have lower visibility than control, relocation, and random sites.

STUDY AREA

The Fra Cristobal Mountains (FCM) are located approximately 32 km northeast of Truth or Consequences in Sierra and Socorro Counties in south-central New Mexico, USA. The entire range lies within the privately-owned Armendaris Ranch (Krausman et al. 2001). The Rio Grande Valley and Elephant Butte Reservoir bound the range to the west, and the Jornada del Muerto Basin to the east. The FCM are an east-tilted horst block. The mountains are characterized by massive granite cliffs and horizontally layered limestone cliff steps (Nelson 1986). Elevations range from 1,400 - 2,109 m, and the range is approximately 5 km wide by 24 km long (105 km^2). The FCM are near the northernmost extent of the Chihuahaun Desert (Hunt 1974). Vegetation associations consist of a mosaic of desert scrub and desert grassland at lower elevations, patchy montane scrub at higher elevations typically between 1,850 and 1,950 m, and a limited amount of open coniferous woodland near the summit above 1,950 m (Miller 1999). Five apron water catchment units capable of storing ~19,000 L were developed in 1995 (Dunn 1991) to augment the 3 perennial springs located on the range. Approximately 68% of precipitation occurred during May through September (Brown 1982), and precipitation at Elephant Butte Dam averaged 23.6 cm annually (Bangs et al. 2005a, b). The carrying capacity of the range for bighorn was estimated at 100 to 150 individuals (NMDGF 2003). The FCM contain approximately 65 km^2 of suitable desert bighorn sheep habitat, with 22.7 km^2 of escape terrain (Dunn 1994). A relatively frequent fire regime has been suggested on the FCM due to evidence of 2 relatively recent wildfires (Miller 1999). No known domestic sheep herds occurred within 50 km of the range, and little evidence of domestic livestock herbivory was observed. Though their proximity to the San Andres Mountains (55 km east of the FCM) with an extant population and the habitat quality of the FCM made their occurrence probable, we found no evidence that desert bighorn sheep occupied the FCM. In 1907, 1 desert bighorn sheep ram was observed in the Caballo Mountains (25 km south of the FCM; Sandoval 1979). Potential predators of bighorn on the FCM include cougars, bobcats, coyotes, and golden eagles (Frey 1999, Truett et al. 1999).

METHODS

Monitoring Mortality

We translocated 37 radio-collared desert bighorn sheep (13 rams and 24 ewes) from the RRWA to the FCM in autumn 1995, and augmented this population with 7 additional radio-collared rams in autumn 1997. We conducted a helicopter and net-gun capture of 16 adult ewes (9 of which were previously radio-collared) in autumn 1999 to maintain radio-telemetric contact with the herd. We captured and radio-collared desert bighorn lambs (n = 21) during the spring of 2001 and 2002. All VHF radio-collars were equipped with mortality sensors (Telonics, Mesa, Arizona, USA).

We monitored radio-collar signals for mortality via radio-telemetry from the field on a daily basis for the first 6 months following the initial release. We subsequently monitored the herd with periodic fixed wing aircraft flights and annual helicopter surveys in autumn. We monitored bighorn sheep daily from the field via radio-telemetry and direct visual observation from July 1997 to August 2000; January to August 2001; January to August 2002; and less frequently from September through December of 2000, 2001, and 2002. We plotted locations on 1:24,000 scale topographical maps when bighorn sheep were visually relocated in the field.

Assessing Cause of Mortality

When we received a mortality signal, we located the collar and examined the site and carcass. We occasionally located un-collared desert bighorn sheep carcasses incidentally during ground based monitoring efforts and while monitoring radio-collared cougars. We considered the location of the carcass to be the kill site unless track or other site evidence indicated otherwise. We determined the cause of death by examining site and carcass characteristics. We considered predation the cause of death when there was sign of a struggle at the site, blood on the ground or vegetation, track evidence on the ground, or subcutaneous hemorrhaging at wound sites. We looked for evidence such as hair, feathers, tracks, scats, vomit, bed sites, toilets, scrapes, whether the carcass was buried, wounds on the carcass, and the parts of the carcass consumed to determine the species of predator responsible for death (O'Gara 1978, Wade and Bowns 1982, Hatter 1984, Kunkel 1997, Kunkel and Pletscher 2000). We incorporated these data into a key to aid in evaluating and categorizing the type of predator involvement.

Measuring Habitat Characteristics

Ground attributes at predation and control sites.— We revisited all ewe, ram, and lamb desert bighorn sheep mortality sites positively identified as cougar predations during the summer of 2002 and collected habitat data from the ground within a 30 m radius plot. We recorded the Universal Transverse Mercator (UTM) coordinates of the location. We recorded slope in degrees using a clinometer, aspect in degrees from a compass, and elevation in meters via GPS. We categorized the vegetation association as desert grassland, desert scrub, montane scrub, or riparian. We determined a ruggedness index by choosing a random compass bearing, and measuring 30 m by line of sight. We then lay down a rope over any contours existing along this line, and measured the length of the rope when drawn taught. We subtracted 30 from the total length, and multiplied the resulting number by 100. We determined percent visibility at 15 and 30 m using the 'staff-ball' method developed by Collins and Becker (2001). For this technique, we mounted a 9 cm ball at 1.5 m (to represent average eye level of desert bighorn sheep) to a pvc pole which we stood at the center of the plot, and then recorded whether we could view the dimensionless-point target (represented by the intersection of the upper arc of the ball with the right side of the staff) with 1 eye from a repetitious stationary posture at specific points (every 15 degrees at a 15 m radius, every 10 degrees at a 30 m radius) along the specified radii at 0.5 m from the ground (to approximate cougar eye level). We then divided the number of points seen by the total number of points sampled to estimate percent cover. We also conducted a 30 m line transect in a random compass direction, for which we measured the distances in cm that the transect was overlapped by vegetation. We then divided the total vegetation cover by the total distance to estimate percent vegetation cover. We collected the same habitat characteristic data on the ground described above for a paired randomly selected control site; these control sites were located 500 m in a random compass bearing direction from their associated predation site. The locations of the control sites were designed to test whether habitat characteristics in the immediate area differed from those at predation sites. Habitat variables measured on the ground represented the finest scale of analysis.

Derived attributes at predation, relocation, and random sites.— We developed a geographic information system (GIS) model using ArcView with Spatial Analyst (Version 3.2, ESRI, Redlands, California, USA) to compare habitat variables at cougar kill sites to those at different spatial scales: areas used by and available for use by desert bighorn sheep. We determined elevation from 10-m spatial resolution digital elevation models from the United States Geological Survey (USGS). We also derived aspect and slope in degrees. We determined substrate (i.e., limestone, granite, shale, etc.) and vegetation (i.e., desert scrub / desert grassland, montane scrub / coniferous woodland, etc.) from existing layers (Neher 1984, Nelson 1986, Miller 1999). We calculated distance to ≥60% slope patches with a minimum size of 1 ha as a surrogate for escape terrain due to ambiguity in incorporating ruggedness (Tilton 1977, Armentrout and Brigham 1988, McCarty and Bailey 1994). We also calculated distance to roads and distance to water sources, including naturally occurring perennial springs as well as artificial water developments. We calculated terrain ruggedness using an existing routine and script (Pincus 1956, Hobson 1972, Durrant 1996). To calculate visibility, we performed a view shed analysis for a 50 m radius with an offset height of 1.5 m to approximate average bighorn sheep eye level (Sorenson and Lanter 1993). We generated a 100% minimum convex polygon (MCP) around all bighorn sheep visual relocations using the Animal Movement extension (Hooge and Eichenlaub 1997). We compared derived habitat characteristics for predation sites with characteristics of all desert bighorn sheep relocation sites, i.e., the scale of habitat used by desert bighorn sheep. We then compared habitat variables at predation sites with random sites (sites randomly selected from within the MCP), i.e., the scale of habitat available for use by desert bighorn sheep.

Data Analysis

Univariate analyses.— We used SPSS (version 13.0, Chicago, Illinois, USA) for statistical analyses. To meet test assumptions, we examined the data for normality using the Shapiro-Wilk test and the Kolmogorov-Smirnov test with Lilliefors significance correction. To reduce non-normality in the ground data, we used a square root transformation on percent vegetation cover and visibility at 15 m, and a logarithmic transformation on visibility at 30 m, and back transformed variables for interpretation. We used univariate analyses to test for differences in each individual continuous variable for each of the 3 different scales of comparison. We used Student's t-test to compare differences in means for paired samples for predation sites and control sites, and for independent samples for predation sites and relocation sites, and predation sites and random sites. For independent samples, we examined the assumption of equality of variances using Levene's test, and when F values were insignificant, we used t values for which equal variances were not assumed. We set significance levels at $P < 0.05$ for all statistical tests. We compared categorical habitat variables using Pearson's chi-square test and Fisher's exact test. We categorized aspect into east (0 – 179 degrees) and west (180 – 359 degrees) facing slopes, due to the FCM running essentially N-S, thereby providing mostly east or west facing slopes. All comparisons that were statistically significant were retained for logistic regression model development.

Logistic regression.— We calculated binary logistic regression models for the 3 sets of sites using the stepwise backward elimination process based on the Wald statistic ($\alpha = 0.05$ to enter and remain) to evaluate whether physiographic characteristics of predation sites of cougars on desert bighorn sheep differed from sites used by or available to bighorn. The dichotomous dependent variable was a predation site or a non-predation site (i.e., a control, relocation, or random site). We examined the covariates for multicollinearity and removed the least explanatory of any highly intercorrelated pair of variables when $r^2 \geq 0.5$. We examined the final models for reliability using the Hosmer-Lemeshow goodness-of-fit test.

RESULTS

We measured habitat variables on the ground at the locations of 26 carcasses of desert bighorn sheep (10 ewes, 10 rams, and 6 lambs) that we confirmed to have been killed by cougars, as well as their paired control sites. These predations occurred from December 1995 through August 2002. All of the lamb mortalities were documented in 1999, 2001, and 2002. We compared GIS physiographic characteristics of 36 desert bighorn sheep predation sites by cougars (10 of which occurred after we finished collecting ground data) with derived characteristics of relocation sites of desert bighorn sheep representing areas used by bighorn, as well as characteristics of random sites selected from within the desert bighorn sheep home range.

Ground-based measurements at predation and control sites were similar in slope, elevation, ruggedness, vegetation cover, aspect, and vegetation classification (Table 1, Figure 1). Average visibility at 15 m was 19.3% less at predation sites than control sites, and visibility at 30 m was 15.7% less. Using logistic regression, only visibility at 15 m successfully predicted whether a site was a mortality or control site (Table 4).

Using GIS and derived physiographic characteristics, we found that slope was 9.4 degrees less at predation sites, elevation was 55 m lower, and ruggedness was 1.37% less than at relocation sites (Table 2). Visibility at 50 m, however, was on average 15.7% higher at predation sites than relocation sites, and we found no difference in ruggedness at 90 m or distance to escape terrain, water, or roads between predation sites and relocation sites. Vegetation and substrate associations were different at predation sites than relocation sites, with predation sites occurring less frequently in desert grassland – montane scrub / granite and desert scrub – desert grassland / alluvium associations than relocations, and more frequently in desert scrub – desert grassland / limestone –granite and desert scrub – desert grassland – montane scrub / limestone associations (Table 3). We found no difference in percent of predation sites on east and west facing slopes compared to relocation sites (Figure 1). Slope and visibility at 50 m were the only variables important in predicting predation sites versus relocation sites using logistic regression (Table 5).

We found that ruggedness at 90 m averaged 1.47% greater, distance to water averaged 884 m closer, and distance to roads averaged 260 m closer at predation sites than random sites (Table 2). We found no difference between sites in slope, elevation, ruggedness at 310 m, visibility at 50 m, or distance to escape terrain. Predation occurred more on east facing slopes than expected based on availability (Figure 1). Predation sites occurred more than expected in desert grassland – montane scrub / granite and desert scrub – desert grassland / limestone – granite associations, and less than expected in desert scrub – desert grassland / limestone associations (Table 3). Ruggedness at 90 m and distance to water were included in the logistic regression model to distinguish between predation and random sites, with predation sites being more rugged and closer to water (Table 6).

DISCUSSION

Spatial scale considerations are important when examining predator and prey habitat selection (Bowyer and Kie 2006). Fine scale habitat characteristics are important when assessing predator-prey interactions (Grant et al. 2005), however data with a coarse grain of resolution may also provide adequate detail to categorize habitat of desert bighorn (Divine 2000). We characterized habitat factors at cougar-caused predation sites at 3 different scales of analysis: 1) by comparing data collected within small (30 m diameter) plots on the ground at predation sites and paired site-specific control sites, 2) by comparing derived attributes at broader areas (visibility at 50 m, ruggedness at 90 and 310 m) for predation sites with relocations of desert bighorn sheep representing areas used by bighorn, and 3) comparing the same derived attributes for predation sites and random sites selected from within an area defined as available for use by bighorn. Deriving attributes for relocation and random sites allowed us to compare many more sites for which collection of ground data was logistically infeasible. While animals generally select habitats which provide the best components for survival and reproduction (Fretwell and Lucas 1970), habitat selection of translocated populations may differ from more established populations.

As predicted, we found that visibility was lower at predation sites than paired control sites. This likely resulted from increased vulnerability to attack by ambush. The features that produced lower visibility at these sites included vegetation, primarily bushes and trees, as well as topography and boulders. Vegetation succession can cause bighorn sheep habitat loss in the absence of a naturally occurring fire regime or habitat management (Wakelyn 1987). Fire has been shown to increase bighorn sheep range carrying capacity (Holl et al. 2004). Bighorn have been shown to increase their use of burned areas, possibly due to increased visibility and improved forage quality and quantity (Bentz and Woodard 1988). Foraging efficiency has been shown to increase with increasing visibility (Risenhoover and Bailey 1985). Prescribed burning has been used to maintain and restore bighorn sheep habitat, and may enhance and expand populations (Smith et al. 1999). Large herbivore habitat selection generally involves tradeoffs between acquiring resources and avoiding predators (Bowyer and Kie 2006), and individuals in prey populations may limit their use of high-quality habitat due to predation risk (Pierce et al. 2004). Visibility may also decrease as ruggedness increases due to topographic obstruction in mountainous terrain.

Also as we predicted, we found that predation sites were less steep, at lower elevations, and less rugged than relocation sites. Contrary to predictions, however, derived visibility was higher at predation sites than relocation sites. We believe this visibility result was due to the limited accuracy of view shed analysis techniques (Maloy and Dean 1991). Alternately, however, it may be because rugged, steep sites may have lower visibility due to topographical obstruction. Bighorn may use areas with lower visibility during lambing periods for hiding cover, sacrificing detection of predators which would benefit from stalking cover, in a strategy of predator avoidance versus predator evasion (Bergerud 1984, 1987; Bangs et al. 2005b).

Behaviors to avoid one predator may make prey more vulnerable to predation by another predator (Atwood et al. 2007). Bangs et al. (2005b) found that young lambs may be most vulnerable to avian predators such as golden eagles on cliffs or extremely steep slopes that would be considered escape terrain. Traditional definitions of escape terrain may be more appropriate for evasion of coursing predators such as wolves and coyotes, as opposed to stalking or ambush predators such as cougars.

We found that predation sites were more rugged and closer to water and roads than random sites, and occurred more on east facing slopes. We believe the results for ruggedness were probably an issue of scale, because sheep selected more rugged areas for use than were generally available in the FCM. The difference we found in aspect was also probably due to scale because habitat available for use by bighorn does not reflect the level of selection represented in areas actually used by bighorn, and the west face has the steepest and most rugged terrain. We suspect bighorn selected against proximity to roads associated with human disturbance (Papouchis et al. 2001), although the level of human disturbance on this private ranch is low, and we found no evidence that cougars preferentially used roads as travel corridors. However, bighorn may be selecting against proximity to water, or conversely cougars may be selecting for proximity to water. Bangs et al. (2005) did not observe bighorn use of artificial water developments, even during periods of below average precipitation. Krausman and Etchberger (1995) also found that water catchments did not attract bighorn sheep, and Broyles and Cutler (1999) found that surface water availability did not affect bighorn populations. Effects of such developments have not been documented (Broyles 1995). Other researchers suggest that water availability is the single most limiting factor of desert bighorn populations (Turner and Weaver 1980, Messing 1990). Although bighorn reliance on water has been shown in some ranges (Werner 1989), bighorn in other ranges are thought to get their water requirements from forage, especially from succulent vegetation such as cacti (Watts 1979, Warrick and Krausman 1989, Oehler et al. 2003). In fact, Rosenstock et al. (1999) speculated that wildlife water developments may have negative impacts by increasing predation, competition, and disease transmission.

Little is known about how habitat characteristics affect the security of bighorn sheep in relation to cougars. Most studies of habitat do not address whether habitat selection affects survival (White and Garrott 1990). We found that desert bighorn sheep are less likely to be killed by cougars in areas with higher visibility, greater slope, higher elevations, more ruggedness, and farther from water and roads; these areas may serve as refugia from stalking predators. These habitat characteristics may be effective in deterring ambush predators such as cougars (Mooring et al. 2004). While desert bighorn sheep population size has been correlated with area of escape terrain (McKinney et al. 2003), the way escape habitat is defined may need to be reassessed. Also, assessments of translocation sites do not normally include quantifying forage quality and quantity (DeYoung et al. 2000). We recommend modeling to refine escape habitat and identify areas in proximity to high quality forage, and then estimate how much of that is available in proposed reintroduction sites. Further, this may have implications for where to target cougar monitoring and management.

MANAGEMENT IMPLICATIONS

We found that there are certain habitat characteristics such as visibility, slope, elevation, and ruggedness that affected the vulnerability of desert bighorn sheep to predation by cougars. These areas need to be better identified and managed by wildlife professionals, and their juxtaposition with foraging areas should be analyzed. They should also be selected for when considering areas for potential translocations and reintroductions. Range managers should examine if encroachment of trees and shrubs has reduced visibility in bighorn sheep habitat. Prescribed burning may be used to improve habitat for desert bighorn sheep by increasing visibility and decreasing predation risk to cougars, as well as improving forage quality and quantity. Bighorn, mule deer, and predator use of artificial water developments should be investigated. If cougars and mule deer are utilizing water catchments, this may encourage cougar and bighorn overlap, potentially increasing incidental predation as well as increasing the potential for learned behavior in targeting bighorn as prey and facilitating potential competition and disease transmission. Wildlife managers may consider removing or modifying artificial water developments to preclude use by predators and mule deer.

ACKNOWLEDGMENTS

We thank J. Anderson, G. Brennan, K. Eulinger, K. Foresman, E. Goldstein, R. Guty, K. Honness, D. Hunter, D. Klinka, P. Krausman, J. Mabe, M. Phillips, H. Provencio, E. Rominger, J. Thomas, R. B. Turner, R. E. Turner, D. Verhelst, T. Waddell, D. Wayne, D. Weybright, A. Whitelaw, and H. Whitlow. We also thank J. Olson and R. Small, in memoriam. Contributing organizations included the Boone and Crockett Wildlife Conservation Program, Foundation for North American Wild Sheep, National Fish and Wildlife Foundation, New Mexico Department of Game and Fish, New Mexico Ranch Properties Incorporated, Turner Endangered Species Fund, and the University of Montana.

LITERATURE CITED

Anderson, A. E. 1983. A critical review of literature on puma (Felis concolor). Colorado Division of Wildlife, Wildlife Research Section. Special Report Number 54.

Armentrout, D. J., and W. R. Brigham. 1988. Habitat suitability rating system for desert bighorn sheep in the Basin and Range Province. U.S. Bureau of Land Management technical note 384.

Atwood, T. C., E. M. Gese, and K. E. Kunkel. 2007. Comparative patterns of predation by cougars and recolonizing wolves in Montana's Madison Range. Journal of Wildlife Management 71:1098-1106.

Bangs, P. D., P. R. Krausman, K. E. Kunkel, and Z. D. Parsons. 2005. Habitat use by female desert bighorn sheep in the Fra Cristobal Mountains, New Mexico, USA. European Journal of Wildlife Research 51:77-83.

Bangs, P. D., P. R. Krausman, K. E. Kunkel, and Z. D. Parsons. 2005. Habitat use by desert bighorn sheep during lambing. European Journal of Wildlife Research 51:178-184.

Bentz, J. A. and P. M. Woodard. 1988. Vegetation characteristics and bighorn sheep use on burned and unburned areas in Alberta. Wildlife Society Bulletin 16:186-193.

Berger, J. 1993. Persistence of mountain sheep: methods and statistics. Conservation Biology 7:219-220.

Berger, J. 1990. Persistence of different-sized populations: an empirical assessment of rapid extinctions in bighorn sheep. Conservation Biology 4:91-98.

Bergerud, A. T., H. E. Butler, and D. R. Miller. 1984. Antipredator tactics of calving caribou: dispersion in mountains. Canadian Journal of Zoology 62:1566-1575.

Bergerud, A. T., and R. E. Page. 1987. Displacement and dispersion of parturient caribou at calving as antipredator tactics. Canadian Journal of Zoology 65:1597-1606.

Bowyer, R. T., and J. G. Kie. 2006. Effects of scale on interpreting life-history characteristics of ungulates and carnivores. Diversity and Distributions 12:244-257.

Brown, D. E. 1982. Chihuahuan desertscrub. Desert Plants 4:169-179.

Brown, J. S., J. W. Laundre, and M. Gurung. 1999. The ecology of fear: optimal foraging, game theory, and trophic interactions. Journal of Mammalogy 80:385-399.

Broyles, B. 1995. Desert wildlife water developments: questioning use in the southwest. Wildlife Sociey Bulletin 23:663-675.

Broyles, B., and T. L. Cutler. 1999. Effect of surface water on desert bighorn sheep in the Cabeza Prieta National Wildlife refuge, southwestern Arizona. Wildlife Society Bulletin 27:1082-1088.

Buechner, H. K. 1960. The bighorn sheep in the United States, its past, present, and future. Wildlife Monographs 4:1-174.

Collins, W. B., and E. F. Becker. 2001. Estimation of horizontal cover. Journal of Range Management 54:67-70.

Creeden, P. J., and V. K. Graham. 1997. Reproduction, survival, and lion predation in the Black Ridge/Colorado National Monument desert bighorn herd. Desert Bighorn Council Transactions 41:37-43.

DeYoung, R. W., E. C. Hellgren, T. E. Fulbright, W. F. Robbins, and I. D. Humphreys. 2000. Modeling nutritional carrying capacity for translocated desert bighorn sheep in western Texas. Restoration Ecology 8:57-65.

Divine, D. D., D. W. Ebert, and C. L. Douglas. 2000. Examining desert bighorn habitat using 30-m and 100-m elevation data. Wildlife Society Bulletin 28:986-992.

Dunn, W. C. 1991. Evaluation of desert bighorn sheep habitat in New Mexico. New Mexico Department of Game and Fish, Santa Fe, New Mexico, USA.

Dunn, W. C. 1994. Evaluation of desert bighorn sheep habitat in New Mexico: A revision. New Mexico Department of Game and Fish, Santa Fe, New Mexico, USA.

Management 66:75-85.

Durrant, A. V. 1996. Vectors in physics and engineering. Chapman and Hall, London, UK.

Fretwell, S. D., and L. H. Lucas. 1979. On territorial behavior and other factors that influence habitat distributions in birds: I. Theoretical development. Acta BioTheoretica 19:16-36.

Frey, J. K. 1999. Native mammals of the Fra Cristobal Mountains, Sierra County, New Mexico. Turner Biodiversity Division, Truth or Consequences, New Mexico, USA.

Goodson, N. J. 1994. Persistence and population size in mountain sheep: why different interpretations? Conservation Biology 8:617-618.

Grant, J., C. Hopcraft, A. R. E. Sinclair, and C. Packer. 2005. Planning for success: Serengeti lions seek prey accessibility rather than abundance. Journal of Animal Ecology 74:559-566.

Hatter, I. W. 1984. Effects of wolf predation on recruitment of black-tailed deer on Northeastern Vancouver Island. Thesis, University of Idaho, Moscow, Idaho, USA.

Hayes, C. L., E. S. Rubin, M. C. Jorgensen, R. A. Botta, and W. M. Boyce. 2000. Mountain lion predation of bighorn sheep in the Peninsular Ranges, California. Journal of Wildlife Management 64:954-959.

Hobson, R. D. 1972. Surface roughness in topography: quantitative approach. Pages 221-245 in R. J. Chorley, editor. Spatial analysis in geomorphology. Methuen, London, UK.

Holl, S. A., V. C. Bleich, and S. G. Torres. 2004. Population dynamics of bighorn sheep in the San Gabriel Mountains, California, 1967-2002. Wildlife Society Bulletin 32:412-426.

Hooge, P. N., and B. Eichenlaub. 1997. Animal movement extension to arcview, version 1.1. U.S. Geological Survey, Anchorage, Alaska, USA.

Hunt, C. B. 1974. Natural regions of the United States and Canada. W. H. Freeman, San Francisco, California, USA.

Kamler, J. F., R. M. Lee, J. C. deVos Jr., W. B. Ballard, and H. A. Whitlaw. 2002. Survival and cougar predation of translocated bighorn sheep in Arizona. Journal of Wildlife Management 66:1267-1272.

Kelly, W. E. 1980. Predator relationships. Pages 186-198 *in* G. Monson and L. Sumner, editors. The Desert Bighorn. University of Arizona Press, Tucson, Arizona, USA.

Krausman, P. R. 2000. An introduction to the restoration of bighorn sheep. Restoration Ecology 8:3-4.

Krausman, P. R., P. Bangs, K. Kunkel, M. K. Phillips, Z. Parsons, and E. Rominger. 2001. Mountain sheep restoration through private/public partnership. Pages 231-242 *in* D. S. Maehr, R. F. Noss, and J. L. Larkin, editors. Large Mammal Restoration. Island Press, Washington, D.C., USA.

Krausman, P. R., and R. C. Etchberger. 1995. Response of desert ungulates to a water project in Arizona. Journal of Wildlife Management 59:292-300.

Krausman, P. R., R. C. Etchberger, and R. M. Lee. 1993. Persistence of mountain sheep. Conservation Biology 7:219.

Krausman, P. R., A. V. Sandoval, and R. C. Etchberger. 1999. Natural history of desert bighorn sheep. Pages 139-191 *in* R. Valdez and P. R. Krausman, editors. Mountain sheep of North America. University of Arizona Press, Tucson, Arizona, USA.

Krausman, P. R. and D. M. Shackleton. 2000. Bighorn sheep. Pages 517-544 *in* S.

Demarais and P. R. Krausman, editors. Ecology and Management of Large Mammals in North America. Prentice Hall, Upper Saddle River, New Jersey, USA.

Kunkel, K. E. 1997. Predation by wolves and other large carnivores in northwestern Montana and southeastern British Colombia. Dissertation, University of Montana, Missoula, Montana, USA.

Kunkel, K. E., and D. H. Pletscher. 2000. Habitat factors affecting vulnerability of moose to predation by wolves in southeastern British Columbia. Canadian Journal of Zoology 78:150-157.

Laundre, J. W., and L. Hernandez. 2003. Winter hunting habitat of pumas Puma concolor in northwestern Utah and southern Idaho, USA. Wildlife Biology 9:123-129.

Logan, K. A., and L. L. Irwin. 1985. Mountain lion habitats in the Big Horn Mountains, Wyoming. Wildlife Society Bulletin 13:257-262.

Maloy, M. A., and D. J. Dean. 2001. An accuracy assessment of various GIS-based viewshed delineation techniques. Photogrammetric Engineering and Remote Sensing 67:1293-1298.

McCarty, C. W., and J. A. Bailey. 1994. Habitat requirements of desert bighorn sheep. Colorado Division of Wildlife, Denver, Colorado, USA.

McKinney, T., S. R. Boe, and J. C. deVos Jr. 2003. GIS-based evaluation of escape terrain and desert bighorn sheep populations in Arizona. Wildlife Society Bulletin 31:1229-1236.

McKinney, T., T. W. Smith, and J. C. deVos Jr. 2006. Evaluation of factors potentially influencing a desert bighorn sheep population. Wildlife Monographs 164:1-36.

Messing, H. J. 1990. Wildlife catchments as mitigation for Central Arizona Project canals, roads, and reservoirs. Proceedings of the Wildlife Water Development Symposium

1:175-179.

Miller, M. E. 1999. Vegetation of the Fra Cristobal Range, Southern New Mexico. Turner Biodiversity Division, Truth or Consequences, New Mexico, USA.

Mooring, M. S., T. A. Fitzpatrick, T. T. Nishihira, and D. D. Reisig. 2004. Vigilance, predation risk, and the allee effect in desert bighorn sheep. Journal of Wildlife Management 68:519-532.

Neher, R. E. 1984. Soil surveys of Sierra County Area, New Mexico. U.S. Department of Agriculture, Soil Conservation Service, Washington, D.C., USA.

Nelson, E. P. 1986. Geology of the Fra Cristobal Range, south-central New Mexico. New Mexico Geology Society Guide 37:83-91.

New Mexico Department of Game and Fish. 1995. New Mexico's long-range plan for desert bighorn sheep management, 1995-2000. New Mexico Department of Game and Fish, Santa Fe, New Mexico, USA.

New Mexico Department of Game and Fish. 2003. Plan for the recovery of desert bighorn sheep in New Mexico, 2003-2013. New Mexico Department of Game and Fish, Santa Fe, New Mexico, USA.

Oehler, M. M., R. T. Bowyer, and V. C. Bleich. 2003. Home ranges of mountain sheep: effects of precipitation in a desert ecosystem. Mammalia 69:337-354.

O'Gara, B. W. 1978. Differential characteristics of predator kills. Proceedings of the Biennial Pronghorn Antelope Workshop 8:380-393.

Pierce, B. M., R. T. Bower, and V. C. Bleich. 2004. Habitat selection by mule deer: forage benefits or risk of predation? Journal of Wildlife Management 68:533-541.

Pincus, H. J. 1956. Some vector and arithmetic operations on two-dimensional orientation variates, with applications to geologic data. Journal of Geology 64:533-557.

Riley, S. J., and R. A. Malecki. 2001. A landscape analysis of cougar distribution and abundance in Montana, USA. Environmental Management 28:317-323.

Risenhoover, K. L., and J. A. Bailey. 1985. Foraging ecology of mountain sheep: implications for habitat management. Journal of Wildlife Management 49:797-804.

Rominger, E. M., H. A. Whitlaw, D. L. Weybright, W. C. Dunn, and W. B. Ballard. 2004. The influence of mountain lion predation on bighorn sheep translocations. Journal of Wildlife Management 68:993-999.

Rosenstock, S. S., W. B. Ballard, and J. C. DeVos JR. 1999. Benefits and impacts of wildlife water developments. Journal of Range Management 52:302-311.

Sandoval, A. V. 1977. Preferred habitat of desert bighorn sheep in the San Andreas Mountains, New Mexico. Thesis, Colorado State University, Fort Collins, Colorado, USA.

Sawyer, H., and F. Lindzey. 2002. A review of predation on bighorn sheep (*Ovis canadensis*). Wyoming Cooperative Fish and Wildlife Research Unit, Laramie, Wyoming, USA.

Schaefer, R. L., S. G. Torres, and V. C. Bleich. 2000. Survivorship and cause-specific mortality in sympatric populations of mountain sheep and mule deer. California Game and Fish 86:127-135.

Singer, F. J., C. M. Papouchis, and K. K. Symonds. 2000. Translocations as a tool for restoring populations of bighorn sheep. Resoration Ecology 8:6-13.

Smith, T. S., P. J. Hardin, and J. T. Flinders. 1999. Response of bighorn sheep to clear-cut logging and prescribed burning. Wildlife Society Bulletin 27:840-845.

Sorensen, P., and D. Lanter. 1993. Two algorithms for determining partial visibility and reducing data structure induced error in viewshed analysis. Photogrammetric Engineering and Remote Sensing 59:1149-1160.

Tilton, M. E. 1977. Habitat selection and use by bighorn sheep (Ovis canadensis) on a north-western Montana winter range. Thesis, University of Montana, Missoula, Montana, USA.

Truett, J. C., T. Savage, and L. Vance. 1999. Breeding season birds of the Fra Cristobal Mountains, New Mexico. Turner Biodiversity Division, Truth or Consequences, New Mexico, USA.

Turner, J. C., and R. A. Weaver. 1980. Water. Pages 100-112 *in* G. Monson and L. Sumner, editors. The Desert Bighorn. University of Arizona Press, Tucson, Arizona, USA.

Wade, D. A., and J. E. Bowns. 1985. Procedures for evaluating predation on livestock and wildlife. Texas A&M University, San Angelo, Texas, USA.

Wakelyn, L. A. 1987. Changing habitat conditions on bighorn sheep ranges in Colorado. Journal of Wildlife Management 51:904-912.

Warrick, G. D., and P. R. Krausman. 1989. Barrel cacti consumption by desert bighorn sheep. Southwestern Naturalist 34:483-486.

Watts, T. J. 1979. Status of the Big Hatchet desert sheep population, New Mexico. Desert Bighorn Council Transactions 23:92-94.

Wehausen, J. D. 1999. Rapid extinction of mountain sheep populations revisited. Conservation Biology 13:378-384.

Werner, W. 1989. Water Development. Pages 163-173 *in* R. M. Lee, editor. The desert bighorn sheep in Arizona. Arizona Game and Fish Department, Phoenix, Arizona, USA.

White, G. C., and R. A. Garrott. 1990. Analysis of wildlife radio-tracking data. Academic Press, San Diego, California, USA.

Associate editor:

Figure 1. Percent of predation (*n* = 36), control (*n* = 26), relocation (*n* = 12,658), and random (*n* = 3,000) sites of desert bighorn sheep derived from GIS (except for control which was measured on the ground) occurring on eastern or western facing slopes, FCM, New Mexico, USA.

Table 1. Habitat variables measured on the ground at cougar predation sites (n = 26, df = 25) on desert bighorn sheep compared to paired control sites, FCM, New Mexico, USA.

	Predation		Control			
Variable	$\overline{X}$	SE	$\overline{X}$	SE	t	P
Slope (°)	14.4	1.85	17.4	1.86	-1.277	0.213
Elevation (m)	1661	22.2	1666	21.8	-0.274	0.786
Ruggedness index	13.0	1.82	16.2	4.25	-0.661	0.515
Visibility, 15 m (%)	49.1	0.14	68.4	0.10	-2.806	0.010
Visibility, 30 m (%)	27.5	1.13	43.2	1.09	-4.192	0.000[a]
Vegetation cover (%)	32.4	0.05	34.7	0.02	-0.643	0.526

[a]$P \leq 0.001$.

Table 2. Habitat variables derived from GIS at cougar predation sites (*n* = 36) on desert bighorn sheep compared to relocation sites (*n* = 12,658) and random sites (*n* = 3,000), FCM, New Mexico, USA.

	Predation		Relocation		Random	
Variable	$\overline{X}$	SE	$\overline{X}$	SE	$\overline{X}$	SE
Slope (°)	20.3	1.53	29.7[a]	0.10	19.3	0.20
Elevation (m)	1651	20.4	1706[a]	0.97	1687	2.40
Ruggedness, 90 m (%)	3.73	0.62	3.45	0.03	2.26[b]	0.05
Ruggedness, 310 m (%)	5.97	0.65	7.34[a]	0.03	4.84	0.06
Visibility, 50 m (%)	64.7	2.82	49.0[a]	0.13	62.7	0.33
Distance to escape terrain (m)	1092	158	831	7.24	941	13.9
Distance to water (m)	1399	164	1381	8.68	2283[b]	23.3
Distance to roads (m)	588	80.3	550	3.05	848[b]	13.2

[a]Predation site differed from relocation site (df = 35, $P < 0.05$).

[b]Predation site differed from random site (df = 35, $P < 0.05$).

Table 3. Vegetation and substrate associations (%) derived from GIS at predation (n = 36), relocation (n = 12,658), and random (n = 3,000) sites of desert bighorn sheep, FCM, New Mexico, USA.

	Vegetation / Substrate Association[a]									
Site	0	1	2	3	4	5	6	7	8	9
Predation	36.1	0	0	11.1	36.1	8.3	0	0	8.3	0
Relocation	45.3	0	0.2	25.8	14.5	10.4	1.0	0.8	1.6	0.3
Random	16.7	1.3	6.0	36.1	13.9	8.7	0.4	2.3	11.9	2.7

[a]0 = Desert grassland – montane scrub / granite, 1 = Desert scrub / alluvium, 2 = Desert scrub – desert grassland / alluvium, 3 = Desert scrub – desert grassland / limestone, 4 = Desert scrub – desert grassland / limestone – granite, 5 = Desert scrub – desert grassland / shale, 6 = Desert scrub – desert grassland / sandstone, 7 = Desert scrub – desert grassland / volcanic cinders and basalt flows, 8 = Desert scrub – desert grassland – montane scrub / limestone, 9 = Montane scrub – coniferous woodland / limestone.

Table 4. Logistic regression results from ground measurements at predation sites (n = 26) versus paired control sites of desert bighorn sheep, FCM, New Mexico, USA.

Variable	B	SE	W_1[a]	*P*	χ^2_7[b]	*P*
Visibility, 15 m (%)	-0.034	0.014	6.193	0.013	5.125	0.645
Constant	2.106	0.907	5.385	0.020		

[a]Wald's statistic.

[b]Hosmer-Lemeshow goodness-of-fit test.

Table 5. Logistic regression results from GIS derived characteristics at predation sites (*n* = 36) versus relocation sites (*n* = 12,658) of desert bighorn sheep, FCM, New Mexico, USA.

Variable	B	SE	W_1[a]	*P*	χ^2_8[b]	*P*
Slope (°)	-0.058	0.020	8.489	0.004	4.928	0.765
Visibility, 50 m (%)	0.053	0.013	17.13	0.000[c]		
Constant	-7.469	1.072	48.51	0.000[c]		

[a]Wald's statistic.

[b]Hosmer-Lemeshow goodness-of-fit test.

[c]$P \leq 0.001$.

Table 6. Logistic regression results from GIS derived characteristics at predation sites (n = 36) versus random sites (n = 3,000) of desert bighorn sheep, FCM, New Mexico, USA.

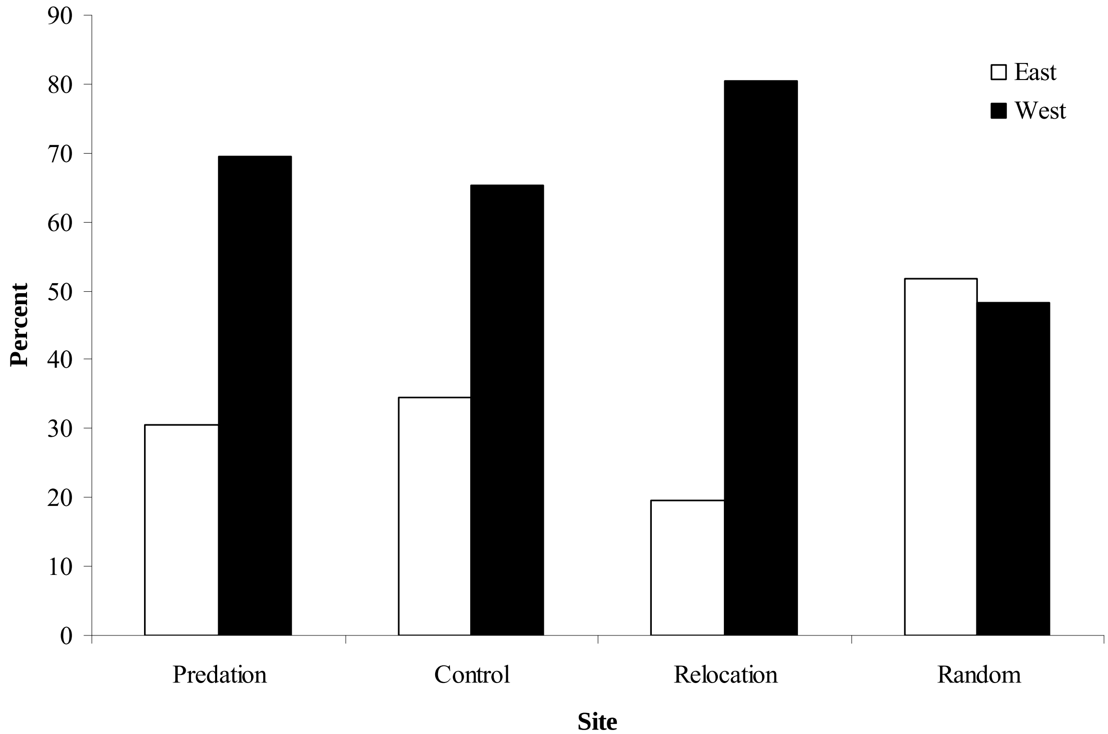
Variable	B	SE	W_1[a]	P	χ^2_8[b]	P
Ruggedness, 90 m (%)	0.120	0.042	8.011	0.005	3.912	0.865
Distance to water (m)	-0.001	0.000	13.69	0.000[c]		
Constant	-3.577	0.353	102.7	0.000[c]		

[a]Wald's statistic.

[b]Hosmer-Lemeshow goodness-of-fit test.

[c]$P \leq 0.001$.

Figure 1


90
80
70
60
50
40
30
20
10
0
Percent
East
West
Predation
Control
Relocation
Random
Site