

CAUSE SPECIFIC MORTALITY OF
DESERT BIGHORN SHEEP LAMBS IN THE
FRA CRISTOBAL MOUNTAINS, NEW MEXICO, USA

By

Zachary David Parsons

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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.

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2 Zachary D. Parsons
3 Wildlife Biology Program
4 Department of Ecosystem and Conservation Sciences
5 University of Montana
6 Missoula, MT 59812
7 406/243-5272; Fax: 406/243-4557
8 zachary.parsons@umontana.edu
9
10 RH: Desert Bighorn Lamb Capture Techniques • Parsons et al.

11 **Capture Techniques for Desert Bighorn Sheep Lambs**

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

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

16 Kyran E. Kunkel,² Turner Endangered Species Fund, 1123 Research Drive, Bozeman, MT
17 59718, USA

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

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

22

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

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

40

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

43

44 Bighorn sheep (*Ovis canadensis*) were widely distributed over western North America in the
45 early 19th century (Buechner 1960), however, present geographic distributions as well as

46 population numbers are considerably reduced (Krausman and Shackleton 2000). By the early
47 1900s, most populations were extirpated due to a combination of factors including excessive
48 hunting and competition with and diseases introduced by domestic livestock as well as other
49 anthropogenic factors (Krausman 2000). Use of isolated precipitous mountain terrain by bighorn
50 sheep results in naturally fragmented habitat (Krausman et al. 1999). Desert bighorn sheep (*O. c.*
51 *mexicana*) likely inhabited most of the mountain ranges in central and southern New Mexico,
52 and their historic occurrence was documented in 14 of these arid ranges (New Mexico
53 Department of Game and Fish [NMDGF] 1995). Only 2 populations remained in New Mexico
54 by 1955, and desert bighorn sheep were listed as an endangered species in 1980. The NMDGF
55 established a captive breeding population at the Red Rock Wildlife Area (RRWA) in 1972.
56 Between 1979 and 1999, desert bighorn sheep were translocated from the RRWA to augment
57 existing populations, reestablish locally extinct populations, and establish new populations,
58 resulting in 8 mountain ranges with desert bighorn sheep populations. Translocations have
59 become a common approach in bighorn sheep conservation and restoration efforts (Singer et al.
60 2000). Removal of desert bighorn sheep from the state endangered species list requires a
61 minimum of 500 free-ranging desert bighorn sheep in at least 3 geographically distinct
62 populations or metapopulations, each containing at least 100 bighorn (NMDGF 2003). Threats
63 to bighorn include habitat degradation from extensive livestock overgrazing and fire suppression,
64 cougar (*Puma concolor*) predation, competing public interests and increasing human pressure,
65 which may exacerbate inherently low rates of increase, difficulty in colonizing new habitats, and
66 sensitivity to diseases and human disturbances. Desert bighorn sheep populations have been
67 slow to increase or are declining in all of these mountain ranges, most populations have suffered

68 significant increases in mortality due to cougar predation, and no animals have been observed
69 during autumn helicopter surveys in 2 of these ranges since 2000 (NMDGF 2003).

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

76 Knowledge of the causes of mortality of bighorn sheep lambs may improve predictive
77 ability of models and suggest management strategies for improving the recovery of small
78 populations of bighorn sheep. However, causes of mortality of bighorn sheep lambs are rarely
79 investigated due to the extreme difficulty in locating carcasses of un-collared lambs, and the lack
80 of technology until recent years for safely and successfully radio-collaring lambs (DeForge and
81 Scott 1982, Nette et al. 1984, Festa-Bianchet 1988, Hass 1989, Etchberger and Krausman 1999).
82 Scotton (1998) examined causes of Dall sheep (*O. dalli*) lamb mortality in Alaska, and Hass
83 (1989) and Goldstein (2001) investigated causes of Rocky Mountain bighorn sheep (*O. c.*
84 *canadensis*) lamb mortality in Montana and South Dakota, respectively. However, with the
85 exception of Etchberger and Krausman (1999; $n = 2$), nobody has reported on the causes of
86 desert bighorn sheep lamb mortality. Capturing and radio-collaring bighorn sheep lambs is
87 essential to accurately determine cause-specific mortality. Appropriate techniques for capturing
88 desert bighorn sheep lambs may differ from those used for capturing adults, as well as Dall sheep
89 and Rocky Mountain bighorn sheep lambs.

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

104 Alternate or modified capture techniques are necessary when capturing bighorn sheep
105 lambs. The use of drop-nets and drive-nets requires extensive planning and long handling times
106 as many sheep are caught at once, and the presence of adults in the captured group increase the
107 risk of physical trauma to lambs. Chemical immobilizers pose high risks to bighorn sheep due to
108 their susceptibility to capture myopathy (Jorgenson et al. 1990, 1991; Kock 1991; Jessup 1992).
109 Andryk et al. (1983) speculated that net-gunning from a helicopter would be better than darting
110 from a helicopter for capturing bighorn sheep lambs due to the potential for overdosing and
111 injury from poor dart placement. Scotton and Pletscher (1998) successfully captured Dall sheep
112 lambs by hand capture after stepping or jumping from a helicopter. Neonates of various ungulate

113 species such as white-tailed deer (*Odocoileus virginianus*; Kunkel and Mech 1994), guanaco
114 (*Lama guanicoe*; Franklin and Johnson 1994), and Mongolian gazelles (*Procapra gutturosa*;
115 Olson et al. 2005) have been hand captured from a ground approach after radio-telemetric or
116 observational monitoring of mothers' behavioral and/or physical characteristics indicative of
117 parturition.

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

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

132 **STUDY AREA**

133 The Fra Cristobal Mountains (FCM) are located in south-central New Mexico in Sierra and
134 Socorro Counties approximately 32 km northeast of Truth or Consequences; they lie entirely
135 within the privately-owned Armendaris Ranch (Krausman et al. 2001). The range is bounded on

136 the west by the Rio Grande Valley and Elephant Butte Reservoir, and on the east by the Jornada
137 del Muerto Basin. The FCM are an east-tilted horst block characterized by massive granite cliffs
138 and horizontally layered limestone cliff steps (Nelson 1986). The range is approximately 5 km
139 wide by 24 km long (105 km²), and elevations range from 1,400 - 2,109 m. Near the
140 northernmost extent of the Chihuahaun Desert, vegetation associations consisted of a mosaic of
141 desert scrub and desert grassland at lower elevations, patchy montane scrub at higher elevations
142 typically between 1,850 and 1,950 m, and a limited amount of open coniferous woodland near
143 the summit above 1,950 m (Miller 1999). Three perennial springs were located on the range, and
144 5 apron water catchment units capable of storing ~19,000 L were developed in 1995 (Dunn
145 1991). Precipitation at Elephant Butte Dam averaged 23.6 cm annually (Bangs et al. 2005a), and
146 approximately 68% occurred during May through September (Brown 1982). The FCM contain
147 approximately 65 km² of suitable desert bighorn sheep habitat, with 22.7 km² of escape terrain
148 (Dunn 1994), and carrying capacity of the range for bighorn was estimated at 100 individuals.
149 Evidence of 2 relatively recent wildfires suggested that a frequent fire regime has existed on the
150 FCM. Little evidence of domestic livestock herbivory was observed, and no known domestic
151 sheep herds occurred within 50 km of the range. No evidence existed that desert bighorn sheep
152 occupied the FCM, though their proximity to the San Andres Mountains (55 km east of the
153 FCM) with an extant population and the habitat quality of the FCM made their occurrence
154 probable. Also, 1 desert bighorn sheep ram was observed in the Caballo Mountains (25 km
155 south of the FCM) in 1907 (Sandoval 1979). A translocation of 37 desert bighorn sheep (13
156 rams and 24 ewes) to the FCM was conducted from the RRWA in autumn 1995, with an
157 augmentation of 7 additional rams in autumn 1997. A helicopter and net-gun capture of 16 adult
158 ewes was conducted in autumn 1999 to re-instrument ewes and maintain radio-telemetric contact

159 with the herd. Potential bighorn predators on the FCM include cougars, bobcats (*Lynx rufus*),
160 coyotes (*Canis latrans*), and golden eagles (*Aquila chrysaetos*; Frey 1999, Truett et al. 1999).

161 **METHODS**

162 **Monitoring Natalty**

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

172 **Capture Techniques**

173 *Hand-capture from the ground.*— When we detected the presence of a newborn lamb, we
174 assessed its degree of mobility according to visual observations of any ambulatory movements or
175 the lack thereof. Often, the lamb's age was known to within 1 to 2 days due to prior
176 observations of the dam. Otherwise, age was determined during capture on the basis of new hoof
177 growth measurements and texture, umbilicus condition, behavioral characteristics such as
178 mobility, the presence of afterbirth, and wet hair. We attempted a hand-capture from the ground
179 if we believed that we could capture the lamb due to its mobility and approximate age of ≤ 3
180 days, and the lamb and dam were in terrain where we could attempt an approach. Prior to a
181 capture attempt, we waited until the animals bedded down. Solitary ewe-lamb pairs were

182 preferred. However, we also attempted captures of lambs associated with small groups of ewes.
183 Once the animals bedded down, we noted the location of the animals in relation to topography
184 and notable landmarks. Two handlers then stalked the animals to as close as possible without
185 detection; e. g. by climbing up the opposite side of a ridge, ideally ending up above the animals.
186 When there was no more available cover we rapidly approached the animals by running directly
187 toward them. The ewe would flee this perceived threat, and the lamb would hide or attempt to
188 flee. After a short search or chase the lambs were manually restrained.

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

200 When a lamb became separated from a group and subsequently tried to hide against a
201 sheer rock face or boulder, two handlers, one at a time, released their harnesses, stepped onto the
202 skid, and jumped or stepped to the ground. Handlers departed the helicopter when they felt they
203 could land safely and not incur self injury; jumps seldom exceeded 1 m. The handlers then
204 approached the lamb from 5 to 10 m in front of the cliff from different angles. When the lamb

205 tried to flee, handlers attempted to manually restrain it. The helicopter then moved >500 m away
206 to minimize stress to the captured lamb.

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

217 **Handling**

218 Processing gear including radio collar, nut driver and extra hardware, scale, GPS, sling, extra
219 rubber gloves, measuring tape, blindfold, ear swab, fecal and hair sample tins, and a data sheet
220 was stored in a small backpack to leave the catcher's hands free. All handlers wore latex gloves
221 throughout processing and tagging. Captured lambs were blindfolded. We radio-collared
222 (recording frequency, serial number, lamb #, and dam frequency and #), sexed, and weighed the
223 lamb with a sling and spring scale. Transmitters (MOD-305) with a two-hour mortality delay
224 were attached to stretchable nylon beige-colored collars (CB-6) with expansion loops and
225 breakaway tabs, and weighed approximately 0.175 kg (Telonics, Mesa, Arizona, USA).
226 Measurements of chest girth, neck girth, shoulder height, and hind foot length were taken, as
227 well as an ear swab, hair, and fecal samples. We recorded the date, capture method, general

228 location, Universal Transverse Mercator (UTM) coordinates, ambient temperature, capture crew,
229 pursuit time (start and finish), and handling time (start and finish) to the nearest minute. We
230 described lamb reaction upon release (e.g., the lamb jumped up and ran bleating; the lamb
231 remained quiet and motionless in the bedded position) and the reaction of the dam during the
232 capture (e.g., ewe fled initially, but remained in the immediate vicinity, and was seen upon
233 leaving the capture site) when possible. The distance of the lamb from the dam upon release was
234 visually estimated and recorded when possible, and the maximum time until the lamb reunited
235 with the dam (i.e., when researchers first visually observed them together following capture) was
236 noted when possible. We strived to keep handling time to <5 minutes.

237 **Data Analysis**

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

243 **RESULTS**

244 We captured desert bighorn sheep lambs during 2001 and 2002 using each of the 3 different
245 capture techniques (Table 1). Hand capture from the ground resulted in 29% of total successful
246 captures, while hand capture from a helicopter accounted for 19% of captures, and 52% were
247 attributed to net-gun capture from both types of helicopter. We captured 8 males and 13
248 females; thus sex ratio of lambs at capture was skewed in favor of females (62%). Estimated
249 ages of captured lambs ranged from < 1 to 71 days. Average estimated age of lambs captured by
250 hand from the ground was significantly younger than average estimated age of lambs captured

251 with all helicopter methods ($t = -12.281$, $df = 19$, $P \leq 0.001$); mean estimated age at capture was
252 1.8 days ($SE = 0.40$, $n = 6$) for hand captures from the ground, and mean estimated age at capture
253 for all helicopter methods was 57.8 days ($SE = 2.83$, $n = 15$). Average pursuit time and average
254 handling time were similar among all 3 capture techniques (Table 2); we found no statistically
255 significant differences in pursuit or handling time between hand and net-gun capture from the
256 Hughes 500, net-gun capture from the Hughes 500 and the Bell 206 JetRanger, or hand capture
257 from the ground and the Hughes 500. No lambs suffered any physical injuries during any of the
258 capture events by any of the 3 techniques. Mean estimated distance of the ewe from the lamb at
259 release for hand captures from the ground was 391.7 m ($SE = 135.66$, $n = 6$); however, ewe
260 distance from the lamb at release was not obtainable for any of the helicopter captures. Mean
261 maximum time to reunification of the lamb and dam was 15.3 hrs ($SE = 4.16$, $n = 6$) for hand
262 captures on the ground, and 32.9 hrs ($SE = 3.91$, $n = 8$) for all captures from the helicopters;
263 average maximum time to reunification of the lamb and dam following capture and release was
264 significantly shorter for hand capture from the ground compared to captures from helicopters ($t =$
265 -3.033 , $df = 12$, $P = 0.010$). Ambient temperature averaged 10.9° C ($SE = 0.80$, $n = 14$) for all
266 captures, and although wind conditions varied during hand captures on the ground, wind speeds
267 were low to negligible during helicopter captures. No dams attempted to defend their lambs
268 with protective behaviors such as aggression towards the handlers during processing.

269 No lambs died immediately as a result of our capture and handling. One lamb was not
270 visually confirmed to have reunited with its mother after capture. In this case, the lamb was
271 hand captured from a ground approach in the late afternoon; by evening, telemetry triangulation
272 indicated the ewe and lamb were in the same location, as well as on the next several days. A
273 visual observation was not attempted due to their location and concern of further disturbing

274 them. The lamb's radio collar remained in the active mode for 3 days. When a mortality signal
275 was received on the fourth day following capture, the ewe was located on the same slope that the
276 lamb carcass was eventually found, and the lamb had been killed by a golden eagle.

277 **DISCUSSION**

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

285 Time to reunification of the lamb and dam were maximums since they represented the
286 time from release at the end of capture to the first time observed together; ewe and lamb may
287 have rejoined earlier than first seen back together, and in some cases lambs captured in the
288 afternoon or evening were first seen together the following morning but likely reunited the
289 previous day. Monitoring frequency was the same throughout the study. Contrary to our
290 predictions, we did not find any differences in pursuit and handling times between methods.
291 Ewe distance from lamb upon release could not be estimated for helicopter captures due to the
292 flight response of ewes to the helicopter. During previous annual autumn helicopter surveys, we
293 observed movement responses of desert bighorn sheep before the helicopter became visible. For
294 ground captures, the identity of the dam was known, and the dam always stayed at least within
295 telemetric contact if not visual contact. During helicopter captures, the identity of the dam of
296 captured lambs was rarely known immediately, and in some cases even after groups of sheep

297 reunited, pairs could not be confirmed until observed nursing. In one instance, in the afternoon
298 following a helicopter capture, we observed a solitary ewe with two lambs; when she was
299 subsequently observed with other sheep on the following day, the temporarily adopted lamb had
300 rejoined with its mother.

301 Relatively quick reunification with the mother after the capture event is critical for lamb
302 survival (Byers 1997). Handlers wore latex gloves to minimize scent transfer to lambs, and
303 pursuit and handling times were kept as short as possible in order to minimize the duration and
304 the intensity of the disturbance, and thus minimize capture related stress and the potential for
305 capture induced abandonment, and to facilitate reunification (Livezey 1990) Garrott et al. (1985)
306 found no difference in mortality rates between ear-tagged and radio-collared fawns, indicating
307 radio-collars did not make fawns more conspicuous to predators as compared to ear-tags. Byers
308 (1997) also found no evidence of increased mortality risk to neonatal ungulates due to handling
309 in his study of young pronghorns.

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

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

330 Bighorn sheep are susceptible to disturbance from aircraft, especially helicopters
331 (Krausman and Hervert 1983, Miller and Smith 1985). Stockwell et al. (1991) found that
332 helicopters modified bighorn sheep behavior by reducing foraging efficiency. Bleich et al.
333 (1990, 1994) found that helicopter disturbance caused dramatic response in bighorn sheep,
334 reporting movements 2.5 times farther following a helicopter survey, and concluded that the
335 negative influence of the helicopter was extreme. Indeed, when comparing capture methods for
336 bighorn sheep, Kock (1991) stated the contribution of the helicopter to the degree of stress
337 experienced would be impossible to evaluate. Jessup (1992) followed by saying helicopter
338 pursuit of bighorn sheep adds significantly to capture stress, and the use of helicopters to capture
339 bighorn sheep should be avoided, if possible.

340 We applied a hand capture technique that had been used on white-tailed deer fawns
341 (Kunkel and Mech 1994) and South American guanaco neonates (Franklin and Johnson 1994)
342 but had never been used on desert bighorn sheep. The precocial nature of desert bighorn lambs

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

355 **MANAGEMENT IMPLICATIONS**

356 Wildlife biologists must continually evaluate techniques we use to capture, handle, and
357 monitor wildlife populations. Wildlife managers can safely capture desert bighorn sheep lambs
358 by helicopter and net-gun, a technique that has also been applied to Rocky Mountain bighorn
359 lambs, as well as proven effective for adult bighorn sheep and many other ungulate species.
360 Researchers should attempt to hand capture young neonates from helicopters over net-gunning
361 whenever possible to eliminate the potential risk of physical injury inherent in net-gunning.
362 Both of these techniques may be more efficient when applied to neonate populations with more
363 strongly synchronized birthing seasons. However, the effects of aerial harassment of wildlife
364 should be critically evaluated and minimized by wildlife professionals. Through observation of
365 maternal behavior and movements, wildlife biologists can take advantage of a common neonate

366 ungulate predator evasion strategy, hiding versus fleeing, to hand capture desert bighorn sheep
367 lambs on the ground. Given the extremely precocial nature of desert bighorn sheep lambs, the
368 lack of a synchronized birthing season, low population density, ruggedness of terrain, lack of
369 parturition site fidelity, and lack of habituation to people, we believe this technique for capturing
370 and handling neonates has broad applicability to a wide variety of other ungulate species,
371 especially for small populations where knowledge of the causes of neonate mortality may
372 contribute to better understanding population dynamics and could give valuable insights for
373 population viability and ultimately population persistence.

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544 Table 1. Results of number of desert bighorn sheep lambs captured by different techniques on
545 the Fra Cristobal Mountains, New Mexico, USA during 2001 and 2002.
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548	549	550	551
Year	Capture technique		<i>n</i>
552	553	554	555
2001	Ground by hand		6
	556	557	558
	Helicopter (Hughes 500) by hand		4
	559	560	561
	Helicopter (Hughes 500) by net-gun		4
562	563	564	565
2002	Helicopter (Bell 206 JetRanger) by net-gun		7
566	567	568	569
Total			21

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590 Table 2. Results of pursuit and handling times (min) of desert bighorn sheep lambs captured by
 591 different techniques on the Fra Cristobal Mountains, New Mexico, USA during 2001 and 2002.
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594 595 596 597 598 599 Capture technique	Pursuit time			Handling time		
	\bar{X}	SE	<i>n</i>	\bar{X}	SE	<i>n</i>
600 601 602 Ground by hand	5.0	2.10	6	5.8	0.75	6
603 604 Helicopter (Hughes 500) by hand	4.8	0.85	4	5.0	0.00	4
605 606 Helicopter (Hughes 500) by net-gun	5.0	0.82	4	5.0	0.58	4
607 608 Helicopter (Bell 206 JetRanger) by net-gun	3.4	1.25	5	6.4	0.75	5

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636 15 December 2007
637 Zachary D. Parsons
638 Wildlife Biology Program
639 Department of Ecosystem and Conservation Sciences
640 University of Montana
641 Missoula, MT 59812
642 406/243-5272; Fax: 406/243-4557
643 zachary.parsons@umontana.edu
644
645 RH: Desert Bighorn Lamb Mortality • Parsons et al.

646 **Cause Specific Mortality of Desert Bighorn Sheep Lambs**

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

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

651 Kyran E. Kunkel,⁶ Turner Endangered Species Fund, 1123 Research Drive, Bozeman, MT
652 59718, USA

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

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

657

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

658 **ABSTRACT** Anthropogenic factors such as hunting and diseases brought by domestic livestock
659 caused declines in bighorn sheep (*Ovis canadensis*) distribution and abundance by the early
660 1900s. In New Mexico, all of the small, isolated populations of desert bighorn sheep (*Ovis*
661 *canadensis mexicana*), a state endangered species, have been slow to increase or are declining.
662 Low and variable lamb recruitment is one of the factors negatively affecting these population
663 growth rates. No one has previously reported cause-specific mortality rates for desert bighorn
664 lambs. We captured and radio-collared lambs during the spring lambing seasons of 2001 and
665 2002 to determine the causes, extent, and timing of desert bighorn sheep lamb mortality on the
666 Fra Cristobal Mountains in south central New Mexico. We then monitored the lambs for
667 mortality daily via radio telemetry, as well as visually monitoring ewe behavior indicative of
668 lamb mortality. We examined carcass and site characteristics to determine cause of mortality.
669 We found that the primary mortality agent of desert bighorn lambs was cougar (*Puma concolor*)
670 predation, followed by golden eagle (*Aquila chrysaetos*) predation. Although 1 lamb died from
671 pneumonia (*Pasturella multocida multocida b*), disease did not appear to be a critical factor
672 affecting lamb recruitment. We suggest selective removal of cougars that become habitual sheep
673 killers over the short term may be an appropriate management strategy to enhance the recovery
674 of desert bighorn populations. Maintaining cougars that pose no apparent significant threat to
675 sheep populations is also important.

676

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

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

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

700 Desert bighorn sheep must reach a threshold of 500 animals in 3 populations, each
701 containing at least 100 individuals, to be removed from the state endangered species list.
702 Restoration challenges include sensitivity to diseases and human disturbance, difficulty in

703 colonizing new habitats, and inherently low rates of increase (Singer et al. 2000). Current threats
704 to bighorn sheep populations are mortality due to cougar (*Puma concolor*) predation, increasing
705 human development, competing public interests for land use, and habitat degradation from fire
706 suppression and livestock overgrazing.

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

721 Few radio telemetry studies have been conducted on bighorn sheep lambs (DeForge and
722 Scott 1982, Nette et al. 1984, Festa-Bianchet 1988, Hass 1989, Etchberger and Krausman 1999).
723 Most investigations into bighorn (*O. c. spp.*) lamb survival rely on annual aerial helicopter or
724 aircraft flights, or ground observations (Woodard et al. 1974, Spraker and Hibler 1977, Berger
725 1982, Douglas and Leslie 1986, Douglas 2001). Scotton (1998) attributed most of the mortality

726 of Dall sheep (*Ovis dalli*) lambs to predation by coyotes (*Canis latrans*), golden eagles (*Aquila*
727 *chrysaetos*), and wolves (*Canis lupus*). Hass (1989) found that coyotes likely accounted for most
728 of the mortality of Rocky Mountain bighorn lambs (*O. c. canadensis*). Goldstein (2001) found
729 that Rocky Mountain bighorn lambs died from cougar predation, disease (contagious ecthyma),
730 accidental falls, and predation possibly by a bobcat (*Lynx rufus*). The only study that addressed
731 desert bighorn sheep lambs (*O. c. mexicana*) was that of Etchberger and Krausman (1999) in
732 Arizona. They captured and radio-collared 2 lambs and reported 2 lamb mortalities, 1 from a fall
733 and the other from being stepped on by other bighorn. No studies on causes of desert bighorn
734 sheep lamb mortality have been conducted in New Mexico.

735 Significant recent attention has been given to the issue of cougar predation of bighorn
736 sheep. Recent increases in cougar predation may be responsible for bighorn sheep population
737 declines in California, Arizona, and New Mexico (Wehausen 1996, Hayes et al. 2000, Kamler et
738 al. 2002, Holl et al. 2004, Rominger et al. 2004). Population declines of the primary prey of
739 cougars, mule deer (*Odocoileus hemionus*), may lead to increased predation on bighorn sheep
740 (Hayes et al. 2000, Kamler et al. 2002, Holl et al. 2004). Cougars also kill domestic calves as
741 alternate prey, and Rominger et al. (2004) hypothesized that this supports higher cougar
742 populations during periods of mule deer decline. However, Polisar et al. (2003) found that
743 cougars hunted selectively rather than opportunistically and preyed on livestock despite adequate
744 natural prey. Cougar predation on bighorn as alternative prey may increase in areas where
745 bighorn sheep and mule deer are sympatric (Schaefer et al. 2000, Hayes et al. 2000). The
746 primary management strategy for sheep in New Mexico is cougar population reduction (NMDGF
747 2003). Whether such a strategy also enhances populations via lamb recruitment is unknown.
748 The benefits of such a strategy may be even greater if cougars are a significant and additive

749 predator on lambs. Benefits of cougar control then may further outweigh costs of this
750 controversial strategy (Reiter et al. 1999).

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

756 **STUDY AREA**

757 The Fra Cristobal Mountains (FCM) lie entirely within the privately-owned Armendaris Ranch,
758 located approximately 32 km northeast of Truth or Consequences, Sierra County, New Mexico,
759 USA (Krausman et al. 2001). The Jornada del Muerto basin lies to the east of the range, and the
760 Rio Grande valley and Elephant Butte Reservoir lie to the west. The FCM are an east-tilted fault
761 block characterized by horizontally layered limestone cliff steps and massive granite cliffs
762 (Nelson 1986). Elevations range from 1,400 - 2,109 m. The range is approximately 5 km wide
763 by 24 km long (105 km²). The FCM are located near the Chihuahaun Desert's northernmost
764 extent (Hunt 1974). Vegetation associations consist of desert scrub and desert grassland at lower
765 elevations, montane scrub at higher elevations, and coniferous woodland near the summit (Miller
766 1999). Three perennial springs are located in the middle of the range < 0.75 km apart (Dunn
767 1991). Five water catchments capable of storing approximately 19,000 L were developed
768 throughout the range in 1995 (Dunn 1994). Annual precipitation at Elephant Butte Dam
769 averaged 23.6 cm (Bangs et al. 2005a, b). Approximately 68% of precipitation occurred during
770 May through September (Brown 1982). Desert bighorn sheep carrying capacity of the range was
771 estimated at 100 to 150 (NMDGF 2003). The FCM contain 22.7 km² of escape terrain and

772 approximately 65 km² of suitable desert bighorn sheep habitat (Dunn 1994). Evidence of 2
773 recent wildfires suggested that a relatively frequent fire regime has existed on the FCM. Little
774 evidence of domestic livestock herbivory was observed on the range, and no domestic sheep
775 grazed within 50 km of the range. No historical evidence exists that desert bighorn sheep
776 occupied the FCM. However, in 1907, 1 desert bighorn sheep ram was observed in the Caballo
777 Mountains (25 km south of the FCM; Sandoval 1979), the FCM are in close proximity to the San
778 Andres Mountains (55 km east of the FCM) with an extant population, and the FCM have good
779 habitat quality, all of which suggest that their occurrence was probable. Potential predators of
780 desert bighorn sheep which occur within the study area included cougars, bobcats, coyotes, and
781 golden eagles (Frey 1999, Truett et al. 1999).

782 **METHODS**

783 NMDGF translocated 37 desert bighorn sheep from the RRWA to the FCM in October 1995.
784 All sheep (24 females, 13 males) were fitted with VHF telemetry collars with mortality sensors
785 (Model 500, Telonics, Mesa, Arizona, USA). The herd was augmented with an additional
786 translocation of 7 radio-collared rams from the RRWA in 1997. We used a helicopter and net-
787 gun technique described by Krausman et al. (1985) to capture and radio-collar 16 females in
788 November 1999; 9 of these females were radio-collared previously. We monitored radio-
789 collared ewes via radio-telemetry and direct observation on a near daily basis for movement
790 patterns indicative of parturition, and for the presence of newborn lambs during the spring
791 lambing periods of 2001 (January through May) and 2002 (December through May). We believe
792 27 ewes in 2001 and 26 in 2002 were capable of reproducing. Fourteen radio-collared ewes
793 were present in the FCM herd in 2001 and 13 in 2002. Un-collared ewes were difficult to
794 monitor, especially when they left groups for parturition; however, we observed un-collared

795 individuals when with groups containing collared individuals or when otherwise incidentally
796 visually detected.

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

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

816 All radio-collar signals were monitored for mortality on a near daily basis from January
817 through August, and less frequently from September through December of 2001 and 2002. We

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

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

840 0.001; females: $y = 0.148x + 5.267$, $R^2 = 0.826$, $P \leq 0.001$). For all statistical tests, significance
841 levels were set at $P < 0.05$.

842 RESULTS

843 We visually detected lambs born ($n = 47$) from late December through late May during this
844 study, with 64% of lambs born within the first 3 weeks of the lambing period in late December
845 and early January (Figure 1). Lamb production was high during both years (Table 1). All radio-
846 collared ewes were observed to have lambs, and only 3 un-collared mature adult ewes (11%)
847 were observed without lambs in each of the years 2001 and 2002. We captured and radio-
848 collared 14 lambs in 2001 and 7 in 2002. Mean capture age for all methods was 42 days (SE =
849 6.03, $n = 21$). Mean age for lambs captured on the ground was 1.5 days (SE = 0.34, $n = 6$), while
850 mean age for lambs captured from helicopters was 58 days (SE = 2.83, $n = 15$).

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

863 lamb necropsies or ear swab examinations.

864 The annual survival rate was 0.37 for radio-collared lambs in 2001 (Table 3) and 1.00 for
865 radio-collared lambs in 2002; the cougar caused mortality rate was 0.18. Surviving lambs were
866 similar in birth mass to lambs that died ($t = -1.08$, $df = 18$, $P = 0.294$; Table 4). The age of dams
867 of surviving lambs was also similar to those of dying lambs ($t = 0.19$, $df = 17$, $P = 0.856$).
868 However, surviving lambs were born significantly earlier than dying lambs ($t = -2.63$, $df = 23$, P
869 $= 0.015$). We did not find an interaction between lamb birth date and the estimated mass of
870 lambs at birth (Figure 2).

871 Age of lambs at death ranged from 2 days to almost 6 months; however 36% occurred
872 within the first week of life (Figure 3). Two un-collared lambs disappeared during 2001, and 1
873 disappeared in 2002; the causes of these mortalities were unknown. Recruitment was higher in
874 2002 than in 2001. In 2001, 50% of collared lambs and 70% of un-collared were recruited, while
875 in 2002, 100% of collared and 75% of un-collared were recruited.

876 **DISCUSSION**

877 We captured and radio-collared 58% of the 2001 lamb population and 30% of the 2002
878 population and believe our results are representative of this population. While lamb production
879 was high, our estimates should be viewed as minimum values because lambs may have been
880 born and died before being seen by observers. However, only 3 un-collared ewes were not
881 observed with lambs each year; we don't know if these ewes did not produce lambs, or if the
882 lambs were killed before detection. Thus, there was a maximum of 3 mortalities of young lambs
883 each year for which the cause may have been unknown. Similarly, we observed 3 lambs (2001:
884 $n = 2$, 2002: $n = 1$) that we were unable to capture that subsequently went missing; these were
885 the only lambs that we know died for which we could not attempt to determine the cause. While

886 radio-collaring lambs was instrumental in finding lamb mortalities, by closely observing ewes
887 and their behaviors we increased lamb mortalities examined by 36%. Lamb recruitment to 1
888 year on the FCM for the past 5 years since release has ranged from 13 – 81%, and averaged
889 45.6% (Kunkel et al. 2007b); thus since 58 and 83% of lambs were recruited in 2001 and 2002
890 respectively, lamb recruitment was above average during our study. While bighorn lamb
891 survival is extremely variable, typical or average survival is roughly 50% (Hass 1989).

892 Cougars were the largest cause of lamb mortality in the FCM in 2001 and 2002, and
893 cougar predation was the primary proximate factor limiting lamb recruitment. Because this is
894 similar to our findings for adults, management directed at cougars will likely benefit both
895 survival and recruitment rates in sheep. Goldstein (2001) also found cougars were the largest
896 cause of Rocky Mountain bighorn sheep lambs in South Dakota. Most cougars do not prey on
897 bighorn sheep, however, some individuals develop a learned behavior for successful predation on
898 bighorn (Ross et al. 1997, Kamler et al. 2002, Mooring et al. 2004). Selective removal of
899 offending cougars that have killed bighorn sheep is more efficient than prophylactic measures
900 such as indiscriminate cougar control which results in killing cougars that don't necessarily prey
901 on sheep (Ernest et al. 2002, Mooring et al. 2004). Festa-Bianchet et al. (2006) found that each
902 of 3 bighorn populations experienced cougar predation leading to declines, and that population
903 extinction can be caused cougars that specialize on bighorn. They believed that predator-prey
904 equilibria are unlikely given habitat fragmentation and may only occur at large geographic and
905 temporal scales. However, others have suggested that the time lag may be short term (< 10
906 years) for cougar populations to decline following mule deer population declines (Kamler et al.
907 2002). Thus, for small populations of bighorn sheep in immediate danger of extirpation due to

908 cougar predation, short-term cougar removal may be needed to prevent declines (Ernest et al.
909 2002, Kamler et al. 2002).

910 Golden eagles were the second largest lamb mortality agent during our study. Scotton
911 (1998) found that eagles also killed Dall sheep lambs in Alaska. DeForge and Scott (1982)
912 observed eagles in peninsular bighorn range in California but did not observe eagle caused lamb
913 deaths. Also, 1 anecdotal account described a golden eagle killing a desert bighorn sheep lamb
914 (*O. c. mexicana*) in New Mexico (Kennedy 1948). While we did not observe any coyote
915 predation on lambs, coyotes were the primary mortality agent of Dall (Scotton 1998) and Rocky
916 Mountain bighorn (Hass 1989) lambs. Hass (1989) reported that her study area in Montana was
917 probably not historic sheep habitat and may have lacked sufficient precipitous escape terrain for
918 coyote avoidance. Bobcats did not kill desert bighorn sheep lambs on the FCM during our study.
919 Although deaths from falls have been documented (Brundige 1987, Etchberger and Krausman
920 1999) we did not find any lambs that died from falls.

921 While some researchers have suggested density may affect lamb survival (Douglas and
922 Leslie 1986, Portier et al. 1998), density is likely not a factor limiting the population we studied
923 because the number of individual bighorn was estimated at approximately 60 to 70 during the
924 time of the study and NMDGF (2003) suggested this mountain range was capable of supporting
925 100 to 150 individuals. Dunn (1994), however, estimated carrying capacity to be 30-50 sheep on
926 the FCM. None of the lambs killed by predators appeared to be in poor nutritional condition.
927 Therefore, cougar predation appeared to be additive rather than compensatory to other causes of
928 mortality.

929 Goldstein (2001) identified lambs that died from disease, namely contagious ecthyma.
930 Deforge et al. (1982) stated contagious ecthyma may have been an initiating factor to the

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

945 The primary factor related to lamb mortality was date of birth. We speculate that the
946 reason surviving lambs were found to have been born earlier than dying lambs on average was
947 that the majority of lambs were born early in the lambing season during this study. Testa (2002)
948 speculated that predators may alter searching behaviors in response to the presence of newborn
949 offspring as vulnerable prey, and that early born individuals would have an advantage by being
950 first to develop mobility necessary for predator evasion. Rubin (2000) and Festa-Bianchet
951 (1988) also found that bighorn lambs born earlier had greater survival than those born later.

952 While there was a significant range in the ages of lambs at death, observational data for
953 this herd showed lambs dying from 1 to 12 weeks of age and averaging 4.9 weeks at death

954 during the 2 years prior to this study, 1999 and 2000; 4 lambs went missing within their first
955 week in 2000 (Kunkel et al. 2007b). Other studies have similarly shown young lambs have the
956 highest mortality rates. Harper (1984) reported 60% of lamb mortality occurred within the first 3
957 weeks postpartum. Lambing periods of bighorn sheep at more southern latitudes begin earlier
958 and last longer than those at higher latitudes (Bunnell 1982, Thompson and Turner 1980, Hass
959 1997). This may be in response to unpredictable vegetation growth patterns in desert habitats
960 due to erratic precipitation.

961 Large carnivores are important to ecosystem health by contributing to species diversity
962 and influencing ecosystem structure and function (Miller et al. 2001). Top predators such as
963 cougars probably reduce the number of mesopredators such as coyotes, which may reduce this
964 potential cause of lamb mortality. Indeed, predator removal can lead to decreased species
965 richness and diversity and increased microherbivore density and mesopredator abundance,
966 demonstrating faunal community structure influenced by a keystone predator (Henke and Bryant
967 1999). Predation can serve an important role in reducing disease among prey populations.
968 Through trophic cascades, cougar declines can affect vegetation structure and terrestrial and
969 aquatic species abundance (Ripple and Beschta 2006). Appropriate cougar management should
970 be implemented on a regional scale (Sweaner et al. 2000). Ernest et al. (2002) strongly
971 recommended assessment of effects of predator control in removal of cougars to restore bighorn
972 populations in danger of extinction so that conservation of 1 species does not imperil another.

973 The role of precipitation as a possible ultimate limiting factor of desert bighorn sheep
974 mortality should be investigated. In xeric desert environments, erratic precipitation and its
975 influence on available forage and thus dam nutritional status and fitness, and lamb health and
976 vulnerability to predation should not be overlooked, especially with changing future climatic

977 conditions. Several studies have examined the effect of weather on survival of bighorn sheep
978 lambs and correlated survival with precipitation during various periods of the year (Douglas and
979 Leslie 1986, Portier et al. 1998, Douglas 2001). Enk et al. (2001) demonstrated a correlation
980 between summer climatic conditions and lamb production and survival, and that forage
981 nutritional quality influenced susceptibility to disease as well as herd productivity. Rubin et al.
982 (2000) found that the ultimate factors affecting the breeding season of bighorn sheep were
983 climate patterns. Some have found an affect of precipitation on bighorn lamb survival
984 independent of population density (Portier et al. 1998). However, precipitation, through forage
985 quality and quantity, limited a population of desert bighorn sheep in New Mexico by affecting
986 production or survival of lambs in a density dependent manner (Bender and Weisenberger 2005).

987 **MANAGEMENT IMPLICATIONS**

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

1000 the small populations of desert bighorn sheep in New Mexico. Such evidence is important given
1001 the controversial nature of cougar control and the social and ecological costs.

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1202 Figure 1. Date of birth for desert bighorn sheep lambs on the Fra Cristobal Mountains, New
1203 Mexico, USA during 2001 and 2002.

1204 Figure 2. Estimated birth date (x) and birth mass (y) for dying (●) and surviving (○) radio-
1205 collared desert bighorn sheep lambs in the Fra Cristobal Mountains, New Mexico, USA during
1206 2001 and 2002 ($y = 2.356x + 10.397$, $R^2 = 0.026$, $P = 0.499$).

1207 Figure 3. Age at death for desert bighorn sheep lambs on the Fra Cristobal Mountains, New
1208 Mexico, USA during 2001 and 2002.

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1225 Table 1. Visually observed production and recruitment to 1 year of desert bighorn sheep lambs
 1226
 1227 on the Fra Cristobal Mountains, New Mexico, USA during 2001 and 2002.
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1230	1231	1232	1233	1234	1235	1236	1237
Year	Ewes	Natality	Production	Mortality	Recruitment	Lambs : 100 Ewes	
1238	1239	1240	1241	1242	1243	1244	1245
2001	27	24	89%	10	58%	52	
1246	1247	1248	1249	1250	1251	1252	1253
2002	26	23	88%	4	83%	73	

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1271 Table 2. Known causes of mortality for desert bighorn sheep lambs on the Fra Cristobal
 1272
 1273 Mountains, New Mexico, USA during 2001 and 2002.
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Cause of death	Year		Total
	2001	2002	
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

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1317 Table 3. Survival to 1 year and cause-specific mortality rate estimates of 7 radio-collared desert
 1318 bighorn sheep lambs in the Fra Cristobal Mountains, New Mexico, USA for 2001.
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Parameter	Estimate	Variance	95% Confidence Limits	
			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

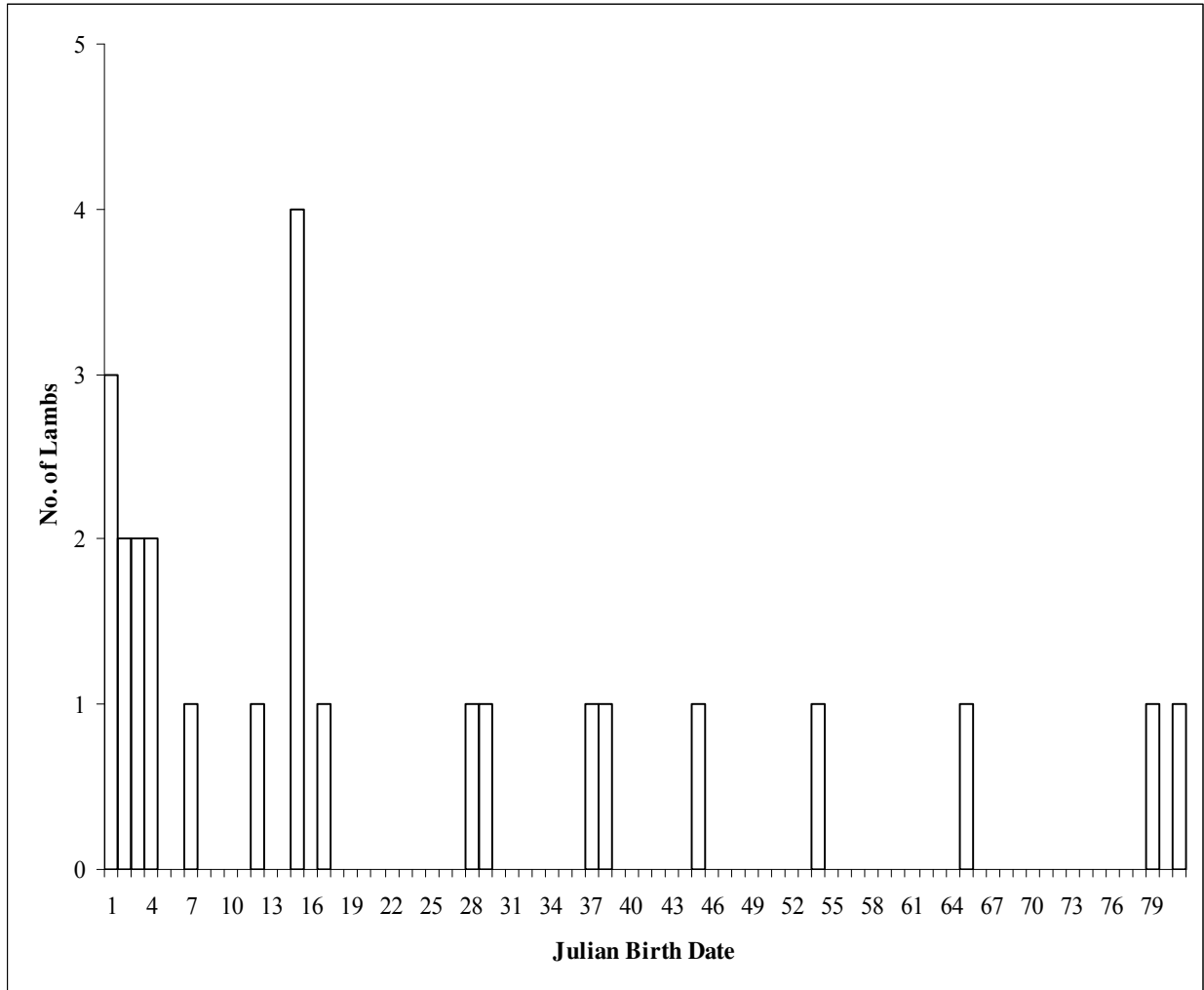
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1363 Table 4. Estimated birth mass (kg), dam age (yr), and birth date (Julian) of dying and surviving
 1364 desert bighorn sheep lambs on the Fra Cristobal Mountains, New Mexico, USA during 2001 and
 1365
 1366
 1367 2002.
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	Dying			Surviving				
	X	SE	n	X	SE	n	t	p
1376 Birth mass	5.54	0.50	6	4.60	0.65	14	-1.08	0.294
1378 Dam age	7.94	0.92	8	8.14	0.63	11	0.19	0.856
1381 Birth date	33.09	8.86	11	9.57	3.84	14	-2.63	0.015

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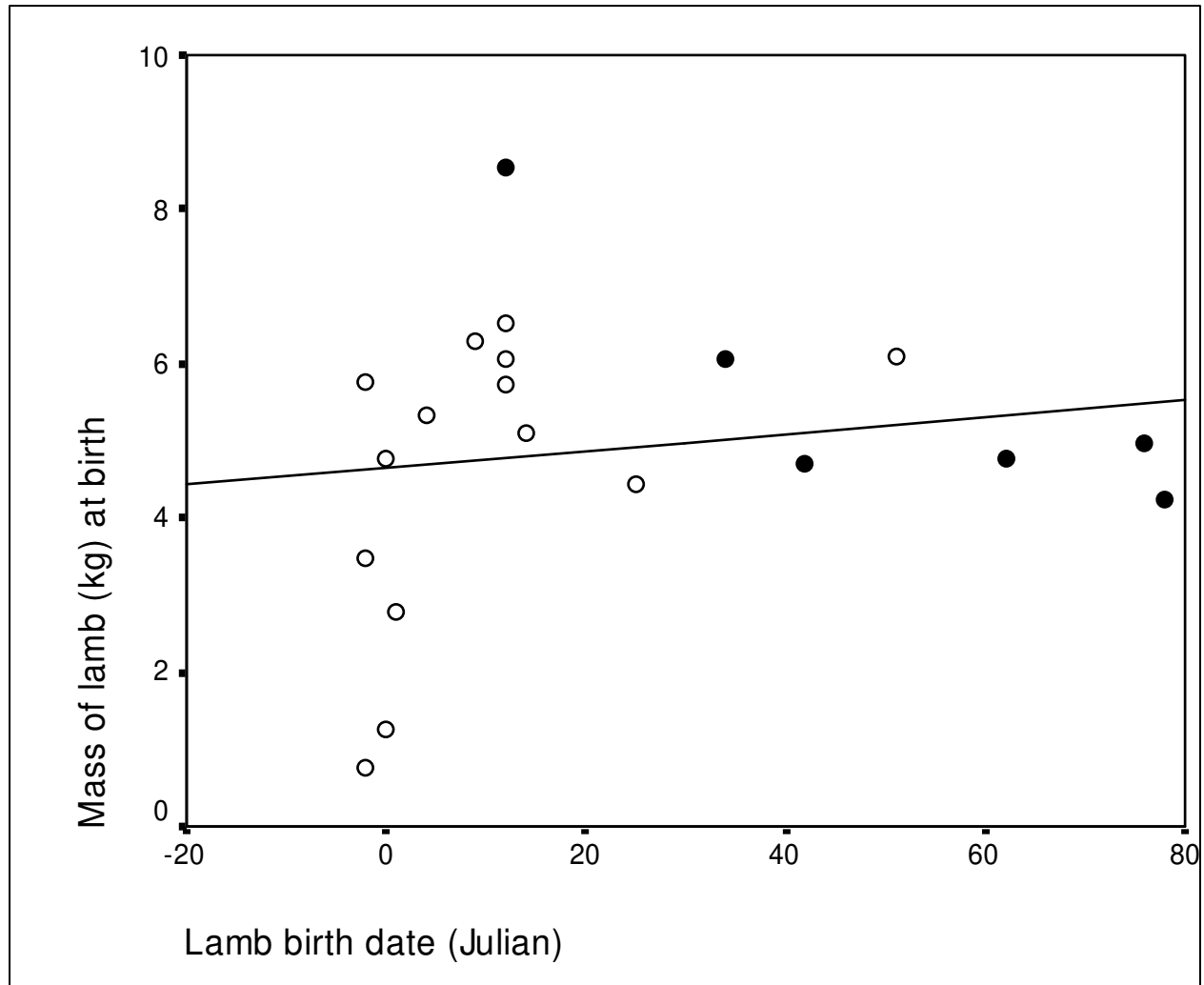
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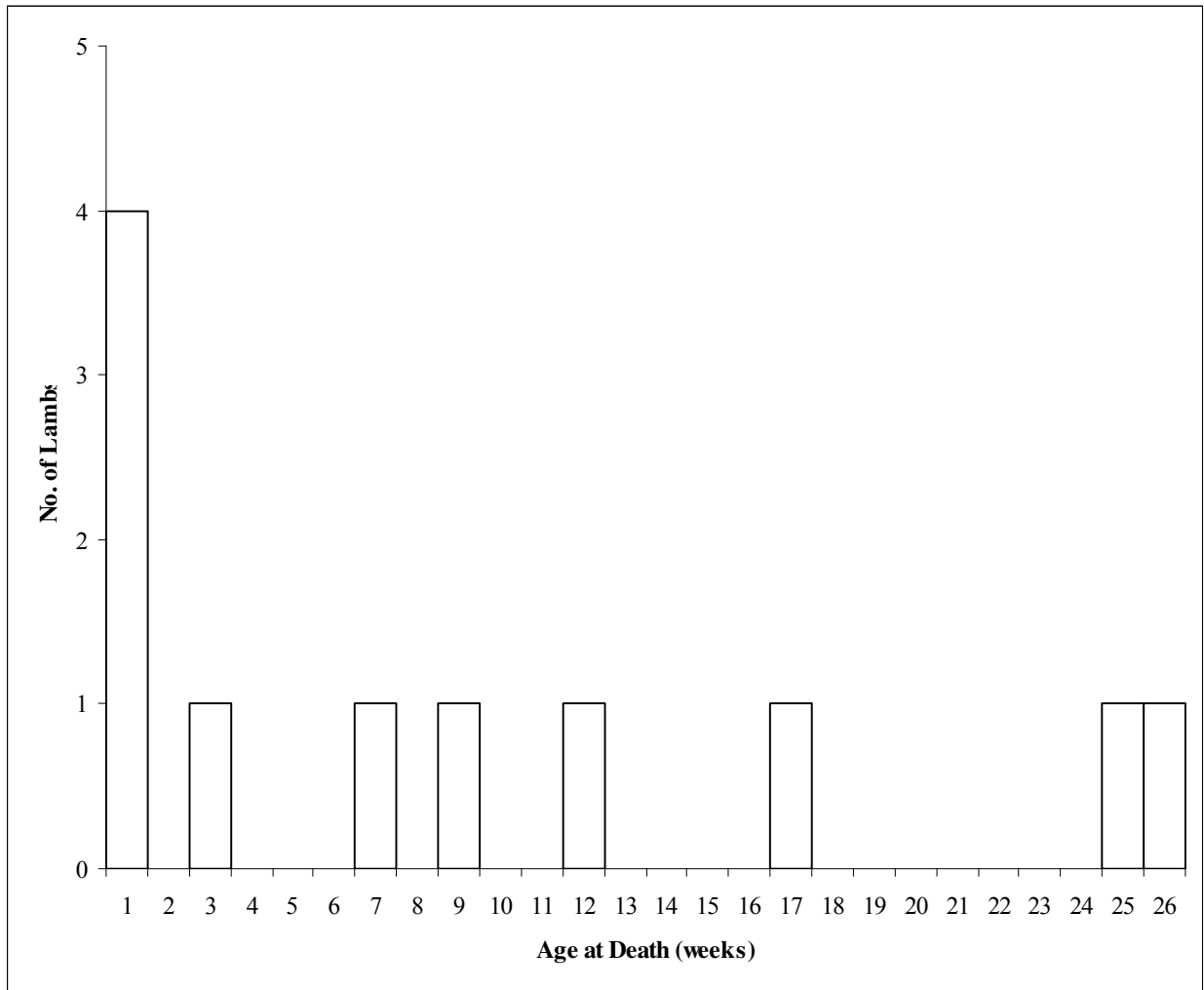
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1474 Figure 3
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1494 Zachary D. Parsons
1495 Wildlife Biology Program
1496 Department of Ecosystem and Conservation Sciences
1497 University of Montana
1498 Missoula, MT 59812
1499 406/243-5272; Fax: 406/243-4557
1500 zachary.parsons@umontana.edu
1501
1502 RH: Habitat at Cougar Predation Sites of Bighorn • Parsons et al.

1503 **Habitat Characteristics of Cougar Predation Sites on Desert Bighorn Sheep**

1504 Zachary D. Parsons,⁹ Wildlife Biology Program, Department of Ecosystem and Conservation
1505 Sciences, University of Montana, Missoula, MT 59812, USA

1506 Kyran E. Kunkel,¹⁰ Turner Endangered Species Fund, 1123 Research Drive, Bozeman, MT
1507 59718, USA

1508 Daniel H. Pletscher, Wildlife Biology Program, Department of Ecosystem and Conservation
1509 Sciences, University of Montana, Missoula, MT 59812, USA

1510 Peter D. Bangs,¹¹ Wildlife Sciences, School of Natural Resources, University of Arizona,
1511 Tucson, AZ 85721, USA

1512 Anthony L. Wright,¹² Hornocker Wildlife Institute/Wildlife Conservation Society, 2023 Stadium
1513 Drive, Suite 1A, Bozeman, MT 59715, USA

1514

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

1515 **ABSTRACT** Bighorn sheep (*Ovis canadensis*) populations suffered declines in distribution and
1516 abundance by the early 1900s. Desert bighorn sheep (*Ovis canadensis mexicana*) were listed as
1517 an endangered species in New Mexico in 1980, and significant resources have been invested in
1518 captive breeding and translocations to restore populations. However, many of the small, isolated
1519 populations of desert bighorn have been slow to increase or are declining, and 1 of the factors
1520 affecting their population growth rates is high mortality due to cougar (*Puma concolor*)
1521 predation. Our objectives were to characterize habitat factors at all known desert bighorn sheep
1522 mortality sites due to cougar predation on the Fra Cristobal Mountains, New Mexico, USA. We
1523 monitored all translocated, radio-collared desert bighorn sheep, as well as additional augmented
1524 radio-collared rams, subsequently re-instrumented ewes, and radio-collared lambs for mortality
1525 signals, and examined carcass and site characteristics to determine the cause of mortality. We
1526 measured habitat characteristics at sites where bighorn were killed by cougars and the same
1527 characteristics at paired control sites. At a broader scale, we developed a geographic information
1528 system to derive habitat characteristics at predation sites, relocation sites representing used areas,
1529 and random sites representing available areas. Visibility was lower at predation sites than nearby
1530 control sites. Slope, elevation, and ruggedness were lower at predation sites than relocation sites,
1531 and predation sites were closer to water and roads than random sites. Wildlife managers should
1532 consider prescribed burning to reduce the encroachment of woody vegetation and increase
1533 visibility, and potentially increase available forage quantity and quality. Managers should also
1534 assess bighorn and cougar use of artificial water developments.

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1536 **KEY WORDS** cougar, desert bighorn sheep, habitat, mortality, New Mexico, *Ovis canadensis*
1537 *mexicana*, predation, *Puma concolor*.

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1539 In the early 19th century, bighorn sheep (*Ovis canadensis*) were widely distributed over western
1540 North America (Buechner 1960). Present distributions and abundances have been significantly
1541 reduced (Krausman and Shackleton 2000). A combination of anthropogenic factors including
1542 excessive hunting, and competition with and diseases introduced by domestic livestock, resulted
1543 in the extirpation of most populations by the early 1900s (Krausman 2000). Bighorn sheep
1544 habitat is naturally fragmented due to their use of isolated, precipitous mountain terrain
1545 (Krausman et al. 1999). The historic occurrence of desert bighorn sheep (*O. c. mexicana*) was
1546 documented in 14 ranges in central and southern New Mexico (New Mexico Department of
1547 Game and Fish [NMDGF] 1995). By 1955, only 2 populations remained and, in 1980, desert
1548 bighorn sheep were listed as an endangered species in New Mexico. In 1972, a captive breeding
1549 population was established at the Red Rock Wildlife Area (RRWA) north of Lordsburg, New
1550 Mexico. Between 1979 and 1999, translocations from the RRWA augmented existing desert
1551 bighorn sheep populations, re-established locally extinct populations, and established new
1552 populations. Translocations as a conservation and restoration tool have become widespread
1553 (Singer et al. 2000). These efforts resulted in 8 mountain ranges with desert bighorn sheep
1554 populations. The requirement for removal from the state endangered species list for desert
1555 bighorn sheep is a minimum of 500 free-ranging animals in at least 3 geographically distinct
1556 populations, each containing at least 100 individuals (NMDGF 2003). Challenges to desert
1557 bighorn sheep restoration include their inherently low rates of increase, difficulty in colonizing
1558 new habitats, and sensitivity to diseases and human disturbances. Threats to bighorn include
1559 predation, habitat degradation from livestock overgrazing and fire suppression, and competing
1560 public interests and increasing human pressure. Desert bighorn sheep populations have been

1561 slow to increase or are declining in all of these mountain ranges. Most populations have suffered
1562 significant mortality due to cougar predation (*Puma concolor*). No animals have been observed
1563 during autumn helicopter surveys in 2 of these ranges since 2000 (NMDGF 2003). While there
1564 has been debate over predicting extinction probabilities for populations of various sizes,
1565 researchers agree that small populations of bighorn sheep are more vulnerable to extinction than
1566 large populations (Berger 1990, 1993; Krausman et al. 1993; Goodson 1994; Wehausen 1999).
1567 Inverse density dependence may contribute to increased predation risk to small groups of
1568 bighorn sheep (Mooring et al. 2004).

1569 Bighorn sheep and cougars have coexisted in the southwest for the past 10,000 years
1570 (Kelly 1980), along with other potential bighorn predators including bobcats (*Lynx rufus*),
1571 coyotes (*Canis latrans*), and golden eagles (*Aquila chrysaetos*). While the primary prey for
1572 cougars is mule deer (*Odocoileus hemionus*), cougars are known to prey on bighorn sheep,
1573 especially in areas where bighorn and deer are sympatric (Anderson 1983, Hayes et al. 2000,
1574 Schaefer et al. 2000). The decline of mule deer populations may contribute to more frequent
1575 bighorn predation by cougars (Kamler et al. 2002, Holl et al. 2004), and Rominger et al. (2004)
1576 speculated that domestic cattle predation subsidized cougar populations, preventing declines in
1577 cougar populations following declines in naturally occurring prey populations. Cougars have
1578 been the primary proximate cause of recent bighorn population declines from California to
1579 Arizona and New Mexico (Hayes et al. 2000, Kamler et al. 2002, Holl et al. 2004, Rominger et
1580 al. 2004, McKinney et al. 2006).

1581 Many studies have been conducted on desert bighorn sheep habitat, however, no studies
1582 have examined the correlation between habitat and sheep mortality. In the absence of a naturally
1583 occurring fire regime, encroachment of trees and shrubs has reduced visibility in bighorn sheep

1584 habitat (Wakelyn 1987). This reduction of habitat visibility may increase predation risk to
1585 cougars, which are ambush predators (Rominger et al. 2004). Bighorn sheep increase their use
1586 of habitat in burned areas likely due to a combination of factors including increased forage as
1587 well as increased visibility (Bentz and Woodard 1988, Smith et al. 1999), and Smith et al. (1999)
1588 suggested that range burning may be an effective management tool to increase bighorn sheep
1589 populations.

1590 Brown et al. (1999) and Laundre and Hernandez (2003) proposed that because cougars
1591 are an ambush predator adept at traveling and killing in rugged terrain, there may be very few
1592 places sheep are not vulnerable to cougars. Predation of desert bighorn sheep by cougars in New
1593 Mexico involved primarily desert bighorn sheep near escape terrain (Creeden and Graham 1997),
1594 consistent with the idea that escape terrain may provide limited benefit for avoidance of cougar
1595 predation (Sawyer and Lindzey 2002, Mooring et al. 2004). Cougars use steep, rugged
1596 topography in many ways similar to the same habitats used by sheep (Logan and Irwin 1985,
1597 Riley and Malecki 2001). Knowledge of habitat characteristics that may affect predation risk of
1598 bighorn sheep to cougars could improve habitat models, lead to specific range management
1599 strategies to improve desert bighorn sheep habitat quality, and enhance recovery of the small
1600 populations of desert bighorn sheep in New Mexico.

1601 Our objective was to determine the role of habitat in desert bighorn sheep mortality by
1602 cougars. We predicted that habitat characteristics at sites where bighorn sheep were killed by
1603 cougars would differ from nearby control sites, relocation sites of bighorn sheep, and random
1604 sites within the home range of bighorn. We predicted that predation sites would be less steep,
1605 lower in elevation, less rugged, and have lower visibility than control, relocation, and random
1606 sites.

1607 **STUDY AREA**

1608 The Fra Cristobal Mountains (FCM) are located approximately 32 km northeast of Truth or
1609 Consequences in Sierra and Socorro Counties in south-central New Mexico, USA. The entire
1610 range lies within the privately-owned Armendaris Ranch (Krausman et al. 2001). The Rio
1611 Grande Valley and Elephant Butte Reservoir bound the range to the west, and the Jornada del
1612 Muerto Basin to the east. The FCM are an east-tilted horst block. The mountains are
1613 characterized by massive granite cliffs and horizontally layered limestone cliff steps (Nelson
1614 1986). Elevations range from 1,400 - 2,109 m, and the range is approximately 5 km wide by 24
1615 km long (105 km²). The FCM are near the northernmost extent of the Chihuahaun Desert (Hunt
1616 1974). Vegetation associations consist of a mosaic of desert scrub and desert grassland at lower
1617 elevations, patchy montane scrub at higher elevations typically between 1,850 and 1,950 m, and
1618 a limited amount of open coniferous woodland near the summit above 1,950 m (Miller 1999).
1619 Five apron water catchment units capable of storing ~19,000 L were developed in 1995 (Dunn
1620 1991) to augment the 3 perennial springs located on the range. Approximately 68% of
1621 precipitation occurred during May through September (Brown 1982), and precipitation at
1622 Elephant Butte Dam averaged 23.6 cm annually (Bangs et al. 2005a, b). The carrying capacity
1623 of the range for bighorn was estimated at 100 to 150 individuals (NMDGF 2003). The FCM
1624 contain approximately 65 km² of suitable desert bighorn sheep habitat, with 22.7 km² of escape
1625 terrain (Dunn 1994). A relatively frequent fire regime has been suggested on the FCM due to
1626 evidence of 2 relatively recent wildfires (Miller 1999). No known domestic sheep herds
1627 occurred within 50 km of the range, and little evidence of domestic livestock herbivory was
1628 observed. Though their proximity to the San Andres Mountains (55 km east of the FCM) with
1629 an extant population and the habitat quality of the FCM made their occurrence probable, we

1630 found no evidence that desert bighorn sheep occupied the FCM. In 1907, 1 desert bighorn sheep
1631 ram was observed in the Caballo Mountains (25 km south of the FCM; Sandoval 1979).
1632 Potential predators of bighorn on the FCM include cougars, bobcats, coyotes, and golden eagles
1633 (Frey 1999, Truett et al. 1999).

1634 **METHODS**

1635 **Monitoring Mortality**

1636 We translocated 37 radio-collared desert bighorn sheep (13 rams and 24 ewes) from the RRWA
1637 to the FCM in autumn 1995, and augmented this population with 7 additional radio-collared
1638 rams in autumn 1997. We conducted a helicopter and net-gun capture of 16 adult ewes (9 of
1639 which were previously radio-collared) in autumn 1999 to maintain radio-telemetric contact with
1640 the herd. We captured and radio-collared desert bighorn lambs ($n = 21$) during the spring of
1641 2001 and 2002. All VHF radio-collars were equipped with mortality sensors (Telonics, Mesa,
1642 Arizona, USA).

1643 We monitored radio-collar signals for mortality via radio-telemetry from the field on a
1644 daily basis for the first 6 months following the initial release. We subsequently monitored the
1645 herd with periodic fixed wing aircraft flights and annual helicopter surveys in autumn. We
1646 monitored bighorn sheep daily from the field via radio-telemetry and direct visual observation
1647 from July 1997 to August 2000; January to August 2001; January to August 2002; and less
1648 frequently from September through December of 2000, 2001, and 2002. We plotted locations on
1649 1:24,000 scale topographical maps when bighorn sheep were visually relocated in the field.

1650 **Assessing Cause of Mortality**

1651 When we received a mortality signal, we located the collar and examined the site and carcass.
1652 We occasionally located un-collared desert bighorn sheep carcasses incidentally during ground

1653 based monitoring efforts and while monitoring radio-collared cougars. We considered the
1654 location of the carcass to be the kill site unless track or other site evidence indicated otherwise.
1655 We determined the cause of death by examining site and carcass characteristics. We considered
1656 predation the cause of death when there was sign of a struggle at the site, blood on the ground or
1657 vegetation, track evidence on the ground, or subcutaneous hemorrhaging at wound sites. We
1658 looked for evidence such as hair, feathers, tracks, scats, vomit, bed sites, toilets, scrapes, whether
1659 the carcass was buried, wounds on the carcass, and the parts of the carcass consumed to
1660 determine the species of predator responsible for death (O’Gara 1978, Wade and Bowns 1982,
1661 Hatter 1984, Kunkel 1997, Kunkel and Pletscher 2000). We incorporated these data into a key to
1662 aid in evaluating and categorizing the type of predator involvement.

1663 **Measuring Habitat Characteristics**

1664 *Ground attributes at predation and control sites.*— We revisited all ewe, ram, and lamb
1665 desert bighorn sheep mortality sites positively identified as cougar predations during the summer
1666 of 2002 and collected habitat data from the ground within a 30 m radius plot. We recorded the
1667 Universal Transverse Mercator (UTM) coordinates of the location. We recorded slope in
1668 degrees using a clinometer, aspect in degrees from a compass, and elevation in meters via GPS.
1669 We categorized the vegetation association as desert grassland, desert scrub, montane scrub, or
1670 riparian. We determined a ruggedness index by choosing a random compass bearing, and
1671 measuring 30 m by line of sight. We then lay down a rope over any contours existing along this
1672 line, and measured the length of the rope when drawn taught. We subtracted 30 from the total
1673 length, and multiplied the resulting number by 100. We determined percent visibility at 15 and
1674 30 m using the ‘staff-ball’ method developed by Collins and Becker (2001). For this technique,
1675 we mounted a 9 cm ball at 1.5 m (to represent average eye level of desert bighorn sheep) to a pvc

1676 pole which we stood at the center of the plot, and then recorded whether we could view the
1677 dimensionless-point target (represented by the intersection of the upper arc of the ball with the
1678 right side of the staff) with 1 eye from a repetitious stationary posture at specific points (every 15
1679 degrees at a 15 m radius, every 10 degrees at a 30 m radius) along the specified radii at 0.5 m
1680 from the ground (to approximate cougar eye level). We then divided the number of points seen
1681 by the total number of points sampled to estimate percent cover. We also conducted a 30 m line
1682 transect in a random compass direction, for which we measured the distances in cm that the
1683 transect was overlapped by vegetation. We then divided the total vegetation cover by the total
1684 distance to estimate percent vegetation cover. We collected the same habitat characteristic data
1685 on the ground described above for a paired randomly selected control site; these control sites
1686 were located 500 m in a random compass bearing direction from their associated predation site.
1687 The locations of the control sites were designed to test whether habitat characteristics in the
1688 immediate area differed from those at predation sites. Habitat variables measured on the ground
1689 represented the finest scale of analysis.

1690 *Derived attributes at predation, relocation, and random sites.*— We developed a
1691 geographic information system (GIS) model using ArcView with Spatial Analyst (Version 3.2,
1692 ESRI, Redlands, California, USA) to compare habitat variables at cougar kill sites to those at
1693 different spatial scales: areas used by and available for use by desert bighorn sheep. We
1694 determined elevation from 10-m spatial resolution digital elevation models from the United
1695 States Geological Survey (USGS). We also derived aspect and slope in degrees. We determined
1696 substrate (i.e., limestone, granite, shale, etc.) and vegetation (i.e., desert scrub / desert grassland,
1697 montane scrub / coniferous woodland, etc.) from existing layers (Neher 1984, Nelson 1986,
1698 Miller 1999). We calculated distance to $\geq 60\%$ slope patches with a minimum size of 1 ha as a

1699 surrogate for escape terrain due to ambiguity in incorporating ruggedness (Tilton 1977,
1700 Armentrout and Brigham 1988, McCarty and Bailey 1994). We also calculated distance to roads
1701 and distance to water sources, including naturally occurring perennial springs as well as artificial
1702 water developments. We calculated terrain ruggedness using an existing routine and script
1703 (Pincus 1956, Hobson 1972, Durrant 1996). To calculate visibility, we performed a view shed
1704 analysis for a 50 m radius with an offset height of 1.5 m to approximate average bighorn sheep
1705 eye level (Sorenson and Lanter 1993). We generated a 100% minimum convex polygon (MCP)
1706 around all bighorn sheep visual relocations using the Animal Movement extension (Hooge and
1707 Eichenlaub 1997). We compared derived habitat characteristics for predation sites with
1708 characteristics of all desert bighorn sheep relocation sites, i.e., the scale of habitat used by desert
1709 bighorn sheep. We then compared habitat variables at predation sites with random sites (sites
1710 randomly selected from within the MCP), i.e., the scale of habitat available for use by desert
1711 bighorn sheep.

1712 **Data Analysis**

1713 *Univariate analyses.*— We used SPSS (version 13.0, Chicago, Illinois, USA) for
1714 statistical analyses. To meet test assumptions, we examined the data for normality using the
1715 Shapiro-Wilk test and the Kolmogorov-Smirnov test with Lilliefors significance correction. To
1716 reduce non-normality in the ground data, we used a square root transformation on percent
1717 vegetation cover and visibility at 15 m, and a logarithmic transformation on visibility at 30 m,
1718 and back transformed variables for interpretation. We used univariate analyses to test for
1719 differences in each individual continuous variable for each of the 3 different scales of
1720 comparison. We used Student's t-test to compare differences in means for paired samples for
1721 predation sites and control sites, and for independent samples for predation sites and relocation

1722 sites, and predation sites and random sites. For independent samples, we examined the
1723 assumption of equality of variances using Levene's test, and when F values were insignificant,
1724 we used t values for which equal variances were not assumed. We set significance levels at $P <$
1725 0.05 for all statistical tests. We compared categorical habitat variables using Pearson's chi-
1726 square test and Fisher's exact test. We categorized aspect into east (0 – 179 degrees) and west
1727 (180 – 359 degrees) facing slopes, due to the FCM running essentially N-S, thereby providing
1728 mostly east or west facing slopes. All comparisons that were statistically significant were
1729 retained for logistic regression model development.

1730 *Logistic regression.*— We calculated binary logistic regression models for the 3 sets of
1731 sites using the stepwise backward elimination process based on the Wald statistic ($\alpha = 0.05$ to
1732 enter and remain) to evaluate whether physiographic characteristics of predation sites of cougars
1733 on desert bighorn sheep differed from sites used by or available to bighorn. The dichotomous
1734 dependent variable was a predation site or a non-predation site (i.e., a control, relocation, or
1735 random site). We examined the covariates for multicollinearity and removed the least
1736 explanatory of any highly intercorrelated pair of variables when $r^2 \geq 0.5$. We examined the final
1737 models for reliability using the Hosmer-Lemeshow goodness-of-fit test.

1738 **RESULTS**

1739 We measured habitat variables on the ground at the locations of 26 carcasses of desert bighorn
1740 sheep (10 ewes, 10 rams, and 6 lambs) that we confirmed to have been killed by cougars, as well
1741 as their paired control sites. These predations occurred from December 1995 through August
1742 2002. All of the lamb mortalities were documented in 1999, 2001, and 2002. We compared GIS
1743 physiographic characteristics of 36 desert bighorn sheep predation sites by cougars (10 of which
1744 occurred after we finished collecting ground data) with derived characteristics of relocation sites

1745 of desert bighorn sheep representing areas used by bighorn, as well as characteristics of random
1746 sites selected from within the desert bighorn sheep home range.

1747 Ground-based measurements at predation and control sites were similar in slope,
1748 elevation, ruggedness, vegetation cover, aspect, and vegetation classification (Table 1, Figure 1).
1749 Average visibility at 15 m was 19.3% less at predation sites than control sites, and visibility at 30
1750 m was 15.7% less. Using logistic regression, only visibility at 15 m successfully predicted
1751 whether a site was a mortality or control site (Table 4).

1752 Using GIS and derived physiographic characteristics, we found that slope was 9.4
1753 degrees less at predation sites, elevation was 55 m lower, and ruggedness was 1.37% less than at
1754 relocation sites (Table 2). Visibility at 50 m, however, was on average 15.7% higher at predation
1755 sites than relocation sites, and we found no difference in ruggedness at 90 m or distance to
1756 escape terrain, water, or roads between predation sites and relocation sites. Vegetation and
1757 substrate associations were different at predation sites than relocation sites, with predation sites
1758 occurring less frequently in desert grassland – montane scrub / granite and desert scrub – desert
1759 grassland / alluvium associations than relocations, and more frequently in desert scrub – desert
1760 grassland / limestone –granite and desert scrub – desert grassland – montane scrub / limestone
1761 associations (Table 3). We found no difference in percent of predation sites on east and west
1762 facing slopes compared to relocation sites (Figure 1). Slope and visibility at 50 m were the only
1763 variables important in predicting predation sites versus relocation sites using logistic regression
1764 (Table 5).

1765 We found that ruggedness at 90 m averaged 1.47% greater, distance to water averaged
1766 884 m closer, and distance to roads averaged 260 m closer at predation sites than random sites
1767 (Table 2). We found no difference between sites in slope, elevation, ruggedness at 310 m,

1768 visibility at 50 m, or distance to escape terrain. Predation occurred more on east facing slopes
1769 than expected based on availability (Figure 1). Predation sites occurred more than expected in
1770 desert grassland – montane scrub / granite and desert scrub – desert grassland / limestone –
1771 granite associations, and less than expected in desert scrub – desert grassland / limestone
1772 associations (Table 3). Ruggedness at 90 m and distance to water were included in the logistic
1773 regression model to distinguish between predation and random sites, with predation sites being
1774 more rugged and closer to water (Table 6).

1775 **DISCUSSION**

1776 Spatial scale considerations are important when examining predator and prey habitat selection
1777 (Bowyer and Kie 2006). Fine scale habitat characteristics are important when assessing
1778 predator-prey interactions (Grant et al. 2005), however data with a coarse grain of resolution may
1779 also provide adequate detail to categorize habitat of desert bighorn (Divine 2000). We
1780 characterized habitat factors at cougar-caused predation sites at 3 different scales of analysis: 1)
1781 by comparing data collected within small (30 m diameter) plots on the ground at predation sites
1782 and paired site-specific control sites, 2) by comparing derived attributes at broader areas
1783 (visibility at 50 m, ruggedness at 90 and 310 m) for predation sites with relocations of desert
1784 bighorn sheep representing areas used by bighorn, and 3) comparing the same derived attributes
1785 for predation sites and random sites selected from within an area defined as available for use by
1786 bighorn. Deriving attributes for relocation and random sites allowed us to compare many more
1787 sites for which collection of ground data was logistically infeasible. While animals generally
1788 select habitats which provide the best components for survival and reproduction (Fretwell and
1789 Lucas 1970), habitat selection of translocated populations may differ from more established
1790 populations.

1791 As predicted, we found that visibility was lower at predation sites than paired control
1792 sites. This likely resulted from increased vulnerability to attack by ambush. The features that
1793 produced lower visibility at these sites included vegetation, primarily bushes and trees, as well as
1794 topography and boulders. Vegetation succession can cause bighorn sheep habitat loss in the
1795 absence of a naturally occurring fire regime or habitat management (Wakelyn 1987). Fire has
1796 been shown to increase bighorn sheep range carrying capacity (Holl et al. 2004). Bighorn have
1797 been shown to increase their use of burned areas, possibly due to increased visibility and
1798 improved forage quality and quantity (Bentz and Woodard 1988). Foraging efficiency has been
1799 shown to increase with increasing visibility (Risenhoover and Bailey 1985). Prescribed burning
1800 has been used to maintain and restore bighorn sheep habitat, and may enhance and expand
1801 populations (Smith et al. 1999). Large herbivore habitat selection generally involves tradeoffs
1802 between acquiring resources and avoiding predators (Bowyer and Kie 2006), and individuals in
1803 prey populations may limit their use of high-quality habitat due to predation risk (Pierce et al.
1804 2004). Visibility may also decrease as ruggedness increases due to topographic obstruction in
1805 mountainous terrain.

1806 Also as we predicted, we found that predation sites were less steep, at lower elevations,
1807 and less rugged than relocation sites. Contrary to predictions, however, derived visibility was
1808 higher at predation sites than relocation sites. We believe this visibility result was due to the
1809 limited accuracy of view shed analysis techniques (Maloy and Dean 1991). Alternately,
1810 however, it may be because rugged, steep sites may have lower visibility due to topographical
1811 obstruction. Bighorn may use areas with lower visibility during lambing periods for hiding
1812 cover, sacrificing detection of predators which would benefit from stalking cover, in a strategy of
1813 predator avoidance versus predator evasion (Bergerud 1984, 1987; Bangs et al. 2005b).

1814 Behaviors to avoid one predator may make prey more vulnerable to predation by another
1815 predator (Atwood et al. 2007). Bangs et al. (2005b) found that young lambs may be most
1816 vulnerable to avian predators such as golden eagles on cliffs or extremely steep slopes that would
1817 be considered escape terrain. Traditional definitions of escape terrain may be more appropriate
1818 for evasion of coursing predators such as wolves and coyotes, as opposed to stalking or ambush
1819 predators such as cougars.

1820 We found that predation sites were more rugged and closer to water and roads than
1821 random sites, and occurred more on east facing slopes. We believe the results for ruggedness
1822 were probably an issue of scale, because sheep selected more rugged areas for use than were
1823 generally available in the FCM. The difference we found in aspect was also probably due to
1824 scale because habitat available for use by bighorn does not reflect the level of selection
1825 represented in areas actually used by bighorn, and the west face has the steepest and most rugged
1826 terrain. We suspect bighorn selected against proximity to roads associated with human
1827 disturbance (Papouchis et al. 2001), although the level of human disturbance on this private
1828 ranch is low, and we found no evidence that cougars preferentially used roads as travel corridors.
1829 However, bighorn may be selecting against proximity to water, or conversely cougars may be
1830 selecting for proximity to water. Bangs et al. (2005) did not observe bighorn use of artificial
1831 water developments, even during periods of below average precipitation. Krausman and
1832 Etchberger (1995) also found that water catchments did not attract bighorn sheep, and Broyles
1833 and Cutler (1999) found that surface water availability did not affect bighorn populations.
1834 Effects of such developments have not been documented (Broyles 1995). Other researchers
1835 suggest that water availability is the single most limiting factor of desert bighorn populations
1836 (Turner and Weaver 1980, Messing 1990). Although bighorn reliance on water has been shown

1837 in some ranges (Werner 1989), bighorn in other ranges are thought to get their water
1838 requirements from forage, especially from succulent vegetation such as cacti (Watts 1979,
1839 Warrick and Krausman 1989, Oehler et al. 2003). In fact, Rosenstock et al. (1999) speculated
1840 that wildlife water developments may have negative impacts by increasing predation,
1841 competition, and disease transmission.

1842 Little is known about how habitat characteristics affect the security of bighorn sheep in
1843 relation to cougars. Most studies of habitat do not address whether habitat selection affects
1844 survival (White and Garrott 1990). We found that desert bighorn sheep are less likely to be
1845 killed by cougars in areas with higher visibility, greater slope, higher elevations, more
1846 ruggedness, and farther from water and roads; these areas may serve as refugia from stalking
1847 predators. These habitat characteristics may be effective in deterring ambush predators such as
1848 cougars (Mooring et al. 2004). While desert bighorn sheep population size has been correlated
1849 with area of escape terrain (McKinney et al. 2003), the way escape habitat is defined may need
1850 to be reassessed. Also, assessments of translocation sites do not normally include quantifying
1851 forage quality and quantity (DeYoung et al. 2000). We recommend modeling to refine escape
1852 habitat and identify areas in proximity to high quality forage, and then estimate how much of that
1853 is available in proposed reintroduction sites. Further, this may have implications for where to
1854 target cougar monitoring and management.

1855 **MANAGEMENT IMPLICATIONS**

1856 We found that there are certain habitat characteristics such as visibility, slope, elevation, and
1857 ruggedness that affected the vulnerability of desert bighorn sheep to predation by cougars. These
1858 areas need to be better identified and managed by wildlife professionals, and their juxtaposition
1859 with foraging areas should be analyzed. They should also be selected for when considering areas

1860 for potential translocations and reintroductions. Range managers should examine if
1861 encroachment of trees and shrubs has reduced visibility in bighorn sheep habitat. Prescribed
1862 burning may be used to improve habitat for desert bighorn sheep by increasing visibility and
1863 decreasing predation risk to cougars, as well as improving forage quality and quantity. Bighorn,
1864 mule deer, and predator use of artificial water developments should be investigated. If cougars
1865 and mule deer are utilizing water catchments, this may encourage cougar and bighorn overlap,
1866 potentially increasing incidental predation as well as increasing the potential for learned behavior
1867 in targeting bighorn as prey and facilitating potential competition and disease transmission.
1868 Wildlife managers may consider removing or modifying artificial water developments to
1869 preclude use by predators and mule deer.

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2085 Figure 1. Percent of predation ($n = 36$), control ($n = 26$), relocation ($n = 12,658$), and random (n
2086 = 3,000) sites of desert bighorn sheep derived from GIS (except for control which was measured
2087 on the ground) occurring on eastern or western facing slopes, FCM, New Mexico, USA.

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2108 Table 1. Habitat variables measured on the ground at cougar predation sites ($n = 26$, $df = 25$) on
 2109 desert bighorn sheep compared to paired control sites, FCM, New Mexico, USA.
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2112 2113 2114 2115 2116 2117 2118 Variable	2119 2120 2121 Predation		2122 2123 2124 Control		2125 2126 2127 t	2128 2129 P
	2130 \bar{X}	2131 SE	2132 \bar{X}	2133 SE		
2134 Slope ($^{\circ}$)	2135 14.4	2136 1.85	2137 17.4	2138 1.86	2139 -1.277	2140 0.213
2141 Elevation (m)	2142 1661	2143 22.2	2144 1666	2145 21.8	2146 -0.274	2147 0.786
2148 Ruggedness index	2149 13.0	2150 1.82	2151 16.2	2152 4.25	2153 -0.661	2154 0.515
2155 Visibility, 15 m (%)	2156 49.1	2157 0.14	2158 68.4	2159 0.10	2160 -2.806	2161 0.010
2162 Visibility, 30 m (%)	2163 27.5	2164 1.13	2165 43.2	2166 1.09	2167 -4.192	2168 0.000 ^a
2169 Vegetation cover (%)	2170 32.4	2171 0.05	2172 34.7	2173 0.02	2174 -0.643	2175 0.526

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2154 Table 2. Habitat variables derived from GIS at cougar predation sites ($n = 36$) on desert bighorn
 2155 sheep compared to relocation sites ($n = 12,658$) and random sites ($n = 3,000$), FCM, New
 2156 Mexico, USA.
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2161 2162 2163 2164 Variable	2162 2163 Predation		2162 2163 Relocation		2162 2163 Random	
	2165 2166 \bar{X}	2165 2166 SE	2165 2166 \bar{X}	2165 2166 SE	2165 2166 \bar{X}	2165 2166 SE
2167 2168 Slope (°)	20.3	1.53	29.7 ^a	0.10	19.3	0.20
2169 2170 Elevation (m)	1651	20.4	1706 ^a	0.97	1687	2.40
2171 2172 Ruggedness, 90 m (%)	3.73	0.62	3.45	0.03	2.26 ^b	0.05
2173 2174 Ruggedness, 310 m (%)	5.97	0.65	7.34 ^a	0.03	4.84	0.06
2175 2176 Visibility, 50 m (%)	64.7	2.82	49.0 ^a	0.13	62.7	0.33
2177 2178 Distance to escape terrain (m)	1092	158	831	7.24	941	13.9
2179 2180 Distance to water (m)	1399	164	1381	8.68	2283 ^b	23.3
2181 2182 Distance to roads (m)	588	80.3	550	3.05	848 ^b	13.2

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2185 ^aPredation site differed from relocation site ($df = 35$, $P < 0.05$).
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2187 ^bPredation site differed from random site ($df = 35$, $P < 0.05$).
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2200 Table 3. Vegetation and substrate associations (%) derived from GIS at predation ($n = 36$),
 2201 relocation ($n = 12,658$), and random ($n = 3,000$) sites of desert bighorn sheep, FCM, New
 2202 Mexico, USA.
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2208 Vegetation / Substrate Association^a

2209 Site	2210 0	2211 1	2212 2	2213 3	2214 4	2215 5	2216 6	2217 7	2218 8	2219 9
2220 Predation	2221 36.1	2222 0	2223 0	2224 11.1	2225 36.1	2226 8.3	2227 0	2228 0	2229 8.3	2230 0
2231 Relocation	2232 45.3	2233 0	2234 0.2	2235 25.8	2236 14.5	2237 10.4	2238 1.0	2239 0.8	2240 1.6	2241 0.3
2242 Random	2243 16.7	2244 1.3	2245 6.0	36.1	13.9	8.7	0.4	2.3	11.9	2.7

2221 ^a0 = Desert grassland – montane scrub / granite, 1 = Desert scrub / alluvium, 2 = Desert
 2222 scrub – desert grassland / alluvium, 3 = Desert scrub – desert grassland / limestone, 4 = Desert
 2223 scrub – desert grassland / limestone – granite, 5 = Desert scrub – desert grassland / shale, 6 =
 2224 Desert scrub – desert grassland / sandstone, 7 = Desert scrub – desert grassland / volcanic cinders
 2225 and basalt flows, 8 = Desert scrub – desert grassland – montane scrub / limestone, 9 = Montane
 2226 scrub – coniferous woodland / limestone.
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2246 Table 4. Logistic regression results from ground measurements at predation sites ($n = 26$) versus
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 2248 paired control sites of desert bighorn sheep, FCM, New Mexico, USA.
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2250	2251	2252						
2252	2253	B	SE	W_1^a	P	$\chi^2_7^b$	P	
2254	2255	Visibility, 15 m (%)	-0.034	0.014	6.193	0.013	5.125	0.645
2256	2257	Constant	2.106	0.907	5.385	0.020		

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 2260 ^aWald's statistic.

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 2262 ^bHosmer-Lemeshow goodness-of-fit test.
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2292 Table 5. Logistic regression results from GIS derived characteristics at predation sites ($n = 36$)
 2293 versus relocation sites ($n = 12,658$) of desert bighorn sheep, FCM, New Mexico, USA.
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2304	2304	2304	2304	2304	2304	2304	2304
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2335	2335	2335	2335	2335	2335	2335	2335
2336	2336	2336	2336	2336	2336	2336	2336
2337	2337	2337	2337	2337	2337	2337	2337

2307 ^aWald's statistic.

2308 ^bHosmer-Lemeshow goodness-of-fit test.

2309 ^c $P \leq 0.001$.

2338 Table 6. Logistic regression results from GIS derived characteristics at predation sites ($n = 36$)
 2339 versus random sites ($n = 3,000$) of desert bighorn sheep, FCM, New Mexico, USA.
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2343	2344	2345	2346	2347	2348	2349	2350
Variable	B	SE	W_1^a	P	$\chi^2_8^b$	P	
2346	2347	2348	2349	2350	2351	2352	2353
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			

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2354 ^aWald's statistic.

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2356 ^bHosmer-Lemeshow goodness-of-fit test.

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2358 ^c $P \leq 0.001$.

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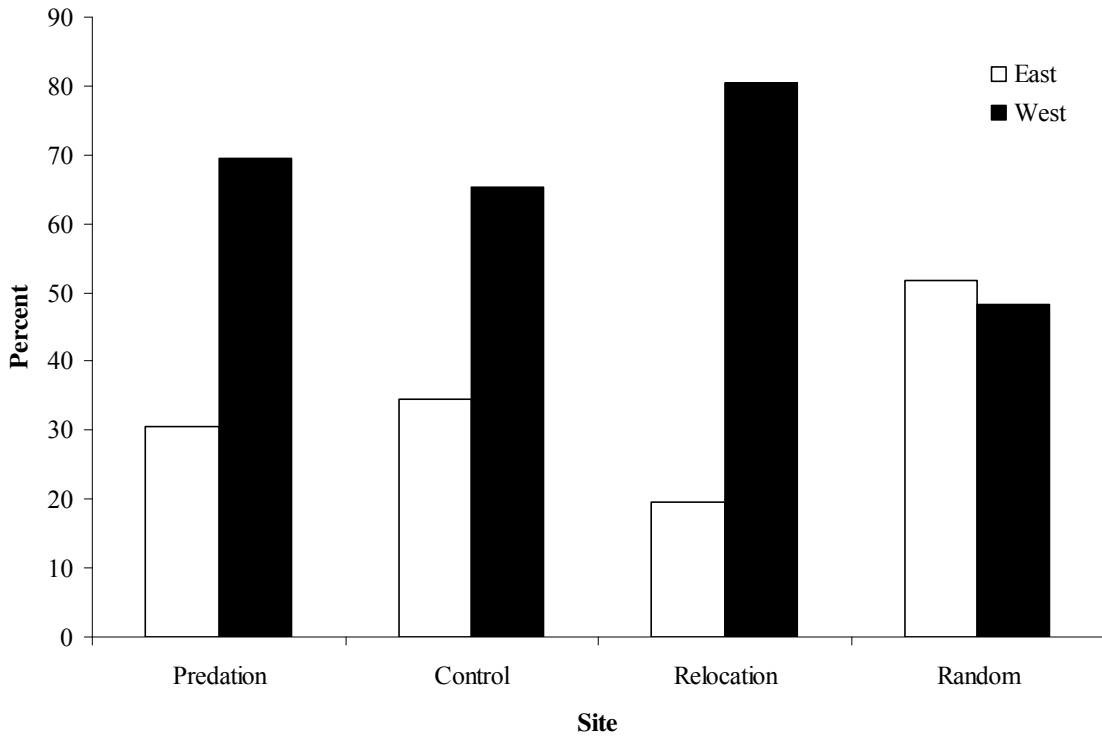
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2384 Figure 1
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