A COMPARISON OF MORTALITY RATES FOR DESERT AND ROCKY MOUNTAIN BIGHORN SHEEP UNDER TWO COUGAR REMOVAL REGIMES

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Abstract: Desert bighorn sheep (*Ovis canadensis nelsoni*) were listed as a state endangered species in New Mexico in 1980 when their numbers were <70 animals in the wild. In the 1990s, radiocollaring and monitoring efforts documented that approximately 85% of known-cause mortality was due to cougar (*Puma concolor*) predation. A cougar removal program in desert bighorn ranges was initiated in 2001, and new herds were subsequently added to the program as bighorn were reintroduced into new ranges. Overall average annual mortality declined from 0.21 (SE = 0.01) to 0.11 (SE < 0.01) and cause-specific average annual mortality from cougar predation declined from 0.16 (SE = 0.01) to 0.05 (SE < 0.01) from the time prior to implementing cougar removal (1992–2002) to the time following implementing cougar removal (2002–2011). Desert bighorn historically occupied the San Francisco River (SFR) in the Gila National Forest. Following their extirpation in the first half of the 1900s, the New Mexico Department of Game and Fish introduced Rocky Mountain bighorn sheep (*Ovis canadensis canadensis*) into the area because no desert bighorn were available for transplant. Cougar removal has never been implemented to protect the SFR herd; however, overall average annual mortality increased from 0.19 (SE = 0.03) in 1997–2001 during the period prior to cougar removal in desert herds, to 0.24 (SE = 0.02) in 2003–2011 during the period following cougar removal in desert herds. Cause-specific average annual mortality from cougar predation increased from 0.08 (SE = 0.03) to 0.13 (SE = 0.03) in the same time periods. Cougar-caused mortality sharply increased from October 2009–2011, with a cause-specific average annual mortality rate of 0.31 (SE = 0.06). These data suggest that without cougar removal in desert bighorn herds, mortality rates may have been much higher. A recently implemented cougar removal program in the SFR is designed to prevent the bighorn herd from being extirpated.

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Key words: bighorn sheep, *Ovis canadensis*, cougar, *Puma concolor*, mortality rate, New Mexico, predation.

Historically, thousands of desert bighorn sheep (*Ovis canadensis nelsoni*) were likely distributed in most arid mountain ranges in southern and central New Mexico. Evidence of their occupation is available for 14 ranges (Buechner 1960). During European settlement of New Mexico, as in other western states, bighorn populations declined rapidly due to diseases introduced by domestic livestock and illegal hunting (Buechner 1960). Bighorn are particularly sensitive to bacterial pneumonia, a disease carried by domestic sheep and easily transmitted to wild sheep. Approximately 5 million domestic sheep grazed annually in New Mexico by the 1880s (Scurlock 1998); these sheep were likely a major factor in bighorn population declines. Bighorn hunting was prohibited in 1889, but uncontrolled market hunting continued to be an important cause of mortality in some areas.

In 1980, with <70 desert bighorn in the wild, desert bighorn were listed as a state endangered species in New Mexico (NMDGF 2003). In the 1960s, the New Mexico Department of Game and Fish reintroduced bighorn to the San Francisco River (SFR) and Turkey Creek areas in the Gila National Forest. No desert bighorn were available

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at the time; therefore, Rocky Mountain bighorn (*Ovis canadensis canadensis*) were released instead. In the 1980s and 1990s, translocation of desert bighorn, primarily out of the Red Rock captive breeding facility, was the principal management action used to increase population numbers. The first transplant occurred in 1979. Despite transplanting 249 bighorn between 1979 and 2001, the desert bighorn population remained below 170 individuals.

Through monitoring radiocollared bighorn in the 1990s, it was documented that cougar (*Puma concolor*) predation was the principal limiting factor in all desert bighorn populations where radiocollared individuals were monitored (Rominger and Dunn 2000, Rominger et al. 2004), with 85% of all known-cause mortalities attributed to cougar predation (NMDGF 2003). Cougar predation has been documented to limit desert bighorn populations throughout their range (Wehausen 1996, Hayes et al. 2000, Creeden and Graham 1997, Kamler et al. 2002, Rominger et al. 2004). Predator control of top-carnivores is controversial (Reiter et al. 1996, Minteer and Collins 2005, Rominger et al. 2006); however, predator control is a recommended management action for the conservation of endangered species (Hecht and Nickerson 1999). In 2001, the New Mexico Department of Game and Fish implemented a cougar removal program to protect the remaining state endangered desert bighorn.

The purpose of this study was to compare desert bighorn mortality rates from all causes of mortality and from cause-specific cougar predation mortality during the period prior to cougar removal to the period following cougar removal. Although cougar removal was not implemented in the SFR Rocky Mountain bighorn population during these time periods, mortality rates in SFR can serve as a comparison group with which to evaluate efficacy of the program in desert bighorn herds, and recommend management actions in the SFR herd.

STUDY AREA

This study took place in 5 mountain ranges in the Chihuahuan desert of southern New Mexico: the Hatchet, Peloncillo, Ladron, Fra Cristobal, and San Andres mountains. The vegetation was classified as desert grassland (Dick-Peddie 1993), and was dominated by grama (*Bouteloua* spp.), juniper (*Juniperus* spp.), agave (*Agave* spp.), yucca (*Yucca baccata, Y. schotti*), sotol (*Dasylirion wheeleri*), oak (*Quercus* spp.), and mountain mahogany (*Cercocarpus montanus*; Sandoval 1979). Elevation ranges from approximately 1300 m to a maximum of 2510 m (San Andres Peak), and contains steep, rocky slopes. Average daytime maximum temperatures range from 13^0 C in December and January, to 34^0 C in June and July. Average daytime minimum temperatures range from -6^0 C in January to 18^0 C in July. Average annual precipitation is 26.4 cm with approximately 65% falling between July–October (National Oceanic and Atmospheric Administration 2012 and Western Regional Climate Center 2013).

This study also included the SFR drainage. The predominant vegetation was classified as pinion-juniper woodland (Dick-Peddie 1993), and was dominated by juniper and pinion pine (*Pinus edulis*), and by willows (*Salix* spp.) and cottonwood (*Populus fremontii*) in the riparian zone. Desert scrub comprised of oaks, mesquite (*Prosopis juliflora*), cat-claw acacia (*Acacia greggii*), mountain mahogany (*Cercocarpus montanus*), and yucca (*Yucca* spp.), with grama grasses (*Bouteloua* spp.) in the understory was also found in the area. Elevation ranges from approximately 1280 m to 1770 m. Average daytime maximum temperatures range from 14^0 C in January to 33^0 C in June and July. Average daytime lows range from -5^0 C in November and December to 14^0 C in July. Average annual precipitation is 45.5 cm with 53% falling between July–October (Western Regional Climate Center 2013).

METHODS

Bighorn Sheep Capture and Monitoring

From 1992–2011 desert and Rocky Mountain bighorn were captured using the helicopter netgun method (Barrett et al. 1982). Rocky Mountain bighorn were also captured using drop-nets and dart-guns with a Carfentanil (Wildlife Pharmaceuticals, Inc., Fort Collins, CO) and xylazine hydrochloride (Rompun®; Bayer, Inc., Etobicoke, Ontario, Canada) cocktail. Both subspecies of bighorn were radiocollared with mortality sensor collars from a variety of manufacturers (AVM Instrument Co., Livermore, CA, USA; Advanced Telemetry Systems, Isanti, MN; Lotek, Newmarket, Ontario, CA; Telemetry Solutions, Concord, CA, USA; and Telonics, Mesa, Arizona, USA).

Bighorn sheep were monitored during fixed-wing telemetry flights conducted approximately monthly, and from the ground with varying intensity. When a mortality signal was obtained, biologists went to the mortality site to assess cause of mortality. Cougar predation was considered cause of mortality in the presence of: a dragline from the kill to cache site; cougar tracks at the kill or cache site; canine puncture wounds in the neck or face; canine punctures or claw slices on the radiocollar; rumen extracted and uneaten or buried; carcass partially or completely buried with rocks, sticks, grass, etc.; broken neck; rostrum bones eaten back >10 cm; braincase cracked (female bighorn only); humerus and/or femur cracked; cougar hair or scrapes present at or near the kill or cache site; or multiple cache sites.

Cougar Removal Policy

Contracted houndsmen and snaremen began removing cougars in the Peloncillo, Hatchet, and Ladron mountains in October 2001, the San Andres in October 2002, and the Fra Cristobals in 2006. Following the first year of implementation, the cougar removal policy in the San Andres was different than in the other ranges; therefore, only data from the first year of cougar removal is included for the San Andres. Snaremen were required to use leg-hold snares and to check snares a minimum of once every 48 hours, with a minimum of once daily checks in certain circumstances.

STATISTICAL ANALYSIS

We used the nest-survival model in program MARK (White and Burnham 1999) to calculate bighorn mortality rates. We examined average annual mortality rates from all causes of mortality and from cougar predation only. For desert bighorn, we divided mortality data into 2 time periods: 1) a period prior to implementation of cougar removal which includes the period when no cougars were being removed to protect bighorn and the first year cougar removal was initiated (Table 1); and 2) a period following implementation of cougar removal that begins one year after implementing cougar removal in each herd (Table 1). We hypothesized that one year of the management action would sufficiently reduce cougar numbers to afford protection for bighorn herds, and be sufficient time to induce a bighorn population response. Mortality rates were calculated on a state-wide level and for individual herds. For SFR Rocky Mountain bighorn, we calculated mortality rates for all causes of mortality and for cougar predation only for time periods generally corresponding to dates prior to cougar removal (1997–2001) and following cougar removal in the desert (2003–2011), although cougars were never removed in SFR. We also calculated annual mortality rates for SFR.

We used Akaike's Information Criterion corrected for small sample size (AIC_c) to determine if the model differentiating between cougar removal periods for desert bighorn, the model differentiating between time periods corresponding to the two cougar removal periods in the SFR, and the model differentiating between desert bighorn herds and the SFR during the two cougar removal periods, had more support than their respective dot models (models that contain all data and do not specify covariates).

RESULTS

Bighorn Capture

Desert bighorn: from 1992–2001, we monitored 167 radiocollared bighorn (151 radiocollars were deployed on transplanted bighorn, 12 were deployed on extant bighorn, and 4 were previously deployed and still alive). A total of 176 bighorn were transplanted and released into the wild during that time. From 2002–2011, we monitored 359 radiocollared bighorn (196 radiocollars were deployed on transplanted bighorn, 136 were deployed on extant bighorn, and 27 were previously deployed and still alive. Of the 27 previously radiocollared bighorn, 20 of them were included in the 1992–2001 analysis). A total of 216 bighorn were transplanted and released into the wild during that time.

SFR: from 1997–2001, we monitored 15 radiocollared bighorn (3 radiocollars were deployed on transplanted bighorn, and 12 were

Table 1. Dates for 2 different cougar removal policies in 5 desert bighorn herds in New Mexico, 1992–2011.

Cougar Removal Period	Mountain Range				
	Peloncillos	Sierra Ladron	Hatchets	San Andres	Fra Cristobals
Prior to cougar removal	Nov. 1997–May 1999; Oct. 2000–Sept. 2002	Oct. 1992–Sept. 2002	Nov. 1997–Sept. 2002	Oct. 1992–Aug. 1997; Oct 2002–Sept 2003	Oct. 1995–Sept 1999
Following cougar removal	May 1999–Sept. 2000; Oct. 2002–Sept. 2011	Oct. 2003–Sept. 2011	Oct. 2003–Sept. 2011	N/A	Oct. 2006–Sept. 2011

Table 2. Average annual mortality rate of bighorn sheep in New Mexico (1992–2011) from all causes of mortality and from cougar predation only prior to and following cougar removal in 5 desert bighorn herds, and in the San Francisco River Rocky Mountain bighorn herd during the same time periods in the absence of cougar removal.

Herd	Prior to Cougar Removal		Following Cougar Removal	
	All Causes of Mortality (SE)	Cougar Predation (SE)	All Causes of Mortality (SE)	Cougar Predation (SE)
All Desert Herds	0.21 (0.01)	0.16 (0.01)	0.11 (<0.01)	0.05 (<0.01)
San Francisco River	0.19 (0.03)	0.08 (0.03)	0.24 (0.02)	0.13 (0.03)
Peloncillos	0.25 (0.03)	0.22 (0.03)	0.09 (0.02)	0.05 (0.01)
San Andres	0.23 (0.02)	0.13 (0.02)	N/A	N/A
Ladrones	0.21 (0.02)	0.14 (0.02)	0.11 (0.03)	0.02 (0.01)
Hatchets	0.20 (0.03)	0.14 (0.03)	0.11 (0.03)	0.08 (0.01)
Fra Cristobals	0.18 (0.02)	0.18 (0.02)	0.17 (0.03)	0.07 (0.02)

deployed on extant bighorn). A total of 4 bighorn were transplanted into the herd during that time. From 2003–2011, we monitored 31 bighorn (14 radiocollars were deployed on transplanted bighorn, and 17 were deployed on extant bighorn. None of the animals were included in the 1997–2001 analysis). A total of 14 bighorn were transplanted into the herd during that time.

Mortality Rates

The overall average annual mortality rate for desert bighorn from all causes of mortality declined from 0.21 (SE = 0.01) prior to cougar removal to 0.11 (SE < 0.01) following cougar removal (Table 2). The average annual cause-specific mortality rate from cougar predation declined from 0.16 (SE = 0.01) to 0.05 (SE < 0.01) during the same time period. The average annual mortality rate for SFR Rocky Mountain bighorn from all causes of mortality increased from 0.19 (SE = 0.03) to 0.24 (SE = 0.02) and the cause specific average annual mortality rate from cougar predation increased from 0.08 (SE = 0.03) to 0.13 (SE = 0.03) during the same time periods in the absence of cougar removal (Table 2).

Average annual mortality rates for each desert herd prior to cougar removal ranged from 0.18 (SE = 0.02) to 0.25 (SE = 0.03) for all causes of mortality; the SFR mortality rate of 0.19 (SE = 0.03) fell within that range (Table 2). Cougar predation mortality for each desert herd prior to cougar removal ranged from 0.13 (SE = 0.03) to 0.22 (SE = 0.03), with the SFR mortality rate of 0.08 (SE = 0.03) lower than any desert herd. Following cougar removal in desert herds, total mortality rates declined and ranged from 0.09 (SE = 0.02) to 0.17 (SE = 0.03). During that period the SFR total mortality rate increased to 0.24 (SE = 0.02), which was higher than during the period prior to cougar removal in desert herds, and surpassed all desert herds during the period of cougar removal. Cougar predation mortality rates

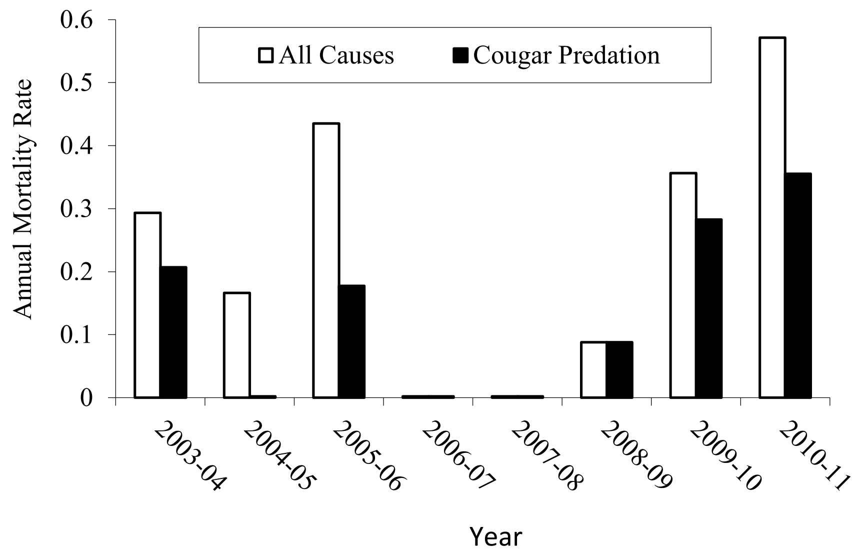

Fig. 1. Annual mortality rates from all causes of mortality and from cougar predation only in the San Francisco River Rocky Mountain bighorn herd, New Mexico from 2003–2011. All SE are between 0.02 and 0.06, with the exception of cougar predation mortality rates for 2009–10 and 2010–11 which are 0.08 and 0.09, respectively.

in desert herds declined following cougar removal and ranged from 0.05 (SE = 0.01) to 0.08 (SE = 0.01), while the SFR cougar predation mortality rate of 0.13 (SE = 0.03) increased from the period prior to cougar removal in desert herds, and surpassed all desert herds during the period of cougar removal (Table 2). Average annual cougar predation rate in SFR from 2009–2011 was 0.31 (SE = 0.06). Mortality rates for individual years for SFR bighorn from 2003–2011 ranged from 0.0 (SE = 0.00) to 0.57 (SE = 0.05) and cougar predation mortality rates ranged from 0.0 (SE = 0.00) to 0.36 (SE = 0.09; Fig. 1).

Model Selection

When evaluating mortality rates from all causes and from cougar predation only for desert bighorn, only the models that separate cougar removal periods had any support (Tables 3 and 4). In contrast, for models describing all causes of mortality and cougar predation mortality in the SFR, both the model combining cougar removal periods and the model separating cougar removal periods show support. However, the model combining cougar removal periods had a higher model weight and likelihood (0.7 and 1, respectively) compared with the model separating cougar removal periods (0.3 and 0.5, respectively), making it the top model. Finally, when comparing mortality rates for all causes of mortality for all bighorn herds during each of the cougar removal policies, only the model separating the desert herds from the SFR had any support. In contrast, when comparing mortality rates from cougar predation for all bighorn herds during each of the cougar removal periods, both the model separating desert herds from the SFR and the model combining them received support. However, the model combining the desert herds and the SFR had a higher model weight and likelihood (0.7 and 1, respectively) compared with the model separating the desert herds from the SFR (0.3 and 0.4, respectively; Tables 3 and 4).

Desert Bighorn Population Response

The statewide desert bighorn population increased from <170 animals prior to implementing cougar removal in 2001 to approximately 650 in 2011 (Fig. 2). The SFR to approximately 50 animals, the population remained stable until it declined again starting in 2009. The 2011 population estimate was 35 bighorn (Fig. 3).

Cougar Removal

Cougars are a game animal in New Mexico, with a year-round season and a bag limit of 1 cougar per hunter. On average, 2.6 cougars are

Table 3. The model structure, Akaike's Information Criterion adjusted for sample size (AIC_c), differences in AIC_c (ΔAIC_c), model weights, model likelihood, and the number of parameters for models predicting bighorn sheep mortality rates in New Mexico, 1997–2011.

Model	AIC_c	ΔAIC_c	AIC_c Weight	Model Likelihood	No. Parameters
Desert bighorn					
Cougar removal policy	1627.9	0	1.0	1.0	2
(.)	1640.7	12.8	0	0	1
SFR					
(.)	306.2	0	0.7	1.0	1
Cougar removal policy	307.8	1.6	0.3	0.5	2
Different cougar removal policies					
Deserts vs. SFR	1935.7	0	0.92	1.0	4
(.)	1940.7	5.0	0.08	0.08	2

Table 4. The model structure, Akaike's Information Criterion adjusted for sample size (AIC_c), differences in AIC_c (ΔAIC_c), model weights, model likelihood, and the number of parameters for models predicting cougar predation mortality rates for bighorn sheep in New Mexico, 1997–2011.

Model	AIC_c	ΔAIC_c	AIC_c Weight	Model Likelihood	No. Parameters
Desert bighorn					
Cougar removal policy	1128.4	0	1.0	1.0	2
(.)	1147.7	19.3	0	0	1
SFR					
(.)	155.7	0	0.7	1.0	1
Cougar removal policy	157.0	1.3	0.3	0.5	2
Different cougar removal policies					
Deserts vs. SFR	1296.8	0	0.7	1.0	4
(.)	1298.8	1.99	0.3	0.4	2

killed per mountain range per year under the cougar removal program, although the number removed from each range varies (Table 5). Bighorn ranges in which cougars are removed constitute approximately 1% of cougar habitat in New Mexico, and cougar sign is observed in all bighorn mountain ranges annually.

DISCUSSION

Traditionally, four subspecies of desert bighorn sheep have been recognized, with desert bighorn in New Mexico belonging to the subspecies *mexicana*. Although this designation often persists, mitochondrial genetic research by Ramey (1995) suggests that lack of mitochondrial genetic and morphological variation between the desert bighorn subspecies makes it more reasonable to consider them a single subspecies. For this reason, in this publication we have chosen to designate desert bighorn in New Mexico, as well as all desert bighorn, as the subspecies *nelsoni*.

Cougar removal implementation varied in each mountain range. Although the objective was to minimize cougar numbers, houndsmen and snaremen worked part time and effort was not evenly distributed in each mountain range at all times. Gaps in coverage were primarily due to administrative processes and contractor availability. As such, this analysis is of the

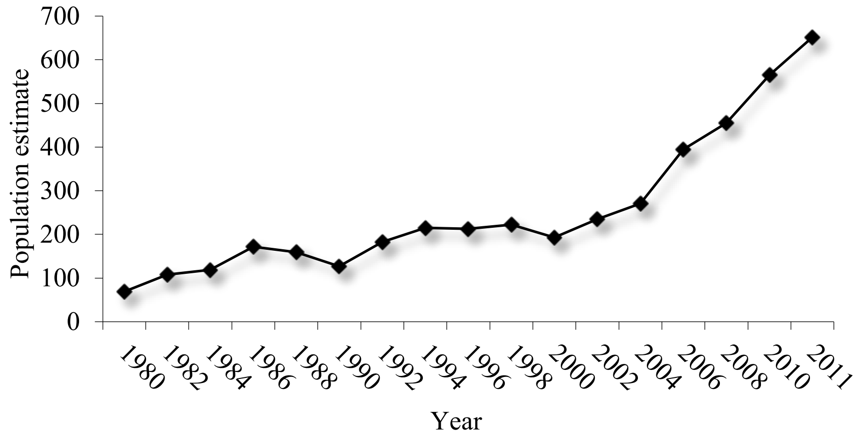

Fig. 2. Desert bighorn population trend in New Mexico, 1980–2011.

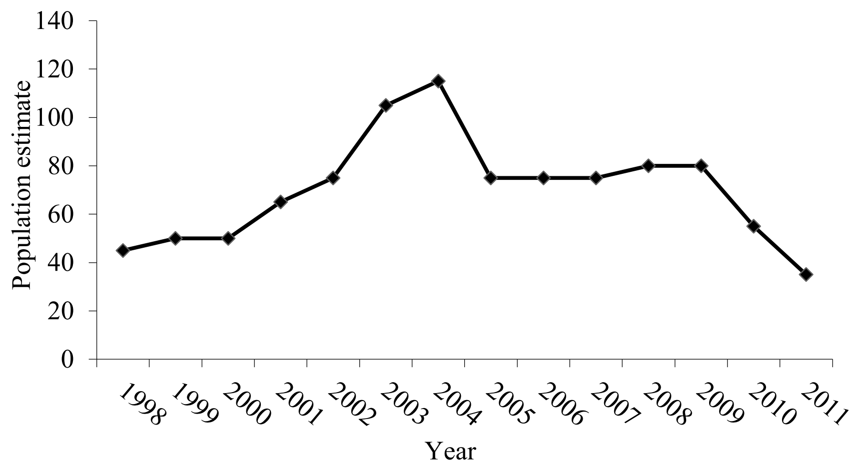

Fig. 3. San Francisco River, NM Rocky Mountain bighorn population trend, 1998–2011.

management action as we were able to implement it.

SFR was historically populated with desert bighorn. Habitat differs from desert bighorn habitat in the 5 herds comprising this study primarily because it is a river canyon as opposed to a sky-island, defined as a mountain that is isolated by surrounding lowlands of a dramatically different environment. The current population in SFR is composed of Rocky Mountain bighorn, further differentiating this herd from the desert populations. The differences between desert bighorn herds and the SFR are great enough that the SFR population cannot be used as a control herd even though cougar control was never implemented in the SFR. However, it can be used as a comparison herd.

The mortality rate in desert bighorn herds declined 48% from the period prior to cougar removal to the period following cougar removal, and the cause-specific mortality rate from cougar predation declined 68%. In contrast, in the SFR where cougar removal did not occur, total mortality increased 21% during the same time period and cougar predation increased 38%. It is likely that in the absence of cougar removal, mortality rates in desert bighorn herds would not have decreased between the two time periods. Mortality rates from causes other than cougar predation remained constant in desert herds (0.05) during both time periods, demonstrating that cougar predation is an additive source of mortality. It also remained constant in SFR (0.11). The majority of other causes of mortality were unknown, although known causes included disease, old age, infection, fence entanglement, and legal harvest (Peloncillos only).

Mortality rates and causes in SFR varied greatly year to year. Low population numbers in the late 1990s resulted from a pneumonia epidemic that caused a large population decline. The population increased in the early 2000s and recovered to just over 100 animals when another pneumonia outbreak in 2005–6 caused another population decline. Average annual cougar predation mortality rates were high at 0.21 and 0.18 in 2003–4 and 2005–6 respectively, but no cougar predation was documented on radiocollared bighorn from 2006–2008. Cougar predation may have had a negative impact on SFR bighorn in some years, but other causes such as pneumonia were responsible for population declines in other years.

During the time period prior to implementing cougar removal in desert bighorn herds when cougar removal was not implemented in SFR, the mortality rate in SFR was similar to desert bighorn

Table 5. Number of cougars killed in 5 mountain ranges October 2001–September 2011 to protect desert bighorn; additional cougars removed by sport harvest/road kill/livestock depredation in parentheses.

Year	Peloncillos	Sierra Ladrones	Hatchets	San Andres	Fra Cristobals	Total
2001–2002	4 (2)	4	1 (1)	-	1 (1)	10 (4)
2002–2003	5 (2)	7 (2)	4 (1)	16	5	37 (5)
2003–2004	5	0	0 (2)	3 (1)	3 (1)	11 (4)
2004–2005	0	4	1 (3)	3	4	12 (3)
2005–2006	0	2	6	3	2	13 (0)
2006–2007	3	4	1	4	3	15 (0)
2007–2008	0	10 (1)	1	0	2	13 (1)
2008–2009	1	2	0	1	4	8 (0)
2009–2010	5	7	1	0	1	14 (0)
2010–2011	0	8	1	0	3	12 (0)
Total	23 (4)	48 (3)	16 (7)	30 (1)	28 (2)	145(17)

herds, but the cause-specific mortality rate from cougar predation was 50% lower in SFR. Lower cougar predation rates excluded cougar removal from SFR. The cougar predation average annual mortality rate of 0.08 in SFR prior to cougar removal in the desert herds remained consistent during the first 6 years (2003–2009) of the time period following cougar removal in the desert but not SFR herds. The cougar predation mortality rate subsequently increased to 0.26 in 2009–10 and 0.36 in 2010–11, and total mortality rates increased to 0.36 and 0.57, respectively. Negative impacts of two years of high mortality caused the population estimate to decline from 80 to 35 animals.

Cougar removal has been successful in New Mexico because of the animal's social structure, which is quite different from mesocarnivores such as coyotes, where removal has not always been effective. Cougars are solitary animals that are relatively slow to recolonize vacated areas, and any individual cougar may prey upon desert bighorn (Logan and Sweanor 2001). In contrast, coyotes are pack animals and it is necessary to remove the alpha male and female to slow reproduction and predation (Blejwas et al. 2002). Decreased mortality rates in combination with transplants into the wild resulted in statewide desert bighorn population numbers increasing from approximately 170 to 650 animals in the 10 year period between 2001 and 2011, and enabled them to be removed from the New Mexico state list of threatened and endangered species in 2011.

Although cougar predation is not always a limiting source of mortality in SFR it is currently driving the population to extinction. Small populations of wild ungulates are more vulnerable to impacts of predation (Compton et al. 1995, Wehausen 1996, Hayes et al. 2000, Rominger and Weisenberger 2000, Wittmer et al. 2005). A policy of range-wide removal until the population recovers to levels where less aggressive removal actions could be implemented was found to be superior in reducing extinction risk compared to less aggressive strategies (Ernest et al. 2002). Although cougar removal may not be needed in all years in SFR, based on population trends in New Mexico desert bighorn herds prior to and following cougar removal, it is likely that SFR bighorn will go extinct without implementing a cougar removal program in the near future. For this reason, the New Mexico Department of Game and Fish commenced cougar removal and removed 8 cougars from May–November 2012 and will continue. Population monitoring will show if the bighorn population experiences the anticipated decline in cougar predation and subsequent increase in population numbers.

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