Invited Paper
The restoration of desert bighorn sheep in the Southwest, 1951–2007: factors influencing success

Brian F. Wakeling,[1] Raymond Lee,[2] David Brown,[3] Ron Thompson,[1] Melanie Tluczek,[3] and Mara Weisenberger[4]

[1] Arizona Game and Fish Department, Game Branch,
5000 West Carefree Highway, Phoenix, AZ 85086, USA

[2] Wild Sheep Foundation, 720 Allen Avenue, Cody, WY 82414, USA

[3] Arizona State University, Polytechnic campus,
7001 East Williams Field Road, Mesa, AZ 85212, USA

[4] U. S. Fish and Wildlife Service, San Andres National Wildlife Refuge,
5686 Santa Gertrudis Drive, Las Cruces, NM 88012, USA

Abstract The restoration of desert bighorn sheep (*Ovis canadensis*) to abundant populations at the end of the twentieth century following historic low numbers during the first half of the same century is a testament to the North American Model of Wildlife Conservation. Hunters, wildlife conservation organizations, and wildlife management agencies invested tens of millions of dollars in translocations, water developments, disease mitigation, and predation management over the past several decades. Nonetheless, despite continued efforts to further increase bighorn sheep numbers, several individual desert bighorn sheep populations have recently declined and some have been extirpated. We evaluate the relative influence of management activities on several populations and suggest insights into the efficacy and limitations of restoration and management activities. We recommend management considerations and suggest hypotheses for researchers and managers to consider during future restoration and management actions.

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The restoration of desert bighorn sheep (*Ovis canadensis*) from historic low numbers between 1900 and 1950 to population numbers that are substantially higher (in some instances by orders of magnitude), support regulated hunting, and provide wildlife viewing opportunities is a direct result of focused management efforts funded and supported by hunters, wildlife conservation organizations, and wildlife management agencies. Beginning in the late 1930s, restoration efforts included the establishment of national wildlife refuges, reducing the number of competing ungulates, developing hundreds of waters, and translocating thousands of bighorn sheep. Tens of millions of dollars have been spent on management and research activities including population surveys, investigating and mitigating bighorn sheep diseases, redesign of highways and other impediments, and attempts to reduce losses due to predation. The primary funding source for most of these actions has been directly tied to hunting and donations from hunting organizations. As an example, Arizona has expended about $6.5 million since 1984 on bighorn sheep management funded through the sale of special big game license tags offered by the Arizona Game and Fish Commission and marketed by the Arizona Desert Bighorn Sheep Society (ADBSS), Wild Sheep Foundation, and the Arizona Big Game Super Raffle.

While these efforts have succeeded in increasing total numbers of bighorn sheep, several populations have recently declined in the Southwest. Putative explanations for population declines have included droughts, disease episodes, and increased predation. Our objective was to examine population index trends for several southwestern desert bighorn sheep populations and compare those trends with factors that may be influencing bighorn sheep numbers. We then suggest additional testable hypothesis for future evaluation.

Study Areas

To evaluate the effects of past management efforts in the Southwest, we analyzed historical data for the state of Arizona, along with comparable data for 9 populations having long term survey and hunt information. These areas include: the Kofa National Wildlife Refuge in Arizona (KNWR), San Andres National Wildlife Refuge in New Mexico (SANWR), Cabeza Prieta National Wildlife Refuge in Arizona (CPNWR), the Black Mountains in Arizona's Game Management Unit (Unit) 15 (BM), Eagletail Mountains in Arizona's Unit 41 (ET), Catalina Mountains in Arizona's Unit 33 (CM), Silver Bell Mountains in Arizona's Unit 37A (SB), Fra Cristobal Range on the Armendaris Ranch in New Mexico (FCR), and Tiburon Island in Mexico's Gulf of California (TI) (Figure 1).

Methods

To test the effects of known and suspected influences on bighorn sheep population levels, we obtained data from the Arizona Game and Fish Department, KNWR, SANWR, and Armendaris Ranch from 1951–2007 on annual mule deer (*Odocoileus hemionus*) harvests, bighorn sheep observed on surveys, bighorn sheep harvests, bighorn sheep translocations, numbers of developed waters, and mountain lion (*Puma concolor*) harvests (both hunter and agency removal). We obtained regional Palmer Drought Severity Indices (PDSI; Palmer 1965) for March from the National Climatic Data Center. We also recorded the dates of any known disease outbreaks.

We used linear and forward-stepwise multiple linear regression (Zar 1996) techniques to infer the relative correlative properties among PDSI, mule deer harvests, water developments, and mountain lion harvests with bighorn sheep observed and harvested.

Results

Bighorn sheep populations in Arizona seem to have increased between

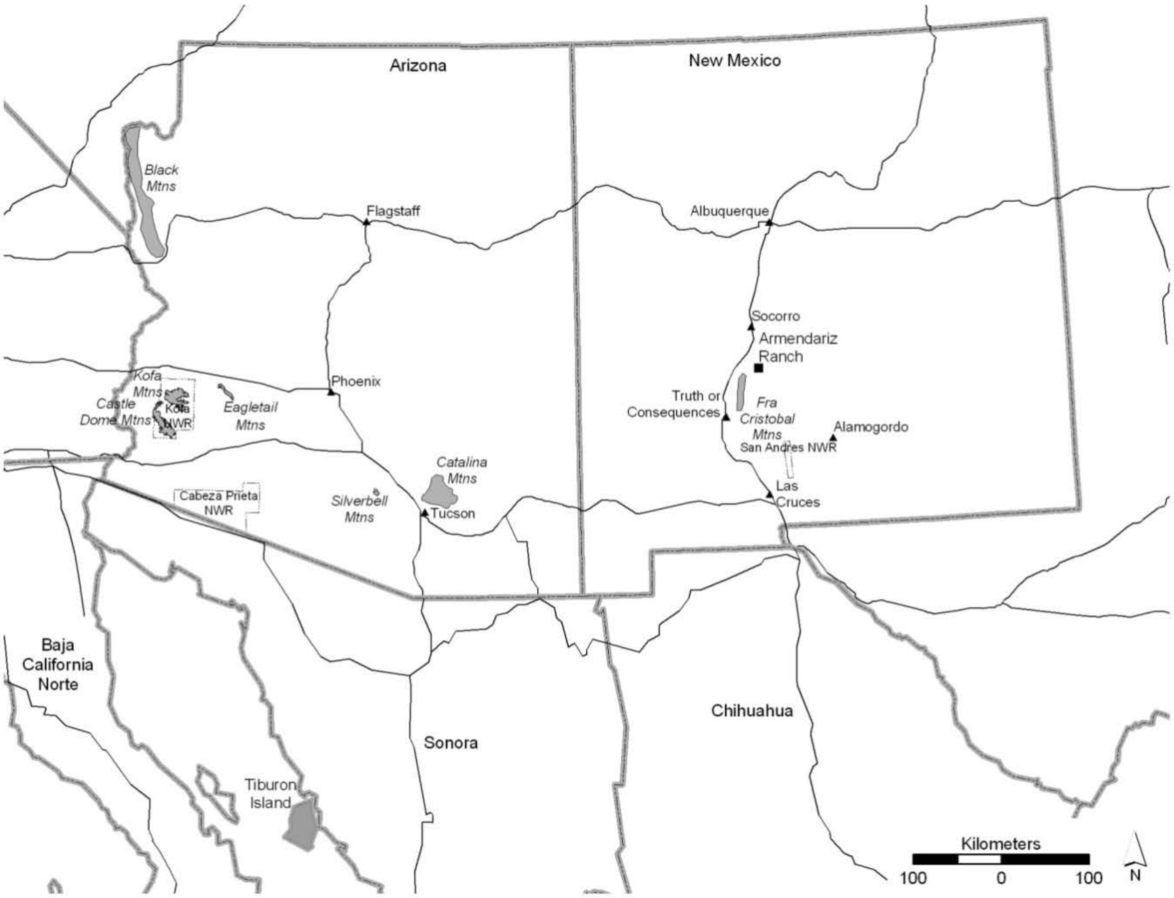

Figure 1. Bighorn sheep populations trends were evaluated in Arizona; the Kofa National Wildlife Refuge, Arizona; San Andres National Wildlife Refuge, New Mexico; Cabeza Prieta National Wildlife Refuge, Arizona; Black Mountains, Arizona, Eagletail Mountains, Arizona; Catalina Mountains, Arizona; Silver Bell Mountains, Arizona; Fra Cristobal Range, New Mexico; and Tiburon Island, Mexico.

1951 and 1993, based on the annual number of bighorn sheep observed and harvested (Figure 2). Beginning in the 1990s, however, Arizona changed annual survey effort to survey individual populations only once every third year excepting those populations of management concern, which were still surveyed annually. Bighorn sheep harvests declined between 1999 and 2005, but increased after that date. Annual bighorn sheep observations were positively influenced with the number of mule deer harvested and the number of waters developed with ADBSS assistance, yet negatively related to the total number of waters developed within bighorn sheep habitat (Table 1). Bighorn sheep harvests were positively related to ADBSS waters (Table 1). There was no apparent relationship with the other variables obtained for statewide population comparisons.

Bighorn sheep observations followed the same basic trend on KNWR as observed for the state of Arizona, although the decline in total observations did not involve changes in survey methodology (Figure 3). Harvests declined concurrent with reductions in observations. Mountain lions, a rare occurrence on the KNWR before 2000, increased in abundance after that date (Germaine et al. 2000, Naidu 2009). No mountain lions were removed by hunter harvest near KNWR during the years of our study, but 4 have been recently removed administratively.

Bighorn sheep observations on KNWR were positively related to the number of developed waters (Table 1), and bighorn sheep harvest was positively influenced with the number of developed waters and mule deer harvest (Table 1). The remaining variables did not correlate with bighorn sheep observations or harvests.

Patterns in bighorn sheep observations and harvest at SANWR differed in timing from what was observed in Arizona (Figure 4); bighorn sheep at SANWR suffered from a debilitating scabies outbreak in the late 1970s (Lange et al. 1980), eliminating bighorn sheep hunting since that time. Bighorn sheep populations have begun to increase recently concurrent with translocations and mountain lion removal, yet no statistically meaningful relationships could be developed among variables at SANWR.

Bighorn sheep populations on CPNWR have sustained increasing harvests, while experiencing a population decline between 1997 and 2004 (Figure 5). Survey observations have followed a similar trend with an increase in observations in 2006 and 2007. Bighorn sheep observations were positively related to developed waters (Table 1), whereas bighorn sheep harvests were positively related to developed waters and negatively influenced by March PDSI values (Table 1). The remaining variables did not correlate with bighorn sheep observations or harvest.

Bighorn sheep observations and harvest in BM (Figure 6) demonstrated a pattern similar to that observed on KNWR (Figure 2). Mountain lion-caused mortality increased after the early 1990s (Cunningham et al. 1992) to accounting for almost 75% of all documented mortality (Arizona Game and Fish Department 2010). Total developed waters were negatively related to bighorn sheep observations and harvest (Table 1). No other variables were statistically correlated with bighorn sheep observations or harvests.

Within ET, bighorn sheep observations and harvest declined in the late 1970s and early 1980s, but then increased following a translocation into this population (Figure 7). No meaningful statistical relationships could be developed among bighorn sheep observations, bighorn

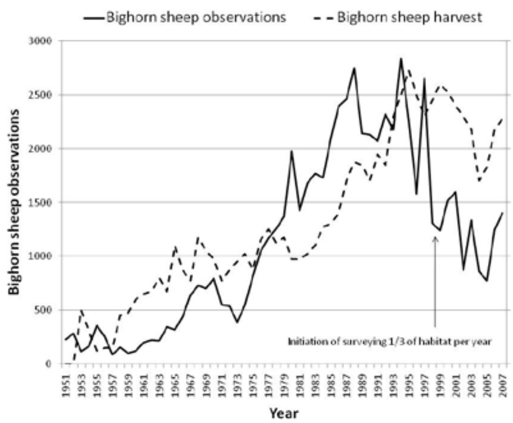

Figure 2. Bighorn sheep observations and harvest within Arizona, 1951–2007.

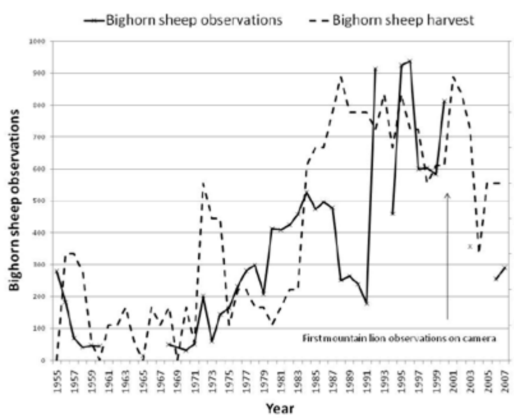

Figure 3. Bighorn sheep observations and harvest on the Kofa National Wildlife Refuge, Arizona, 1955–2007.

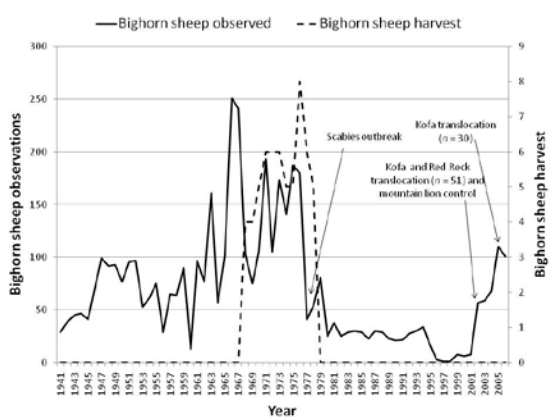

Figure 4. Bighorn sheep observations and harvest from San Andres National Wildlife Refuge, New Mexico, 1941–2006.

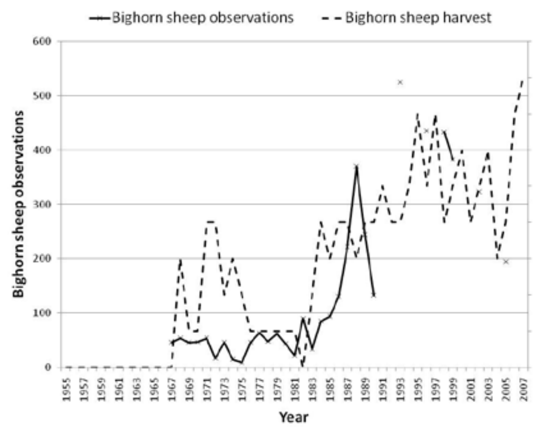

Figure 5. Bighorn sheep observations and harvest on Cabeza Prieta National Wildlife Refuge, Arizona, 1955–2007.

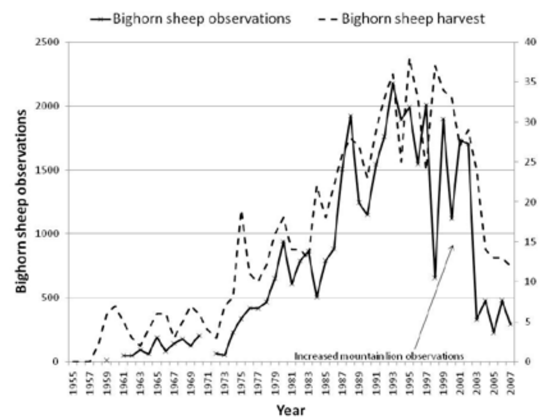

Figure 6. Bighorn sheep observations and harvest in the Black Mountains, Arizona, 1955–2007.

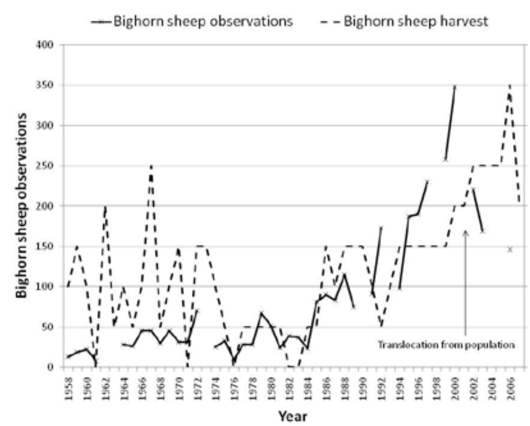

Figure 7. Bighorn sheep observations and harvest in the Eagletail Mountains, Arizona, 1958–2007.

Table 1. Correlations among bighorn sheep observations and harvest with annual mule deer harvest, bighorn sheep translocations, number of developed waters, and mountain lion harvest in 10 bighorn sheep population, 1951–2007.

Population[a]	Regression equation[b]	Adjusted r^2	*P*
Arizona	BSO = 1437.6 - 27.9 TDW + 0.1 MDH + 24.7 DWA	0.649	<0.001
Arizona	BSH = 25.3 + 0.5 DWA	0.829	<0.001
BM	BSO = 5932.4 - 246.7 TDW	0.337	0.004
BM	BSH = 80.9 - 2.9 TDW	0.301	0.007
CM	BSO = -27.7 + 0.2 MDH	0.457	0.002
CM	BSH = -1.4 + 0.1 MDH	0.579	<0.001
CPNWR	BSO = -747.4 + 61.6 TDW	0.381	<0.001
CPNWR	BSH = -8.8 - 0.2 MPDSI + 0.8 TDW	0.544	<0.001
ET	BSO = No statistical relationship		
ET	BSH = No statistical relationship		
FCR	BSO = No statistical relationship		
KNWR	BSO = -203.8 + 22.0 TDW	0.358	<0.001
KNWR	BSH = -12.6 + 0.7 TDW + 0.1 MDH	0.809	<0.001
SANWR	BSO = No statistical relationship		
SANWR	BSH = No statistical relationship		
SB	BSO = No statistical relationship		
SB	BSH = No statistical relationship		
TI	BSO = No statistical relationship		

[a] Populations modeled include: Arizona = Arizona's statewide desert bighorn sheep population, BM = Black Mountains, CM = Catalina Mountains, CPNWR = Cabeza Prieta National Wildlife Refuge, ET = Eagletail Mountains, FCR = Fra Cristobal Range, KNWR = Kofa National Wildlife Refuge, SANWR = San Andres National Wildlife Refuge, SB = Silver Bell Mountains, and TI = Tiburon Island

[b] Variables in the regression equations include: BSH = bighorn sheep harvest, BSO = bighorn sheep observations, DWA = waters developed with Arizona Desert Bighorn Sheep Society Assistance, MDH = mule deer harvest, MPDSI = March Palmer Drought Severity Index, TDW = total developed waters

Table 2. Number of bighorn sheep captured, translocated, and dying during the capture effort by decade within the Southwest, 1950–1990.

Years	Captured	Released	Mortalities
1951-1960	38	19	12
1961-1970	18	7	5
1971-1980	50	46	4
1981-1990	627	582	27[a]

[a] During the decade of 1981–1990, mortality rate dropped even further from 6.2% in the first 5 years to 1.3% in the latter 5 years

sheep harvest, or other variables in this population.

Bighorn sheep observations in CM declined after the early 1980s until disappearing in the late 1990s (Figure 8). Hunting had ceased by the early 1990s. Although many causes for the decline have been speculated, no conclusive determination has been made. Deer harvest positively influenced bighorn sheep observations and bighorn sheep harvest (Table 1). No other variables statistically correlated with observations or harvest of bighorn sheep.

Within SB, bighorn sheep observations and harvest were influenced by disease outbreak in the early 2000s (Jansen et al. 2006). The observations and harvest increased from low levels during 1963–1991, but were reduced substantially following the disease outbreak in 2003 (Figure 9). No meaningful statistical relationships could be developed among bighorn sheep observations, bighorn sheep harvest, or other variables in this population.

FCR was limited in the amount of bighorn sheep observations with no harvest data (Figure 10). Population observations have increased over time concurrent with mountain lion removal. TI has had increasing observations over time, with a reduction following initial translocations from the population (Figure 11). TI observations increased after the initial reduction. However, no meaningful statistical relationships were detected among bighorn sheep observations, bighorn sheep harvest, or other variables in either of these populations.

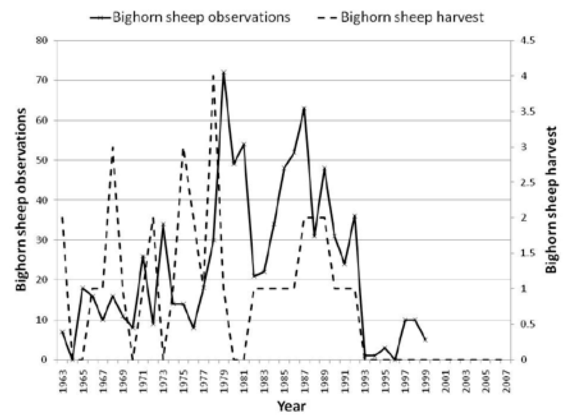

Figure 8. Bighorn sheep observations and harvest within the Catalina Mountains, Arizona, 1963–2007.

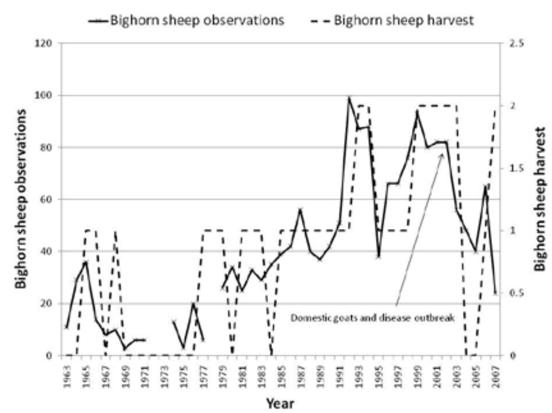

Figure 9. Bighorn sheep observations and harvest in the Silver Bell Mountain, Arizona, 1963–2007.

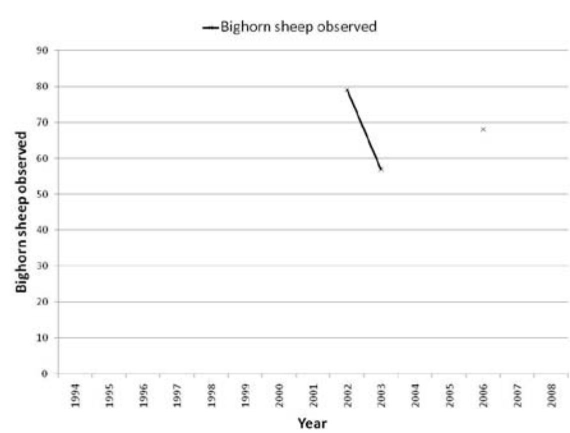

Figure 10. Bighorn sheep observations in the Fra Cristobal Range, New Mexico, 1994–2008.

Figure 11. Bighorn sheep observations on Tiburon Island, Mexico, 1975–2006.

Discussion

Mule deer and bighorn sheep harvests.—Harvest data are arguably the most consistent long-term index for many big game species in the Southwest because harvest recommendations are adjusted annually to reflect the perceived sustainable harvest, whereas survey methodologies and indices may change depending on budgets, logistics, and technological advances. Mule deer harvests have decreased within all populations we studied since the early 1980s, whereas most bighorn sheep harvests seemed to have peaked in the late 1990s to early 2000s, declining in most cases since then. Mule deer harvest was positively related to bighorn sheep harvest or observations in 2 of the study populations, with no statistically meaningful relationships in the other populations. Although in some instances there may be a relationship in harvest trends between the species, this relationship is not consistent across the Southwest. Factors that influence the abundance of mule deer may not be the same as those that influence the abundance of bighorn sheep.

Water development.—Water developments did not have a consistent influence on bighorn sheep harvest or observations. Bighorn sheep harvest was positively related to developed waters in 3 areas, whereas it was negatively related to developed waters in 1. Observations of bighorn sheep during surveys was positively related to numbers of water developments in 3 areas, yet negatively influenced in another. Statewide within Arizona, bighorn sheep observations were positively related to the number of waters developed with ADBSS assistance, yet negatively related to total water developments.

Water developments have been a major component of most bighorn sheep management programs. In the 1940s, wildlife agencies determined that water for wildlife was lacking in desert mule deer and bighorn habitat, and that developing permanent waters was the most practical means of improving conditions in those areas where food and habitat were adequate (Wright 1959). Agencies initiated the construction of water developments in 1945, and in 1950, studies were initiated on the effects of constructed waters. By the 1950s, most water sources had been modified to benefit livestock, and bighorn sheep use was generally confined to natural rock pools called tinajas. Many springs, formerly reliable, were no longer so. Wright (1959) reported that "there are fewer watering places today than there were at the beginning of the 18th Century." Russo (1956) recommended developing waters to benefit bighorn sheep in their natural habitat to prevent competition and reduce mortality.

However, the efficacy of water developments in increasing bighorn sheep numbers remains contentious (e.g., Broyles 1995, Rosenstock et al. 1999, Dolan 2006). The argument against water developments states that desert wildlife is adapted to xeric conditions and their numbers were historically robust without artificial waters. Alternatively, the argument for water developments states that habitat alteration and fragmentation have created conditions that differ substantially from those when historical populations existed, and artificial water sources are important and useful bighorn sheep management tools.

Water developments seem to have differing values to bighorn sheep depending on their location and surrounding habitat characteristics (Hansen 1980, Cunningham 1989). Waddell et al. (2007) found that bighorn sheep used one water source in the KNWR to a greater extent during the warmer months, with little to no documented use during the months of December–February. Bighorn sheep water use patterns are difficult to infer range-wide from a single study at a single water source, yet Waddell et al. (2007) suggests some seasonal periodicity in water use may occur with bighorn sheep. While lacking substantive quantification, other studies have suggested that bighorn sheep may exist for periods of several months without the need for free water if other factors, such as humidity and forage succulence, are favorable (Mendoza 1976, Watts 1979, Krausman and Leopold 1986). TI population abundance was substantially higher than that observed within other desert bighorn sheep populations, yet no specific water developments for bighorn sheep have been constructed on the island. Turner (1973) documented that bighorn sheep require about 4% of their body weight daily in water, yet bighorn sheep plainly need not drink daily nor at certain times of the year. It is also conceivable that certain predators may be more reliant on free water, especially at certain times of the year, than desert adapted ungulates. However, we could detect no statistical relationship in which mountain lion harvest was related to bighorn sheep observations or harvest.

Water developments do not seem to always prevent bighorn sheep population declines during times of drought. Forage quality or quantity influence recruitment rates and population declines in ungulates regardless of water availability (Wehausen et al. 1987, Bender and Weisenberger 2005). Precipitation, but not free water, improves the production and nutritional quality of vegetation, which in turn benefits ungulate recruitment and population trends (Short 1981, DeYoung et al. 2000, Wakeling and Bender 2003).

Translocations.— Although many populations of bighorn sheep throughout the Southwest were reestablished through translocations, they did not statistically influence our study populations. Populations in ET and TI both dropped substantially in population indices following supplemental translocations, yet the TI population seems to have recovered to levels prior to translocation initiation whereas the ET population did not. Other factors purportedly confounded relationships in ET, including drought, forage quantity and quality, and predation.

Translocation, conducted according to established protocols that identify suitable habitat (e.g., Hansen 1980, Cunningham 1989) and using effective capture protocols (e.g., Remington and Fuller 1989), was the single most important tool in restoring bighorn sheep populations. Translocation of wild bighorn sheep for management purposes occurred in the U.S. as early as 1922. However, it was not until the mid-1950s that translocations were commonly used by wildlife management agencies, and particularly for desert bighorn sheep. In Arizona, for example, the first transplant efforts occurred during the summer of 1955. This joint Arizona Game and Fish Department-Texas Parks and Wildlife Department project was designed to capture bighorn sheep in the KNWR for release in Aravaipa Canyon in Arizona and in the Black Gap Wildlife Management Area in Texas. The results were not encouraging; in

5 years of effort, only 22 bighorn sheep were successfully released.

Through time, capture methods improved. The corral traps of the 1960s, gave way to tranquilizer drugs being fired from helicopters in the 1970s, to the net gun of the 1980s, to the professional capture crews of the 1990s. The development of a technique using drop nets and baits during the mid-1980s enhanced capture efforts in areas where this technique was feasible. These improvements led to greater numbers of bighorn sheep being captured for translocation and fewer mortalities resulting from the effort (Table 2).

Despite the lack of statistical relationship, many states' hunting opportunities for bighorn sheep have benefitted substantially from translocations. In 2007, the Arizona Game and Fish Department conducted its one hundredth bighorn sheep transplant, having moved some 1,874 wild sheep (O'Dell 2010). More than 33% of the hunting permits offered in Arizona today are for populations reestablished through translocations. California wildlife officials estimated that the state originally had 50 native herds. Over time, 29 of these were extirpated. Translocation efforts have led to 9 reintroduced herds, with 3 others being augmented. Desert bighorn sheep in Colorado were first released in 1979. Today a population of 340 animals supports a harvest of 4 rams; with 6 permits being issued for 2009. Nevada had 23 remnant herds in 1960. Since then, Nevada has reestablished 36 herds through the translocation of 1,773 animals; more than half of Nevada's hunting permits are for these populations. From 1987–2006, New Mexico moved 361 sheep (170 since 2001). These translocations, coupled with predator and habitat management, have allowed the state's population to grow to >450 animals. Texas lost its entire native bighorn sheep population by 1900. An aggressive translocation program has led to the establishment of several herds; the total population is now estimated at about 1,500 bighorn sheep, with 15 hunting permits offered in 2009. Like other western states, Utah nearly lost its desert bighorn sheep, and by the 1960s only a small population remained. An aggressive translocation program (first reintroduced desert bighorn sheep in 1973) released some 700 animals and Utah's current population of 3,100 animals is primarily due to translocations. Between 1984 and 2003, hunter harvest increased from 5 to 43 desert bighorn sheep rams.

Mexico has also been using translocations to repopulate historic habitats. Sonora initiated this process with the establishment in the mid-1970s of a population on TI. Chihuahua has received transplants, as has Coahuila, and Nuevo Leon. This year Chihuahua issued its first 2 hunting permits for bighorn sheep. Since 1996, TI has been a source population for over 500 animals translocated to mainland Mexico. In Baja California Sur, a similar program translocated sheep from the peninsula to Carmen Island in the mid-1990s.

Predators and predation management.—Although Russo (1956) found little evidence of mountain lions in BM, and virtually none in other Arizona bighorn sheep ranges, increased predation by mountain lions has been documented in the last decade within KNWR and BM. Mountain lion predation has the ability to reduce bighorn sheep populations in some situations (Wehausen 1996, Rubin et al. 2002) and was suggested to have played a role in the extirpation of CM bighorn sheep. Kamler et al. (2002) found the incidence of predation on translocated bighorn sheep has been increasing in Arizona, and Wakeling and Riddering (2007) determined these losses were not due to differences in habitat suitability at release locations. Mountain lion-induced population changes are now well documented in the Southwest (Rominger et al. 2004; McKinney et al. 2006*a*, *b*). Nevertheless, in our analysis we found no statistically meaningful relationships between mountain lion harvest and bighorn sheep population indices.

Within the Fra Cristobal Mountains in New Mexico, Kunkel (2008) found a direct relationship between the number of mountain lions removed and the number of bighorn sheep females present ($r^2 = 0.56$, $P = 0.06$), whereas inverse relationships were detected between mountain lion-caused mortality rate with mountain lions removed ($r^2 = 0.77$, $P = 0.02$) and ewe population trend ($r^2 = 0.44$, $P = 0.06$). Despite an aggressive mountain lion removal program, >50% of the mountain lions that used the Fra Cristobal Mountains during 1999–2006 were not captured (Kunkel et al. 2008). In addition, new immigrants replaced removed mountain lions at the rate of about 1.8/year. The abundant mule deer in this mountain range was suspected to serve as a substantial attractant to mountain lions in the area (Truett 2008), which has been supported in other studies (e.g., McKinney et al. 2010).

With putative evidence that mountain lion abundance and predation on bighorn sheep have increased, the factors that influence that increase are imperfectly understood. Reproducing populations of mountain lions were historically rare or absent in many bighorn sheep ranges, and changes in water distributions, habitat conditions, and isolation mechanisms have occurred, yet may not be well documented quantitatively. However, statistically meaningful relationships were detected in only 3 instances. Water developments had low explanatory ability (Arizona [$r^2 = 0.160$, $P = 0.001$], KNWR [$r^2 = 0.044$, $P = 0.069$], and SA [$r^2 = 0.059$, $P = 0.028$]).

Predation of bighorn sheep by mountain lions typically is sporadic and can vary over time and space. The selection of bighorn sheep as prey and population-level influence of predation may be a function of individual mountain lion behavior (Wehausen 1996, Harris et al. 2009). However, mountain lions may permanently inhabit areas occupied by bighorn sheep where sympatric mule deer provide a primary food source and/or where permanent water sources exist.

State predator management programs for mountain lions and other predators have become increasingly expensive and controversial, and knowledge based on sound biological data is increasingly critical for meeting the public's demands for conservation and management actions. Present management prescriptions to alleviate lion predation on bighorn sheep typically incorporate reactive measures enacted subsequent to apparent bighorn sheep population declines. Future management prescriptions should proactively involve measures such as predator management when considering reintroductions or supplemental translocations of bighorn sheep. Such actions, however, should also consider changes in mountain lion abundance and distribution, and other wildlife population objectives.

Disease.—Disease has been implicated in several bighorn sheep population reductions. Disease resulted in the extirpation of the SANWR bighorn sheep population (Boyce and Weisenberger 2005) and severely reduced the SB bighorn sheep population. Scabies was widespread in the U.S. in the late 1800s, with the most recent outbreak occurring in 1978 at SANWR when all 5 of the rams harvested that year had mites and lesions. That population declined from an estimated 200 animals in 1975 to 70 in 1979 (Lange et al.

1980, Sandoval 1980, Hoban 1990). The last native bighorn sheep on SANWR died in 2003. Infectious keratoconjunctivitis ostensibly contracted from domestic goats was the apparent cause of the decline in the SB population (Jansen et al. 2006).

Sinusitis due to the sheep bot fly larvae seems chronically persistent in some bighorn sheep populations, but does not routinely influence population levels. Contagious ecthyma has been found in high incidences in some populations, yet primarily influences recruitment rather than mortality. This infection was detected in the SB population at the same times as the infectious keratoconjunctivitis. Elevated titers for epizootic hemorrhagic disease and blue tongue virus are common in desert bighorn sheep populations, which indicate a common exposure to these disease agents.

Respiratory infections seem to be the most debilitating diseases acquired by desert bighorn sheep. Pneumonia may be stimulated by stress, although exposure to a mammalian bacterial vector is the most common form of transmission. The most common host seems to be domestic sheep or goats (e.g., Foreyt and Jessup 1982, Jessup 1985, Callan et al. 1991), although cattle may also pose a risk (e.g., Wolfe et al. 2010). Wild ungulates may also act as a host in some instances.

Summary.—Looking at the entire body of data, and the few statistically valid relationships, it seems that the biggest factor in bighorn sheep population increases during the 1950–2000 period were the result of translocations and the biggest losses were due to disease. It also seems that, water developments, coupled with reduced ungulate competition, contributed to a numerical increase in bighorn sheep numbers until about 2000, after which predation and other mortality causes resulted in population declines. Whether increases in the predation rate by mountain lions is related to the increase in water developments is currently unsupported, yet merits further experimentation as does the effect of droughts on population recruitment and mortality.

Our analysis may have overlooked an intrinsically important factor: people and their support infrastructure. The states with the largest desert bighorn sheep populations are Nevada and Arizona. Both states' human populations have increased over 30 fold in the past century: in Nevada from 82,000 in 1910 to 2.7 million in 2010; while in Arizona from 204,000 in 1910 to 6.4 million in 2010. The fact that we have more desert bighorn sheep in these states today than we had in 1910 is an incredible accomplishment in the face of this human flood. What we have been able to document in this paper is that disease and predation can (but not always) reduce bighorn sheep populations, while translocations and water developments can (but not always) increase them. Historical relationships may be changing due to predator and bighorn sheep abundance, habitat fragmentation and isolation, and other anthropogenic influences.

Research and Management Implications: Suggested Hypotheses

All research should pose questions. Retrospective analysis of data such as ours, which was not collected for the specific purpose to which it is applied, nor for which was the collection designed, can lead to weak or erroneous conclusions (Ioannidis 2005). However, observed or implied relationships should be noted, and testable hypotheses developed. Weinberg (1993:204) noted, "…*in order for a theory to be regarded as satisfactory it not only must agree with the results of experiments that have been done but also must make predictions that are at least plausible for* *experiments that in principle could be done*." We therefore offer the following hypotheses for future investigation. We recognize the inadequacy of the structure of these hypotheses, yet we encourage future research efforts to address the concepts they contain.

Translocations have proven to be the most effective method of establishing populations, yet removal of animals from a source population has the potential to negatively influence its trajectory. Quantitative data regarding when a population can best sustain removal and how many can be removed are unknown and in need of further analysis. Further, genetic data as to when supplemental translocations may be warranted is lacking. Evaluation of supplemental translocation costs and benefits remains difficult (e.g., Wakeling 2003, 2004).

H_1 = There is a threshold, as a proportion of the total population or a minimum number in the source population, above which translocations will have no effect on the source population trend.

H_2 = Quantitative decision points may be developed at which a supplemental translocation is likely to provide sufficient benefit to warrant cost based on genetic measures of variation, numerical population estimates, and/or release population trend.

Water developments have played a major role in habitat enhancement efforts. Bighorn sheep use these developments, as do other species including predators. Little research has been conducted to determine the role of enhanced water availability on the presence, distribution, and abundance of either bighorn sheep or their predators. In addition, managed water availability may influence predator distribution. Further attention should be given to the source population from which bighorn sheep translocations are obtained as those that come from habitats where mountain lions occur may be able to avoid predators more than those that come from areas in which mountain lion predation may be a novel event.

H_3 = Seasonal (e.g., winter) removal of water in and surrounding bighorn sheep habitat may change predator distribution and abundance more than bighorn sheep distribution and abundance.

H_4 = Water availability may be provided differentially to bighorn sheep and predators (e.g., easily accessible to bighorn sheep, restricted to mountain lions) in a manner that is not detrimental to other wildlife species dependent on those water sources.

H_5 = Bighorn sheep from source populations with mountain lions should have lower post-release mortality from mountain lion predation than bighorn sheep from source populations without mountain lions.

Disease is probably the greatest threat to bighorn sheep populations. The risk of disease transmission effects not only the reestablishment of bighorn sheep populations, but often places extant populations at risk as well. The ability to determine the risk of disease transmission during a translocation also remains more of an art than a quantitative science (but see Dubay et al. 2002, Cassaigne et al. 2010). Reestablishment of bighorn sheep populations into historical range often places these populations at risk of exposure to domestic livestock that may have created the original extirpation.

H_6 = Based on disease prevalence, virulence, and vector proximity and knowledge of source and release location herd exposure, an effective rapid risk assessment may be developed to evaluate when supplemental translocations are suitable.

Bighorn sheep management is complex for a variety of factors. The present situation is similar to what has been observed in other game species that were once at low numbers, only to be restored through the efforts of wildlife management agencies and interested hunters (Porter et al. In press). The challenge of increasing bighorn sheep population numbers when at low levels can be met through relatively straightforward management actions. However, as population numbers attain what more closely approximates the carrying capacity of existing habitats, multiple factors interact to limit λ. Future successes will require new knowledge of limiting factors.

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Brian F. Wakeling *is the editor of the* Desert Bighorn Council Transactions *and the Game Branch Chief for the Arizona Game and Fish Department. He has served for the Arizona Game and Fish Department since 1988 as a Research Biologist and Big Game Management Supervisor before assuming his current position in January 2009. Brian received his B.S and M.S. from Arizona State University in 1985 and 1989, respectively. Brian has authored other research papers on turkeys (Gould's and Merriam's), mule deer, elk, bison, mountain lions, and urban lizards.* ***Ray Lee*** *spent 10 years enjoying the academic environment of Arizona State University. He then worked as the Statistician and then the Big Game Management Supervisor for the Arizona Game and Fish Department for 18 years. He left the Department to serve for 8 years as the President of the Wild Sheep Foundation (formerly the Foundation for North American Wild Sheep). Ray left the Foundation to run his own wildlife*

consulting company, and is presently conducting a number of wildlife management projects - including several with wild sheep in Mexico. ***David Brown*** *received a B.A. in Natural Resources Conservation from San Jose State College in California in 1961. He was hired by the Arizona Game and Fish Department in 1961 as a Wildlife Manager. He promoted to Small Game Management Supervisor in 1968, then served as Big Game Management Supervisor from 1981–1984. David again promoted to Game Branch Chief, where he served until his retirement in 1987. He has served as an adjunct professor at Arizona State University since his retirement with the Department, although he has worked on several independent projects internationally (primarily in Mexico) as well.* ***Ron Thompson*** *recently collaborated on major portions of the book entitled* Managing Cougars in North America *(Western Association of Fish and Wildlife Agencies). Ron served a 20-year career with the Arizona Game and Fish Department as a Wildlife Manager, Investigator, and Law Program Manager before retiring, and subsequent rehiring, by the Department, as the large carnivore biologist for the Department between 2008–2010. Between employment periods with the Department, he was a contract wildlife biologist capturing and radiocollaring mountain lions for a desert bighorn sheep-mountain lion interaction study in Arizona. He was a past contractor for the Turner Endangered Species Fund which included using adaptive management strategies for mountain lions. For the past five years, he has also been working on livestock conflicts and management with private ranch owners in Sonora, Mexico.* ***Melanie Tluczek*** *is a graduate student at Arizona State University Polytechnic campus in the Wildlife and Restoration Program. Originally intending to study Anthropology, she was converted to Wildlife Biology through a wildlife techniques course in which she fell in love with fieldwork. Since then she has spent the last 3 years crawling after a herd of pronghorn antelope on Perry Mesa, Arizona as part of her thesis project. In between working on her thesis and spending time with her new daughter, Melanie enjoys hiking, hunting, and stargazing.* ***Mara Weisenberger*** *is currently a Wildlife Biologist with the Fish and Wildlife Service, San Andres National Wildlife Refuge. She previously worked at Kofa National Wildlife Refuge. Mara has been the senior wildlife biologist at San Andres National Wildlife Refuge, New Mexico for the past 18 years, and during this time she has served on details to Kodiak Island, Alaska for a brown bear study and at refuges in Colorado and Arizona. Recently her San Andres assignments have included details to the Refuges Division in Washington, D.C., as acting regional biologist for the Southwest Regional Office in Albuquerque, New Mexico and a detail with the DOI International Technical Assistance Program to Tanzania providing training on long-term resource monitoring. She holds a B.A. degree in Psychology with a concentration in animal behavior and a M.S. degree in Wildlife Ecology from the University of Arizona. Mara resides in Las Cruces, New Mexico with her husband and two children, who share her passion for wildlife and the outdoors.*