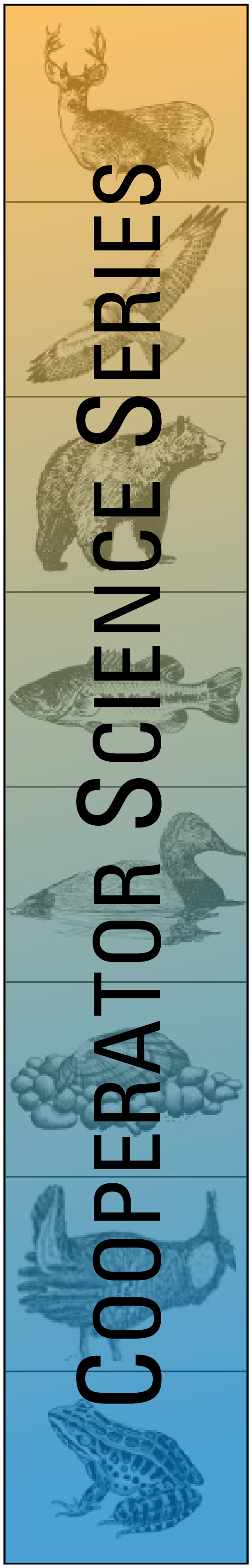

U.S. Fish and Wildlife Service

Adult Survival, Apparent Lamb Survival, and Body Condition of Desert Bighorn Sheep in Relation to Habitat and Precipitation on the Kofa National Wildlife Refuge, Arizona

Matthew W. Overstreet[1]
James W. Cain III[2]
and Colleen A. Caldwell[2]

[1] New Mexico Cooperative Fish and Wildlife Research Unit, New Mexico State University, Las Cruces, NM
[2] U.S. Geological Survey, New Mexico Cooperative Fish and Wildlife Research Unit, New Mexico State University, Las Cruces, NM

Cooperator Science Series # 109-2014

About the Cooperator Science Series:

The Cooperator Science Series was initiated in 2013. Its purpose is to facilitate the archiving and retrieval of research project reports resulting primarily from investigations supported by the U.S. Fish and Wildlife Service (FWS), particularly the Wildlife and Sport Fish Restoration Program. The online format was selected to provide immediate access to science reports for FWS, state and tribal management agencies, the conservation community, and the public at large.

All reports in this series have been subjected to a peer review process consistent with the agencies and entities conducting the research. Authors and/or agencies/institutions providing these reports are solely responsible for their content. The FWS does not provide editorial or technical review of these reports. Comments and other correspondence on reports in this series should be directed to the report authors or agencies/institutions. In most cases, reports published in this series are preliminary to publication, in the current or revised format, in peer reviewed scientific literature. Results and interpretation of data contained within reports may be revised following further peer review or availability of additional data and/or analyses prior to publication in the scientific literature.

The Cooperator Science Series is supported and maintained by the FWS, National Conservation Training Center at Shepherdstown, WV. The series is sequentially numbered with the publication year appended for reference and started with Report No. 101-2013. Various other numbering systems have been used by the FWS for similar, but now discontinued report series. Starting with No. 101 for the current series is intended to avoid any confusion with earlier report numbers.

The use of contracted research agencies and institutions, trade, product, industry or firm names or products or software or models, whether commercially available or not, is for informative purposes only and does not constitute an endorsement by the U.S. Government.

Contractual References:

This document fulfills reporting requirements for FWS agreement number 01572HR059. Previously published documents that partially fulfilled any portion of this contract are referenced within, when applicable. (USGS IPDS #: IP-056470)

Recommended citation:

Overstreet M. W., J. W. Cain III and C. A. Caldwell. 2014. Adult Survival, Apparent Lamb Survival, and Body Condition of Desert Bighorn Sheep in Relation to Habitat and Precipitation on the Kofa National Wildlife Refuge, Arizona. U.S. Department of Interior, Fish and Wildlife Service, Cooperator Science Series FWS/CSS-109-2014, Washington, D.C.

For additional copies or information, contact:

New Mexico Cooperative Fish and Wildlife Research Unit
Department of Fish, Wildlife and Conservation Ecology
P. O. Box 30003, MSC 4901
New Mexico State University
Las Cruces, NM 88003-0003
Phone: (575) 646 - 6053
E-mail: jwcain@nmsu.edu

FINAL REPORT

Adult Survival, Apparent Lamb Survival, and Body Condition of Desert Bighorn Sheep in Relation to Habitat and Precipitation on the Kofa National Wildlife Refuge, Arizona

to

U.S. Fish and Wildlife Service,
Kofa National Wildlife Refuge

from

Matthew W. Overstreet
Department of Fish, Wildlife and Conservation Ecology
New Mexico State University

James W. Cain III and Colleen A. Caldwell
U.S. Geological Survey
New Mexico Cooperative Fish and Wildlife Research Unit
Department of Fish, Wildlife and Conservation Ecology
New Mexico State University

August 2014

EXECUTIVE SUMMARY

The decline of desert bighorn sheep on the Kofa National Wildlife Refuge (KNWR) beginning in 2003 stimulated efforts to determine the factors limiting survival and recruitment. We 1) determined pregnancy rates, body fat, and estimated survival rates of adults and lambs; 2) investigated the relationship between precipitation, forage conditions, previous year's reproductive success, and adult body condition; 3) assessed the relative influence of body condition of adult females, precipitation, and forage characteristics on apparent survival of lambs; and 4) determined the prevalence of disease. To assess the influence of potential limiting factors on female desert bighorn sheep on the KNWR, we modeled percent body fat of adult females as a function of previous year's reproductive effort, age class, and forage conditions (i.e., seasonal NDVI and seasonal precipitation). In addition, we assessed the relative influence of the body condition of adult females, precipitation, and forage conditions (NDVI) on length of time a lamb was observed at heel.

Adult female survival was high in both 2009 (0.90 [SE = 0.05]) and 2010 (0.96 [SE = 0.03]). Apparent lamb survival to 6 months of age was 0.23 (SE = 0.05) during 2009-2010 and 0.21 (SE = 0.05) during 2010-2011 lambing seasons. Mean body fat for adult females was 12.03% (SE = 0.479) in 2009-2010 and 11.11% (SE= 0.486) in 2010-2011 and was not significantly different between years. Pregnancy rate was 100% in 2009 and 97.5% in 2010.

Models containing the previous year's reproductive effort, spring NDVI and previous year's reproductive effort and spring precipitation best approximated data on percent body fat in adult females in 2009-2010. In 2010-2011, the two highest-ranking models included the previous year's reproductive effort and winter NDVI and previous year's reproductive effort, and winter and spring NDVI. None of the models assessing the influence of maternal body fat, precipitation, or forage conditions were particularly useful for predicting apparent lamb survival.

The high pregnancy rates and body fat levels in excess of 11% do not indicate that this population of desert bighorn was nutritionally stressed during our study and are thus likely not contributing to the low lamb survival estimates we observed. However, body condition data during the population decline is not available and whether this population was nutritionally limited during the initial population decline remains unknown.

The prevalence of disease in the Kofa herd may be a limiting factor; however, due to a lack of disease monitoring during the population decline it is uncertain if disease contributed to the decline. Further research is needed to fully understand the complex interaction of disease in this population at the individual and population level and determine to what extent disease predisposes individuals to predation or other causes of mortality.

BACKGROUND

Concern regarding the decline of desert bighorn sheep on the Kofa National Wildlife Refuge (Refuge) stimulated efforts to identify factors that were limiting reproduction, survival and recruitment (USFWS 2007). The cause of the population decline is unknown, but potential factors include decreased adult ewe survival, decreased lamb survival, effects of decreased adult ewe body condition due to drought impacts on forage resources, predation by a new or expanding mountain lion (*Puma concolor*) population, disease (USFWS 2007) or some combination of these factors. Therefore, there was a need to assess whether population growth was limited by nutritional stress, poor survival, declining parturition, disease, predation or some combination of these factors.

The goal of this research was to examine some of the potential limiting factors influencing the population desert bighorn sheep on the Refuge. Specifically, we: 1) determined pregnancy rates; 2) investigated the relationship between precipitation, forage conditions, previous year's reproductive success, and adult body condition; 3) assessed the relative influence of body condition of adult females, precipitation, and forage characteristics on apparent survival of lambs; and 4) determined the prevalence of disease.

METHODS

Animal Capture and Body Condition

Thirty-four adult female desert bighorn sheep were captured using a net gun fired from a helicopter (Krausman et al. 1985) in November 2009. Thirty-six animals were captured in 2010, which consisted of 28 animals that were originally captured in 2009 plus an additional eight animals to replace those lost to mortality or collar failure. In total, 42 different sheep were captured for this study. Captured animals were transported via helicopter to a staging area for processing. Age was estimated by tooth eruption patterns (Mahon 1975) and counting horn annuli (Geist 1971). All captured animals were marked with numbered and colored ear-tags and fitted with either GPS (North Star Inc., King George, Maryland, USA) or VHF radiocollars equipped with a mortality sensor (Sirtrack, Auckland, New Zealand); GPS collars were programmed to acquire three locations per day. All animals were returned to the site of capture for release. Capture and handling procedures followed acceptable methods established by the American Society of Mammalogists (Sikes et al. 2011) and were approved by the New Mexico State University Institutional Animal Care and Use Committee (IACUC protocol #2008-009). Body condition was assessed using ultrasonography (Stephenson et al. 1998, 2002). A portable ultrasound was used to measure maximum subcutaneous fat thickness immediately posterior to the cranial process of the tuber ischium (Maxfat) and maximum thickness of the longissimus dorsi between the 12th and 13th ribs (Stephenson et al. 1998, 2002). Overall body condition was estimated using a scoring system similar to that described by Cook et al. (2001). Rump body condition score (rBCS) was estimated by palpating the sacral ridge and soft tissue of the rump at the base of the tail; measurements were scored on a scale of 1 to 6, in intervals of 0.25, where 1 = emaciated and 6 = obese. Total body fat (BF) was estimated using two predictive equations from ultrasound measurements of rump fat when present (Stephenson et al., 1998, 2002; Cook et al., 2007):

(1) $BF = (13.28^{*}Maxfat) + 7.78$

If no measurable subcutaneous fat (Maxfat) was detected, we calculated body fat using body condition scores (rBCS) as:

(2) $BF = (3.92^{*}rBCS) - 1.48$

In most cases, pregnancy was determined by ultrasonography (Harper and Cohen 2008). When pregnancy could not be determined using ultrasound, serum samples were assayed for pregnancy-specific protein B (Bio Tracking Inc., Moscow, Idaho, USA; Drew et al. 2001). Serum samples and nasal swabs were also collected and assayed for *Mycoplasma ovipneumoniae*, Bluetongue virus, epizootic hemorrhagic disease (EHD), bovine respiratory syncytial virus (BRSV) and contagious ecthyma.

Demographic Monitoring

GPS-collared animals were monitored daily via satellite downloads. In addition, all collared adults were relocated via VHF signals on a monthly basis from January 1st through August 1st during which time, the observer confirmed if a collared female was rearing a lamb through visual observation of maternal care (i.e., nursing). When each study animal was relocated, the location was recorded with a handheld GPS unit, and survival status (live or dead), and presence of a lamb was noted. Length of time an adult was with a lamb was calculated by summing the number of days between the date of the first observation with a lamb and the 1st of August, or six months of age, or the last date observed with a lamb, whichever came first. Lamb age was estimated based on the period of time (i.e., number of monthly observations) that adult females were observed with lambs, and age-specific characteristics described in Hansen (1965), Hansen and Deming (1980).

Necropsies were conducted in the field in an effort to identify cause of death. Mortalities of collared females were investigated and classified as disease, accidental, or predation. Predation-related mortalities were classified based on mortality site characteristics (e.g., blood splatter, presence of drag trails, signs of a struggle, cache site, removal of rumen, rib bones clipped, organs removed, subcutaneous hemorrhaging, and canine puncture wounds; Shaw et al. 2007). Predation was not classified as mountain lion related unless subcutaneous hemorrhaging, consistent with the canine spacing of mountain lions, was found during the necropsy in an effort to reduce the possibility of misidentifying scavenging as predation (Bauer et al. 2005). Mortalities occurring within 30 days following a capture were censored from survival analyses (Berringer et al. 1996).

Home Ranges

Animal locations obtained during relocation of animals with VHF collars as well as those recorded via GPS collars were mapped for each season in ArcGIS 9.3 (Environmental Systems Research Institute [ESRI], Redlands, California, USA). Seasonal designations were based on long-term seasonal precipitation and temperature data from Kofa Mine weather station on the Refuge (WRCC 2011), and the reproductive cycle (i.e., parturition, lactation, mating, early gestation and late gestation) of desert bighorn sheep in Arizona: winter (1 December - 31 March) as the cool and wet season-time of parturition, spring (1 April to 30 June) as the hot and dry season-time of lamb weaning, summer (1 July - 30 September) as the hot and wet season-mating season, and fall (1 October - 30 November) as warm and dry season with females in mid to late gestation. The Hawth's Tools extension (Beyer 2004) was applied in ArcGIS to estimate 50% core use areas (Worton 1989), and least squares cross validation to determine the smoothing parameter (Worton 1989, Seaman and Powell 1996, Seaman et al. 1998). The 50% core use area was selected because of the more intense use of these areas, particularly when a newborn lamb was present, which would restrict movements of females and result in a disproportionate influence of forage conditions within the core area on adult female body condition.

Forage Conditions and Precipitation

Normalized difference vegetation index (NDVI) was derived from satellite imagery collected by the MODIS Terra platform as a measure of forage conditions (Pettorelli et al. 2007). MODIS data were downloaded from NASA land processes distributed active archive center (NASA 2011). We used the HDF-EOS GeoTIFF Conversion Tool to extract the NDVI layer and re-project the NDVI data from a sinusoidal projection to WGS 84. The NDVI layers were assessed in16-day intervals to capture vegetation response to precipitation at a spatial resolution of 250 x 250 m. The NDVI images were collected for each 16-day period and organized seasonally. All images were rescaled using the Spatial Analyst General Math Tools in ArcGIS 9.3 (ESRI, Redlands, California, USA). A seasonal NDVI raster was created using the Cell Statistics in the Spatial Analyst Tools to average the values of each overlapping NDVI pixel across NDVI images within each season. All seasonal NDVI raster data files were clipped using a 3 kilometer buffer around the boundaries of the Refuge. We extracted the seasonal NDVI data for each individual core area, and calculated the mean NDVI for each core use area (50% kernel). To account for the asymptotic nature of NDVI data, NDVI values were transformed using the natural log (ln) transformation (Fan et al., 2009; Ryan et al., 2012).

Twenty Rainwise™ rain gauge data loggers (Rainwise Inc., Bar Harbor, ME) were spaced 8 km apart throughout occupied sheep habitat to collect precipitation data. Rain gauge locations were plotted in ArcGIS 9.3 and overlaid with the seasonal core use areas. For each rain gauge, precipitation was totaled for each season and year of the study. Seasonal precipitation totals for each rain gauge within 2 km of each seasonal core area were extracted to estimate the average total seasonal precipitation for each animal's seasonal core use area. Monthly precipitation was compared with long-term average (1952-2011) obtained from the Arizona Kofa Mine (024702) data summary, Western Regional Climate Center (Accessed 25 April 2013; http://www.wrcc.dri.edu/climatedata/climsum/).

ANALYSES

Demographic analysis

The known fate model in program MARK (White and Burnham 1999) was used to estimate survival rates of adult females. Although we had originally planned to model the survival of adult females in relation to individual covariates (e.g., percent body fat, age class, seasonal NDVI, seasonal precipitation), the limited number of adult mortalities precluded a meaningful analysis using individual covariates. Therefore, annual survival of adult females was estimated.

The Lukacs young survival model in program MARK (White and Burnham 1999) was used to estimate apparent survival of lambs to six months of age. Apparent survival was then calculated over the entire lambing period by the product of the survival estimates for each observation period (i.e., month) and standard error of apparent survival was calculated using the delta method (Cooch and White 2012). Originally, the Lukacs Young Survival model in program MARK was to model the apparent survival of lambs in relation to individual covariates (e.g., percent body fat, age class, seasonal NDVI, seasonal precipitation); however, inconsistent and infrequent lamb detections precluded use of program MARK to incorporate covariates in models of lamb survival.

Adult body condition

Mean percent body fat was compared between 2009-2010 and 2010-2011 using a paired *t*-test in SPSS 17.0 (IBM, Chicago, Illinois). Percent body fat of adult females was modeled as a function of previous year's reproductive effort (i.e., length of time with lamb at heel), age class, and forage conditions (i.e., seasonal NDVI and seasonal precipitation) using general linear models in SPSS 17.0. Several sets of a priori models (Appendices 1 and 2) were developed to evaluate the relative influence of previous reproductive effort, age class, and forage conditions on percent body fat in adult females. Model structures assessed the relative influence of forage conditions and precipitation on adult female percent body fat during specific seasons.

Using general linear models in SPSS 17.0, total length of time a lamb was observed with a collared female was modeled as a function of age class, maternal body fat, seasonal NDVI, and seasonal precipitation. A set of a priori models (Appendix 3) was developed to evaluate the relative influence of forage conditions and maternal body condition, on the total length of time a lamb was observed with a female. Model structures were developed to assess the relative influence of forage conditions and precipitation during specific periods in the reproductive cycle: late gestation (i.e., fall NDVI and precipitation), early parturition (i.e., winter NDVI and precipitation), and the post-weaning period (i.e., spring NDVI and precipitation).

Although two indices of forage conditions (NDVI and seasonal precipitation) are highly correlated, both were used in the analyses. To assess the utility of each index for modeling female body condition, NDVI and precipitation were not included in the same models to avoid issues with multicollinearity, but they were included in the same model set. Rain gauge data was not available for the fall period of 2009; thus, models containing fall precipitation were not included for the 2009-2010 analyses.

An information-theoretic approach was used to select the most parsimonious models using AIC corrected for a small sample size (AIC_c) to evaluate *a priori* models. Models with $\Delta AIC_c < 2.0$ were considered to have equivalent support (Burnham and Anderson 2002, Anderson 2010). Model uncertainty was accounted for by calculating model-averaged parameter estimates (± standard error, SE) using multi-model averaging for individual covariates in the highest-ranking models (Burnham and Anderson 2002).

RESULTS

Precipitation

Precipitation was 104.9 mm in 2008-2009, 309.8 mm in 2009-2010, and 105.5 mm in 2010-2011. The long-term annual precipitation averaged 163.01 mm. Notably, this study spanned periods with both below and above average precipitation conditions (Table 1).

Pregnancy

Pregnancy was 100% in 2009. Ultrasound revealed that 28 of the 34 sheep were pregnant and five were pregnant based on protein B assays. One test using the protein B was a false-negative (i.e., we know this animal subsequently had a lamb within 4 months of capture, thus we know that it was pregnant at the time of capture). In 2010, 97.5% of the animals were pregnant with one yearling ewe not pregnant. However, primiparity as yearlings is rare in bighorn sheep (Festa-Bianchet et al. 1995).

Cause-specific Mortality and Survival Rates

Presence of mountain lion and coyote (*Canis latrans*) at mortality sites was determined by tracks, scat, cache methods, and canine tooth width. Three mortalities occurred from 2009 to 2010. One female died of unknown causes, one was a probably mountain lion predation, and one mortality was attributed to mountain lion predation. Mountain lions were present at the two of the three mortality sites and coyotes were detected at one of the three mortality sites. From 2010 to 2011, one adult female died due to mountain lion predation and two females died of unknown causes.

Adult female survival was high in both years. Thus, a meaningful assessment of the influence of the individual covariates on adult female survival was not possible due to the small number of adult female mortalities. Survival of adult females was 0.90 (SE = 0.05) from October 2009 through September 2010 and 0.96 (SE = 0.03) from October 2010 through September 2011. Apparent lamb survival to 6 months-of-age was 0.23 (SE = 0.05) during 2009-2010 and 0.21 (SE = 0.05) during 2010-2011 lambing seasons.

Factors Influencing Adult Female Body Condition

Mean body fat for adult females was 12.03% (SE = 0.479) in 2009-2010 and 11.11% (SE= 0.486) in 2010-2011 and was not significantly different between years ($\overline{x}$ difference = 0.388, SE = 0.542, $t_{27} = 0.716$, $P = 0.480$).

Adult body condition 2009-2010. When comparing all potential models for factors influencing percent body fat in 2009-2010, we found that the model containing the previous year's reproductive effort and spring NDVI best explained the results (Table 2). The second highest ranking model included previous year's reproductive effort and spring precipitation. However, Akaike weight (w_i), suggested that the top model ($w_i = 0.468$) had nearly twice as much support as the next best candidate model ($w_i = 0.283$; Table 2).

Percent body fat of adult females was associated with spring precipitation (slope = 74.3 [SE = 16.66]) and spring NDVI (slope = 16.8 [SE = 3.55]) within the 50% core use area, as well as with the previous year's reproductive effort (Table 3). Summer seasonal precipitation (slope = 5.3 [SE = 22.97]) and NDVI (slope = 2.2 [SE = 6.98]) were positively associated with percent body fat of females in the fall, but slopes were not as large as spring precipitation and NDVI (Table 3).

Table 1. Climatic conditions during 2009 – 2011 in comparison with the seasonal long-term (59 years; 1952-2011 at Kofa Mine), average daily high and low temperatures and average total seasonal precipitation on the Kofa National Wildlife Refuge, Arizona.

Climate Variable	**Fall** (1 October - 30 November)			
	2009	2010	2011	Long-term Average
Average daily high temp (°C)	27.1	25.8	26.9	26.5
Average daily low temp (°C)	15.5	15.4	15.7	19.9
Precipitation (mm)	0.00	13.7	26.4	22.1
	Winter (1 December - 31 March)			
	2008-2009	2009-2010	2010-2011	Long-term Average
Average daily high temp (°C)	21.0	19.5	21.3	19.5
Average daily low temp (°C)	10.4	9.7	10.0	8.7
Precipitation (mm)	67.5	185.1	39.4	65.0
	Spring (1 April - 30 June)			
	2009	2010	2011	Long-term Average
Average daily high temp (°C)	32.9	31.6	32.2	32.4
Average daily low temp (°C)	19.5	17.5	18.6	18.4
Precipitation (mm)	4.1	4.1	7.4	8.6
	Summer (1 July - 30 September)			
	2009	2010	2011	Long-term Average
Average daily high temp (°C)	39.8	39.2	39.7	37.9
Average daily low temp (°C)	26.8	26.2	27.0	24.9
Precipitation (mm)	33.3	106.9	32.3	67.5

Table 2. Five highest-ranking a priori models assessing the influence of previous reproductive effort[1], precipitation, and seasonal forage conditions on the percent body fat of female desert bighorn sheep on the Kofa National Wildlife Refuge, Arizona, 2009-2010. Number of parameters (K), Akaike's Information Criterion adjusted for small sample size (AIC_c), ΔAIC_c, and Akaike weights (w_i). Models ranked according to AICc from best to worst.

Model Structure	**K**	**AIC_c**	**ΔAIC_c**	**w_i**
0809 Total Days + Spring NDVI	4	36.39	0	0.468
0809 Total Days + Spring Precip	4	37.39	1.01	0.283
0809 Total Days + Spring NDVI + Summer NDVI	5	39.21	2.82	0.115
0809 Total Days + Spring Precip + Summer Precip	5	40.15	3.76	0.072
0809 Total Days + Spring NDVI + Summer NDVI + Fall NDVI	6	41.54	5.15	0.036

[1]Defined as the length of time a female was observed with a lamb the previous year (2009-2010 Total Days)

Table 3. Model averaged regression coefficient estimates, standard errors (SE), and 95% confidence limits for variables in the best approximating models assessing previous year's reproductive effort, precipitation, and seasonal forage conditions on percent body fat of female desert bighorn sheep on the Kofa National Wildlife Refuge, Arizona, 2009-2010.

	Model Averaged Coefficient		95% Confidence Limits	
Variable	**Estimate**	**SE**	**Lower CL**	**Upper CL**
Spring Precip	74.3	16.66	41.62	106.91
Spring NDVI	16.8	3.55	9.79	23.74
Summer NDVI	2.2	6.98	-11.45	15.90
0809 Total Days	0.01	0.01	0.001	0.030

Adult body condition 2010-2011. In the analysis of the relationship between body fat, reproductive effort, age class, and forage conditions in 2010-2011, the highest-ranking model included the previous year's reproductive effort and winter NDVI (Table 4). The second-ranked model included previous year's reproductive effort, winter, and spring NDVI. However, the top model (w_i = 0.320) had twice as much support as the next best candidate model (w_i = 0.173; Table 4).

The percent body fat of adult females in fall was positively related to NDVI during the previous winter (slope = 14.2 [SE = 8.35]) and negatively associated with length of time a ewe was observed with a lamb the previous year (slope= -0.002 [SE = 0.01]). NDVI during spring (slope = -7.02 [SE = 6.97]) and fall (slope = -4.99 [SE = 5.10]) were both negatively associated with percent body fat of adult females (Table 5). However, the confidence limits for the regression slopes all included zero, indicating that zero is a plausible value for the slope (i.e., no relationship) between the predictor variables and percent body fat during 2010-2011.

Table 4. Five highest-ranking a priori models assessing the influence of previous reproductive effort and seasonal forage conditions on the percent body fat of female desert bighorn sheep on the Kofa National Wildlife Refuge, Arizona, 2010-2011. Number of parameters (K), Akaike's Information Criterion adjusted for small sample size (AIC_c), ΔAIC_c, and Akaike weights (w_i). Models ranked according to AICc from best to worst.

Model Structure	**K**	**AIC_c**	**ΔAIC_c**	**w_i**
0910 Total Days + Winter NDVI	4	54.25	0.00	0.32
0910 Total Days + Winter NDVI + Spring NDVI	5	55.48	1.23	0.17
0910 Total Days + Fall NDVI + Winter NDVI	5	56.35	2.10	0.11
0910 Total Days + Fall NDVI + Winter NDVI + Spring NDVI	6	57.52	3.26	0.06
0910 Total Days + Winter NDVI + Spring NDVI + Summer NDVI	6	58.27	4.02	0.04

Table 5. Model averaged regression coefficient estimates, standard errors, and 95% confidence limits for variables in the best approximating models assessing previous year's reproductive effort and seasonal forage conditions on percent body fat of female desert bighorn sheep on the Kofa National Wildlife Refuge, Arizona, 2010-2011.

	Model Averaged Coefficient		95% Confidence Limits	
Variable	**Estimate**	**SE**	**Lower CL**	**Upper CL**
Winter NDVI	14.2	8.35	-2.23	30.54
0910 Total Days	-0.002	0.01	-0.02	0.02
Fall NDVI	-4.99	5.10	-14.99	5.00
Spring NDVI	-7.02	6.97	-20.70	6.67

Factors Influencing Length of Time Lambs Were Observed with Adult Females

Lamb 2009-2010. There were no individual models with the majority of support that described the relationship between the length of time a ewe was observed with a lamb in 2009-2010 and the individual covariates. When comparing all potential models we found that a model containing the age class of the adult ewe best approximated the data; however, support was low and there was substantial model selection uncertainty (Table 6). The high degree of model selection uncertainty indicated that none of the covariates were particularly useful in modeling the length of time a ewe was observed with a lamb at heel (Table 7).

Lamb 2010-2011. There were no individual models with overwhelming support that described the relationship between the length of time a ewe was observed with a lamb and the individual covariates. When comparing all potential models for influencing the length of time a ewe was observed with a lamb, we found that a model containing the winter NDVI best approximated the data (Table 8). However, there were also several competing models (i.e., ΔAICc values <2.0). Support for the top model was low (w_i = 0.128) but was 35% higher than the second highest-ranking model (w_i = 0.083; Table 8).

Summer NDVI, percent body fat, and winter precipitation were all positively related to the length of time a ewe was observed with a lamb (Table 9). Spring, fall and winter NDVI had negative associations with the length of time a ewe was observed with a lamb (Table 9); however, all confidence limits included zero indicating that there was no relationship between these predictor variables and the length of time a ewe was observed with a lamb.

Table 6. Six highest-ranking a priori models assessing the influence of age class, precipitation, and seasonal forage conditions for the length of time lambs (n = 31) were observed with a female desert bighorn sheep on the Kofa National Wildlife Refuge, Arizona, 2009-2010. Number of parameters (K), Akaike's Information Criterion adjusted for small sample size (AIC_c), ΔAIC_c, and Akaike weights (w_i). Models ranked according to AICc from best to worst approximating model.

Model Structure	K	AIC_c	ΔAIC_c	w_i
Age Class	3	244.64	0.00	0.11
Winter NDVI	3	245.61	0.97	0.07
Age Class + Spring Precip	4	245.91	1.26	0.06
Age Class + Winter NDVI	4	246.12	1.48	0.05
Age Class + Summer Precip	4	246.25	1.61	0.05
Age Class + Winter Precip	4	246.73	2.09	0.04

Table 7. Model averaged regression coefficient estimates, standard errors, and 95% confidence limits for variables in the best approximating models assessing the influence of maternal body fat, age class, seasonal forage conditions for the length of time lambs (n = 31) were observed with a female desert bighorn sheep on the Kofa National Wildlife Refuge, Arizona, 2009-2010.

	Model averaged coefficient		95% Confidence limits	
Variable	**Estimate**	**SE**	**Lower CL**	**Upper CL**
Spring Precip	298.02	294.472	-279.15	875.18
Winter NDVI	122.93	109.849	-92.38	338.23
Age Class	21.88	13.874	-5.32	49.07
Winter Precip	-0.95	2.785	-6.41	4.51
Summer Precip	-1.56	1.282	-4.07	0.96

Table 8. Six highest-ranking a priori models assessing the influence of maternal body fat and seasonal forage conditions for the length of time lambs (n = 37) were observed with a female desert bighorn sheep on the Kofa National Wildlife Refuge, Arizona, 2010-2011. Number of parameters (K), Akaike's Information Criterion adjusted for small sample size (AIC_c), ΔAIC_c, and Akaike weights (w_i). Models ranked according to AICc from best to worst.

Model Structure	**K**	**AIC_c**	**ΔAIC_c**	**w_i**
Winter NDVI	3	233.33	0.00	0.13
Percent Body Fat + Winter NDVI	4	234.20	0.87	0.08
Fall NDVI + Winter NDVI	4	235.03	1.70	0.05
Winter Precip	3	235.09	1.76	0.05
Summer NDVI	3	235.29	1.97	0.05
Spring NDVI	3	235.78	2.45	0.04

Table 9. Model averaged regression coefficient estimates, standard errors, and 95% confidence limits for variables in the best approximating models assessing the influence of maternal body fat and seasonal forage conditions for the length of time lambs (n = 37) were observed with a female desert bighorn sheep on the Kofa National Wildlife Refuge, Arizona, 2010-2011.

	Model averaged coefficient		95% Confidence limits	
Variable	**Estimate**	**SE**	**Lower CL**	**Upper CL**
Summer NDVI	65.34	60.225	-52.70	183.38
Percent Body Fat	2.02	2.412	-2.71	6.74
Winter Precip	1.53	1.535	-1.48	4.54
Spring NDVI	-23.64	60.745	-142.70	95.42
Fall NDVI	-39.71	61.611	-160.47	81.04
Winter NDVI	-130.94	73.016	-274.05	12.17

Disease Prevalence

Disease testing in 2009-2010 and 2010-2011 revealed 76% and 57% of the population was exposed to *M. ovipneumoniae*, respectively. Eighty eight percent tested positive for exposure to contagious ecthyma in 2009 and 79% in 2010. Positive Bluetongue titers were detected in 2.9% and 2.8% of the samples in 2009 and 2010, respectively. EHD was not detected in any samples in 2009, but was detected in 2.8% of the captured sheep in 2010. Positive titers for BSRV and PI3 were detected in most of the study animals. Seventy nine percent of the samples tested positive for BSRV titers in 2009, increasing to 100% in 2010, whereas titers for PI3 were detected in 71% of the samples in 2009 and 89% in 2010.

DISCUSSION

From 1957 to 2003, the Refuge supported one of the largest and most stable populations of desert bighorn sheep in North America, serving as a primary source of bighorn sheep for translocations throughout the Southwest. Beginning about 2003, the population at the Refuge declined from an estimated 812 to 428 (95% CI 376-492) animals by 2012 (Arizona Department of Fish and Game 2012).

During 2009-2010, precipitation was almost twice (305.01 mm) the long-term annual mean of (163.01 mm). Abundant winter rainfall likely increased vegetation greenness during the 2009-2010 winter and subsequent spring. However, during 2010-2011, winter and summer precipitation was below average. The timing and storage of body fat is largely dependent on the amount of rainfall and subsequent vegetation response during the seasons prior to body fat measurements (Marshal et al. 2008, Cook et al. 2013). The previous spring precipitation and NDVI of 2009 were positively associated with body fat during the fall. The spring is a critically important season for adult females and is characterized by high temperatures and low precipitation prior to the monsoon season. Thus, fat deposits (i.e., body fat) sampled in fall during late gestation were apparently influenced by the prior spring precipitation and NDVI during the dry year only. Models were inconclusive for 2010. We hypothesize that the reason for the inconsistent relationship was due to difference in rainfall between years. In 2009, winter and spring rainfall were approximately average, while summer rainfall was 50% below average, thus small amounts of rainfall during the spring could be expected to have a larger effect. Whereas body condition assessed during 2010 was influenced by rainfall that was 300% and 58% above average during the preceding winter and summer, respectively. The high 2009-2010 winter rainfall likely resulted in good foraging conditions that carried over into the spring season, minimizing the influence of the limited spring rainfall. Alternatively, the differing results between rainfall, forage conditions, and percent body fat may have also been due to the limitations of NDVI in wet years. The spatial scale of NDVI measurements either did not detect differences in forage conditions that might have influenced body condition or that forage conditions across home ranges of individual animals were high enough to result in mean body fat measurements in excess of 11%, even for those animals that occupied home ranges with lower NDVI values.

An animal's ability to survive and reproduce is dependent upon environmental constraints and their ability to meet nutritional demands (Parker et al. 2009). Body condition (i.e., accrued body fat) of a female bighorn is a measurable correlate linking the animal to the landscape. The late winter in north-temperate regions represents a period of nutritional stress for adult females due to the increase in energetic demands associated with fetal growth during late gestation during when forage abundance and quality typically are limited. Nutritional demands increase during the spring due to costs of lactation however forage quality and quantity typically increase during the post-parturition period for north-temperate ungulates (Parker et al. 2009, Cook et al. 2001). For desert bighorn sheep in the Southwest, however, winter is a more favorable season, both nutritionally and physiologically. Abundant and high quality forage is widely available across the landscape and thermal and water stressors are minimal. Conversely, the spring period or pre-monsoon summer (April – June) with its high temperatures and low rainfall is arguably the most nutritionally and physiologically stressful season. Unlike ungulates inhabiting north-temperate environments, those inhabiting the Southwest likely reach their lowest body condition during spring and summer, particularly during years with below average precipitation.

We sampled body fat only during late fall or mid- to late-gestation because we chose to not capture animals during the heat of summer to lessen the risk of capture mortalities. Although our sampling period did not correspond directly with the hypothesized stressful seasons, spring and summer, mean percent body fat did not differ between years when sampled in the fall. An average percent body fat in excess of 11% across both years does not indicate that this population was nutritionally limited during this study. For example, body fat levels representative of good body condition are > 8% for elk (Cook et al. 2013) and caribou (Gerhart et al. 1996). Furthermore, the 98-100% pregnancy rate during the time of study also reflects that individuals sampled in this population were not nutritionally stressed.

Across both years (2009-2010 and 2010-2011), no individual models garnered overwhelming support describing the relationship between the numbers of days a female was observed with a lamb at heel. Support for the top models was low and there was substantial model selection uncertainty indicating that none of the covariates were particularly useful in modeling the length of time a ewe was observed with a lamb at heel. A major limitation of the lamb analyses was that the fate of lambs and causes of lamb mortality could not be determined. While adult survival was high during both years, apparent lamb survival to 6 months of age was less than 25%. Although we were unable to model apparent lamb survival to recruitment age, juvenile recruitment may be hampering the recovery of this desert bighorn population.

Mountain lion predation on bighorn sheep populations is commonplace throughout the western United States (Wehausen 1996, Mckinney et al. 2006a,b). For example Mckinney et al. (2006a,b) concluded that bighorn sheep can be limited by predation from mountain lions, particularly when facing lower quality forage conditions during drought. We attempted to measure adult female mortality caused by predation; however, predator control was occuring at the time of this study and we were unable to assess how predation might have influenced the population in the absence of predator removals. Due to the initial design of this project, lambs were not fit with radiocollars. Consequently, we were unable detect lamb predation or to examine how lamb predation may have impacted juvenile recruitment. In addition to mountain lions, coyotes, bobcat (*Lynx rufus*), golden eagles (*Aquila chrysaetos*), and gray fox (*Urocyon cinereoargenteus*) have all been reported as predators on bighorn sheep lambs (Hass 1989, Parsons 2007, Karsch 2014, Smith et al. 2014). While we were unable to determine the cause of lamb mortalites in this study, two studies in New Mexico on desert bighorn lamb mortality found that predation was the leading proximate cause of mortality (Parsons 2007, Karsch 2014). In addition, previous work on lamb mortality of Dall's sheep (Scotton and Pletcher 1998, Arthur and Prugh 2010), and Rocky Mountain bighorn sheep (Hass 1989) also reported predation as the primary cause of lamb mortailty, whereas Smith et al. (2014) reported that disease was implicated in 36% and predation 30% of the mortalities of Rocky Mountain bighorn lambs in the Black Hills, South Dakota.

Previous research postulated that body fat of adult females was correlated to birth mass of offspring and neonate survival (Smith et al. 1998, Cook et al. 2004). Our models, however, showed no significant influence of female body condition on reproductive performance which may be due to the timing of our assessment. Due to the variability in precipitation across home ranges, percent body fat would likely have also varied between the fall and spring at which time nutritional demands increased due to lactation. Thus, animals can have similar body condition during the fall following a favorable monsoon season, but inherent differences between individual home ranges in the abundance or quality of forage might manifest themselves as changes in body condition during the spring when nutritional demands are high and forage quality and quantity are limited. Individuals with home ranges containing higher quality and quantity of forage would be expected to lose disproportionately less body fat during the spring, produce higher quality milk and lambs born to these animals would be exposed to better forage conditions. In addition, the high levels of body fat observed indicated that the population was not nutritionally limited during this study.

The introduction of disease into bighorn sheep populations throughout the western United States has dramatically affected population growth and abundance (Cassirer and Sinclair 2007, McClintock and White 2007). We directly sampled all captured sheep across both years for diseases common to desert bighorn sheep. Across both years of the study, prevalence of all diseases for which we tested was found in the Kofa population. The prevalence of disease in the Kofa herd may be a limiting factor. However, we do not have data on disease prevalence during the population decline. Further research is needed to fully understand the complex interaction of disease in this population at the individual and population level, and determine to what extent disease predisposes individuals to other causes of mortality.

MANAGEMENT RECOMMENDATIONS

Accrued body fat of individual females is a metric of past forage quality and nutritional expenditures that can be used by managers to predict adult survival and recruitment (Stephenson et al. 2002). Continued assessment of individual body fat pre- and post-parturition would provide a working baseline to determine herd condition over time with varying climatic conditions. Furthermore, continued monitoring of body fat would enable limiting factors to be identified at the population level.

Establishing a long-term program for monitoring body condition would be beneficial to managers. Moreover, identifying a herd-specific body fat average pre- and post-parturition would enable managers to identify a herd carrying capacity and estimate a harvestable surplus for translocations (Cook et al. 2001). Establishing a herd-specific body fat average would also enable managers to monitor population growth by having a metric to gauge carrying capacity. When long-term body condition averages begin to stabilize or decline over time, biologists can use this information in combination with population estimates, to estimate a harvestable surplus for translocation. Furthermore, desert bighorn sheep in optimal condition when used in translocations would potentially be less affected from capture and handling stress, adjust more quickly, have higher survival, and be less likely to be preyed upon after release at the translocation site.

Continued validation of the body fat predictive equation is needed to further refine the ability to predict small amounts of accrued body fat at the lower end of the range (where body condition scores rather than ultrasound measurements are used) in bighorn sheep found in arid ecosystems. Further, research should be conducted to gain a more comprehensive understanding of female body condition and its influence on lamb recruitment. To gain a better understanding of lamb survival and factors influencing recruitment, capturing and collaring of lambs could provide valuable information for the management of desert bighorn on the Kofa NWR.

ACKNOWLEDGEMENTS

We thank Susanna Henry and Lindsay Smythe of U.S. Fish and Wildlife Service, Kofa National Wildlife Refuge and Bob Henry, Anne Justice-Allen, and Ron Thompson of the Arizona Game and Fish Department for logistical support. This work could not have been completed without the assistance of Thomas Stephenson, California Department of Fish and Wildlife. Funding was provided by the U.S. Geological Survey and U.S. Fish and Wildlife Service through the Science Support Partnerships

Program. Additional support was provided by the Agriculture Experiment Station and Department of Fish, Wildlife, and Conservation Ecology at New Mexico State University. Additional technical assistance was provided by Paul R. Krausman. Comments by V. C. Bleich and E. M. Rominger improved an earlier draft of this report. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

LITERATURE CITED

Arthur, S. M., and L. R. Prugh. 2010. Predator-mediated indirect effects of snowshoe hares on Dall's sheep in Alaska. Journal of Wildlife Management 74:1709–1721.

Arizona Game and Fish Department. 2012. Kofa National Wildlife Refuge. http://www.azgfd.gov/w_c/bhsheep/index.shtml. Accessed 5 August 2014.

Bauer, J. W., K. A. Logan, L. L. Sweanor, and W. M. Boyce. 2005. Scavenging behavior in puma. Southwestern Naturalist 50:466–471.

Berringer J., L. P. Hansen, W. Wilding, J. Fischer, and S. L. Sheriff. 1996. Factors affecting capture myopathy in white-tailed deer. Journal of Wildlife Management 60:373–380.

Beyer, H. 2004. Hawth's Analysis Tools for ArcGIS. Available at http://www.spatialecology.com/htools.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multi–model inference: a practical information–theoretic approach. Second edition. Springer–Verlag, New York, New York, USA.

Cassirer, E. F., and A. R. E. Sinclair. 2007. Dynamics of pneumonia in a bighorn sheep metapopulation. Journal of Wildlife Management 71:1080–1088.

Cooch, E., and G. C. White (eds). 2012. Program MARK: a gentle introduction. 11th edition. <http://www.phidot.org/software/mark/docs/book/> Accessed October 2012.

Cook, R. C., J. G. Cook., D. L. Murray., P. Zager., and B. K. Johnson. 2001. Nutritional condition models for elk: which are the most sensitive, accurate, and precise? Journal of Wildlife Management 65:988–997.

Cook, R. C., T. R. Stephenson, W. L. Myers, J. G Cook, and L. A. Shipley. 2007. Validating predictive models of nutritional condition for mule deer. Journal of Wildlife Management 71:1934–1943.

Cook, R. C., J. G. Cook, D. J. Vales, B. K. Johnson, S. M. McCorquodale, L. A. Shipley, R. A. Riggs, L. L. Irwin, S. L. Murphie, B. L. Murphie, K. A. Schoenecker, F. Geyer, P. B. Briggs Hall, R. D. Spencer, D. A. Immell, D. H. Jackson, B. L. Tiller, P. J. Miller, and L. Schmitz. 2013. Regional and seasonal patterns of nutritional condition and reproduction in elk. Wildlife Monographs 184:1–45.

Cook, J.G., B.K. Johnson, R.C. Cook, R.A. Riggs, T. Delcurto, L.D. Byant, and L.L. Irwin. 2004. Effects of summer-autumn nutrition and parturition date on reproduction and survival of elk. Wildlife Monographs 155.

Drew, M. L., V. C. Bleich, S. G. Torres, and R. G. Sasser. 2001. Early pregnancy detection in mountain sheep using a pregnancy-specific protein B assay. Wildlife Society Bulletin 29:1182–1185

Fan, L., Y. Gao, H. Brück, and C. Bernhofer. 2009. Investigating the relationship between NDVI and LAI in semi–arid grassland in Inner Mongolia using in–situ measurements. Theoretical and Applied Climatology 95:151–156.

Festa-Bianchet, M., J. T. Jorgenson, M. Lucherini, and W. D. Wishart. 1995. Life history consequences of variation in age of primiparity in bighorn ewes. Ecology 76:871–881.

Geist, V. 1971. Mountain Sheep: a study in behavior and evolution. University of Chicago Press, Illinois, USA.

Gerhart, K. L., R. G. White., R. D. Cameron., and D. E. Russell. 1996. Estimating fat content of caribou from body condition scores. Journal of Wildlife Management 60:713–718.

Hansen, C. G. 1965. Growth and development of desert bighorn sheep. Journal of Wildlife Management 29:387-391.

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

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

Harper, W. L., and R. D. H. Cohen. 2008. Accuracy of Doppler ultrasound in diagnosing pregnancy in bighorn sheep. Journal of Wildlife Management 49:793–796.

Justice–Allen, A. E., C. J. Luedtke, M. Overstreet, J. W. Cain III, and T. R. Stephenson. 2011. Prevalence of Mycoplasma ovipneumoniae in desert bighorn sheep in Arizona. 2011 Desert Bighorn Council Transactions 51:1–10.

Karsch, R. C. 2014. Desert bighorn sheep adult female and lamb survival, cause-specific mortality, and parturient female habitat selection in the Peloncillo Mountains, New Mexico, USA. M.S. Thesis, New Mexico State University, Las Cruces, USA.

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

Mahon, C. 1975. Aging desert bighorn by teeth. Desert Bighorn Council Transactions 19:57.

Marshal, J. P., P. R. Krausman, and V. C. Bleich. 2008. Body condition of mule deer in the Sonoran Desert is related to rainfall. Southwestern Naturalist 53:311–318.

McClintock, B. T., and G. C. White. 2007. Bighorn sheep abundance following a suspected pneumonia epidemic in Rocky Mountain National Park. Journal of Wildlife Management 71:183–189.

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

McKinney, T., J.C. devos Jr., Ballard, W. B., and S. R. Boe. 2006*b*. Mountain lion predation of translocated desert bighorn sheep in Arizona. Wildlife Society Bulletin 34:1255-1263.

NASA Land Processes Distributed Active Archive Center (LP DAAC). 2011. MODIS_LandSat07.

Parker, K. L., P. S. Barboza, and M. P. Gillingham. 2009. Nutrition integrates environmental responses of ungulates. Functional Ecology 23:57–69.

Parsons, Z. D. 2007. Cause specific mortality of desert bighorn sheep lambs in the Fra Cristobal Mountains, New Mexico, USA. M.S. thesis, University of Montana, Missoula, USA.

Pettorelli, N., F. Pelletier, A. V. Hardenburg, and M. Festa–Bianchet. 2007. Early onset of vegetation growth vs. rapid green–up: impacts on juvenile mountain ungulates. Ecology 88:381–390.

Ryan, S. J., P. C. Cross, J. Winnie, R. Hay, J. Bowers, and W. M. Getz. 2012. The utility of normalized difference vegetation index for predicting African buffalo forage quality. Journal of Wildlife Management 76:1499–1508.

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

Seaman, D. E., and R. A. Powell. 1996. An evaluation of the accuracy of kernel density estimators for home range analysis. Ecology 77:2075–2085.

Seaman, D. E., B. Griffith, and R. A. Powell. 1998. KERNLHR: a program for estimating animal home ranges. Wildlife Society Bulletin 26:95–100.

Shaw, H. G., P. Beier, M. Culver, and M. Grigione. 2007. Puma field guide. The Cougar Network, Concord, Massachusetts.

Sikes, R.S., W.L. Gannon, and the Animal Care and Use Committee of the American Society of Mammalogists. 2011. Guidelines of the American Society of Mammalogists for the use of wild mammals in research. Journal of Mammalogy 92:235–253.

Smith, B. L., and S. H. Anderson. 1998. Juvenile survival and population regulation of the Jackson elk herd. Journal of Wildlife Management 62:1036-1045.

Smith, J. B., J. A. Jenks, T. W. Grovenburg, and R. W. Klaver. 2014. Disease and predation: sorting out causes of a bighorn sheep (*Ovis canadensis*) decline. PLoS ONE 9: e88271.

Stephenson, T. R., K. J. Hundertmark, C. C. Schwarts, and V. Van Ballenberghe. 1998. Predicting body fat and body mass in moose with ultrasonography. Canadian Journal of Zoology 76:717–722.

Stephenson, T. R., V. C. Bleich., B. M. Pierce., and G. P. Mulcahy. 2002. Validation of mule deer body composition using in vivo and post–mortem indices of nutritional condition. Wildlife Society Bulletin 30:557–564.

U.S. Fish and Wildlife Service (USFWS). 2007. Investigative report and recommendations for the Kofa bighorn sheep herd. U.S. Fish and Wildlife Service Report.

White, G. C., and K. P. Burnham. 1999. Program Mark: survival estimation from populations of marked animals. Bird Study 46(Supplement):120–138.

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

Worton, B. J. 1989. Kernel methods for estimating the utilization distribution in home–range studies. Ecology 70:164–168.

Appendix 1. Model structure for *a priori* models assessing the influence of previous reproductive effort[1], age class[2], and seasonal forage conditions[3] on the percent body fat of female desert bighorn sheep on the Kofa National Wildlife Refuge, Arizona, 2009-2010.

Model	Model Structure
1	0809 Total Days + Spring NDVI
2	0809 Total Days + Spring Precip
3	0809 Total Days + Spring NDVI + Summer NDVI
4	0809 Total Days + Spring Precip + Summer Precip
5	0809 Total Days + Spring NDVI + Summer NDVI + Fall NDVI
6	Spring NDVI
7	Spring Precip
8	Spring NDVI + Summer NDVI + Fall NDVI
9	Spring NDVI + Summer NDVI
10	Age Class + Spring NDVI
11	Spring Precip + Summer Precip
12	Age Class + Spring Precip
13	Age Class + Spring NDVI + Summer NDVI
14	Age Class + Spring Precip + Summer Precip
15	Age Class + Spring NDVI + Summer NDVI + Fall NDVI
16	0809 Total Days
17	0809 Total Days + Summer NDVI + Fall NDVI
18	0809 Total Days + Summer NDVI
19	0809 Total Days + Fall NDVI
20	Age Class
21	Summer NDVI
22	Summer Precip
23	Age Class + Summer NDVI
24	Fall NDVI
25	Age Class + Fall NDVI
26	Summer NDVI + Fall NDVI
27	Age Class + Summer NDVI + Fall NDVI

[1]Defined as the length of time a female was observed with a lamb the previous year (2008-2009 Total Days)

[2] Age classes were organized by three subcategories (age class 1 (1-2), age class 2 (3-4), and age class 3 (5+)) due to the difficulty in age identification in horn annuli of desert subspecies.

[3] Seasons defined: Winter (1 December - 31 March) as the cool and wet season-time of parturition, spring (1 April - 30 June) as the hot and dry season-time of lamb weaning, summer (1 July - 30 September) as the hot and wet season-mating season, and fall (1 October - 30 November) as warm and dry season with females in mid to late gestation.

Appendix 2. Model structure for *a priori* models assessing the influence of previous reproductive effort[1], age class, and seasonal forage conditions on the percent body fat of female desert bighorn sheep on the Kofa National Wildlife Refuge, Arizona, 2010-2011.

Model	Model Structure
1	0910 Total Days + Winter NDVI
2	0910 Total Days + Winter NDVI + Spring NDVI
3	0910 Total Days + Fall NDVI + Winter NDVI
4	0910 Total Days + Fall NDVI + Winter NDVI + Spring NDVI
5	0910 Total Days + Winter NDVI + Spring NDVI + Summer NDVI
6	0910 Total Days
7	0910 Total Days +Fall Precip + Winter Precip +Spring Precip + Summer Precip
8	0910 Total Days +Spring Precip + Summer Precip
9	0910 Total Days + Summer NDVI
10	0910 Total Days + Winter Precip
11	0910 Total Days + Fall NDVI
12	0910 Total Days + Fall NDVI + Winter NDVI + Spring NDVI + Summer NDVI
13	0910 Total Days + Spring Precip
14	Winter NDVI
15	0910 Total Days + Winter Precip + Spring Precip + Summer Precip
16	0910 Total Days + Winter Precip + Spring Precip
17	0910 Total Days + Spring NDVI
18	0910 Total Days + Fall Precip
19	Age Class + Winter NDVI
20	0911 Total Days +Fall Precip + Winter Precip + Spring Precip
21	0910 Total Days + Fall Precip + Winter Precip
22	Fall NDVI + Winter NDVI
23	0910 Total Days + Spring NDVI + Summer NDVI
24	Winter NDVI + Spring NDVI
25	Fall NDVI + Winter NDVI + Spring NDVI
26	Age Class
27	Winter NDVI + Spring NDVI + Summer NDVI
28	Fall NDVI
29	Age Class + Fall NDVI
30	Age Class + Fall Precip
31	Summer NDVI
32	Age Class + Summer NDVI
33	Winter Precip
34	Age Class + Spring NDVI
35	Fall Precip
36	Spring NDVI
37	Age Class + Spring Precip
38	Spring Precip
39	Age Class + Spring Precip + Summer Precip + Fall Precip
40	Age Class + Summer Precip + Fall Precip
41	Age Class + Spring Precip + Summer Precip
42	Age Class + Summer NDVI + Fall NDVI
43	Age Class + Spring NDVI + Summer NDVI
44	Spring + Summer NDVI-50
45	Age Class + Spring + Summer + Fall NDVI-50

[1]Defined as the length of time a female was observed with a lamb the previous year (2009-2010).

Appendix 3. *A priori* models to assess influence of maternal body fat, age class, and seasonal forage conditions on the observation of lambs with female desert bighorn on the Kofa National Wildlife Refuge, 2009-2010.

Model	Model Structure
1	Age Class
2	Winter NDVI
3	Age Class + Spring Precip
4	Age Class + Winter NDVI
5	Age Class + Summer Precip
6	Age Class + Winter Precip
7	Spring Precip
8	Summer NDVI
9	Spring NDVI
10	Winter Precip
11	Summer Precip
12	Fall NDVI
13	Percent Body Fat
14	Age Class + Summer NDVI
15	Age Class + Spring NDVI
16	Age Class + Fall NDVI
17	Age Class + Spring Precip + Summer Precip
18	Winter NDVI + Spring NDVI
19	Fall NDVI + Winter NDVI
20	Percent Body Fat + Winter NDVI
21	Age Class + Winter Precip + Spring Precip
22	Age Class + Winter NDVI + Spring NDV
23	Age Class + Fall NDVI + Winter NDVI
24	Winter Precip + Spring Precip
25	Percent Body Fat + Summer NDVI
26	Spring Precip + Summer Precip
27	Percent Body Fat + Spring Precip
28	Spring + Summer NDVI-50
29	Percent Body Fat + Spring NDVI
30	Percent Body Fat + Winter Precip
31	Percent Body Fat + Summer Precip
32	Percent Body Fat + Fall NDVI
33	Age Class + Winter Precip + Spring Precip + Summer Precip
34	Age Class + Spring NDVI + Summer NDVI
35	Percent Body Fat + Winter NDVI + Spring NDVI
36	Winter NDVI + Spring NDVI + Summer NDVI
37	Fall NDVI + Winter NDVI + Spring NDVI
38	Percent Body Fat + Fall NDVI + Winter NDVI
39	Age Class + Winter NDVI + Spring NDVI + Summer NDVI
40	Winter Precip + Spring Precip + Summer Precip
41	Age Class + Fall NDVI + Winter NDVI + Spring NDVI
42	Percent Body Fat + Winter Precip + Spring Precip
43	Percent Body Fat + Spring NDVI + Summer NDVI
44	Percent Body Fat + Spring Precip + Summer Precip
45	Percent Body Fat + Fall NDVI + Winter NDVI + Spring NDVI
46	Percent Body Fat + Winter NDVI + Spring NDVI + Summer NDVI
47	Fall NDVI + Winter NDVI + Spring NDVI + Summer NDVI
48	Percent Body Fat + Winter Precip + Spring Precip + Summer Precip
49	Age Class + Fall NDVI + Winter NDVI + Spring NDVI + Summer NDVI
50	Percent Body Fat + Fall NDVI + Winter NDVI + Spring NDVI + Summer NDVI