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Original Article

Mule Deer Habitat Selection Following Vegetation Thinning Treatments in New Mexico

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ABSTRACT Mule deer (*Odocoileus hemionus*) survival and population growth in north-central New Mexico, USA, was previously reported to be limited by nutritional constraints due to poor forage conditions in degraded habitats. Management recommendations suggested thinning of pinyon–juniper to improve habitat quality for mule deer. To evaluate the influence of these vegetation treatments, we monitored habitat selection by 48 adult female mule deer from 2011 to 2013 in a population previously reported to be nutritionally limited. Monitoring occurred 1–4 years after completion of treatments that were intended to improve forage conditions, including mechanical reduction of pinyon pine (*Pinus edulis*) and juniper (*Juniperus* spp.) density and senescent brush (*Quercus gambelii–Cercocarpus montanus*) cover. During the summer season, deer selected recently treated areas, but odds ratios decreased with treatment age. However, during winter, deer avoided more recently treated areas and selected thinned areas >4 years old. Deer selected mixed oak (*Quercus* spp.) and pinyon–juniper savanna vegetation cover types with a moderately open canopy and ponderosa pine (*Pinus ponderosa*) forests while avoiding grasslands and montane shrublands across all seasons. Deer selected areas closer to water and developed areas, northeast aspects, on gentle slopes, and at lower elevations. Creating a savanna-like cover type may elicit a positive deer response as a result of their strong avoidance of dense, closed canopy pinyon–juniper woodlands.

KEY WORDS habitat enhancements, mule deer, New Mexico, *Odocoileus hemionus*, pinyon–juniper woodland, resource selection, restoration.

The slow recovery of mule deer (*Odocoileus hemionus*) populations following previous population declines has challenged wildlife managers to identify factors limiting population growth (Gill et al. 2001; Bergman et al. 2011, 2014*a*; Mule Deer Working Group 2015). Recent research and management efforts have primarily focused on determining the relative influence of predation and forage conditions as limiting factors for mule deer populations (Long et al. 2008, Bishop et al. 2009, Hurley et al. 2011, Pierce et al. 2012, Bergman et al. 2014*a*), with much of this research occurring in the northern and western portions of mule deer range. However, comparatively few studies have been conducted in the southern and more arid portions of mule distribution range. Previous studies suggested that poor nutrition was limiting mule deer populations in north-central New Mexico, USA (Bender et al. 2007*a*,*b*; Lomas and Bender 2007). Adult female mule deer occupying semi-arid pinyon–juniper woodlands (*Pinus edulis*, *Juniperus scopulorum*, *J. monosperma*) were reported to be nutritionally compromised, leading to poor fawn survival and reduced herd productivity (Bender et al. 2007*a*, 2010; Lomas and Bender 2007).

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Managers commonly manipulate vegetation to reduce tree canopy cover and stem densities to increase forage production and enhance forage quality for ungulates. Kramer et al. (2015) reported that conifer thinning in the pinyon–juniper range of New Mexico can increase the abundance of selected forage species for mule deer, but the duration of positive effects is dependent on precipitation during the posttreatment recovery period. Similarly, mule deer in ponderosa (*Pinus ponderosa*) and mixed conifer vegetation types in the Jemez Mountains of New Mexico selected more strongly for thinned areas with increasing posttreatment recovery (Roerick et al. 2019). Bender et al. (2013) reported that adult female mule deer use of open pinyon–juniper savannas and mechanically treated juniper was inversely associated with home range sizes and positively associated with body condition, suggesting that treatments increased forage resources, allowing deer to meet their needs within a smaller home range. Pinyon–juniper removal followed by reseeding with selected forages and chemical weed control improved overwinter fawn survival for mule deer by 10% (Bergman et al. 2014*a*). In addition, body fat in adult females tended to be greater in animals occupying treated areas (mean ingesta-free body fat = 7.38%) compared with reference sites (mean ingesta-free body fat = 6.97%; Bergman et al. 2014*b*). Improvements in forage conditions through vegetation treatments has the potential to enhance female mule deer diets, body condition, survival, and reproductive success, ultimately improving population performance (Cook et al. 2007, 2010; Bishop et al. 2009).

Improvement of forage conditions is necessary to recover populations that declined as a result of nutritional limitations. We monitored habitat selection by adult female mule deer from 2011 through 2013 in north-central New Mexico following a series of mechanical treatments in pinyon–juniper woodlands and oak brush (*Quercus gambelii*) communities intended to improve habitat conditions, forage quality, and nutritional condition of mule deer. Following the vegetation treatments, we expected adult female mule deer would select treated areas over other cover types as a result of improved foraging conditions.

STUDY AREA

Our study area was located on the 13,400-ha National Rifle Association Whittington Center near Raton, Colfax County (~36°44′N, 104°30′W), New Mexico. The area was characteristic of the foothills of the southern Rocky Mountains and formed the transition zone between the shortgrass High Plains and conifer forests of the Rocky Mountains. Domestic livestock previously grazed the area but were excluded since 1973 (Hild and Wester 1998).

Vegetation types included lower elevation (~1,900 m) grasslands, pinyon–juniper woodlands and ponderosa pine–Douglas fir forests (*Pinus ponderosa–Pseudotsuga menziesii*) at higher elevations (>2,400 m). Common grasses included blue grama (*Bouteloua gracilis*), sideoats grama (*B. curtipendula*), little bluestem (*Schizachyrium scoparium*), and sand dropseed (*Sporobolus cryptandrus*). Large dense brush communities were characterized by Gambel oak (*Quercus gambelii*) and mountain mahogany (*Cercocarpus montanus*), which were intermixed with skunkbush sumac (*Rhus aromatica*), big sagebrush (*Artemisia tridentata*), fringed sage (*Artemisia frigida*), winterfat (*Krascheninnikovia lanata*), and fourwing saltbush (*Atriplex canescens*). Mid-elevation was primarily pinyon–juniper woodlands characterized by Rocky Mountain juniper (*Juniperus scopulorum*), one-seeded juniper (*J. monosperma*), and pinyon pine. Mixed ponderosa pine and Douglas fir forests occupied areas above 2,400 m. This study predominantly took place on the lower transition zone, which occupied the area from montane shrublands through mid-elevation pinyon–juniper woodlands into low-elevation mixed-grass prairie.

Average daily high and low summer temperatures were 28.0° C (SD = 1.5) and 10.7° C (SD = 0.8) in July while average daily high and low winter temperatures were 7.5° C (SD = 2.4) and −10.0° C (SD = 1.7) in January (Raton Crews Municipal Airport, approx. 4.5 km southwest of study area; NOAA 2014). The 34-year average annual precipitation in the lower elevations was 40.1 cm (SD = 12.1 cm; NOAA 2014), with the majority (62%) occurring as rainfall between May and August. The greatest snowfall (150–230 cm) occurred at the higher elevations while the lower elevations received 50–65 cm of snowfall a year (Hild 1995). Snowfall accumulation on the lower grassland and pinyon–juniper range during this study was minimal (i.e., 35 cm total for study period; G.E. Sorensen unpublished data). During the study, total precipitation was 27.9 cm, 24.2 cm, and 40.2 cm in 2011, 2012, and 2013, respectively (NOAA 2014). In 2011 and 2012, the area was in the midst of a drought with total annual precipitation 30% and 40% below average.

We defined spring–summer season (summer) as 15 March through 15 September and the autumn–winter season (winter) encompassed 16 September through 14 March. Mule deer were nonmigratory during our study and stayed within the lower elevation oak brush and pinyon–juniper range throughout all seasons.

METHODS

Vegetation Treatments

Following habitat management recommendations by Hoenes and Bender (2007), we initiated vegetation treatments to reverse pinyon–juniper expansion, increase forage quality, and provide selected habitat characteristics for mule deer. We completed treatments on areas where the mechanical equipment could reach, as well as those areas that were available to mule deer and would provide the most benefit to ungulates. We created multiple habitat units and randomly assigned a treatment. We thinned areas totaling 130 ha of pinyon–juniper and Gambel oak in 2008–2009 with the goal over 2 years for 80% reduction in the cover of woody vegetation. We used a hydraulic tree shredder to remove large pinyon–juniper (>15 cm diameter at breast height [DBH]) trees and senescent brush (Gambel oak, mountain mahogany) stands, primarily on gentle (<12%)

slopes in the southern pinyon–juniper lower elevation transition zone. We thinned an additional 29 ha of pinyon–juniper with a hydro-axe in the spring of 2010. We completed further treatments in the autumn of 2010 and summer of 2011 using a hydraulic rotary mulching attachment on an excavator to cut and mulch shrubs and small trees (<10 cm DBH and <2 m height) to ground level in the lower shrubland–grassland communities. By November 2011, we treated 281 ha. Habitat enhancements accounted for approximately 13% of the total low- to mid-elevation area but were in areas commonly utilized by mule deer. Our monitoring occurred 1–4 years posttreatment with oak brush treatments being the most recent.

Deer Capture

In March 2011, we captured 36 adult female mule deer using aerial net-gunning and aerial darting (Krausman et al. 1985); deer were immobilized with 1.5 mg/kg of xylazine hydrochloride and 5.1 mg/kg of ketamine hydrochloride. After capture, we hobbled, blindfolded, and transported deer to the staging area for processing. We fitted all deer with either a very-high-frequency (VHF) or Global Positioning System (GPS) telemetry collar (Advanced Telemetry Systems, Inc., Isanti, MN, USA: VHF Model M2520B, GPS Store on Board Model G2110D 400 g, GPS Iridium Model G2110E; SirTrack, New Zealand: VHF Model J19350) and a unique ear tag. We fitted 33 deer with VHF collars and 3 with store-on-board GPS collars. All collars were equipped with a VHF transmitter and an 8-hour mortality switch. We administered 0.2 mg/kg yohimbine as a reversal and released deer at capture sites.

In March 2012 and 2013, we captured 12 additional deer with clover traps and via roadside darting using xylazine and ketamine, 2 of which we fitted with VHF collars, 2 with store-on-board GPS collars, and 8 with GPS-Iridium collars. All handling procedures were the same as those described above. We captured and handled all deer in accordance with Texas Tech University Institutional Animal Care and Use Protocol (TTU IACUC Approval 11005-003). We did not observe or capture deer above 2,150 m in elevation and, of the deer that we captured (VHF and GPS), none of them moved out of the area or to higher elevations, which demonstrates the nonmigratory status of these local mule deer herds. Therefore, the entire focus of this study occurred on the low- to mid-elevation areas.

Monitoring

We relocated all VHF-collared mule deer 3–4 times/week during crepuscular (0600–0900 and 1800–2100) periods and 2–3 times/week during the midday resting period (1100–1600) in the spring and summer. During the autumn and winter seasons, we located each VHF radio-collared deer 2–3 times/week during the crepuscular period and at least once a week during midday. We located all VHF-collared deer by homing with a receiver and yagi antenna until individual identification was absolute. We observed deer at a distance >50 m with binoculars to confirm the location of the individual. We recorded the behavior (i.e., feeding, resting, moving) of collared deer at the time of observation if their behavior appeared unaffected by our presence (i.e., deer did not run away or become vigilant to our presence upon relocation). However, we did not record habitat data until the animal had moved away from its initial point of relocation as part of its normal activity. Once the deer left the area, we recorded Universal Transverse Mercator coordinates for each deer location using handheld GPS units (Garmin 60CX GPS; Garmin International Inc., Olathe, KS, USA), time of day, and general cover type (i.e., oak brush, pinyon–juniper woodland, treated brush).

Store-on-board GPS collars recorded locations at 0000, 0600, 1200, and 1800 daily from March 2011 through May 2013. GPS-Iridium collars recorded locations at 0000, 0500, 0600, 0700, 0800, 1200, 1800, 1900, 2000, and 2100 daily from March 2012 through December 2013.

Habitat Selection Modeling

We separated relocation data into VHF- and GPS-collared animals for all analyses. We generated seasonal 95% fixed-kernel home ranges for each deer (Worton 1989, Manly et al. 2010) in Geospatial Modelling Environment (Beyer 2014) with smoothing factor determined by least-squares cross-validation. We then generated random points equal to the number of used points within each individual 95% home range for each season and year. We obtained 10-m × 10-m elevation model (digital elevation model [DEM]) and land cover data (National Land Cover Database [NLCD] 2006, Fry et al. 2011) from the U.S. Geological Survey National Map Seamless Server (available online at http://seamless.usgs.gov/) and high-resolution (~1-m) orthoimagery (2009) from the NRCS Geospatial Data Gateway (available online at http://datagateway.nrcs.usda.gov). We mapped treated areas, developed areas, and known perennial water sources in the field using a handheld GPS unit (Trimble GEO-explorer XT; Trimble Navigation, Sunnyvale, CA USA). Finally, we developed a high-quality (<30 m) land-cover map for the lower elevation transition zone on the Whittington Center by digitizing the high-resolution orthoimage. We validated the land cover map by comparing it with the NLCD raster file and ground-truthed vegetation classifications recorded at used locations.

Next, we extracted covariate values to used and random points in ArcMap 10.2.2 (ESRI 2014) including aspect and slope (°; calculated from the DEM), treated areas, and vegetation type. We also calculated the distance to nearest perennial water source, and human development (i.e., roads, housing, shooting ranges, camp sites; Sorensen 2015). We dummy-coded aspect as a northeast and southwest with aspects from 0°–112.5° and 292.5°–360° as northeast and 112.5°–292.5° as southwest, with southwest set as the reference level. We used this classification for aspect because of the 2 markedly different subclimates that exist in the study area based on prevailing aspects. Northeastern aspects often retain more moisture, thereby providing different cover and forage conditions compared with southwestern aspects, which tend to be more xeric and open. Vegetation cover types included montane shrubland, ponderosa pine forest, pinyon–juniper woodlands, pinyon–juniper savanna, oak shrubland savanna, and grassland. The pinyon–juniper woodlands were distinguished from pinyon–juniper savanna based on tree density and canopy cover along with diversity of shrubs and open grassland. Pinyon–juniper savanna was characterized by low to moderate densities of pinyon–juniper typically <40% tree canopy cover; patches of oak and mountain mahogany shrubs are common and intermixed with patches of grasslands. Pinyon–juniper woodlands were characterized by dense pinyon–juniper-dominated stands with canopy closure >60% but often exceeding 80% (Sorensen 2015). We combined cover types of pinyon–juniper savanna and oak shrubland savanna into a single cover type of savanna because of their similarities in vegetation species composition, cover, and topography (Sorensen 2015). The combined savanna cover type is characteristic of an intermixed vegetation type containing both oak and mountain mahogany shrubs and pinyon–juniper cover with extensive patches of open grasslands. For the vegetation types, we set pinyon–juniper woodlands as the reference level. Used and random locations were also classified using dummy coding with respect to treatment status and treatment age (e.g., untreated, 2-yr-old treatment, 3-yr-old treatment) with untreated set as the reference level. Year of data collection and treatment age were confounded; therefore, we did not include year as a covariate in our models. Locations were limited during winter, so we combined treatments for 2- and 3-year-old treatments (i.e., 0 = untreated, 2 = 2- and 3-yr-old treatments combined, 3 = 4-yr-old treatments). Additionally, we did not detect deer fitted with VHF collars in montane shrubland during the winter. Therefore, montane shrubland and pinyon–juniper vegetation types were combined and set as the reference level vegetation type in winter habitat-selection models.

We developed 8 *a priori* models for each season to assess habitat selection by adult female mule deer using mixed-effects logistic regression (Table 1; PROC GLIMMIX, SAS Institute, Carey, NC, USA). We included deer ID as a random effect. We modeled the covariance of the locations for each deer using a Toeplitz structure, which is similar to an autoregressive covariance structure (Kincaid 2005). This covariance structure accounted for the partial correlation that can exist between successive locations collected on the same individual. Prior to analysis, we assessed multicollinearity among covariates using pairwise correlation. We used Akaike's Information Criterion corrected for small sample size to assess model support (AIC_c; Burnham and Anderson 2002). We evaluated each model set to assess differences in habitat selection for each season by collar type. We removed the winter of 2011 from the analysis because of the small sample size of individual deer during the first winter, which effectively limited our ability to produce reliable parameter estimates. We calculated modeled-averaged parameter estimates for variables in the most supported models (i.e., those models with the greatest model weight) across all models for each season. We

Table 1. Model structures used in the modelling of habitat selection by adult female mule deer on the National Rifle Association Whittington Center, Raton, New Mexico, USA, 2011–2013.

Model structure
Vegetation type[a] + Treatment[b]
Vegetation type + Treatment + Distance to water[c]
Vegetation type + Distance to water + Distance to development[c]
Vegetation type + Treatment + Distance to water + Distance to development
Vegetation type + Treatment + Distance to water + Distance to development + Aspect[d] + Slope[e]
Vegetation type + Treatment + Distance to water + Aspect + Slope
Vegetation type + Treatment + Aspect + Slope
Vegetation type + Distance to water + Distance to development + Aspect + Slope

[a] Vegetation type includes savanna, grassland, ponderosa, and montane shrubland.
[b] Treatment includes treatment age starting at 2 yr posttreatment. Years 2 and 3 are combined for the winter models.
[c] Distance variables represent the distance in meters from a water sources or developed area.
[d] Aspect is represented as a northeast and southwest with aspects from 0°–112.5° and 292.5°–360° as northeast and 112.5°–292.5° as southwest.
[e] Slope is represented as degrees.

modeled relocation data separately because of the differences in timing and intensity of data collection between the 2 collar types. The GPS collars collected data with a more intensive schedule, including night locations, whereas VHF-data collection focused predominantly during the crepuscular and midday time periods.

RESULTS

From March 2011 to December 2013, we recorded 5,684 VHF and 22,556 GPS locations. Over the course of the 3-year study, 98% of the radiocollared deer had home ranges within 1.5 km of treated areas; 88–92% of the collared mule deer had home ranges that overlapped treated areas. Thus, treated areas were available to all of our study animals. Based on observations recorded during relocation of VHF-collared deer, feeding (63%), followed by resting (33%), accounted for the most observed behaviors with feeding occurring in greater proportion ($\chi^2_{5363} = 455.45$, $P < 0.001$; 4% other, i.e., moving, vigilant). During summer, feeding accounted for 44%, 57%, and 72% of the relocations in 2011, 2012, and 2013, respectively. During winter of 2012 and 2013, feeding accounted for 72% and 71% of relocations, respectively. Feeding was the most common behavior recorded for VHF-collared deer throughout the study across both summer and winter seasons ($P < 0.05$).

During summer, the most supported models for both VHF- ($w_i = 0.747$; Table 2) and GPS-collared deer ($w_i = 0.999$; Table 2) included vegetation type, vegetation treatment, distance to water, distance to development, aspect, and slope, although there was more model selection uncertainty in the models for VHF-collared deer. Odds of selection decreased by 2.8–3.2% with every 1° increase in slope, and mule deer were 15–28% more likely to select northeast aspects than southwest aspects. Odds of selection decreased by 12–22% with every 1 m increase in the distance

Table 2. The highest ranking *a priori* models for mule deer habitat selection on the National Rifle Association Whittington Center, Raton, New Mexico, USA, 2011–2013. For each model, the number of parameters (K), Akaike's Information Criterion adjusted for small sample size (AIC_c), ΔAIC_c, and model weight are given.

Season (collar type)	Model	K	AIC_c	ΔAIC_c	Weight
Summer	Vegetation type + Distance to water + Distance to development + Treatment + Aspect + Slope	13	37,048.1	0.00	0.999
(GPS)	Vegetation type + Distance to water + Distance to development + Aspect + Slope	10	37,067.5	19.41	0.0001
Summer	Vegetation type + Distance to water + Distance to development + Treatment + Aspect + Slope	13	8,097.9	0.00	0.747
(VHF)	Vegetation type + Distance to water + Distance to development + Aspect + Slope	10	8,090.1	2.17	0.253
Winter	Vegetation type + Distance to water + Distance to development + Treatment + Aspect + Slope	12	19,019.1	0.00	0.998
(GPS)	Vegetation type + Distance to water + Distance to development + Aspect + Slope	10	19,031.2	12.15	0.002
Winter	Vegetation type + Distance to water + Distance to development + Aspect + Slope	7	5,932.1	0.00	0.849
(VHF)	Vegetation type + Distance to water + Distance to development + Treatment + Aspect + Slope	11	5,935.6	3.46	0.151

to water and decreased by 27–28% with every 1-m increase in distance from developed areas (Table 3). Mule deer were 2–3 times more likely to select savanna and 34% more likely to select ponderosa pine than pinyon–juniper woodlands (Table 3). Grasslands were 44% less likely to be selected compared with pinyon–juniper woodlands for the VHF-collared deer; odds ratio for the GPS-collared deer was also <1 but 95% confidence intervals included 1. Deer were 66–80% less likely to select montane shrubland than pinyon–juniper woodlands (Table 3). The GPS-collared deer were 45% more likely to select treated areas 2 years after treatment and 25% less likely to select treated areas

Table 3. Model-averaged parameter estimates, standard error, odds ratio, and 95% confidence limit for the odds ratios for the variables in the most supported habitat selection model for mule deer on the National Rifle Association Whittington Center, Raton, New Mexico, USA, 2011–2013.

					95% Confidence limit	
Season (collar type)	Variable	β	SE	Odds ratio	Lower CL	Upper CL
Summer	Savanna	1.136	0.056	3.119	2.795	3.481
(GPS)	Grassland	−0.059	0.053	0.943	0.849	1.047
	Ponderosa	0.295	0.060	1.344	1.193	1.513
	Montane shrubland	−0.662	0.112	0.516	0.414	0.643
	2-yr-old treatments	0.368	0.113	1.445	1.158	1.803
	3-yr-old treatments	0.064	0.048	1.066	0.970	1.172
	4-yr-old treatments	−0.285	0.081	0.752	0.641	0.881
	Distance to water	−0.126	0.017	0.882	0.854	0.911
	Distance to development	−0.330	0.016	0.719	0.697	0.741
	Slope	−0.029	0.003	0.972	0.966	0.977
	Aspect (NE)	0.138	0.027	1.148	1.088	1.211
Summer	Savanna	0.823	0.119	2.277	1.804	2.876
(VHF)	Grassland	−0.576	0.120	0.562	0.445	0.711
	Ponderosa	0.294	0.134	1.342	1.032	1.747
	Montane shrubland	−0.799	0.366	0.450	0.219	0.921
	2-yr-old treatments	0.005	0.175	1.005	0.713	1.417
	3-yr-old treatments	−0.020	0.117	0.980	0.779	1.233
	4-yr-old treatments	−0.366	0.129	0.693	0.539	0.892
	Distance to water	−0.244	0.027	0.784	0.743	0.826
	Distance to development	−0.311	0.029	0.733	0.692	0.776
	Slope	−0.032	0.007	0.968	0.955	0.982
	Aspect (NE)	0.250	0.058	1.284	1.145	1.439
Winter	Savanna	0.695	0.084	2.003	1.700	2.363
(GPS)	Grassland	−0.264	0.082	0.768	0.654	0.902
	Ponderosa	−0.333	0.093	0.717	0.598	0.860
	Montane shrubland	−0.349	0.163	0.706	0.513	0.971
	2–3-yr-old treatments	0.023	0.064	1.023	0.902	1.161
	4-yr-old treatments	0.352	0.089	1.421	1.194	1.692
	Distance to water	−0.296	0.025	0.743	0.707	0.782
	Distance to development	−0.396	0.024	0.673	0.642	0.706
	Slope	−0.016	0.004	0.984	0.975	0.993
	Aspect (NE)	0.146	0.039	1.157	1.073	1.248
Winter	Savanna	0.835	0.168	2.306	1.659	3.204
(VHF)	Grassland	0.340	0.168	1.404	1.011	1.951
	Ponderosa	0.514	0.184	1.672	1.166	2.399
	2–3-yr-old treatments	0.023	0.098	1.023	0.845	1.240
	4-yr-old treatments	0.154	0.212	1.167	0.770	1.769
	Distance to water	−0.112	0.032	0.894	0.840	0.951
	Distance to development	−0.180	0.032	0.835	0.794	0.890
	Slope	−0.024	0.089	0.976	0.959	0.993
	Aspect (NE)	0.316	0.067	1.371	1.202	1.564

4 years after treatments than untreated areas; odds ratio for selection of 3-year-old treatments was >1 but 95% confidence intervals included 1 (Table 3). The VHF-collared deer showed no selection for 2–3-year-old treatments (CIs overlapped 1), but similar to GPS-collared deer, they were 31% less likely to select 4-year-old treatments than untreated areas (Table 3).

During winter, habitat selection by GPS-collared mule deer was best predicted by the full model, which included vegetation type, vegetation treatment, distance to water, distance to development, aspect, and slope ($w_i = 0.998$; Table 2). For VHF-collared deer, the reduced model, which removed vegetation treatment, was the highest ranked model ($w_i = 0.849$; Table 2). However, the full model did carry 15% of model weights (Table 2). For both collar types, savanna cover type, distance to water, distance to development, aspect, and slope were positively related to the odds of habitat selection by mule deer. During winter, mule deer were 2–2.3 times more likely to select savanna habitat type than pinyon–juniper woodlands (Table 3). Similar to summer models, GPS-collared deer were 30% less likely to use montane shrubland over pinyon–juniper woodlands. Odds ratios for GPS- and VHF-collared deer differed for grassland and ponderosa pine cover types. GPS-collared deer were 23% and 28% less likely to use grasslands and ponderosa pine forest than pinyon–juniper woodlands respectively; VHF-collared deer were 40% and 67% more likely to use grasslands and ponderosa pine forest than pinyon–juniper woodlands, respectively (Table 3). The odds of use decreased by 11–26%, and by 17–33%, with every 1 m increase in distance to water, and development, respectively (Table 3). Mule deer were 16–37% more likely to select northeast than southwest aspects and slope was inversely related to mule deer use with an odds of use decreasing 2.4–3.2% for every 1° increase in slope (Table 3). During winter, older treatments had greater odds ratios than untreated areas. GPS-collared deer were 42% more likely to use 4-year-old treatments than untreated areas and VHF-collared deer were 17% more likely to use 4-year-old treatments; however, odds ratio confidence intervals included 1 for VHF-collared deer. Odds ratios for the combined 2–3-year-old treatments were >1 for deer fitted with both collar types, but were inconclusive as indicated by confidence intervals that included 1 (Table 3).

DISCUSSION

Mule deer selection for treated areas varied by season and duration of the posttreatment recovery period. During summer, mule deer selected for more recent treatments (e.g., 2-yr-old treatments) and avoided older treatments. Conversely, in the winter, GPS-collared deer show greater odds of use for 4-year-old treatments, but no selection for newer treated areas. Observations during the relocation of VHF-collared deer show that our location data most often represent locations where mule deer were foraging; mule deer of both collar types are likely utilizing more recent treated areas that are richer in selected herbaceous forages and browse during the summer season (Kramer et al. 2015). However, as a treated area ages, fewer herbaceous forages become available during the growing season, which could potentially account for the avoidance of older treatments during summer. Transitioning into the winter season, deer predominately forage on nearly all browse species (Sowell et al. 1985, Sandoval et al. 2005), which is more abundant in older treated areas thus mirroring the increased odds of mule deer selection for 4-year-old treatments during winter.

During the first 2 years (2011 and 2012) of the study, precipitation was 30–40% below average, which may have limited large increases in forage biomass typically observed following vegetation treatments. Precipitation returned to average by 2013. Despite the drought from 2011 to 2012, crude protein in mule deer forage was greater in treated areas (16.62% ± 0.47) than untreated areas (14.76% ± 0.28; Sorensen 2015), but once precipitation returned to normal, forage protein content increased and was similar between treated and untreated areas (18.33% ± 0.57 vs. 17.48% ± 0.57; Sorensen 2015). Abundance of selected forage was greater in treated areas in 2011 but no increase in abundance was found between 2011 and 2012 or between treated areas and control in 2012 (Kramer et al. 2015). These changes in forage dynamics mirror those found in GPS-collared mule deer during summer in that selection for treated areas was greatest when forage quality was improved and tapered off as forage quality returned to untreated levels by year 4 posttreatment. The wider confidence intervals found in VHF collars as compared with GPS collars, which affect interpretation of results, is likely a result of sample size and relocation intensity needed to capture microhabitat selection. Horncastle et al. (2013) reported that mule deer in ponderosa pine forests in northern Arizona, USA, selected areas that were treated by thinning and burning in the previous season. Similarly, in the higher elevation mixed conifer forest of the Jemez Mountains in New Mexico, mule deer selected areas that had been thinned and burned by prescribed fire but avoided thinned areas <5 years old (Roerick et al. 2019). Mule deer in this study also selected thinned areas, but avoided older treated areas except during winter months. Howard et al. (1987) reported that mule deer used cabled pinyon–juniper stands more than untreated stands in the spring–summer season but habitat use was similar from mid-summer through winter and attribute high spring–summer use to increased forage production immediately following the reduction in tree density. Boeker et al. (1972) recommended that pinyon–juniper stands should be reduced to allow for 25–50 shrubs (oak–mahogany) per acre to provide the most benefit for mule deer in New Mexico. Treatments on our study area reduced tree density by 62% (800 tree/ha to 303 trees/ha; Kramer et al. 2015) but fell short of meeting the recommendations of reducing tree and shrub cover to levels that can be the most beneficial for mule deer (i.e., 80% reduction in brush cover; Boeker et al. 1972, Hoenes and Bender 2007). Additionally, the Whittington Center did not reach the recommended total number of management units treated, thus limiting the extent of treated areas available (Hoenes and Bender 2007). Treatment areas were not expansive, so the size of treated areas could potentially explain differences between collar types—a more intense diel sampling regime in the GPS-collars was able to capture use of treated habitats more accurately compared with the more sparse VHF relocations. However, parameter estimates for each age of treatment were generally similar between collar types, but with wider confidence intervals for VHF data.

Treating habitat can improve deer forage quality and body condition, but selection for treated areas can vary considerably by season and year (Everitt 1983, Hobbs and Spowart 1984, Bergman et al. 2014*b*, Sorensen 2015). Additionally, posttreatment recovery time and climatic conditions interact to influence vegetation responses to tree thinning. As found in this study, selection was positive in the growing season for up to 3-years posttreatment; however, by 3–4-years posttreatment, mule deer avoided treatments during summer. Conversely in winter, GPS-collared were more likely to use old treated areas than young treated areas.

We also found that mule deer on the Whittington Center had a strong affinity for savanna vegetation types and generally avoided open grasslands. These savanna cover types likely better provided sufficient year-round forage while also including cover and edge characteristics for security cover compared with dense pinyon–juniper stands. Similarly, in summer, the odds of use increased in ponderosa pine forests, which contained a moderate to open understory that provided sufficient security cover. Mule deer tend to use areas with a mosaic of open and closed cover while avoiding homogenously dense or open stands and concentrate use in habitat types that were near cover and food thus satisfying both needs (Short et al. 1977, Kufeld et al. 1988).

The general trend in selection occurred on the northeast aspects, on gentle slopes, and lower elevations. In this region, northeast slopes are typically more mesic and contain vegetation that is denser, whereas south-west slopes tend to be dry and open (Dick-Peddie 1999). Horncastle et al. (2013) reported that mule deer use intensified on more gentle slopes in areas of thin-and-burn treatments near reliable water sources in northern Arizona. We similarly found that deer selected more gentle slopes at lower elevations, closer to perennial water, and avoided areas of dense pinyon–juniper forests. Mule deer also selected areas near developments. The lower transition zone at the Whittington Center had a large infrastructure of developed areas including roads, shooting ranges, and facilities (i.e., shop, houses) that are maintained throughout the year. The constant manipulation of vegetation near the developed areas could promote the growth of high-quality forages (Everitt 1983). In addition, mule deer use of developed areas has the potential to mitigate predation risk similar to that reported for elk (*Cervus elaphus*), moose (*Alces alces*), and white-tailed deer (*O. virginianus;* Berger 2007, Hebblewhite and Merrill 2007, Kittle et al. 2008).

Longer term studies utilizing GPS-collared deer with a more extended intense period of posttreatment monitoring and larger landscape-level treatment might be needed to elicit stronger deer responses. Nevertheless, our results suggest that removing old dense brush and pinyon–juniper stands can be useful in creating a savanna-type habitat. These open-habitat cover types promote a mosaic of herbaceous forage and browse species that deer will utilize during the growing season. These treatments can improve crude protein content and deer forage quality even in drought years (Sorensen 2015). By varying timing of treatment, a patch work of older treated areas can provide essential browse needed during the winter months. Additionally, deer were more likely to select these moderately open savanna-like habitats that were near water, on northeast-facing aspects, and on gentle low-elevation slopes, thus illustrating the need to manage pinyon–juniper encroachment into low-elevation grasslands.

MANAGEMENT IMPLICATIONS

The creation of savanna habitat cover types selected by mule deer warrants the use of vegetation treatments to reduce the dense pinyon–juniper woodlands avoided by mule deer. Managers could focus on creating a mosaic of open and closed vegetation types that provide heterogeneous habitat conditions for mule deer (Boeker et al. 1972, Kie et al. 2002, Long et al. 2008). Additional habitat treatments could focus on areas with other characteristics that contribute to mule deer habitat selection (i.e., gentle slopes near water), with a focus on opening dense pinyon–juniper woodlands.

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