University of Nevada, Reno

Mule Deer Responses to a Pinyon-Juniper Removal

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Natural Resources and Environmental Science

By

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August 2022

THE GRADUATE SCHOOL

We recommend that the thesis prepared under our supervision by

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entitled

Mule Deer Responses to a Pinyon-Juniper Removal

to be accepted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE

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Thesis Abstract

Mule deer (*Odocoileus hemionus*) are a large-bodied herbivore that is declining in abundance throughout the Intermountain West for a suite of reasons. One of these reasons is expansion of single-leaf pinyon (*Pinus monophylla*) and Utah juniper (*Juniperus osteosperma*) into sagebrush communities in the Great Basin. Pinyon-juniper woodlands are adept at outcompeting herbaceous vegetation that is crucial for mule deer. We administered a pinyon-juniper removal treatment on mule deer winter range in the Toiyabe Range of central Nevada to assess changes in resource selection and diet diversity of mule deer following the treatment. The pinyon-juniper removal treatment was conducted in autumn of 2018. We captured 36 adult female mule deer in winter of 2018 and 2019, deploying GPS collars and collecting fecal samples. My resource selection function analysis revealed that mule deer exhibited increased selection for annual vegetation, perennial vegetation, and tree cover following pinyon-juniper removal. These results lend support to the efficacy of pinyon-juniper removal treatments for mule deer management. I then compared diversity of mule deer diets before and after our treatment. Although dietary diversity declined following our treatment, the preferred winter forage of mule, antelope bitterbrush (*Purshia tridentata*), formed a substantially higher component of mule deer diets than before treatment.

Thesis Overview

Since the mid-19th century, woodlands comprised of single-leaf pinyon (*Pinus monophylla*) and juniper species (*Juniperus* spp.) have been expanding into sagebrush communities throughout the Great Basin (Cottam and Stewart 1940, Blackburn and Tueller 1970, Miller and Wigand 1994, Miller and Tausch 2000, Weisberg et al., 2007). There has been an approximate 10-fold increase in area of pinyon-juniper woodlands since Euro-American settlement during this time period (Weisberg et al., 2007). Woodland expansion is a concerning development for sagebrush obligate species, because sagebrush communities become fragmented as a result of increased fire severity and invasion of annual grasses as pinyon-juniper woodlands become more dense (Brooks et al., 2004, Balch et al., 2013). Additionally, pinyon and juniper species are proficient at locating and using soil water content and nutrients because of long lateral roots, allowing a competitive advantage over forbs and grasses with shallow root systems (Breshears et al., 1997, Morano et al., 2019).

Pinyon-juniper woodlands have been a primary focus for sagebrush restoration and fuel reduction throughout the western US (Springfield, 1976). Thinning of pinyon-juniper woodlands has been shown to increase availability of resources for understory vegetation (Haskins and Gehring, 2004, Owen et al., 2009, Young et al., 2013). Since pinyon and juniper species provide minimal nutritional benefits to ungulates, the resulting increase in water, light, and nutrients from woodland thinning treatments is vital for supporting sufficient availability of nutritious forage for these large mammals (Bender et al., 2007, Bergman et al., 2014). I used mule deer (*Odocoileus hemionus*) as a model species to assess the effect that a pinyon-juniper removal treatment has on selection of resources and diversity of diet. Mule deer are a large-bodied herbivore that functions as a sagebrush obligate throughout the Great Basin (Bender et al., 2007). Inhabiting most of western North America, mule deer are declining in abundance for myriad reasons of both anthropogenic and environmental means, including conifer expansion (Bender et al., 2007, Bishop et al., 2009).

For my first chapter, I analyzed selection of resources by mule deer before and after a pinyon-juniper removal treatment on winter range in the Toiyabe Range of central Nevada. In 2018 and 2019, 36 adult female mule deer were captured via helicopter and fitted with GPS collars, with our pinyon-juniper removal treatment administered by the U.S. Forest Service in autumn of 2018. I used winter movement data in 2018 for pre-treatment resource selection function analysis, and winter movement data in 2019 and 2020 for post-treatment selection of resources. I used mixed-effects models for this analysis because of their ability to discern between individuals as well as differences in duty cycles of GPS collars.

For my second chapter, I examined the composition of mule deer diets in winter before and after our pinyon-juniper removal treatment. I collected fecal samples from adult female mule deer prior to our conifer treatment in winter 2018, and following the treatment in winter of 2019. Diet composition was determined via DNA metabarcoding by Jonah Ventures, LLC. I calculated frequencies of occurrence, relative read abundances, and Shannon-wiener diversity indexes for pre-treatment and post-treatment mule deer diets.

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Acknowledgments

Foremost, I would like to thank my advisor, Dr. Kelley Stewart. She taught me how to think like a scientist and was always supportive of me, both professionally and personally. I'll always be grateful for our chance meeting while I was working on another field project. I also thank her husband, Thad Heater, for all his advice regarding applying for permanent positions. Kelley and Thad were always there for me to confide in while struggling with the difficulties of graduate school, and I am forever thankful for that.

I want to thank the Stewart Lab at UNR for all their support during my time in graduate school. M. Blum, N. Jackson, J. Merrill, M. Osterhout, H. Reich, E. Hagler, and J. Vasquez were all a joy to work with and never hesitated to take time out of their day to help me when I had questions. The Stewart Lab was a great learning environment and I am thankful that I was able to have such a solid team around me while completing my degree.

I would like to thank Dr. Jim Sedinger of the University of Nevada, Reno, and Dr. William Karasov and Dr. Jon Pauli of the University of Wisconsin-Madison for signing letters of recommendation for my admission to the graduate school at the University of Nevada, Reno. It meant a lot to me to have three accomplished scientists endorse my enrollment into graduate school.

I had support from many individuals while at the University of Nevada, Reno, and I'd like to extend my thanks for Tom Dilts, Dr. Tamzen Stringham, and Dr. Franco Biondi. T. Dilts was always willing to help me when I had questions regarding analysis, and Dr. Stringham and Dr. Biondi helped provide supplemental funding at critical times during this project. Additionally, I'd like to thank Cody Schroeder and Joe Bennett with the Nevada Department of Wildlife. It was a pleasure to collaborate with them during the course of my research, and both of them were instrumental in the creation of this project. I also want to thank the Nevada Department of Wildlife, the U.S. Forest Service, the Great Basin Institute, and the Agriculture Experiment Station at the University of Nevada, Reno, as all these organizations provided support during this project.

Lastly, I want to thank my friends and family. Their support during my time in graduate school was vital and immeasurable.

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1 This thesis is composed in accordance to the University of Nevada, Reno's Alternative Formatting for Thesis or Dissertation, in which the following two chapters are being published concurrently with the submission of this thesis

CHAPTER 1: SELECTION OF RESOURCES BY MULE DEER IN RESPONSE TO REMOVAL OF PINYON-JUNIPER WOODLANDS ON WINTER RANGE

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Abstract

Populations of mule deer (*Odocoileus hemionus*) are in decline throughout much of their range for many reasons, including competition from wild and domestic herbivores, wildfire suppression, energy and urban development, mining, and expansion of woody plants. A primary conservation concern for mule deer in the Great Basin ecosystem is expansion and infilling of single-leaf pinyon pine (*Pinus monophylla*) and Utah juniper (*Juniperus occidentalis*), which provide minimal nutritional value to mule deer while outcompeting herbaceous vegetation in the understory. We investigated how removal of those trees affected selection of resources by mule deer on winter range. We captured 36 adult female mule deer in the Toiyabe Range of central Nevada from April 2018 through March 2019, with all individuals fitted with Global Positioning System (GPS) collars. Pinyon-juniper trees on mule deer winter range were removed by the U.S. Forest Service with an affected area of roughly 1,050 hectares. Data obtained from GPS collars were modeled within a resource selection function framework using mixed-effects logistic regression. After removal of pinyon-juniper trees, mule deer exhibited selection towards cover of annual and perennial vegetation, signaling an herbaceous vegetation response to the removal treatment. Mule deer also selected for tree cover following removal of pinyon-juniper trees, potentially for predator avoidance or as a windbreak in winter. These results can help guide habitat improvement efforts for increasing mule deer populations throughout the Western United States.

Key Words: mixed-effects models, mule deer, *Odocoileus hemionus*, pinyon-juniper, resource selection, Toiyabe Range

Introduction

In the Great Basin, expansion of woodlands into sagebrush (*Artemisia tridentata*) habitat has caused declines of many sagebrush-dependent species, including mule deer (*Odocoileus hemionus*) (Miller 2005, Bender et al., 2013). Single-leaf pinyon (*Pinus monophylla*) and various juniper species (*Juniperus* spp.) have been expeditiously expanding into sagebrush ecosystems throughout the Great Basin since the mid-19th century (Cottam and Stewart 1940, Blackburn and Tueller 1970, Miller and Wigand 1994, Miller and Tausch 2000, Weisberg et al., 2007). Pinyon-juniper woodlands are especially adept at exploiting soil water because of their long lateral root systems, thus allowing them a competitive advantage over forbs and grasses with shallow roots that may be nutritionally important to ungulates (Breshears et al., 1997, Morano et al., 2019). Consequently, as the density of pinyon-juniper woodland increases, herbaceous understories decline or disappear with increasing size and density of trees (Miller et al., 2005, Miller et al., 2013). That decline in the nutritionally vital herbaceous vegetation in pinyon-juniper woodlands can hinder overwinter survival of adult and juvenile mule deer (Bartmann 1983). The density of conifer woodlands in the Great Basin is categorized by the stage of woodland succession present in the plant community (Miller et al., 2005). Phase I pinyon-juniper woodlands have relatively sparse canopy cover, phase II woodlands have increased density and become codominant with sagebrush and other herbaceous vegetation, and phase III woodlands are dominant on the landscape with little to no remaining herbaceous understory (Miller et al., 2005, Miller et al., 2013, Coates et al., 2017).

Pinyon-juniper woodlands are prevalent throughout many of the mountain ranges in the Great Basin. Those woodlands are infilling and expanding downslope into critical winter range for mule deer and other sagebrush-dependent species in the Great Basin. Thinning of pinyon-juniper woodlands can be beneficial to sagebrush-dependent species, such as mule deer, by releasing suppressed herbaceous vegetation and increasing forage availability, thereby improving body condition of herbivores and subsequent recruitment (Bergman et al., 2014). Management of pinyon-juniper woodlands provides a unique opportunity to assess the impact that removal of pinyon-juniper trees on winter range can have on forage quality and resource selection of this sagebrush-dependent ungulate.

Winter ecology has been a historically neglected area of research because of presumed biological dormancy of forage during that season (Studd et al., 2021). That view has shifted in recent years, however, as the effect of climate change on northern ecosystems has become an increasingly important area of ecological research (Groisman et al., 2004, Campbell et al., 2005, Barnett et al., 2005). Indeed, the lower temperatures prevailing through the winter season have ubiquitous effects throughout almost all facets of ecology and biology (Clarke 2017). When winters are severe with deep snowpacks, body condition of ungulates can be impacted via direct physiological effects and energy expenditure of moving through snow, and indirectly by changes in phenology and abundance of forage (Nielsen et al., 2012, Searle et al., 2015). To maintain body condition for survival while on lower planes of nutrition, ungulates occupying northern latitudes are evolutionarily adapted to subsist on forage of lower nutritional quality during winter (Silver et al., 1969, Arnold 1985, Reynolds & Hawley 1987, Schmidt 1993). Although ungulates have adaptations to persist despite probable weight loss in winter (Torbit et al., 1985), populations can still decline as a result of the effect that severe winters can have on adult survival (Loveless 1967, Gilbert et al., 1970, Hurley et al., 2011).

Evaluating selection of resources is important for identifying habitat characteristics that are most important for ungulates to meet needs for survival and reproduction (Fretwell 1969, Manly et al., 2002, Northrup et al., 2013). Previous studies have revealed that forage quality on winter range for ungulates is especially important for survival because animals are sustaining themselves on lower planes of nutrition and as a result may be more susceptible to malnutrition and predation (Baker and Hobbs 1985, Bishop et al., 2009, Coe et al., 2018).

Mule deer are a large-bodied herbivore that are distributed throughout many ecosystems in the Western United States (Wallmo 1981, Heffelfinger 2006). Populations of mule deer are declining across much of their historic range, including populations in the Great Basin, for many reasons, including competition from wild and domestic herbivores (Loft et al., 1991, Stewart et al., 2002), wildfire suppression (Peek et al., 2001), invasive plants (Schuyler 2020), energy and urban development (Sawyer et al., 2006), mining (Blum et al., 2015), and expansion of woody plants (Wallmo 1981, Unsworth et al., 1999; Wasley 2004, Heffelfinger 2006, Stewart et al., 2009). This decline is a critical conservation issue because of the important economic and recreational value of mule deer in the Western United States (Heffelfinger and Messmer 2003). Because of lack of improvement in population growth of mule deer throughout much of their range, wildlife managers have sought to identify factors inhibiting population growth (Gill et al., 2001; Bergman et al., 2014).

The objective of this study was to determine how selection of resources by mule deer on winter range changed following thinning of pinyon-juniper woodland. We hypothesized that mule deer will indeed shift their selection of resources after a pinyon-juniper thinning treatment on winter range.

Materials and Methods

Study Area

The Toiyabe Range is located in northern Nye County and southern Lander County, in central Nevada, United States (38° 50′ N 117° 21′ W). This mountain range is the second longest in the state of Nevada, with an approximate length of 193 kilometers. Elevation spans from 1,700 m on Carvers Bench on the eastern side of the Toiyabe Range, to the highest point of 3,589 m at the peak of Arc Dome (Figure 1). This range is inhabited by a migratory population of mule deer that uses summer range at elevations above 2,400 m, while descending to Carvers Bench and the surrounding valley floor during winter. Additionally, transitional habitat between high elevation summer range and the low elevation winter range of mule deer is dominated by phase II and phase III pinyon-juniper woodlands. We conducted this study on mule deer winter range, where pinyon-juniper removal was implemented. Those habitat treatments were coordinated and funded by the U.S. Forest Service, with plots chosen on winter ranges used by mule deer at low elevations in the Humboldt-Toiyabe National Forest, near the town of Carvers, NV. Pinyon and juniper trees were removed with chainsaws via lop-and-scatter techniques during autumn 2018. Lop-and-scatter treatments have been shown to increase perennial forb cover and thus improve forage quality for mule deer (Ross et al., 2012).

Carvers Bench and the surrounding mule deer winter range in the Toiyabe National Forest is primarily composed of big sagebrush (*Artemisia tridentata* spp.) and an assemblage of single-leaf pinyon pine (*Pinus monophylla*)-Utah juniper (*Juniperus osteosperma*). Other dominant shrub species include bitterbrush (*Purshia tridentata*), mountain snowberry (*Symphoricarpos oreophilus*), spiny hop sage (*Grayia spinosa*), curl-leaf mountain mahogany (*Cercocarpus ledifolius*), green rabbitbrush (*Chrysothamnus viscidiflorus*), desert peach (*Prunus andersonii*), and serviceberry (*Amelanchier alnifolia*) (Charlet, 1998; Mozingo, 1987; Trimble, 1989; Tueller and Eckert, 1987). Species of native forbs in this area include spiny phlox (*Phlox hoodia*), common stork's-bill (*Erodium cicutarium*), cushion buckwheat (*Eriogonum ovalifolium*), and other common forbs that occur throughout Great Basin ecosystems.

Field Data Collection

Adult female mule deer were captured by Nevada Department of Wildlife (NDOW) in April 2018 and March 2019 with a net-gun via helicopter (Krausman et al., 1985). Captured individuals were transported to a central processing site via helicopter. Each individual was marked with a uniquely numbered ear tag and fitted with Vectronic GPS-VHF radio collars (Vectronic Aerospace GmbH, Berlin, Germany). Mule deer captured in 2018 had collars programmed to collect a location once every 5 hours and were equipped with a mechanism registered to release 18 months after the date of capture. Individuals captured in 2019 had collars programmed to collect a location once every 2 hours. Collars on all individuals were also equipped with a mortality beacon programmed to activate after 8 hours of immobility. Body temperature was continuously monitored throughout the capture process, and each individual was released at our central processing site. All handling of animals was approved by the Institutional Animal Care and Use Committee at the University of Nevada, Reno (Protocol #: 20-09-1082, exp 11/2024) and followed guidelines established by the American Society of Mammalogists for capture and handling of wild mammals for research (Sikes et al., 2016).

Data preparation and analysis

We used GPS locations for mule deer on winter range during the months of December to May from 2018 to 2020. GPS data were then filtered to remove fixes with dilution of precision (DOP) values >10. The DOP value represents the accuracy of satellite geometry, with higher values indicating poorer location accuracy (Adrados et al., 2002). Any visually apparent outliers were identified and removed from our dataset (Adrados et al., 2002). Since this population migrates from high elevation summer range to low elevation winter range, we visually identified when individuals descended from summer range elevations via ArcGIS (ArcGIS 10.7, Environmental Systems Research Institute [ESRI], Redlands, California, USA). We chose to censor movement data associated with the first and last days that individuals resided on winter range to mitigate any residual selection from the start and end of migrational movements. We constructed a 100% minimum convex polygon (MCP) around winter range GPS locations for all individuals to define our study area. We added a 2-km buffer to our population-level MCP to assure that all available winter range habitat was included in our analysis. All movement data were then combined into a single file of winter range locations, and we extracted values for all habitat variable layers in this study area. Resource selection by mule deer in this study coincided with third-order, or within home range, selection because all locations occurred on winter range (Johnson, 1980, Manly et al., 2002). We estimated resource selection functions (RSFs) in a use-availability design by fitting generalized linear mixed-effects models with binomial error distribution and a logit-link function (Gillies et al., 2006, Bolker et al., 2009, Long et al., 2014, Stewart et al., 2015). We used the "lme4" package in program R v4.1.2 to develop RSFs and evaluated all models for uninformative parameters (Arnold 2010, Bates, Maechler, Bolker, & Walker, 2015; R Development Core Team 2017). We included individual mule deer as random intercepts and slopes in the models (Boyce 2006, Gillies et al., 2006, Long et al., 2014, Stewart et al., 2015). Model selection for both analyses was determined by assessment of Akaike's information criterion corrected for small sample sizes (AICc scores) (Burnham and Anderson 2002, Arnold 2010). Random slope terms were added to help identify variability between individuals in the strength of selection or avoidance of habitat variables (Barr et al., 2013). Mixed-effects logistic regression models have the capability to account for differences in data resolution induced by contrasts in the duty cycles of GPS collars (Manly et al., 2002, Gillies et al., 2006). This capability was important for this study because collars on mule deer captured in 2018 collected fixes once every 5 hours, while those collars deployed in 2019 collected locations once every 2 hours. RSFs were developed within a use-availability framework (Manly et al., 2002, Johnson et al., 2006), with sampled available points generated randomly throughout our winter range MCP equal to two times the number of GPS points. The randomly generated available points were visually assessed to ensure that covariate values were representative of the variability present on mule deer winter range. Our data resolution encompassed 1,474 used locations and 2,948 available locations in the 2018 winter season, 13,315 used locations and 26,612 available locations in 2019, and 9,673 used locations and 19,341 available locations in 2020.

We chose habitat variables to include in this analysis based on what has been demonstrated as crucial for landscape use by mule deer (McKee et al., 2015, Heffelfinger et al., 2020). Variables included in our RSF analysis include slope (degree), elevation, aspect, which were calculated from a Digital Elevation Model encompassing our study area at a 30-m resolution (Landfire, 2014). Because aspect is a circular variable we applied a cosine transformation, for north-south aspect and sine transformation for east-west aspect (Zar 2010). We also used the Rangeland Analysis Platform (RAP) to obtain estimates of cover of annual vegetation, perennial vegetation, trees, and shrubs across all years of the study (www.rangelands.app). Those vegetation cover data are remotely sensed and are a product of model predictions at 30m resolution (www.rangelands.app). Additional variables that we included in our RSFs were distance to water and distance to roads, which were calculated via the Euclidean distance tool in the Spatial Analyst component of ArcGIS (ArcGIS 10.7, Environmental Systems Research Institute [ESRI], Redlands, California, USA). All continuous variables were standardized to support direct comparisons among parameter estimates. We used 95% confidence intervals with model-derived parameter estimates and unconditional standard errors for each habitat variable (Burnham and Anderson 2002).

Results

We evaluated resource selection of 36 female mule deer on winter range during 2018 prior to removal of pinyon-juniper woodlands, and during 2019 and 2020 following treatment. All habitat variables were calculated for used and available locations (Table

1). For our pre-treatment analysis, we selected model #2 as our top model because the addition of perennial cover did not substantially improve model fit and therefore had no additional explanatory power, and model #2 was within 2 AICc scores of the best model (Table 2). Therefore, our top model for resource selection prior to PJ removal included distance to water (m), distance to roads (m), elevation (m), slope (%), tree covern(%), annual cover (%), and northness aspect as habitat variables (Figure 2). Our second analysis evaluated winter resource selection following PJ removal during 2019 and 2020 to identify any changes in selection that occurred after the pinyon-juniper removal treatment. Our chosen model for this analysis was within 1 AICc score of the top model (Table 3). Habitat variables included in this model were distance to water (m), distance to roads (m), elevation (m), slope (%), tree cover (%), annual cover (%), perennial cover (%), northness aspect, and eastness aspect (Figure 3). Shrub cover proved to be an uninformative parameter for our analysis following pinyon-juniper removal, similar to our pre-treatment analysis (Arnold 2010).

For both analyses, standardized parameter estimates were negative for distance to water, indicating selection, and positive for distance to road, indicating avoidance (Figures 2 and 3). Parameter estimates for elevation were negative for both analyses as well, indicating selection for lower elevations (Figures 2 and 3). Mule deer exhibited slight selection for steeper slopes following the pinyon-juniper removal (Figure 3). Neither northness aspect nor eastness aspect were selected or avoided in either analysis indicating use was proportional to availability (Figures 2 and 3). Mule deer selected for cover of annual forbs and grasses before and after pinyon-juniper removal, with a 67% increase in selection for annual cover of forbs and grasses following pinyon-juniper removal (Figures 2 and 3). Tree cover was neither selected for nor avoided prior to our treatment, however mule deer did select for tree cover during the two years following removal of pinyon-juniper trees (Figures 2 and 3). In addition, mule deer also exhibited mild selection for perennial cover after our pinyon-juniper removal treatment (Figure 3).

Discussion

Consistent with our hypothesis, mule deer shifted their selection of resources following removal of pinyon-juniper woodlands. We found that mule exhibited selection for annual and perennial vegetation following the removal of pinyon and juniper trees on winter range. There was an increase in selection for annual vegetation compared to before the pinyon-juniper removal was completed, likely signaling an early herbaceous response to the treatment. Despite perennial vegetation not being in our top model for 2018, mule deer still selected for perennial vegetation following pinyon-juniper removal as well.

An important finding of this study was that mule deer selected for remaining tree cover following pinyon-juniper removal. Morano et al. (2019) showed that mule deer used tree cover during rest periods, especially during summer when shade from the trees provided thermal cover during hot times of day. Another study showed that mule deer did not select for recently treated areas on winter range, but instead had increasing levels of selection for slightly older treatments (e.g., 4-yr-old treatments; Sorensen et al., 2020). That result might be a consequence of more abundant browse species present in treated areas as time passes (Sowell et al., 1985, Sandoval et al., 2005). If this study encompassed further years of data collection, the strength of selection towards tree cover might become stronger as those beneficial shrub species increase in abundance on winter range in areas that pinyon and juniper trees were removed.

Finally, we found that mule deer selected for low elevations on winter range for both analyses, consistent with montane mule deer populations that exhibit elevational migration. Indeed, mule deer exhibited mild selection towards moderately steep slopes following the pinyon-juniper removal. This result might simply be an artifact of selection against the steepest slopes present on winter range, or perhaps forage quality was highest on these intermediate slopes that transition into valley bottoms present on winter range. Morano et al. (2019) found that mule deer selected for mid-slope positions during crepuscular and night time periods when they were actively foraging, so mule deer in the Toiyabe range might also select for intermediate slopes at similar times.

A potential shortcoming of this study is the data resolution prior to our pinyon-juniper removal treatment. Because of the unseasonably mild winter in 2018, our helicopter captures were not able to take place during the intended timeframe because mule deer remained at high elevations used during summer rather than moving to winter range during that mild winter. Mule deer have been observed to remain at high elevation summer range as long as adequate forage was obtainable and snow-depths were manageable (Nicholson et al., 1997, Sawyer et al., 2005, Monteith et al., 2011). High elevation areas in the Toiyabe Range are designated wilderness, thus helicopter captures were legally impossible to conduct while deer remained on summer range. Since our first mule deer capture was delayed until April 10, 2018, our first year's winter range location data had a much smaller sample size than did 2019 and 2020. This effect is especially important to note because our pinyon-juniper removal treatments were conducted in autumn 2018, so that mild winter might have impacted the strength of our pre-treatment analysis. If we had more location data for the entirety of the 2018 winter season, perhaps a detectable signal would have shown that there might indeed be a more compelling difference in selection prior to pinyon-juniper removal. Therefore, we would recommend that future studies involving mule deer response to pinyon-juniper removal treatments have a more robust pretreatment dataset that explicates movement behavior and resource selection prior to implementation of the habitat treatment.

Management of pinyon-juniper woodlands throughout the Western United States is a critical area of research for species considered to be sagebrush obligates during winter, such as mule deer and greater sage-grouse (Bender et al. 2007, Blomberg et al., 2012). Pinyon-juniper woodlands have been shown to exhibit the highest rate of expansion on gradual slopes (Weisberg et al., 2007), which is a common characteristic of winter range habitat for mule deer. This rapid expansion of pinyon-juniper woodland into critical habitat underscores the importance of appropriately managing conifers on winter range, because forage quality and availability is of utmost priority when mule deer are at their lowest body condition prior to spring green-up (Baker & Hobbs 1985, Bishop et al., 2009, Coe et al., 2018). We recommend that managers focus their tree removal efforts on gradual slopes with the highest rates of expansion and infilling, because those areas of habitat are often at the transitional zone between summer and winter ranges. Our results indicate that mule deer selected for low tree cover on the landscape, and thus might be using those thinned stands for avoidance of wind and predators (Bowyer and Kie 2009, Anderson et al., 2012). In conclusion, we believe that lop-and-scatter conifer treatments were successful in providing ecological benefits to mule deer and the herbaceous vegetation that they need for adequate nutrition, while allowing thinned stands to persist on the landscape for potential benefits of a few remaining trees without the negative effect of loss of herbaceous understory in dense woodlands.

Acknowledgments

We would like to thank the Nevada Department of Wildlife for their assistance during mule deer captures as well as financial support of this research project. We thank the United States Forest Service for administrating pinyon-juniper removal treatments in the Toiyabe Range. T. Dilts provided valuable support in data preparation and procurement of GIS layers. This work was supported by the Agriculture Experiment Station at the University of Nevada, Reno.

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Table 1. Descriptive statistics (mean ± SD) of habitat variables for available (random) and used (mule deer locations) for 36 adult female mule deer on Toiyabe winter range, Nevada, USA, 2018-2020. Parameters were standardized prior to analysis. Note: northness aspect included a cosine transformation and eastness aspect included a sine transformation.

Variable	Available (n = 48,901)	Locations (n = 24,462)
Dist. to water (m)	2358 ± 1798.1	1940 ± 1117.9
Slope (°)	16.6 ± 15.2	11.0 ± 9.1
Elevation (m)	2146 ± 440.2	1889 ± 127.2
Dist. To Roads (m)	1207 ± 1460.3	591 ± 400.9
Northness aspect (°)	1.04 ± 0.7	1.06 ± 0.7
Eastness aspect (°)	1.03 ± 0.7	1.09 ± 0.7
Tree Cover (%)	11.2 ± 14.3	7.3 ± 11.3
Shrub Cover (%)	18.8 ± 7.9	18.6 ± 6.1
Annual Forb and Grass Cover (%)	5.0 ± 4.7	8.8 ± 5.5
Perennial Forb and Grass Cover (%)	9.2 ± 9.2	9.6 ± 5.6

Table 2. Model selection for 2018 mule deer resource selection on winter range prior to pinyon-juniper removal in the Toiyabe Range, NV, USA.

#	Model	df	logLik	AICc	Δ AIC	weight
1	Intercept + annual cover – northness – elevation - perennial cover + distance to roads + slope + tree cover – distance to water	10	-1983.2	3986.5	0	0.269
2	Intercept + annual cover – northness – elevation + distance to roads + slope + tree cover – distance to water	9	-1984.9	3987.9	1.37	0.135
3	Intercept + annual cover – northness – elevation – perennial cover + distance to roads + shrub cover + slope + tree cover – distance to water	11	-1983.2	3988.5	2.00	0.099
4	Intercept + annual cover – northness – elevation – perennial cover + distance to roads + eastness + slope + tree cover – distance to water	11	-1983.2	3988.5	2.00	0.099
5	Intercept + annual cover – elevation – perennial cover + distance to roads + slope + tree cover – distance to water	9	-1985.5	3989.1	2.57	0.074

Table 3. Model selection for 2019 and 2020 mule deer resource selection on winter range following pinyon-juniper removal in the Toiyabe Range, NV, USA.

#	Model	df	logLik	AICc	Delta	weight
1	Intercept + annual cover + northness – elevation + perennial cover + distance to roads + shrub cover + eastness + slope + tree cover – distance to water	12	-30835.6	61695.1	0	0.588
2	Intercept + annual cover + northness – elevation + perennial cover + distance to roads + eastness + slope + tree cover – distance to water	11	-30836.9	61695.8	0.71	0.411
3	Intercept + annual cover – elevation + perennial cover + distance to roads + shrub cover + eastness + slope + tree cover – distance to water	11	-30843.2	61708.4	13.35	0.001

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Figure 2. Selection Index based on standardized parameter estimates from resource selection functions (RSF) for mule deer prior to pinyon-juniper removal treatment on Toiyabe winter range, Nevada, USA, 2018. RSFs were calculated by fitting generalized linear mixed models to used and available locations. Individual mule deer were included as a random intercept. Error bars represent 95% confidence intervals.

Figure 3. Selection Index based on standardized parameter estimates from resource selection functions (RSF) for mule deer following pinyon-juniper removal treatment on Toiyabe winter range, Nevada, USA, 2019-2020. RSFs were calculated by fitting generalized linear mixed models to used and available locations. Individual mule deer were included as a random intercept. Error bars represent 95% confidence intervals.

Figure 1 Map of the Toiyabe Range, NV, USA, with delineated mule deer winter range and NEPA-designated treatment units. Inset map shows location of Toiyabe Range within Nevada.

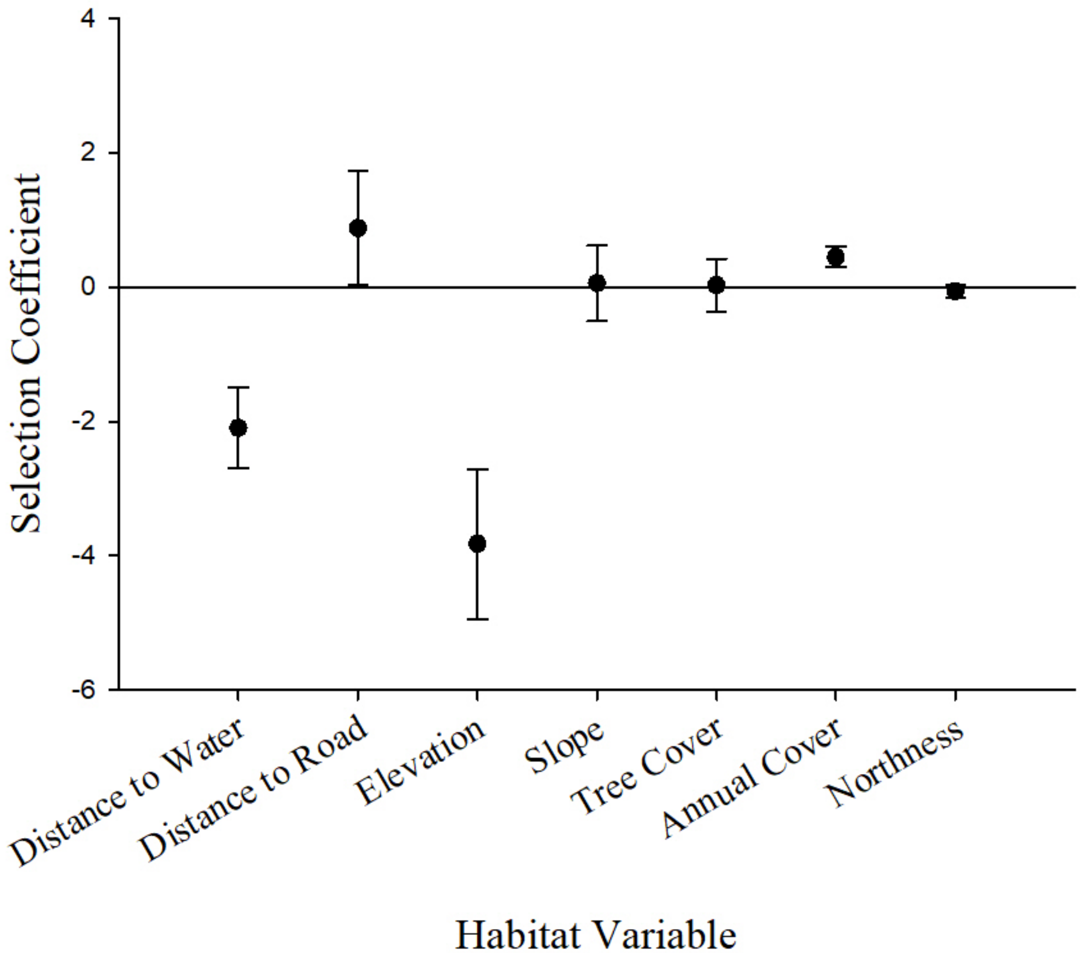

Figure 2. Selection Index based on standardized parameter estimates from resource selection functions (RSF) prior to pinyon-juniper removal treatment for mule deer on Toiyabe winter range, Nevada, USA, 2018. RSFs were calculated by fitting generalized linear mixed models to used and available locations. Individual mule deer were included as a random intercept. Error bars represent 95% confidence intervals.

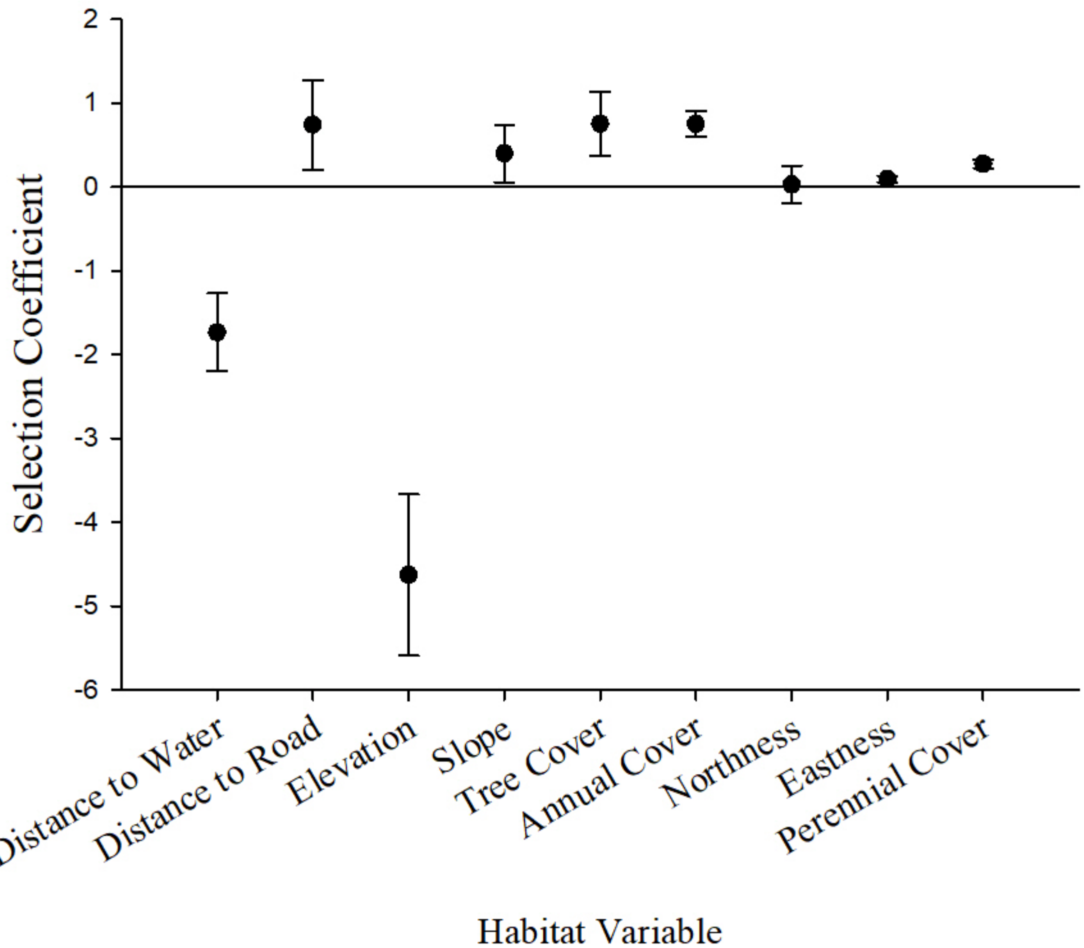

Figure 3. Selection Index based on standardized parameter estimates from resource selection functions (RSF) for mule deer following pinyon-juniper removal treatment on Toiyabe winter range, Nevada, USA, 2019-2020. RSFs were calculated by fitting generalized linear mixed models to used and available locations. Individual mule deer were included as a random intercept. Error bars represent 95% confidence intervals.

CHAPTER 2: EFFECTS OF PINYON-JUNIPER REMOVAL ON DIETS OF MULE DEER ON WINTER RANGE

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Abstract

Populations of mule deer (*Odocoileus hemionus*) are in decline throughout their range for a multitude of reasons, including competition from wild and domestic herbivores, wildfire suppression, energy and urban development, mining, and expansion of woody plants. A primary conservation concern for mule deer in the Great Basin ecosystem is expansion and infilling of single-leaf pinyon pine (*Pinus monophylla*) and Utah juniper (*Juniperus occidentalis*), which provide minimal nutritional value to mule deer while outcompeting herbaceous vegetation in the understory. We investigated how mule diets changed following a pinyon-juniper removal treatment in the Toiyabe Range of central Nevada. We hypothesized that diets would be more diverse following removal of pinyon-juniper woodland. We collected 19 mule deer fecal samples in 2018 prior to pinyon-juniper removal, and 22 mule deer fecal samples in 2019 following our treatment. Diet composition was determined using DNA metabarcoding, and we calculated alpha indices for all fecal samples, including Shannon-Weiner diversity index, species richness, and species evenness. Although diversity declined following our pinyon-juniper removal, bitterbrush (*Purshia tridentata*) made up a high relative abundance of plant taxa present in deer diets, potentially signaling a release following removal of trees on the landscape. Bitterbrush is a highly important forage species for mule deer in winter, and this result lends support to the efficacy of woodland thinning treatments for improving mule deer habitat.

Key Words: DNA metabarcoding, mule deer, *Odocoileus hemionus*, pinyon-juniper, *Purshia tridentata*, Shannon diversity index, Toiyabe Range

Introduction

The science of nutritional ecology is an increasingly important subfield of ecology that seeks to identify nutritional interactions between an animal and its environment (Parker et al. 2009, Monteith et al. 2014). The nutritional ecology and physiology of large mammals are often synthesized to assess the supply and demand of energy and nutrients in these species and the landscapes they inhabit (Barboza et al. 2009). The physiological demands of ungulates for energy, nutrients, and water are modulated by supply in the environment and life-history characteristics of the species (Barboza et al. 2009). Nutritional interactions between ungulates and their foods occur at all levels, including the individual level, the population level, and the ecosystem as a whole (Parker et al. 2009). Nutritional condition is the platform upon which annual production of ungulates is primarily driven (Parker et al. 2009). Indeed, individuals on higher planes of nutrition exhibit higher survival rates and therefore produce more offspring during their lifetime (Stewart et al. 2005, Parker et al. 2009). Animals that are able to obtain higher quality forage also often obtain larger body sizes while maintaining higher body condition than animals on lower planes of nutrition (Cook et al. 2004, Parker et al. 2009, Monteith et al. 2009, Jackson et al. 2021). Moreover, animals on higher planes of nutrition demonstrate increased resilience to environmental extremes and time periods of declining forage quality contrary to individuals in poorer body condition (Mautz 1978, Stewart et al. 2005, Monteith et al. 2014).

Mule deer (*Odocoileus hemionus*) are a large mammal that inhabits much of western North America (McKee et al. 2015, Shoemaker et al. 2018, Morano et al. 2019).

Populations of mule deer are declining across much of their historic range due to a suite of environmental and anthropogenic factors such as competition with herbivores, wildfire suppression, energy and urban development, disease, predation, mining, and expansion and infilling of woody plants of low nutritional value into their habitat (Wallmo 1981, Unsworth et al. 1999, Heffelfinger 2006, Stewart et al. 2009, Bishop et al. 2009, Hurley et al. 2011). This concerning decline in mule deer abundance has resulted in wildlife managers seeking to identify the most limiting factors preventing recovery of populations of this recreationally vital species throughout the Intermountain West (Gill 2001, Heffelfinger & Messmer 2003, Bergman et al. 2014). Ungulate winter ranges are also at low elevations and thus are much closer in proximity to human populations, potentially increasing susceptibility to anthropogenic factors that negatively affect forage quality (Anderson et al. 2012). Mule deer often exhibit migratory behavior to meet energetic and nutritional requirements for reproduction and survival, including directional movements of both long and short distances as well as elevational movements between summer and winter ranges (Nicholson et al. 1997, Sawyer et al. 2005, Monteith et al. 2011, Anderson et al 2012). At the end of the winter season, mule deer are on low planes of nutrition, but often maintain survivable body condition despite lower nutritional quality as a result of evolutionary adaptations (Silver et al. 1969, Arnold 1985, Reynolds & Hawley 1987, Schmidt 1993). Management agencies have focused habitat-improvement efforts for mule deer on winter range with the goal of increasing abundance and quality of nutritionally vital shrubs and forbs (Bergman et al. 2014). Previous studies show that forage availability on winter range, especially at the end of winter and early spring, can have substantial effects on survival for many ungulate species, because animals are subsisting on lower planes of nutrition (Baker & Hobbs 1985, Bishop et al. 2009).

Pinyon-juniper woodlands have been rapidly expanding into sagebrush ecosystems throughout the Intermountain West since Euro-American settlement in the mid-19th century (Miller and Tausch 2000, Weisberg et al. 2007). This expansion and infilling of woodlands into sage-steppe ecosystems has caused population declines of many sagebrush obligate species, including sage grouse, sage sparrows, pygmy rabbits, and mule deer (Rowland et al., 2006, Wisdom et al., 2005, Larrucea and Brussard, 2008, Miller, 2005). Single-leaf pinyon (*Pinus monophylla*) and juniper species (*Juniperus* spp.) are highly proficient at locating and monopolizing available water because of their long, lateral roots, which allows them to outcompete forbs and grasses with shallow roots that are nutritionally crucial for mule deer (Breshears et al. 1997, Morano et al. 2019). Quality of forage is a significant driver of mule deer population dynamics, and studies have shown that pinyon-juniper woodlands provide minimal benefits to forage quality (Bender et al., 2007, Bergman et al., 2014). Other studies have shown that adult female mule deer inhabiting pinyon-juniper woodlands were nutritionally compromised, resulting in low fawn survival, low recruitment, and diminished herd productivity (Lomas and Bender 2007, Bender et al., 2007). For those reasons, managers have administered pinyon-juniper removal treatments to improve forage availability and quality as an attempt to augment diets, body condition, survival, and reproductive success of adult female mule deer (Cook et al., 2007, 2010, Bishop et al., 2009, Sorensen et al., 2020).

The objective of this study was to identify dietary differences in a mule deer population before and after a pinyon-juniper removal in the Toiyabe Range of central

Nevada. We hypothesized that annual and perennial vegetation on mule deer winter range would increase following pinyon-juniper removal, and therefore mule deer diets would exhibit a higher diversity after a lop-and-scatter pinyon-juniper removal treatment.

Materials and Methods

Study Area

The Toiyabe Range extends from northern Nye County into southern Lander County, in central Nevada, United States (38° 50′ N 117° 21′ W). The Toiyabe Range is roughly 193 kilometers long and is the second longest mountain range in Nevada. The lowest point of elevation is approximately 1,700 m on Carvers Bench on the eastern side of the Toiyabe Range, and Arc Dome is the highest point at 3,589 m. Mule deer reside throughout the Toiyabe Range and undergo seasonal migrations, as they use summer range at elevations above 2,400 m and then descend to the Carvers Bench area and the surrounding valley floor for winter. Furthermore, transitional habitat between high elevation summer range and low elevation winter range is saturated by phase II and phase III pinyon-juniper woodlands. This study was carried out on mule deer winter range where our pinyon-juniper removal treatment was implemented (Figure 1). Pinyon-juniper removal was applied in treatment plots delineated on low elevation winter range used by mule deer in the Humboldt-Toiyabe Forest near the town of Carvers, NV. The pinyon-juniper removal was completed during autumn 2018 using lop-and-scatter techniques via chainsaw. Lop-and-scatter tree removal has been shown to increase perennial forb cover and therefore improve quality of forage in habitats used by mule deer (Ross et al., 2012).

Habitat characteristics of winter range of mule deer in the Toiyabe National Forest and the Carvers Bench area consists of big sagebrush (*Artemisia tridentata* spp.) communities interspersed with single-leaf pinyon pine (*Pinus monophylla*) and Utah juniper (*Juniperus osteosperma*) woodlands. Other common shrub species throughout the Toiyabe Range include bitterbrush (*Purshia tridentata*), mountain snowberry (*Symphoricarpos oreophilus*), spiny hop sage (*Grayia spinosa*), curl-leaf mountain mahogany (*Cercocarpus ledifolius*), green rabbitbrush (*Chrysothamnus viscidiflorus*), desert peach (*Prunus andersonii*), and serviceberry (*Amelanchier alnifolia*) (Charlet, 1998; Mozingo, 1987; Trimble, 1989; Tueller and Eckert, 1987). Species of forbs prevalent in the area include spiny phlox (*Phlox hoodia*), common stork's-bill (*Erodium cicutarium*), devil's lettuce (*Amsinckia tessellata*), cushion buckwheat (*Eriogonum ovalifolium*), as well as other species of herbaceous plants common to Great Basin ecosystems. There are also many species of grasses present throughout the study area, including needle-and-thread grass (*Hesperostipa comata*) and the noxious invasive cheatgrass (*Bromus tectorum*).

Field Data Collection

Adult female mule deer were captured with a net-gun via helicopter by Nevada Department of Wildlife (NDOW) on two capture occasions in April 2018 and March 2019 (Karusman et al. 1985). Captured individuals were transported to a central processing site via helicopter. At our processing site, we obtained various morphometric measurements and extracted fecal samples from all captured mule deer. All individuals were marked with a uniquely numbered ear tags and fitted with Vectronic GPS-VHF radio collars (Vectronic Aerospace GmbH, Berlin, Germany). Mule deer captured in

2018 had collars programmed to collect a location once every 5 hours and equipped with a mechanism registered to release 18 months after the date of capture. Individuals captured in 2019, however, had collars programmed to collect a location once every 2 hours. All collars were equipped with a mortality beacon programmed to activate after 8 hours of immobility. Body temperature was continuously monitored throughout the handling process, and each individual was released from our central processing site. All handling of animals was approved by the Institutional Animal Care and Use Committee at the University of Nevada, Reno (Protocol #: 20-09-1082, exp 11/2024) and were in accordance with guidelines established by the American Society of Mammalogists for capture and handling of wild mammals in research (Sikes et al. 2016).

Diet Composition Processing and Analysis

We analyzed 41 fecal samples from our mule deer captures (2018: n = 19, 2019: n = 22) to identify changes in diet composition following removal of pinyon-juniper. We used DNA metabarcoding (www.jonahventures.com), which has been shown to exhibit high accuracy in quantifying diets without observing foraging behavior prior to sample collection (Sousa et al. 2019). Indeed, DNA metabarcoding has been used to accurately identify dietary characteristics in many deer species (Bison et al., 2015, Czernik et al., 2013, Fløjgaard, De Barba, Taberlet, & Ejrnæs, 2017, Rayé et al., 2011). Our pre-treatment and post-treatment datasets were subset to only include exact sequence variants (ESVs) that made up > 1% of the total read counts in each data set to minimize influence of any sequencing errors (Deagle et al., 2019, Nielsen et al., 2021). We used the Basic Local Alignment Search Tool (BLAST) to identify each ESV to the most specific taxonomic level possible. After using the Nucleotide BLAST tool from the National

Center for Biotechnology Information (https://blast.ncbi.nlm.nih.gov), we then cross-referenced our results with the USDA Plants Database (plants.usda.gov) to confirm that each taxa was present within our study area.

We calculated a Shannon-Weiner diversity index (*H*), species richness (*D*), and species evenness (*E*) using the read counts that were filtered to only include ESVs that made up >1% of the total read counts of each dataset (Shannon and Weaver 1949, Margalef 1958, Buzas and Gibson 1969). The differences in diet diversity, richness, and evenness between pre-removal and post-removal were analyzed using a Student's *t*-test. To further identify differences in diet following tree removal, we calculated relative read abundance (RRA) and frequency of occurrence (FOO) for each taxa that was present in >1% of the read counts for pre and post pinyon-juniper removal. RRAs were calculated for each plant taxon to identify the relative contribution to each dataset, while FOOs are a measure of presence/absence of the taxon in each dataset. To determine which plants were significantly associated with pre-removal or post-removal, we used the signassoc function in the *indicspecies* package in R (Cáceres and Legendre, 2009).

Results

We identified a total of 9 plant taxa that occurred in >1% of the total read counts in all fecal samples obtained from captured mule deer (Table 1). Needle-and-thread grass (*Hesperostipa comata)* was only found in fecal samples collected prior to the pinyon-juniper removal, while bristly fiddleneck (*Amsinckia tessellata*) was only found in fecal samples collected following pinyon-juniper removal (Table 1). The most consumed species prior to tree removal were *Eriogonum* spp. (46.05%), *Poaceae* spp. (33.07%), and *Artemisia* spp. (8.17%) (Table 1). Following pinyon-juniper removal, the most consumed species by mule deer were bitterbrush (44.73%), *Eriogonum* spp. (21.39%), and *Poaceae* spp. (18.05%) (Table 1).

Shannon-Weiner diversity indices were $H = 1.015$ for 2018 and $H = 0.8114$ for 2019. Diet diversity was not statistically significant ($t = 1.7121$; df = 39; $p = 0.0948$), but showed a trend of lower diversity following removal of pinyon juniper trees. Species richness did not differ ($t = 0.331$; df = 39; $p = 0.7424$) between 2018 prior to pinyon juniper removal ($D = 4.9473$) and 2019 ($D = 5.09$) following pinyon-juniper removal. Species evenness was significantly different ($t = 2.4085$; df = 39; $p = 0.0208$). between 2018 ($E = 0.6415$), and in 2019 ($E = 0.4843$).

RRAs and FOOs were calculated for 2018 and 2019 (Table 1). Plant taxa that significantly declined in FOO or RRA following pinyon-juniper removal were buckwheat (FOO $p = 0.0099$; RRA $p = 0.02$) and common stork's-bill (FOO $p = 0.019$; RRA $p = 0.0099$) (Table 1). Plant taxa that significantly increased in FOO or RRA after administration of pinyon-juniper removal were bitterbrush (FOO $p = 0.0099$; RRA $p = 0.0099$), cheatgrass (FOO $p = 0.019$; RRA $p = 0.0099$), and bristly fiddleneck (RRA $p = 0.019$) (Table 1).

Discussion

Our hypothesis that mule diets would be more diverse following pinyon-juniper removal was not supported. Indeed, diet diversity actually declined following PJ removal treatment. Despite this difference not being statistically significant, our results indicated a trend of decreasing diet diversity, but those results might be a consequence of small sample sizes. Although the diversity in mule deer diet declined, it is interesting to note that the strong selection for bitterbrush following pinyon-juniper removal might be a direct consequence of more accessible water and soil nutrients for bitterbrush on the landscape following woodland thinning (Roundy et al., 2014, Ernst-Brock et al., 2019). Bitterbrush is a high-quality forage for mule deer in the Great Basin (Kucera 1997, Pierce et al., 2004, 2012). One study found that mule deer will preferentially target bitterbrush for winter forage, only shifting to sagebrush as bitterbrush availability diminishes as a result of heavy browsing (Pierce et al., 2004). Another study showed that bitterbrush cover was significantly greater following various pinyon-juniper removal techniques, including clearcutting, probably as a result of increased availability of water following remove of Pinyon-juniper woodland (Ernst-Brock et al., 2019). Another pinyon-juniper removal study found that bitterbrush was the most abundant shrub species detected following mechanical treatments (Stephens et al., 2016). These studies all support the efficacy of pinyon-juniper removal treatments for improving winter forage for mule deer, and our results also support this response of bitterbrush to pinyon-juniper removal because of the increase of bitterbrush in diets of mule deer following removal of trees.

Following pinyon-juniper removal we observed higher presence of cheatgrass and bristly fiddleneck in the late winter diets of mule deer. Both of those species are annuals, and this result aligns with other studies have shown that annual vegetation is the first to establish following mechanical removal of pinyon-juniper trees (Barney and Frischknecht 1974, Tausch and Tueller 1977, Skousen et al., 1989, Redmond et al., 2013). Another study also found that cheatgrass increased in abundance following woodland reduction treatments and was spatially patchy and variable in treated areas (Ernst-Brock et al., 2019). The timing of the removal treatment could be paramount for reducing cheatgrass invasion following tree removal, another study suggested that treatments administered in winter or early spring can reduce the reaction of cheatgrass if perennial herbaceous vegetation remains mostly intact (Bates and Davies 2017). Some cheatgrass in the diets of mule deer during early green-up is not surprising because new growth of cheatgrass is almost completely digestible with high energy content (Austin et al., 1994, Bishop et al., 2001).

A potential shortcoming of this study is the small samples sizes of mule deer fecal samples obtained before and after pinyon-juniper removal. All of our samples were obtained from mule deer during capture. Additional samples may have provided a more robust dataset for diet composition relative to Pinyon-juniper removal. Additionally, sampling of plants on the landscape could help elucidate additional differences in plant responses after woodland thinning in this sagebrush ecosystem, and this is a common deficiency in vegetation treatment studies (Miller 2005, Baughman et al., 2010). Additionally, long term monitoring after pinyon-juniper removal is ideal as vegetation responses to the treatment might take years or even decades to manifest (Miller 2005, Bates et al., 2017, Havrilla et al., 2017).

Pinyon-juniper woodlands throughout the Intermountain West have been increasing in range, density, and cover for over a century (Miller and Wigand 1994, Chambers et al., 1999, Miller 2005, Weisberg et al., 2007). This expansion and infilling of woodlands in the Great Basin has resulted in reduced shrub and herbaceous cover, and in turn is deteriorating forage quality for sagebrush obligate species, such as mule deer (Tausch et al., 1981, Tausch and Tueller 1990, Miller et al., 2000, Miller 2005, Bender et al., 2007, 2013). We used a DNA metabarcoding approach to analyze mule deer diets before and after a pinyon-juniper removal treatment in the Toiyabe Range of central

Nevada. Although our dataset does have temporal limitations, we still uncovered a beneficial response from bitterbrush, with a higher relative abundance following treatment of that important species for winter nutrition of mule deer. We also had an increase in abundance of herbaceous annual vegetation, consistent with the results of other woodland thinning studies. Our findings support the efficacy of pinyon-juniper removal treatments for improving habitat for mule deer throughout the western United States, however additional research would be beneficial in assessing longer term herbaceous responses to woodland removals to mitigate any problematic infiltrations of invasive species such as cheatgrass.

Acknowledgments

We would like to thank the Nevada Department of Wildlife for their assistance during mule deer captures as well as financial support of this research project. We thank the United States Forest Service for administrating pinyon-juniper removal treatments in the Toiyabe Range. We thank Jonah Ventures, LLC for their DNA metabarcoding service. M. Blum was extremely helpful with R coding. This project also was supported by the Agriculture Experiment Station at the University of Nevada, Reno.

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Table 1. Frequency of occurrence (FOO), relative read abundance (RRA), and associated *p* – values for all plant taxa identified in mule deer fecal samples for 2018 and 2019. Statistical significance assessed by the signassoc function in R package *indicspecies*.

Taxa Identified	*2018 FOO*	*2018 RRA*	*2019 FOO*	*2019 RRA*	*FOO p - Value*	*RRA p - Value*
Eriogonum	1	0.4605	0.7727	0.2139	0.0099	0.02
Poaceae	1	0.3307	0.909	0.1805	0.059	0.1
Artemisia	1	0.0817	0.8181	0.0869	0.59	0.65
Pinus	0.4736	0.0618	0.5909	0.0426	0.49	0.49
Erodium cicutarium	0.9473	0.0311	0.409	0.0025	0.019	0.0099
Hesperostipa comata	0.1052	0.0251	0	0	0.72	0.71
Purshia tridentata	0.1578	0.0073	0.6363	0.4473	0.0099	0.0099
Amsinckia tessellata	0	0	0.4545	0.0144	0.059	0.019
Bromus tectorum	0.2631	0.0015	0.5	0.0115	0.019	0.0099

Figure 1 Map of the Toiyabe Range, NV, USA, with delineated mule deer winter range and NEPA-designated treatment units. Inset map shows location of Toiyabe Range within Nevada.

Thesis Summary

Mule deer (*Odocoileus hemionus*) are a large-bodied herbivore that are widely distributed throughout western North America (Wallmo 1981, Heffelfinger 2006). Populations of mule deer are in decline (Heffelfinger 2006), and wildlife managers have been attempting to identify the environmental factors that are constraining population growth (Gill et al., 2001, Bergman et al., 2014). Conifer expansion is believed to be an environmental component negatively affecting mule deer throughout the Great Basin because of the ability of single-leaf pinyon (*Pinus monophylla*) and Utah juniper (*Juniperus osteosperma*) to outcompete herbaceous vegetation in understories due to long lateral roots (Morano et al., 2019). Therefore, pinyon-juniper management has been an increasingly common way to improve habitat for mule deer (Bender et al., 2007). Pinyon-juniper woodlands exhibit the highest rates of expansion downward from moderate slopes, and consequently impact forage quality on mule deer winter range (Weisberg et al., 2007, Bishop et al., 2009). Conifer management on winter range is especially important because forage quality and availability is critical when mule deer are at their lowest body condition prior to spring green-up (Baker and Hobbs 1985, Bishop et al., 2009, Coe et al., 2018).

After application of a pinyon-juniper removal treatment on winter range in the Toiyabe Range of Nevada, I hypothesized that mule deer would shift their selection of resources. I found that mule deer displayed an increase in selection for annual vegetation, steeper slopes, and tree cover following thinning of pinyon-juniper woodlands on winter range. These results help reveal the potential benefits of pinyon-juniper removals for mule deer management. Higher selection for annual vegetation showed that vegetation responses to woodland thinning treatments can occur within the first 2 years of a treatment. Selection for steeper slopes might also be a consequence of increase in forage quality on mid-slope positions where mule deer often prefer to forage (Morano et al., 2019). The increase in selection for tree cover following our treatment was especially noteworthy as it revealed that mule deer do indeed use smaller stands of conifers during winter, and perhaps there is an ideal woodland density that allows herbaceous vegetation to persist but also allows mule deer to use pinyon-juniper woodlands for horizontal cover.

For my second chapter, I examined the effects of pinyon-juniper removal on the diversity of mule diets on winter range. Because high densities of pinyon-juniper woodlands are associated with decreased diversity of understory vegetation (Miller 2005), I hypothesized that mule deer diets would be more diverse following our treatment. I calculated Shannon-wiener diversity indexes for pre-treatment and post-treatment fecal samples and found that diversity of mule deer diets actually declined following the treatment. Although my hypothesis was incorrect, I did observe that antelope bitterbrush (*Purshia tridentata*) occupied a substantially higher percentage of mule deer diets. This was an exciting result, as antelope bitterbrush is the preferred winter forage of mule deer in the Great Basin (Kucera 1997, Pierce et al., 2004, 2012), and also has been shown to quickly respond to pinyon-juniper removals (Stephens et al., 2016, Ernst-Brock et al., 2019).

Although this study had various temporal limitations, I believe that I uncovered beneficial responses by mule deer to a pinyon-juniper removal treatment, even within just a few years following the treatment. Density of pinyon-juniper woodlands on mule deer winter range is important to monitor, and mule deer forage declines in availability and quality once woodlands attain phase III densities (Miller and Tausch, 2000, Miller 2005, Bender et al., 2007, 2013). Administering pinyon-juniper removals on winter range while leaving trees on the landscape appears to a beneficial way to improve availability of understory vegetation while still allowing trees for use as horizontal cover by mule deer. I also detected a sizable shift in the amount of antelope bitterbrush present in mule deer diets following this treatment, supporting a highly nutritious shrub that is preferred by mule deer during winter (Pierce et al., 2004). Perhaps other pinyon-juniper removal studies that obtain data for a longer time period following the treatment will elucidate even more concrete benefits for mule deer management in the Great Basin.

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