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Monitoring Populations and Movement of Bobcats (*Lynx rufus*) on the Eastern Slope of the Sierra Nevada Mountains of California

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MONITORING POPULATIONS AND MOVEMENT OF BOBCATS (LYNX RUFUS) ON THE EASTERN SLOPE OF THE SIERRA NEVADA MOUNTAINS OF CALIFORNIA

by

Michael Brown

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Wildlife Biology

Approved:

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UTAH STATE UNIVERSITY
Logan, Utah

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ABSTRACT

Monitoring Populations and Movement of Bobcats (*Lynx rufus*) on the Eastern Slope of the Sierra Nevada Mountains of California

by

Michael Brown, Master of Science

Utah State University, 2021

Major Professor: Dr. Mary M. Conner
Department: Wildland Resources

Effective management of wildlife populations require insights into space use of wildlife populations including home range and habitat selection. Furthermore, identifying methods to accurately obtain density and abundance estimates of wildlife populations is imperative for informed management and conservation of wildlife populations. Carnivores hold important roles in the ecosystems. My study examines space use parameters and habitat selection of bobcats (*Lynx rufus*) on the eastern slope of the Sierra Nevada Mountains of California.

In Chapter 2, I explore space use and habitat selection of bobcats by quantifying differences in home range and core area size and habitat selection between male and females and across seasons utilizing resources selection functions (RSF) for male and female bobcats on the eastern slope of the Sierra Nevada Mountains of California, USA from 2015-2018. Mean home range and core area size were calculated using kernel density estimators for 38 bobcats (male *n* = 25, female *n* = 13). Home range and core areas were significantly larger for male bobcats than females with no significant seasonal differences observed. RSF models showed bobcats to select strongly for riparian habitats, and proximity to streams and canyons.

Furthermore, male bobcats preferred areas bordering agriculture areas whereas this selection was not detected as strongly for females.

In Chapter 3, using camera traps, I identify individual bobcats based on unique pelage patterns and compare density estimates using closed capture mark-recapture (CMR) and maximum likelihood spatially explicit capture-recapture (SECR) methods of analysis. Bobcat density estimates were 17.9/10 km^2 and 47.1/km^2 for CMR and SECR, respectively. Density discrepancies in movement and spatial scale parameters between the two methods resulting from insufficient identification and recapture rates of individuals at the extremities of their home ranges. These finding suggest that in a sparsely vegetated, open, and homogenous desert landscape, camera trapping for bobcats using a capture recapture design may not be as effective as other non-invasive genetic methods such as fecal DNA.

These results provide valuable insights to bobcat space use and habitat selection on the eastern slope of the Sierra Nevada Mountains of CA to inform management and conservation. Furthermore, the comparison of camera trapping methods for obtaining density estimates will contribute to bobcat monitoring methods in similar areas across California.

(131 pages)

PUBLIC ABSTRACT

Monitoring Populations and Movement of Bobcats (*Lynx rufus*) on the Eastern Slope of the Sierra Nevada Mountains of California

Michael C. Brown

Monitoring the spatial ecology and population densities of carnivores is critical for effective management and conservation of these populations and the ecosystems in which they exist. However, effective monitoring of carnivore populations through estimates of space use, habitat selection and densities can be difficult due to their relatively low densities and wide ranging, elusive behaviors. Bobcats (*Lynx rufus*) are medium sized, top-level predators which are widely distributed across North America. Quantifying space use, habitat selection and developing effective population monitoring strategies for this species will have important implications for wildlife management.

My first objective was to use telemetry data to evaluate space use parameters such as home range and core area estimates, seasonal movement patters and relative habitat selection of bobcats on the eastern slope of the Sierra Nevada Mountains of California, USA. Using GPS collars, I collected data on 38 bobcats (male *n* = 25, female *n* = 13) from 2015-2018. Using kernel density home range analysis, I was successfully able to estimate home range and core area sizes for male and female bobcats and examine differences in size between sexes and between seasons. Furthermore, I developed resource selection functions (RSF) to explore relative habitat selection of male and female bobcats in the study area.

My second objective was to evaluate accurate, non-invasive monitoring strategies for bobcats. Using camera trap data, I compared closed capture mark-recapture (CMR) and spatially explicit capture-recapture (SECR) methods for estimating densities of bobcats. Data was collected over a 6-week survey period in April-May of 2018. The different methods yielded very different estimates of density and spatial scale parameters. These differences likely stem from a low positive identification rate of bobcats based on pelage patterns. My findings suggest that in sparsely vegetated, open, homogenous desert ecosystems that photographic mark recapture may not be appropriate due to low identification rate of individuals.

To my knowledge, my study provides the first evaluation of space use and habitat selection by bobcats on the eastern slope of the Sierra Nevada Mountains of California. Furthermore, very little research has been conducted evaluating bobcat density and monitoring strategies in this area. The findings from this study will facilitate management and monitoring of bobcats in the eastern Sierra Nevada as well as providing important insights into the spatial ecology of bobcats in this area.

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I would like to thank my major advisor, teacher, and friend, Dr. Mary Conner for her continued support, guidance and generosity throughout my graduate program at Utah State University (USU) and research with the California Department of Fish and Wildlife (CDFW). I met Dr. Conner while working as a scientific aid for CDFW at the beginning of a pilot study monitoring bobcats outside of Bishop, CA. She heard my proposal for pursuing bobcat research as part of a Master of Science program at USU and offered me an incredible opportunity that has grown me as a scientist, researcher, and a person. I cannot thank you enough Mary for seeing the possibilities with carnivore research and guiding me along the way. I would also like to thank my committee of excellent scientists, Julie Young, Kimberly Sullivan, and Alisa Ellsworth from whom I have learned immensely.

To everyone at CDFW who has contributed to this work and helped me along the way, I offer my sincere thanks and respect. I thank Alisa Ellsworth and Dr. Tom Stephenson completely for the ongoing optimism, scientific, and financial support and expertise along the way. I hope this research will facilitate in the ongoing pursuit of information revolving around the incredible ecosystem and species dynamics we focus on in our region. Furthermore, I would like to acknowledge and thank Vicki Davis for patiently teaching me the ways of bobcat trapping. Your expertise has been invaluable, and this study would not have been possible without you. Without Vicki and her husband Jeff Davis' support, I would say our sample sizes would be lacking and I would shy from calling myself a 'trapper'.

Special thanks to all the coworkers that helped with these projects and spent endless hours checking traps, collaring bobcats, and running camera surveys with me. Andi Stewart, Glenden Taylor, Stephen Pfeiler, Shannon Fusaro, Aaron Johnson, Kristen Pfeiler, and Josh

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Analyses incorporated a huge part of this project and I would like to thank Dave German for his time and statistical expertise in helping me analyze and quantify these data. I could not have done it without you. Additionally, I would like to thank Jake Ivan and Sean Murphy for their advice and help with the spatially explicit mark-recapture analysis.

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Michael Cameron Brown

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Predators can exert a top-down effect on the structure, function, and stability of ecosystems (Ray et al. 2005, Berger et al. 2008, Ritchie and Johnson 2009). Carnivores can influence an ecosystem though direct predator-prey interactions, impacting prey populations directly, or through indirect effects on the ecosystem processes and species further down the trophic cascade (Miller et al. 2001, Winnie and Creel 2017). Predators play important ecological roles in ecosystems, and understanding their population densities, movement patterns, and spatial organization can provide insights into effective conservation efforts for both the predator and ecosystem (Ray et al. 2005, Thornton and Pekins 2015).

Predation by carnivores can have profound effects on ecosystems including contributing to balance and sustainability through predatory control of prey species (Winnie and Creel 2017). One way that carnivores contribute to a healthy ecosystem is by limiting the number of herbivores subsequently alleviating pressures on vegetation (Miller et al. 2001). Prior research on the reintroduction of wolves in Yellowstone National Park illustrates the cascading effect that the renewed presence of an apex predator can have on prey population dynamics, species interactions and landscape composition (Boyce 2018). In this case study, reintroduction of gray wolves (*Canis lupus*) resulted in a trophic cascade through predation on elk that subsequently alleviating herbivory pressures on vegetation. Similarly, predator and prey abundance and fluctuations can influence each other over time and produce cyclic influences on prey and predator densities in an ecosystem. Previous research has examined the cyclic changes in abundance of mesocarnivore populations such as the lynx (*Lynx canedensis*) and influence of these densities on snowshoe hare abundance which in turn have a bottom-up effect on lynx abundance over time (Stenseth et al. 1997). In addition, studies of mesocarnivore-prey population dynamic in coyotes (*Canis latrans*) and jackrabbits (*Lepus californicus*) illustrate how mesocarnivore populations can be influenced by prey abundance (Clark 1972).

When predators are overly abundant or exist at unsustainably high levels or in ecosystems in which they are not endemic, predators can have detrimental effects on prey species driving sensitive prey species into decline or even extinction (Mack et al. 2000) and, in turn, entire ecosystems. For example, in the eastern Sierra Nevada Mountains, mountain lion populations can have negative impacts on federally and California state endangered Sierra Nevada Bighorn sheep populations in turn impacting the recovery efforts of this sensitive prey species (Wehausen 1996).

In addition to the ecological importance of carnivore species, carnivores also hold a strong aesthetic and economic value for the public. Many carnivore populations across North America are legally harvestable and have important economic impacts from hunting licenses and tags. In circumstances where carnivores are having a detrimental effect on the vitality of sensitive prey populations, predator control through harvest or facilitated removal may be necessary (Rominger 2018). Additionally, carnivore-human conflict has significant socioeconomic impacts to humans through predation of livestock, destruction of property, and human injury or death (Dickman et al. 2013, Maheshwari et al. 2014). Carnivores often hold strong aesthetic and cultural value to society and the public making appearances in folk lore, on state flags, and in the media. Furthermore, the value of these animals to hunters, trappers and wildlife photographers and enthusiasts contribute to the overarching aesthetic importance these populations hold for people.

Despite the recognized ecological, economic, and aesthetic importance of conserving carnivore populations, terrestrial large mammalian carnivore populations have been declining across many regions of the world (Berger et al. 2008). In order to conserve carnivore populations within a region, wildlife managers must be able to effectively monitor populations, but also understand space use patterns. Bobcats hold important roles in ecosystems as mesocarnivores in which they are both influencing and regulating prey populations and being influenced by relative abundance of primary prey species. For this reason, effective monitoring of populations is important for conservation and management of not only bobcats, but also the other sympatric species that occupy the same habitat. Obtaining accurate density and abundance estimates of bobcats and the ability to detect increases and declines in populations will help evaluate the health and fluctuations of bobcat populations, and perhaps provide insight to sensitive prey species with which they overlap. In addition, the temporal assessment of monitoring population dynamics, understanding the space use of a population can inform multiple aspects of management, including maintaining wildlife movement corridors, understanding potential impacts on prey populations, human-wildlife conflict resolution, carnivore interspecific and intraspecific interactions, and spatial-temporal fluctuation in carnivore populations. Furthermore, specifying relative habitat selection provides the opportunity to identify important habitat and movement corridors to carnivore populations and mitigating for important habitat degradation and destruction.

Prior research has demonstrated the effectiveness of telemetry data collected from GPS collars to examine space use, estimate home range, and provide insights into habitat selection of bobcats (Donovan et al. 2011, Reed et al. 2017, Abouelezz et al. 2018, Little et al. 2018, Young et al. 2019). Home ranges and refined areas of increased use, referred to as core areas, have been identified using kernel density estimators (Donovan et al. 2011). In the past decade, habitat selection by carnivores has been the focus of much research using spatial telemetry data (McNitt et al. 2020). Using these GPS collar data, habitat selection by carnivores has been examined by modelling habitat variables that are important in predicting carnivore use (McNitt et al. 2020). These analyses identifying the relative selection of habitat characteristics by carnivores, can have important implications for conservation and management through reducing habitat degradation and fragmentation and also facilitating movement and connectivity corridors.

Closed capture mark-recapture (CMR) techniques are widely used for estimating abundance and density for wildlife populations. However, traditional CMR sampling often involves invasive techniques such as physical capture and marking of animals (Blanc et al. 2013). Recently, research has focused on non-invasive techniques of monitoring carnivore populations, including remote cameras and genetic sampling (Heilbrun et al. 2006, Fusaro et al. 2017). Samples from cameras are less expensive than genetic samples, but photographic surveys employing closed capture mark-recapture and SECR methods require the ability to individually identify unique individuals. Because bobcats exhibit unique spot and facial markings, individuals are reliably identifiable (Heilbrun et al. 2006, Thornton and Pekins 2015). Consequently, it is possible to use camera sampling for mark-recapture/SECR models. Much research has illustrated the effectiveness of identifying individuals using remote cameras by unique pelage patterns and morphological patterns of individuals (Heilbrun et al. 2003, Jackson et al. 2006, Larrucea et al. 2007, Rich et al. 2014). This alleviates the need to physically capture and mark animals with artificial identification devices such as ear tags or collars. Effective estimates of abundance and density have been acquired through unique identification of individual bobcats using pelage patterns in studies across North America (Heilbrun et al. 2006, Thornton and Pekins 2015, Young et al. 2019).

Although the use of camera traps is less invasive, estimates of abundance and density using CMR methods are highly sensitive to edge effects; the width of the edge buffer determines the effective sampling (i.e., trapping) area over which density is estimated. Estimating the edge buffer size and concomitant sampling area has historically been supplemented by invasive methods such as deployment of GPS collars. Edge effects occur when animals move in and out of the study area, biasing population estimates (Obrien and Kinnaird 2011, Royle et al. 2011). To attenuate biases from edge effects, home range estimates derived from GPS data can be used to estimate the effective trapping area. For this reason, telemetry data is often used to account for this by buffering the trapping grid with a distance calculated by using a spatial or movement function such as home range size of the species of focus (Dice 1938, Efford 2004).

An effective way to account for edge effects with CMR methodology is using spatially explicit capture-recapture (SECR) methods of analysis. SECR analysis incorporates the locations of sampling stations and the movements between stations to estimate the effective trapping area and density simultaneously (Efford 2004, Borches and Efford 2008). SECR methods have been widely shown to accurately estimate abundance and density of carnivore populations while allowing for a completely non-invasive approach. In this study we compare traditional CMR methods to SECR methods for estimating density and abundance of bobcat populations in the eastern Sierra Nevada Mountains. Specifically, we aim to compare the density and spatial movement parameter estimates from more recently developed SECR methods to compare to widely accepted CMR methods combined with telemetry data.

Beginning in 2014, The California Department of Fish and Wildlife (CDFW) has been increasing efforts to effectively monitor bobcats (*Lynx rufus*), an elusive and wide-ranging carnivore, on the eastern slope of the Sierra Nevada Mountains of California. Bobcats are medium-sized solitary carnivores with polygynous mating systems that occupy ranges across much of North America (Ferguson et al. 2009). Their relatively low abundance, elusive behavior, and solitary life histories make bobcats difficult to monitor (Thornton and Pekins 2015).

Historically, monitoring and management of bobcats in California has largely been based upon these harvest records. Prior to 2015, bobcats were legally harvested from the eastern Sierra Nevada by means of fur trapping. In the 2014–15 trapping season, an estimated 987 bobcats were harvested in the state of California (Garcia and Ypema 2015). However, bobcat harvest by means of trapping was made illegal in 2016. Furthermore, in 2019 all legal harvest of bobcats was prohibited in the state of California. Thus, there are currently no effective means of monitoring these bobcat populations through harvest data.

The work presented in this thesis attempt to fill in knowledge gaps about space use and density of bobcats in the eastern Sierra Nevada, as well as to develop a method for monitoring them. In Chapter 2, we quantify movement patterns, habitat selection, and spatiotemporal dynamics of both male and female bobcats on the eastern slope of the Sierra Nevada Mountains using telemetry data from GPS collars. We use RSF methods to determine the relative habitat selection of bobcats in this area. In Chapter 3, we compare closed capture mark-recapture and spatially explicit capture-recapture methods of estimating population parameters of bobcat populations to inform the development of a monitoring plan for bobcats in the Eastern Sierra. We use remote camera trapping techniques to sample bobcat populations within the study area to estimate abundance and density. Through the combination of remote camera survey data and GPS location data for bobcats, along with the comparison of closed CMR and SECR methods, this study seeks to identify accurate, cost-effective and non-invasive monitoring strategies for bobcats and gain insight into their spatial ecology.

THESIS FORMAT

Chapters 2 and 3 were written as individual manuscripts for publication in peer-reviewed journals. Chapter 2 be submitted to the *Journal of Mammalogy* or similar, and Chapter 3 will be submitted to the *Wildlife Society Bulletin* or similar.

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CHAPTER 2

SPACE USE, MOVEMENT PATTERNS, AND HABITAT SELECTION OF BOBCATS (*LYNX RUFUS*) ON THE EASTERN SLOPE OF THE SIERRA NEVADA MOUNTAINS OF CALIFORNIA

ABSTRACT

Carnivores hold crucial roles in an ecosystem and understanding characteristics of space use and habitat selection will have important implications for both conservation and management of these species. We examined space use patterns and habitat selection of 38 GPS collared bobcats (*Lynx rufus*) on the eastern slope of the Sierra Nevada Mountains in California, USA. We analyzed GPS location data using kernel density estimators to explore differences between males and females in space use characteristics, including home range and core area size, home range fidelity, and seasonal spatial patterns. Additionally, we developed resource selection functions (RSF) to quantify relative habitat selection by bobcats. Home range and core area size varied between males and females, with males having larger home ranges and core areas relative to females. Furthermore, bobcats showed very strong selection for riparian habitats and proximity to streams and drainages in our study area relative to available habitat types. We found differences in selection strength of habitat variables between male and female bobcats suggesting female bobcats have a stronger preference for riparian habitat than males. We did not detect any seasonal differences in space use characteristics (i.e. home range and core area size) or habitat selection between seasons for male or female bobcats. Here we provide the first known study of bobcat space use and habitat selection on the eastern slope of the Sierra Nevada Mountains of California.

INTRODUCTION

Understanding carnivore behavior is imperative to wildlife and habitat management due to the crucial roles that carnivores hold in ecosystems and their influence on species and populations throughout trophic systems (Schmitz et al. 2000, Zielinski and Kucera 2005, Vilella et al. 2020). Effective management of carnivore populations must consider characteristics of space use and habitat selection. Spatial and temporal patterns of carnivore behavior and resource selection vary based on various factors such as life history, prey availability (Svoboda et al. 2019), competition, and habitat availability. These spatial patterns are critical to understanding the processes and pressures which influence carnivore habitat selection and ecology and have important implications for both conservation and management efforts (Donovan et al. 2011, Abouelezz et al. 2018). Thus, management of carnivore populations requires an understanding of movement, habitat selection, spatial patterns, and ecological pressures, all of which can influence abundance and densities of wildlife populations.

The bobcat (*Lynx rufus*) is a wide-ranging generalist carnivore which occurs across much of North America. Research on bobcat populations in many regions of North America has identified the importance of understanding space use and habitat selection for management and conservation of bobcats and critical habitat (Donovan et al. 2011, Abouelezz et al. 2018). Bobcats occur across much of North America as prominent mesocarnivores (Fergusen et al. 2009) and can have significant effects on other sympatric carnivore and prey populations. Mesocarnivores hold important trophic roles in ecosystems and can contribute to ecosystem structure and function (Roemer et al. 2009). In the presence of other large apex predators such as grizzly bears, wolves, mountain lions and black bears, bobcats likely hold mid-level trophic roles. However, in the absence of large carnivore competitors and predators, it has been suggested that mesocarnivores can operate more like apex predators (Roemer et al. 2009). The

Sierra Nevada Mountains lack of large carnivores apart from mountain lions and black bears. It is possible that in these ecosystems, bobcats may hold ecological roles more alike apex predators. Understanding parameters and dynamics of bobcat space use (i.e., home range and core area) can inform management issues such as the potential ecological impacts bobcats may be having on prey and competitor populations, human-wildlife conflict, wildlife-vehicle collisions, habitat fragmentation and connectivity. For example, prior research has demonstrated how spatial data can be analyzed to map and inform connectivity for bobcats in the presence of anthropogenic impacts (Farrell et al. 2018). Additionally, studies have analyzed spatial data from bobcats to gain insights into how habitat characteristics (Broman et al. 2014) and prey availability (Knick 1990) influences bobcat spatial ecology. These findings can be used by managers to identify important habitat for conservation purposes along with anticipating how fluctuations in prey populations could impact bobcat movement patterns. As bobcats are generalist carnivores, declines in a primary prey species in an area or increases in bobcat densities could have impacts on sensitive prey populations or prey species with great economic and recreational value such as upland game and waterfowl. For these reasons monitoring bobcat spatial ecology remains an important and valuable aspect of wildlife management.

Bobcats are known to maintain distinct home ranges, and these areas can vary greatly in size and stability between individuals (Fergeson et al. 2009, Donovan et al. 2011). These differences in home range size across regions are suggested to be influenced by habitat quality, prey availability (Litvaitis et al. 1986, Knick 1990, Lovallo and Anderson 1996), and resource distribution (Donovan et al, 2011). Previous research has identified smaller areas with high concentrations of activity within bobcat home ranges referred to as core areas (Bailey 1974, Litvaitis et al. 1986, Nielsen and Woolf 2001, Chamberlain et al. 2003, Plowman et al. 2006). By maintaining these core areas, bobcats may acquire ecological benefits through the reduction of competition and heightened access to prey and other essential resources (Nielsen and Woolf 2001, Plowman et al. 2006).

Bobcat spatial organization and space use is predominantly influenced by survival and reproductive efforts reflecting a polygynous mating system (Bailey 1974, Lynch et al. 2008, Ferguson et al. 2009). Males generally have larger home ranges and core areas along with greater daily movement patterns than females, which tend to utilize smaller home ranges more intensely (Bailey, 1974, Litvaitis et al. 1986, Chamberlain et al. 2003, Diefenbach et al. 2006, Ferguson et al. 2009). Male space use is primarily influenced by access to females whereas females are more influenced by reproductive success, prey abundance and resource accessibility (Bailey 1974, Diefenbach et al. 2006, Lynch et al. 2008, Ferguson et al. 2009, Donovan et al. 2011).

Space use patterns can vary between males and female bobcats on both temporal and seasonal scales (Conner et al. 1999, Chamberlain et al. 2003, Plowman et al. 2006). Factors influencing seasonal differences of space use and habitat selection include prey density, seasonal conditions, reproduction, and competition (Litvaitis et al. 1986, Chamberlain et al. 2003). While little is known about bobcat spatial dynamics on the eastern slope of the Sierra Nevada Mountains, previous studies in other areas suggest that bobcat space use may be dynamic over time (Plowman et al. 2006) and vary between seasons (Conner et al. 1999).

Bobcats occupy a wide range of habitat types across North America, and differential selection of resources has been documented between sexes (Little et al. 2018). Bobcat habitat selection is influenced by a variety of factors including prey availability, access to mates, reproduction and land cover (Donovan et al. 2011, Reed et al. 2017, Abouelezz et al. 2018, Little et al. 2018, Young et al. 2019). Prior research has explored the importance of natural habitat resources influencing bobcat habitat selection such as riparian areas and wetlands (Hass 2009, Reed et al. 2017). Other studies have shown that bobcats successfully occupy anthropogenic areas such as development and agriculture landscapes (Young et al. 2019). Although these previous studies have explored habitat selection of bobcats in some areas in North America, little is known about habitat selection and space use of bobcats on the eastern slope of the Sierra Nevada Mountains in California. Prior to 2019, bobcats were harvestable in California and population monitoring was largely based on harvest reports. However, all bobcat harvest has been banned throughout the state eliminating the primary method of monitoring populations and alleviating any harvest pressure that was exerted on bobcats in this area. The eastern Sierra Nevada Mountains are also habitat for very sensitive species, such as the federally endangered Sierra Nevada bighorn sheep (*Ovis canadensis sierrae*) that are endemic to the Sierra Nevada Mountains (Wehausen and Jones 2014, Forshee 2018). Understanding bobcat spatial ecology in this area is important for a variety of both ecological and economic reasons. First, bobcats can have prey on a wide variety of species (Rose and Prange 2015). By monitoring bobcat space use and habitat selection, managers can evaluate the potential impacts bobcats may be having on prey populations. Bobcats have been known to predate on upland game species such as quail (Tewes et al. 2002) as well as larger ungulates such as mule deer (*Odocoileus hemionus*) and Sierra Nevada bighorn sheep (Forshee 2018, CDFW unpublished data). Furthermore, prior research has demonstrated how bobcats can exist in urban settings in close proximity to humans (Young et al. 2019). This creates potential for bobcat-human conflict in the form of depredation on livestock or pets. Gaining insights into bobcat space use and habitat selection in this area will help guide management and conservation of not only bobcats but the sympatric species in which they interact.

The overall goal of this research is to explore spatial and movement patterns of bobcats in the eastern Sierra Nevada Mountains and identify key patterns of movement and habitat selection by bobcats in this area. Our first objective is to explore and compare home range and core area size estimates for adult male and female bobcats in this area. Second, this study will examine seasonal and temporal shifts in home range and core areas for collared bobcats. Third, we will determine biotic and abiotic environmental factors that influence habitat selection of bobcats across the landscape through the production of a habitat selection model using resource selection functions. Understanding space use and habitat selection of bobcats will have important implications for the effective management of bobcats and conservation of critical habitat.

STUDY AREA

The Sierra Nevada mountains located in central California run 650 km north to south reaching elevations upwards of 4,000 m above sea level (Hill 1975). Our study area was located on the eastern slope of the Sierra Nevada Mountains in the Owens Valley in both Inyo and Mono counties. Elevation ranges from approximately 1,200 m on the valley floor to the highest point of Mt Whitney at 4,421 m (Fig. 2.1). The Owens Valley drainage spans approximately 8,500 km^2 from the crest of the Sierra Nevada Mountains to the western crest of the White-Inyo Mountains (Fig. 2.1). The Owens Valley encompasses a variety of geological features including the Sierra Nevada Escarpment, the White-Inyo mountain escarpment, the Owens Valley fault zone, volcanic fields and tablelands, and effects from glaciation (alluvial fans, glaciated and non-glaciated mountains, glacial erosion, and deposition), (Putman and Smith 1995). The Owens River is sourced at Big Springs near June Lake CA and runs through the Owens Valley (Fig. 2.1). Itis fed by many ephemeral, vernal, intermittent, and perennial streams which make up the few riparian corridors distributed throughout the study area. The higher elevations of the Sierra Nevada mountains are scattered with hundreds of high elevation lakes.

A strong rain shadow limits precipitation east of the Sierra Nevada Crest. The Owens Valley floor receives approximately 12.7 cm of precipitation per year. During summer months (May-September) temperatures can reach upwards of 38° C and precipitation remains limited through autumn (August-November) with the majority occurring in winter (December-February).

The study area is within the following USDA ecoregions: Sierra Nevada, Mono, Southeastern Great Basin, and Mojave Desert. The Owens Valley in which our study area (Fig. 2.1) lies is categorized as high desert rangeland (Danskin 1998). Vegetation alliances from the California Natural Community List include Bitterbrush scrub, Indian rice grass grassland, Pinyon – Juniper woodlands, Fremont Cottonwood forest and woodland, Arroyo willow thickets, Baltic and Mexican rush marshes, Lodgepole pine forest and woodland, and Alpine grasses and forbs (Manual of California Vegetation, 2020 – Appendix A). Additional information regarding dominant vegetation species within these communities are displayed in Appendix A. In addition to these vegetation communities there are other habitat types such as agriculture, urban development, and barren areas devoid of vegetation (rock piles, scree slopes, and rock outcroppings).

Common fauna includes smaller bobcat prey such as quail species, cottontail and jackrabbit species, and rodent species. Mule deer (*Odocoileus hemionus*), Tule elk (*Cervus canadensis nannodes*), feral ass (*Equus asinus*), and federally endangered Sierra Nevada bighorn sheep (*Ovis canadensis sierrae*) also occupy habitats within this study area. Prominent carnivore species within this study area include black bear (*Ursus americanus*), mountain lion (*Felis concolor*), gray fox (*Urocyon cinereoargenteus*), and coyote (*Canis latrins*) (California Wildlife Habitat Relationship database 2020).

The trapping study area centers around the Owens Valley and ranges from the eastern side of the Sierra Nevada Crest to the western slope of the White and Inyo Mountains. The northern limit lies between Benton, CA, and June Lake, CA, and stretches south through the valley to where the Owens River dissipates into the Owens Dry Lake south of Lone Pine, CA (Fig 2.1).

METHODS

Field Methods

We captured bobcats using cage traps (Mercer Lawing, Camtrip Cages) in accordance with animal care and use protocols (IACUC 2824, California Department of Fish and Wildlife Eastern Sierra Nevada Bobcat Capture Plan 2014-2022). We immobilized bobcats using Tiletamine Zolazepam (Telazol) at a dose of 10mg/kg using hand injection with a jab stick. We collected morphometric measurements, including sex, weight, pelage condition, and evidence of injury and/or disease. We fitted adult bobcats (estimated age ≥ 2 years) with Global Positioning System (GPS) collars that were expected to collect data for up to 18 months. Bobcats were fitted with GPS collars weighing no more than 5% of their body weight. To meet this weight requirement, we used three models of GPS collars that had different weights: Advanced Telemetry Systems model G2110L Iridium, Lotek Wireless LiteTrack Iridium 150, and Vectronics VERTEX Lite iridium. We programmed the GPS collars to collect 8 fixes per a day at 1800, 2000, 0000, 0200, 0400, 0600, and 1200. The fix schedule was set to maximize movement data during peak crepuscular and nocturnal times for bobcat activity (Chamberlain et al. 2003, Elizalde-Arellano 2012), and additionally, collecting one diurnal location at 1200pm. All GPS collars were equipped with a timed break-off mechanism, scheduled for approximately 19 months after deployment.

Data Management and Seasonal Classification

We used the location data from GPS collars to analyze space use and relative habitat selection. We filtered out locations where fix quality was low. Points were removed from analysis based on Dilution of Precision (DOP), Horizontal Dilution of Precision (HDOP) and Fixtype (<2D, 2D, or 3D) for all collar models (degree of precision criteria was set at: DOP <10, HDOP <8, or a Fixtype < 3D). We preformed preliminary analyses to explore the relationship between number of GPS fixes and sampling duration with home range/core area statistics. Based on these analyses, we only included individuals with ≥30-40 days (a minimum of approximately 200 fixes) of GPS locations. These analyses provided support that a minimum of 200 points or 30-40 survey days produced home range and core area estimates that were statistically representative of full data sets. See Appendix B for details regarding minimum data requirements for inclusion for spatial analysis. In addition, because the focus of this research was on space use and habitat selection within resident home ranges, we removed two short-term, long-distance dispersal events from the analysis (Golla 2017). Throughout the study period there were 6 bobcats with active collars in 2015 and between 10-21 for 2016-2019.

We classified three seasons of interest based on seasonal patterns and life-history of bobcats: winter and breeding season, spring and kitten-rearing season, and summer-fall and dispersal season. The winter season (Dec-Feb) was characterized by low temperatures and high precipitation. During spring kitten-rearing season (March-May), temperature and precipitation was moderate. Summer-fall season (June-Nov) was characterized by high temperatures and a lack of precipitation.

Space Use Analysis

We estimated the size of bobcat home ranges and core areas using kernel density estimators (KDE) with a plug-in bandwidth estimator, using the “adehabitat” package in Program R (Calenge 2006). We used a 95% KDE for estimating home range size and a 50% KDE for estimating core area size (Neilson and Woolf 2001, Plowman et al. 2006). We tested for differences between male and female home range size and core area size using a Wilcoxon rank sum test. We used a Kruskal-Wallis test to test for differences in home range size and core area size among seasons by sex.

Relative Habitat Selection

We assessed 3rd order relative habitat selection (Krausman 1999) utilizing a used-available resource selection function (RSF) that used an exponential approximation for an inhomogeneous Poisson point process (Lele et al. 2013). Used points for each individual bobcat were derived directly from locational fixes collected by GPS collars. For available points, we started with an available home range area that was a 95% KDE (Kie et al. 2018) for each individual bobcat. We then generated points within all individual home ranges using a 5:1 ratio of stratified random locations to represent available locations (Benson 2013). Each individual bobcat’s home range had a resulting 5:1 ratio of available to used locations to account for random and mixed effect of individual variation between bobcat relative habitat selection. To explore differences in habitat selection characteristics between sexes and seasons, we sampled used-available locations within both sex and season groups. No GPS locations occurred east of the Owens River; thus, we treated the river as a hard boundary and restricted all available locations to the area west of the Owens River.

We selected resource and habitat variables using vegetation, abiotic, and topographic features derived from remote sensing platforms. Vegetation categories were compiled from a California Fire land cover raster (CALFIRE_FRAP or fveg, www.dfg.ca.gov) and vegetation species composition layers were combined into 14 independent covariate groups representing vegetation types deemed important for testing our hypotheses. Topographical variables were derived from rasters containing data referencing slope, elevation (digital elevation model), vector ruggedness, aspect, and topographical positioning index (TPI). TPI was grouped into four variables to capture specific topographical edges in the landscape; Mild Rise: 0-3, Steep Rise: > 3, Mild Valley: -3-0, Deep Valley: <-3. These topographical variables were measured to explore differences in relative habitat selection of bobcats as it relates to the varied and rugged mountainous regions of the study area. We incorporated elevation and slope into our models to explore any differences in selection by bobcats from the Sierra Nevada and White-Inyo crest to the valley floor and additionally the north to south elevational gradient. TPI and ruggedness were used to capture edge effects and differences between areas describing features such as rock piles, volcanic deposit bands and rugged alpine talus fields. The distance to vernal, ephemeral, and permanent streams and drainages was derived from a ‘distance to streams’ raster that was representative of the study area. This distance to stream variable described a continuous distance to a linear stream feature with increasing value as distance from stream feature increased. We measured distance to streams to quantify bobcat use of drainages and paths of least resistance throughout the landscape. In this study area, even when stream beds are dry, they often create natural funnels and clear paths through otherwise steep and rugged terrain. Furthermore, we hypothesize that bobcats are using these corridors both for hunting edges of thick vegetation as well as following the paths of least resistance. An ‘agriculture boundary’ variable was created by buffering agriculture areas by 30 meters and treating this area as an independent landcover variable. Our intention was to capture the edge effect of use by capturing a dramatic change in vegetation composition from agriculture to more densely vegetated areas surrounding crops. This could facilitate predatory and stalking behavior of bobcats and support increased prey abundance. Habitat variables were either continuous (measured by a continuous numerical value) or categorical (assigned a “1” for presence or “0” for absent). To maintain comparability of variable magnitude across models, continuous variables were standardized by subtracting the mean of all values across the study area and dividing by the standard deviation of each variable (Bring 1994).

We examined correlations between resource variables using a Pearson correlation test and determined collinearity using the Pearson correlation coefficient threshold of $|r| \leq 0.6$ (Hosmer and Lemeshow 2000, Dormann et al. 2013, Forshee 2018). Highly correlated variables were explored on a univariate basis and the variable with stronger predictive ability and ecological relevance was retained (Austin 2002, Dormann et al. 2013).

The relationship between habitat variables and used-unused locations was explored through univariate analyses to determine important variables. General linear models were used to test the independent association of habitat variables with used locations of bobcats. We selected combinations of variables to be included in candidate models based upon our hypotheses and univariate analysis. Univariate analyses involved using general linear models to test the relationship between single habitat variables and bobcat use. The strength of influence of these univariate analyses were evaluated by the strength of the resulting standardized β-coefficients. Habitat variables were chosen to be considered for candidate model inclusion if they were relevant to hypotheses or showed a high degree of influence. Variables with very little influence or those with large variances were not included in candidate models. Habitat variables were set as fixed effects and sex, season, and individual bobcat were set as random effects. We built 5 candidate models including all bobcats despite sex using a general linear fixed effect modelling framework. Habitat variables included in top global, male and female models were: riparian, distance to streams, agriculture boundaries, deep valleys, steep rises, tree cover and herbaceous grasses.

We used Akaike's Information Criterion to rank models (Akaike 1974, Burnham and Anderson 1998). Models with the lowest AICc values were most supported by the data, and we considered models <2 AICc units of the best model to be competing models. (Burnham and Anderson 1998, Arnold 2010). We first selected 4 top candidate models based on AIC rank for comparison and cross validation to determine the best fitting top model.

Top candidate models were evaluated using external cross validation (Northrup et al. 2013). We determined the predictive capacity of each candidate model by averaging the output of the Spearman rank coefficients derived from 100 iterations of a k-fold cross validation (Boyce et al. 2002). The strength of standardized fixed effect β-coefficients with non-overlapping confidence intervals were defined as: weak: ≤ 0.1, moderate: ≥ 0.1 and ≤ 0.5, strong: ≥ 0.5 and ≤ 1.0, and very strong: ≥ 1.0 (Bring 1994). We projected the relative probability of selection by bobcats across the study area by multiplying the fixed effect β-coefficients from the top model and the corresponding habitat variable (Forshee 2018). This produced a predictive raster comprised of values illustrating relative selection for habitat variables included in the final top model for all bobcats regardless of sex.

Sex and Seasonal Differences

The best fitting model for all bobcat data, irrelevant of sex or season group, was selected as the model for which to test differences between groups. This bobcat model was then applied to sex and seasonal groups utilizing a general linear mixed-effect model framework

(GLMM) including a random intercept for individual bobcats, different sexes, and season. Following the same process as the all-inclusive bobcat model selection, final top models for male and female bobcats were then built from top candidate models to examine the influence of sex on model strength and to account for the unbalanced sample sizes between individual GPS collared bobcats. Each top model for males and females was then applied to the corresponding male and female data sets including a random intercept for individual (ID) and season (Beyer et al. 2010). Male and female top models were built using habitat variables that tested hypotheses and were shown to be influential through univariate analyses.

RESULTS

Over the course of the study duration (January 2015 – October 2018), we captured and put GPS collars on 42 adult bobcats. However, due to premature collar failure and bobcat mortalities leading to insufficient data collection, data from only 38 adult bobcats (male *n* = 25, female *n* = 13) were used for analysis. The collars collected 44,365 independent location fixes, of which there were 32,072 for males and 12,293 for females. The majority of GPS collars were deployed west of US route 395 although 2 were deployed on bobcats captured in the volcanic tablelands area (Fig. 2.1). Between 6-21 collars were active each year. From the data provided from 42 GPS collars, failed data points were identified and removed with a final fix success rate of 88%. A minimum sampling threshold of 200 total GPS points was set based on preliminary sampling duration analysis (Supplemental analyses – Appendix B). Of the collared bobcats, 2 collars failed immediately and never transmitted data or were ever recovered. Due to collar failure and premature mortality, 4 female bobcats ("BC018", *n* = 59; "BC009", *n* = 100; "BC039", *n* = 33; and "BC036", *n* = 1) failed to meet the minimum limit of survey days since initial capture and GPS fixes to be included in both the spatial and RSF analysis.

Home Ranges:

A 95% kernel density estimator (KDE) estimator used to describe bobcat home ranges produced an average home range size of 32.58 km^2 (*n* = 38, SE = 4.26) for the full sample of bobcats. A 50% kernel density estimator used to describe bobcat core areas produced an average core area size of 6.06 km^2 (*n* = 38, SE = 0.86) for all bobcats (Table 2.1).

Males had an average home range size of 38.66 km^2 (*n*=25, SE=5.04) and an average core area size of 7.30 km2 (*n* = 25, SE = 1.08) compared to females with an average home range and core area size of 20.89 km^2 (*n* = 13, SE = 6.96) and 3.68 km^2 (*n* = 13, SE = 1.24) respectively (Fig. 2.2). The results of a Wilcoxon rank sum test showed the differences in male and female kernel density estimates to be statistically significant for both home range size (W = 77, *p* = 0.008) and core areas (W = 73, *p* = 0.005) (Table 2.1).

A 95% KDE analysis produced average estimates for home range for males and females across three survey seasons: winter, kitten-rearing, and summer (Fig. 2.3 and Fig. 2.4). The Kruskal-Wallis rank sum test showed there were no significant differences in mean home range size across the three seasons for either males (Kruskal-Wallis chi-squared = 0.145, df=2, *p* = 0.9299) or females (Kruskal-Wallis chi-squared = 0.313, df=2, *p* = 0.855). Similarly, there was no significant difference detected in core area size between seasons for males (Kruskal-Wallis chi-squared = 1.615, df = 2, *p* = 0.446) or females (Kruskal-Wallis chi-squared = 0.705, df = 2, *p* = 0.703). Figure 5 presents home range and core area sizes for male and female bobcats across seasons and results without seasonal differentiation.

Relative Selection of Habitat

Data collected from the 38 adult bobcats (male *n* = 25, female *n* = 13) consisting of 44,365 independent GPS used location fixes, were collected by California Department of Fish and Wildlife and used for RSF model building and analysis. Data used for model building and analysis included 12,293 GPS locations from the 13 female bobcats and 32,072 GPS locations from the 25 male bobcats. Used-available points calculated on a 5:1 ratio and treating the Owens River as a hard barrier, produced a total of 222,990 available locations for 44,365 used locations.

Resource Variables

Correlational analyses of data for all bobcats regardless of sex, revealed two resource variables with a high degree of collinearity (Fig. 2.5). These strong correlations included a positive association of elevation with slope ($r = 0.7$) and a positive association of slope with vector ruggedness ($r = 0.6$). Elevation and slope were not found to be influential in the top models and thus were not included in any of the final models. The variables included in the candidate models were not found to be correlated beyond the Pearson's correlation coefficient threshold of $r > 0.6$ (Hosmer and Lemeshow 2000, Dormann et al. 2013, Forshee 2018). Variables included in the top candidate global model were riparian vegetation, steep rise, deep valleys, distance to streams, boundary of agriculture, tree cover, and herbaceous grasses.

Model Fitting and Selection

The final model set for resource selection consisted of four bobcat candidate models regardless of sex (Table 2.2). Variables in these models were chosen to support hypotheses regarding use of riparian areas, agriculture edge effects and the use of stream beds, valleys and drainages. For both sexes, coefficients from the top global model suggested that bobcats selected very strongly for riparian vegetation. This was followed by agriculture boundaries, deep valleys, steep rises and distance to streams and drainages, relative to the habitat available.

Bobcats exhibited relative avoidance to tree cover and herbaceous grass communities (Table 2.2).

Sex and Seasonal Differences

There were relatively low levels of resource selection variation between individual bobcats (*n* = 38, SD = 0.01), however higher levels of variation existed across the study area between sexes (*n* = 2, SD = 0.20). Further, there was very low variation in resource selection across the seasons (*n* = 3, SE = 0.00). Due to higher levels of variation between male and female bobcat resource selection and to test existing hypotheses, separate models were built for each sex.

Females

For female bobcats, resource variables included in top candidate models were riparian vegetation, distance to streams, herbaceous grass communities, tree cover, deep valleys, and steep rises. Four candidate models were ranked by AIC score and the model with the lowest score was selected as the top model best describing female bobcat resource selection across the study area (Table 2.2). The fixed-effect *β* coefficients of the top female bobcat model suggested female bobcats selected most strongly for riparian vegetation. Females exhibited moderate selection for distance to streams and drainages, steep rises, and deep valleys relative to the habitat available across the study area. Female bobcats exhibited moderate avoidance for tree cover and herbaceous grass communities relative to resources available (Table 2.2). Relatively low levels of variation were detected on the individual level for female bobcats (*n* = 13, SE = 0.03).

Males

Resource variables included in top male bobcat candidate models were riparian vegetation, distance to streams, agriculture boundaries, herbaceous grass communities, tree cover, deep valley, and steep rises. Four male candidate models were ranked by AIC score and of the two models with the same lowest AIC score the most parsimonious model was selected as the best-performing top model for explaining male bobcat resource selection (Table 2.2). The fixed effect B-coefficients of the top model depicting relative selection of habitat, suggested that male bobcats strongly select for riparian vegetation, and agriculture boundaries. Male bobcats were found to moderately select for deep valleys, steep rises and distance to streams and drainages. In turn, male bobcats showed moderate avoidance for tree cover, and herbaceous grass communities (Table 2.2) Relatively low levels of variation were detected on the individual level for male bobcats (*n* = 25, SE = 0.012).

Model Testing and Projection

Internal cross-validation tests used to select the final models for male, female, and all-inclusive bobcat groups resulted in high levels of cross validation across the top models and low levels of model uncertainty in selecting top models. The top bobcat model (despite sex) had a mean internal cross validation estimate of 0.95 (SE = 0.0082). The top female and male bobcat models had mean internal cross validation estimates of 0.92 (SE = 0.009) and 0.92 (SE = 0.0145), respectively.

DISSCUSSION

Bobcat Space Use

Understanding space use behavior and habitat selection of bobcats is a key component to developing effective management and conservation strategies for bobcat populations and the ecosystems they inhabit. We analyzed home range and core area sizes, explored spatial dynamics, and defined critical habitat through the relative selection of different habitat types by bobcats on the eastern slope of the Sierra Nevada Mountains. Prior to this study, little was known about space use and habitat selection of bobcats in the eastern Sierra Nevada Mountains of California. Bobcats in this area have historically been heavily harvested as an important furbearers and monitoring of bobcats has predominantly been achieved through harvest records. However, in 2019 all bobcat harvest was banned in the state of California evoking concerns from some regarding how bobcat populations might react. It has been suggested that bobcat space use is tied to population densities (Conner et al. 1999). If bobcat densities increase due to relaxed harvest pressures, it could have impacts on prey and competitor species in which they interact and implications for increased wildlife-human conflict. The findings from this study will provide important information regarding potential ecological impacts to prey and competitor populations, movement and connectivity, habitat conservation, and reducing human wildlife conflict.

Space Use Analysis

Average bobcat home range size, for males and females combined, was comparable to those described in multiple studies across North America (Fergeson et al. 2009). However, a high degree of variation between studies has been documented with some home range sizes much larger than those found in our study (Bailey 1974, Lovallo and Anderson 1996, Ferguson et al. 2009, Donovan et al. 2011).

Previous research suggests that habitat quality is dictated by prey abundance which influences home range size and movement of bobcats. When prey is scarce, the home range size of bobcats will increase to compensate for reduced prey availability (Knick 1990). Conversely, when habitat quality is relatively high, home range size of bobcats may not be influenced by prey availability but could be a function of other factors such as bobcat density, and mate availability. (Conner and Leopold 1999). Therefore, our results depicting comparable or smaller home range sizes for bobcats suggest that bobcat populations on the eastern slope of the Sierra Nevada Mountains may have ample access to prey and/or limited competitive pressures. Furthermore, bobcat core areas represent areas of concentrated use that contain important and dependable resources (Neilson and Woolfe, 2001, Plowman et al. 2006). Average core areas in our study area likely reflect areas of increased prey availability and access to other important resources, such as denning habitat, increased cover and areas of dense cover facilitating an ambush style hunting strategy.

Sex Differences

In our study male bobcats had significantly larger home ranges and core areas than females. We found the home range and core area size for male bobcats was 1.9 and 2.0 times larger than for females. This difference between sexes is consistent with prior research in other areas of North America, with males using generally larger areas than females (Litvaitus et al. 1986, Conner and Leopold 1999, Ferguson et al. 2009, Tucker et al. 2008). Male bobcats using larger home range and core area sizes than females may reflect differences in life histories (Bailey 1974; Lynch et al. 2008, Ferguson et al. 2009). Results from our study support findings from prior research that male bobcats use larger areas to maintain access to females. Alternatively, females use smaller areas more intensely and are more influenced by access to essential resources such as high-quality habitat and reliable prey availability (Bailey 1974, Diefenbach et al. 2006, Lynch et al., 2008, Ferguson et al. 2009, Donovan et al. 2011).

Seasonal Differences

In our study, we found no evidence of seasonal differences in home range size or core area size of bobcats on the eastern slope of the Sierra Nevada Mountains. Some researchers have found that bobcat space use can vary seasonally and annually with home ranges and core areas shifting over time (Plowman et al. 2006, Tucker et al. 2008). Other studies in other areas of North America have found that bobcat home range and core area sizes did not vary over time (Chamberlain et al. 2003). Factors influencing the fidelity and temporal fluctuation of space use and habitat selection include prey density, seasonal conditions, reproduction, and competition (Litvaitus et al. 1986, Chamberlain et al. 2003, Plowman et al. 2006). The lack of seasonal differences in home range size of bobcats suggests that access to resources, prey availability, and competitive pressures did not shift throughout the annual cycle in our study area.

Similar to the overall pattern, we did not detect any seasonal home range and core area differences for either male or female bobcats. Sexual differences in seasonal space use patterns have been documented in bobcats indicating differential pressures on male and female bobcats at certain times of the year, such as breeding and kitten rearing season (Knick 1990, Chamberlain et al. 2003). Prior research found that male bobcats did not exhibit seasonal differences in home range, whereas female bobcats tended to use smaller home ranges during the season when they were expected to have kittens (Tucker et al. 2008).

Although we did not detect seasonal trends across all bobcats, variation between individuals was found where specific bobcats did exhibit changes in space use patterns between seasons. For example, some bobcats were observed to travel to higher elevations and travel larger distances during the summer months although this pattern was not shown to be significant across all bobcats of between sexes. In the Owens valley, we speculate that various behavioral groups of bobcats exist regarding elevational movement patterns. This is supported by many detections of bobcats at high elevations throughout the year (CDFW unpublished data). In this study, all trapping efforts were conducted at lower elevations at the base of the Sierra Nevada Mountains or on the valley floor (approximately <2500 meters). Because we predominately sampled resident individuals that utilize lower elevations exclusively, we likely did not adequately sample individuals that use high elevation areas. Deploying collars and collecting data at higher elevation would provide additional insights into this phenomenon and the spatial patterns of bobcats that regularly use higher elevation habitats. Furthermore, although there was no statistically significant difference, the average size of home range and core area for female bobcats was smaller in winter relative to kitten and summer seasons (Table 2.1). It is possible that home range and core area sizes of females specifically differ within this group in relation to reproductive status (Lovallo and Anderson 1996). Due to the intensity and location of clusters witnessed during kitten season and resources available, we were not able to verify whether all females in fact had kittens or not during this reproductive period. By collecting more data on the known reproductive status of females in this study, this possibility could be further investigated. This suggests that there may be seasonal pressures influencing certain individuals. To further quantify space use seasonal and annual dynamics of bobcats in the eastern Sierra Nevada Mountains, more data must be collected from a larger sample size of individuals. Furthermore, a larger sample size may emphasize sexual differences in temporal space use patterns that we did not detect, especially as it relates to higher elevation bobcat population and the reproductive status of females.

Habitat Selection

On the eastern slope of the Sierra Nevada Mountains, all bobcats very strongly selected for riparian areas and, relatedly, selected for areas close to streams and drainages. This is consistent with prior research which has identified riparian areas as habitat used by bobcats (Hass 2009), yet our findings suggest a strong preferential selection for these areas. Bobcats being ambush predators, selection of habitat for foraging is suggested to be driven by prey availability and adequate cover (McNitt et al. 2020). In this high elevation desert ecosystem, riparian areas represent relatively scarce access to water and provide habitat to a variety of prey species. Additionally, our findings support prior research suggesting bobcats are selecting for riparian areas as movement corridors (Wait et al. 2018). Riparian areas consist of thick vegetation and offer protection and concealment facilitating bobcat hunting and denning. This is consistent with previous studies exemplifying the importance of such dense vegetation to bobcats for hunting and adequate cover (Tucker et al. 2008, McNitt et al. 2020, Serieys et al. 2021). Further, streams and drainages represent topographical relief in the landscape which may facilitate bobcat travel and represent the paths of least resistance throughout the eastern slope of the Sierra Nevada Mountains. Our findings suggest that bobcats are selecting for riparian vegetation communities and general areas because they provide sufficient cover from dense vegetation and potentially increased prey availability and useful travel paths.

Bobcats also selected for the boundary areas of vegetation surrounding agriculture areas. Agricultural land in this area is predominately open fields of crops such as alfalfa bounded by thicker vegetation. Prior research has suggested that bobcats use edges of open areas for concealment and increased prey availability (Wait et al. 2018, McNitt et al. 2020). We speculate that agriculture boundaries in our study area provide an edge of dense vegetation cover for bobcat foraging while allowing access to small mammals such as lagomorphs, which may be foraging in and around agricultural fields. Selection for habitat bordering agriculture is further supported by the lack of evidence we found for any selection for agricultural areas themselves and the relative avoidance of herbaceous grassland habitats. Further, bobcats avoided tree cover. Tree cover was predominantly juniper and pinyon pine forests, which provide relatively little cover in our study area. The lack of cover in these sparsely forested areas further supports the inference that bobcats are selecting for riparian areas and agricultural boundaries because of dense vegetation and hunting opportunities.

Sex Differences in Habitat Selection

Similarities and differences were evident in selection between male and female bobcats on the eastern slope of the Sierra Nevada Mountains (Table 2.3). Male and female bobcats selected similarly for steep rises and deep valleys, and both sexes showed similar avoidance for tree cover and herbaceous grass communities. Male and female bobcats differed in selection strength for riparian, agriculture boundaries, and distance to streams. Both male and female bobcats strongly selected for riparian areas and areas closest to streams and drainages, but this selection was strongest for female bobcats. In contrast, agriculture boundaries were particularly important for males, but females did not exhibit strong or consistent selection for these areas. Previous research has illustrated how agricultural areas are important habitat for bobcats (Little et al. 2018, Conner et al. 1992). While little research focusing specifically on the boundaries of agriculture, our findings support prior studies suggesting that bobcats select for areas closer to agriculture (Little et al. 2018).

Differences in relative selection of habitat variables between male and female bobcats likely reflect alternative life histories and differing motivations of male and female bobcats. Previous research has suggested that female bobcats have more pronounced preference for specific habitat types (Conner et al. 1992, Conner et al. 1999). Our findings of differential selection for certain resources such as riparian habitat and streams/drainages supports the hypothesis that female bobcats are more driven by access to good habitat and resources which provide sufficient cover for denning, hunting and increased prey availability. In contrast, males predominantly choose habitat to access multiple females and show less pronounced preference for habitat. The lack of consistent selection of agriculture boundaries by females, could be due to the lack of data from female bobcats that had access to agriculture within their home ranges. However, as differences in habitat selection between male and female bobcats have been documented (Lovallo and Anderson 1996, Little et al. 2018), this difference could reflect the behavioral ecology of bobcats in this area. Prior research has suggested that females use smaller home ranges and core areas more intensely than males which are motivated by increasing breeding opportunities (Chamberlain et al. 2003). It is possibly that due to the sparse and uneven distribution of agricultural areas in the Owens valley that increased space use by males lead to more opportunities to exploit these areas relative to females. Furthermore, male bobcats could be exhibiting an increase in exploratory behavior to locate mates, prey and habitat compared to females with less behavioral motivations. This could lead to males being bolder in the face of anthropogenic threats such as agriculture leading to the preference of agricultural boundaries. This is further supported by our RSF analysis illustrating more intense selection for habitats by female bobcats relative to males which remained more generalist. Larger sample sizes of female bobcats, especially in proximity to agriculture, could provide more insight into the differences in relative selection of agriculture boundaries between male and female bobcats.

Seasonal Differences in Habitat Selection

Very little variation in selection was detected on the seasonal scale. Previous studies have illustrated temporal changes in habitat use and the importance of specific habitat types during certain seasonal periods of the year (Conner et al. 1999, Kamler and Gipson 2000). Our study found no significant differences in habitat selection by male or female bobcats between winter, kitten-rearing, and summer seasons. Although we did not detect any differences in habitat selection on a seasonal scale, we did observe a few collared bobcats utilizing higher elevations and different areas during summer months. This suggests that there are bobcats who seasonally shift their home ranges and that we may have primarily sampled resident bobcats of the Owens Valley and have high annual fidelity of their space use. Yet, there have been many detections of bobcats at high elevation, but little is known about bobcat space use in these areas (A.Ellsworth and M.Brown, California Department of Fish and Wildlife, unpublished data). Future research in the eastern Sierra Nevada Mountains should focus on monitoring bobcats at higher elevations and conduct initial trapping in different locations of the eastern Sierra Nevada.

Limitations

Our study successfully characterized bobcat home range and core areas in the eastern Sierra Nevada Mountains. Our findings support behavioral inferences relating to varying life strategies illustrated in space use differences between males and females. However, due to the relatively unbalanced sample sizes of males and female bobcats (male n = 25, female n =13), we may not have been able to detect certain differences in space use patterns. These differences in trapping success could be a result of differences in behavior and space use between male and female bobcats. Males occupy larger home ranges and thus could have a higher encounter probability as they have more traps available to them or are more likely to come across a trap within their home range. Furthermore, prior research suggests differing motivations between male and female bobcats influencing space use (Bailey 1974, Diefenbach et al. 2006, Lynch et al. 2008, Ferguson et al. 2009, Donovan et al. 2011). If males are more actively searching for not only forage but for females, then they may exhibit more exploratory behavior and thus be more likely to enter traps and investigate novel stimuli on the landscape. Alternatively, there could have been a skewed sex ratio in the study area, for unknown reasons.

Throughout the study, there were 6 bobcats killed by vehicles, 2 unknown deaths, and 13 collars (of 44) that failed prematurely. The mortality of individuals and considerable collar failure potentially reduced our ability to detect focused space use patterns on a temporal scale. Moreover, the maximum duration of data collected was approximately 18 months per individual bobcat, while this allows exploration of space use within one annual cycle, it has limitations for making inferences about space use over multiple seasons and years. To better explore seasonal dynamics and space use across years, spatial data must be collected over multiple years. Finally, collecting more spatial data from a larger sample of bobcats over a longer period of time could provide insights into understanding bobcat territoriality, degree of spatial overlap and the overall social organization of bobcats in this area.

Our findings relating to road mortality also illustrate the potential impacts that the presence of a major highway might be having on bobcats in the Owens valley. Of the 8 known study animal mortalities, 75% of these were vehicle related. Prior research has suggested that roads can impact urban bobcats (Poessel et al. 2014). In the Owens Valley, US 395 bisects habitat for many species in this area including bobcats and wildlife-vehicle collisions are known to occur throughout this study area. Previous research has demonstrated the effectiveness of crossing structures in reducing wildlife-vehicle collisions (Bissonette and Adair 2008). However, no wildlife crossing structures were present in our study area. Roadkill data can be analyzed to identify roadkill hot spots denoted by high density clustering of roadkill (Basak et al. 2020) and when combined with telemetry and movement data this information can be used to identify important wildlife movement corridors. The locations of these wildlife movement corridors can be used in planning and design of appropriate wildlife crossing structures (Zeller et al. 2020).

More accurate and detailed mapping and raster data would facilitate quantifying habitat selection of bobcats in this area more accurately. A limitation of our habitat selection models is that they can only predict bobcat habitat selection within our area. More data collected from bobcats in other areas of the Sierra Nevada Mountains would increase the confidence in predicting bobcat space use. Furthermore, fine scale and accurate vegetation mapping and categorization for developing RSF models could produce stronger results and allow deeper insight. Our analyses lack the ability to capture selection on a smaller scale. Large rock outcroppings, boulder fields and volcanic lava flows are common features throughout this landscape, all of which provide habitat and cover that is used by bobcats. However, due to the scale of the imagery used to categorize habitat, these areas were not possible to identify in the data.

Future Research

Much research suggests that bobcat habitat selection and space use is influenced by access to prey (Knick 1990). In our study, there is clear bobcat selection for specific habitat types such as riparian vegetation. This suggests that these areas are important for bobcat foraging, reproduction, and survival. However, to better understand the components driving this selection, future research should focus on determining the relative bobcat prey abundance in different habitat types to make inferences about factors driving bobcat habitat selection.

Furthermore, bobcats are wide-ranging generalist predators, their high level of behavioral plasticity combined with the abundance of quality habitat in this area makes uniquely characterizing habitat selection of bobcats in this area relatively challenging. Larger sample sizes, especially of females should be considered in future research on space use and relative habitat selection in the eastern Sierra Nevada Mountains.

Future research on bobcats in the Sierra Nevada Mountains should focus on the potential impacts of bobcats on sensitive species. Bobcats can act as top-level predators, and therefore have significant effects on other sympatric carnivore and prey populations. Much research has suggested that bobcat space use and habitat selection is relative to prey availability and densities (Litvaitis et al. 1986, Conner et al. 1999). Monitoring relative abundance and densities of prey populations in these important habitat types such as riparian corridors and agricultural boundaries could give additional insights into how bobcats are selecting for habitat variables on the landscape. Additionally, monitoring trends of prey populations in these various habitat types could help anticipate impacts on bobcat populations and prey selection. The eastern Sierra Nevada Mountains are habitat for sensitive potential prey species, such as Sierra Nevada bighorn sheep and there have been documented predation events by bobcats in this area (Forshee 2018, CDFW unpublished data). Although the majority of bobcats remained on the valley floor, several bobcats collared during our study did in fact overlap known SNBS herd ranges. This is particularly interesting as there have been recorded incidences of bobcat predation on yearling SNBS (Forshee 2018, T. Stephenson, California Department of Fish and Wildlife, unpublished data), however this remains to be investigated in depth. Collecting data from bobcats in specific areas in close proximity to SNBS herds would provide the opportunity to examine potential predation events of SNBS by bobcats. Findings from this and future studies illustrating space use of bobcats will contribute to the ongoing recovery efforts of SNBS and will provide insight to the impacts of bobcat predation on SNBS populations.

MANAGEMENT IMPLICATIONS

As the first study on bobcat space use and habitat selection in the eastern Sierra Nevada Mountains, our predictive maps will aid in the identification of critical and important bobcat habitat in the region. Resource selection functions suggested bobcats strongly select for riparian areas and that these areas are critical to bobcat fitness and space use in this area. Furthermore, differences in relative selection were detected between male and female bobcats in the eastern Sierra Nevada Mountains, which will allow managers to tailor monitoring efforts to each sex, as well as to identify sex-specific critical habitats for conservation. Based on our findings, we recommend mangers focus on protecting riparian habitat for females and access to agricultural for male bobcats and possibly female bobcats where they have access to these areas. As California continues to experience severe drought conditions, the implications for prime bobcat habitat such as riparian corridors are of increased importance. If low precipitation and extreme heat contribute to the disappearance of riparian areas, bobcat populations could suffer as dense vegetation and increased concentrations of prey also decline. Specifically monitoring riparian habitats and their prey populations are important indicators for evaluating the health of bobcat populations moving forward. In addition, because of the high road mortality observed during the course of this study, our data can be used for identifying important movement corridors near roads to design safe passage across roads in the form of new crossing structures and maintaining relevant existing road culverts. Finally, understanding the spatial ecology of bobcats in this area and how they relate to endangered populations of Sierra Nevada bighorn sheep will have value for recovery efforts.

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TABLES AND FIGURES

Table 2.1. Male and female bobcat home range (95% KDE) and core area (50% KDE) size (Km^2) across seasons and without seasonal differentiation on the eastern slope of the Sierra Nevada Mountains in California.

	Male and Female Mean Home Range and Core Area Size by Season											
	Winter				**Kitten**				**Summer**			
	Home Range		Core Area		Home Range		Core Area		Home Range		Core Area	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Male	36.08	5.83	7.86	1.22	34.76	4.76	7.31	1.13	31.13	3.79	6.02	0.96
Female	11.18	1.12	2.41	0.4	18.62	6.47	3.17	1.11	20.35	8.93	3.91	1.51

	All Seasons			
	Home Range		Core Area	
	Mean	SE	Mean	SE
Male	38.66	5.04	7.3	1.08
Female	20.89	6.96	3.68	1.24

Table 2.2. Top mixed-effect models of resource selection function models evaluating relative selection of habitat by all bobcat s sampled, male bobcats and female bobcats on the eastern slope of the Sierra Nevada Mountains of CA, USA. *K*=number of estimable parameters, LL=Log-likelihood, AIC=Akaike Information Criterion, ΔAIC=difference between the model listed and the AIC of the best model. Habitat covariates included in top models were; Agricultural boundaries (Ag boundary), tree cover, herbaceous grasses, Deep valleys (DV), and steep rises (SR). BASE includes Riparian and Distance to Streams.

All Bobcats				
Model	K^a	LL^b	AIC	ΔAIC
BASE + Ag Boundary + Tree Cover + Herbaceous Grass + DV + SR	7	−117939	235894	0
BASE + Ag Boundary + Tree Cover + Herbaceous Grass	5	−118282	236576	683
BASE + Ag Boundary	4	−118364	236736	843
BASE	3	−118434	236873	980
Male				
Model	K^a	LL^b	AIC	ΔAIC
BASE + Ag Boundary + Tree Cover + Herbaceous Grass + DV + SR	8	−85672	171360	0
BASE + Ag Boundary + Tree Cover + Herbaceous Grass	6	−85915	171842	482
BASE + Ag Boundary + Tree Cover	5	−85960	171930	570
BASE	3	−86067	172141	781
Female				
Model	K^a	LL^b	AIC	ΔAIC
BASE + Tree Cover + Herbaceous Grass + DV + SR	7	−32179	64372	0
BASE + Tree Cover + Herbaceous Grass + DV	6	−32227	64467	95
BASE + Tree Cover	4	−32270	64551	179
BASE	3	−32282	64571	198

Table 2.3. Standardized coefficients and standard errors from the top all bobcat, male, and female general linear mixed-effect models to determine relative selection of habitat by bobcats on the eastern slope of the Sierra Nevada Mountains in California.

ALL BOBCAT MODEL

Model Covariate	**β-coefficients (SE)**
Intercept	- 1.764 (0.03)
Riparian	1.186 (0.03)
Distance to Stream	- 0.169 (0.01)
Agriculture Boundary	0.697 (0.05)
Tree Cover	- 0.382 (0.03)
Herbaceous Grass	- 0.287 (0.03)
Deep Valley	0.329 (0.01)
Steep Rise	0.245 (0.02)

MALE MODEL

Model Covariate	**β-coefficients (SE)**
Intercept	- 1.716 (0.02)
Riparian	1.008 (0.04)
Distance to Stream	- 0.146 (0.01)
Agriculture Boundary	0.742 (0.05)
Tree Cover	- 0.457 (0.04)
Herbaceous Grass	- 0.293 (0.03)
Deep Valley	0.327 (0.016)
Steep Rise	0.221 (0.02)

FEMALE MODEL

Model Covariate	**β-coefficients (SE)**
Intercept	- 1.849 (0.04)
Riparian	1.417 (0.05)
Distance to Stream	- 0.294 (0.02)
Tree Cover	- 0.273 (0.05)
Herbaceous Grass	- 0.252 (0.06)
Deep Valley	0.299 (0.03)
Steep Rise	0.302 (0.03)

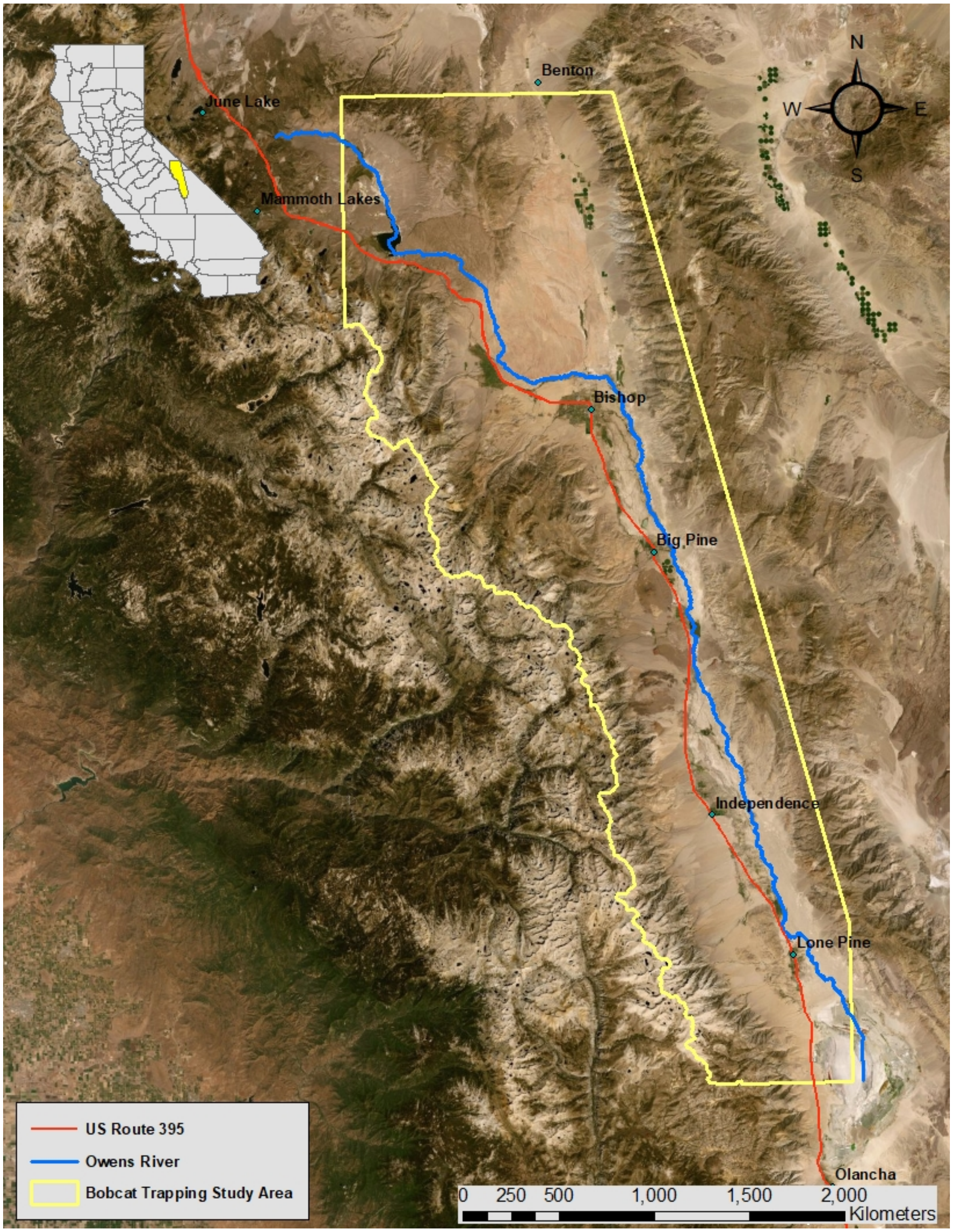


Figure 2.1. Bobcat trapping and RSF study area in Mono and Inyo counties located on the eastern slope of the Sierra Nevada Mountains centered within the Owens Valley. The Owens Valley lies between the Sierra Nevada Mountains to the west and the White-Inyo Mountains to the east.

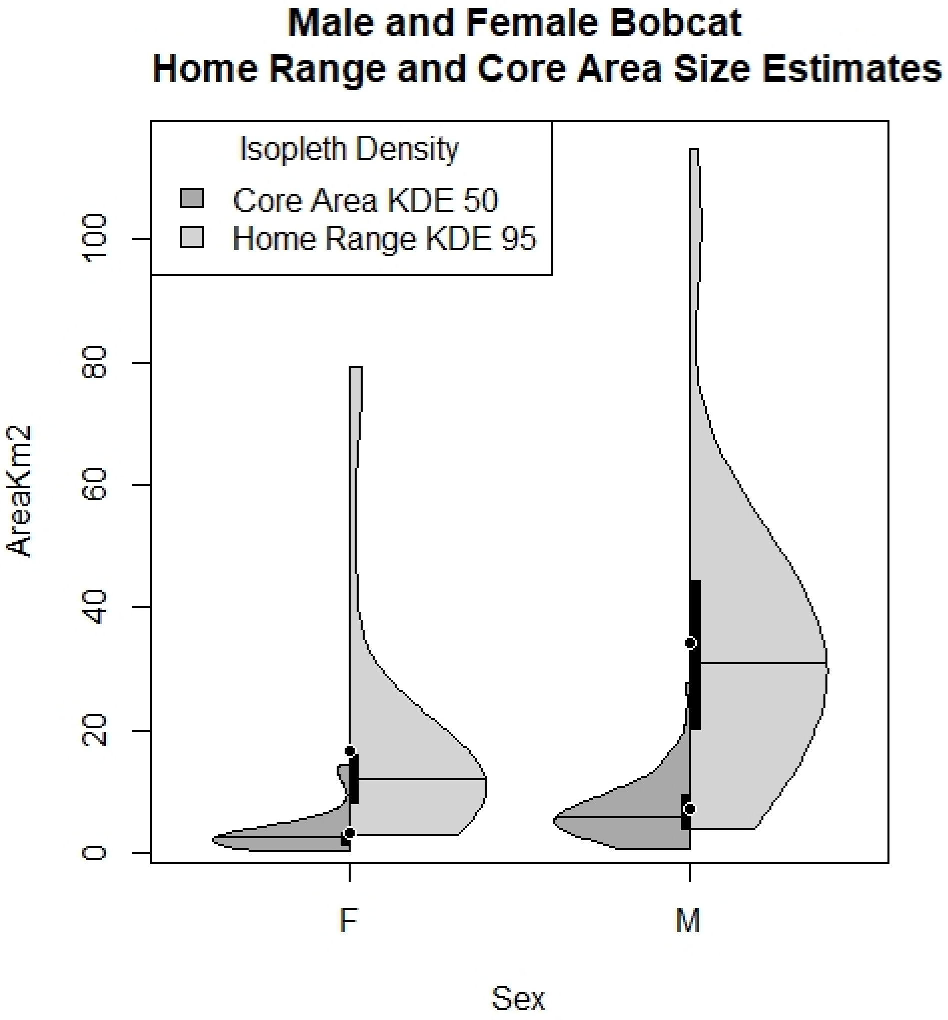


Figure 2.2. Mean bobcat home range (95% KDE) and core area (50% KDE) size for male and female bobcats on the eastern slope of the Sierra Nevada Mountains in California.

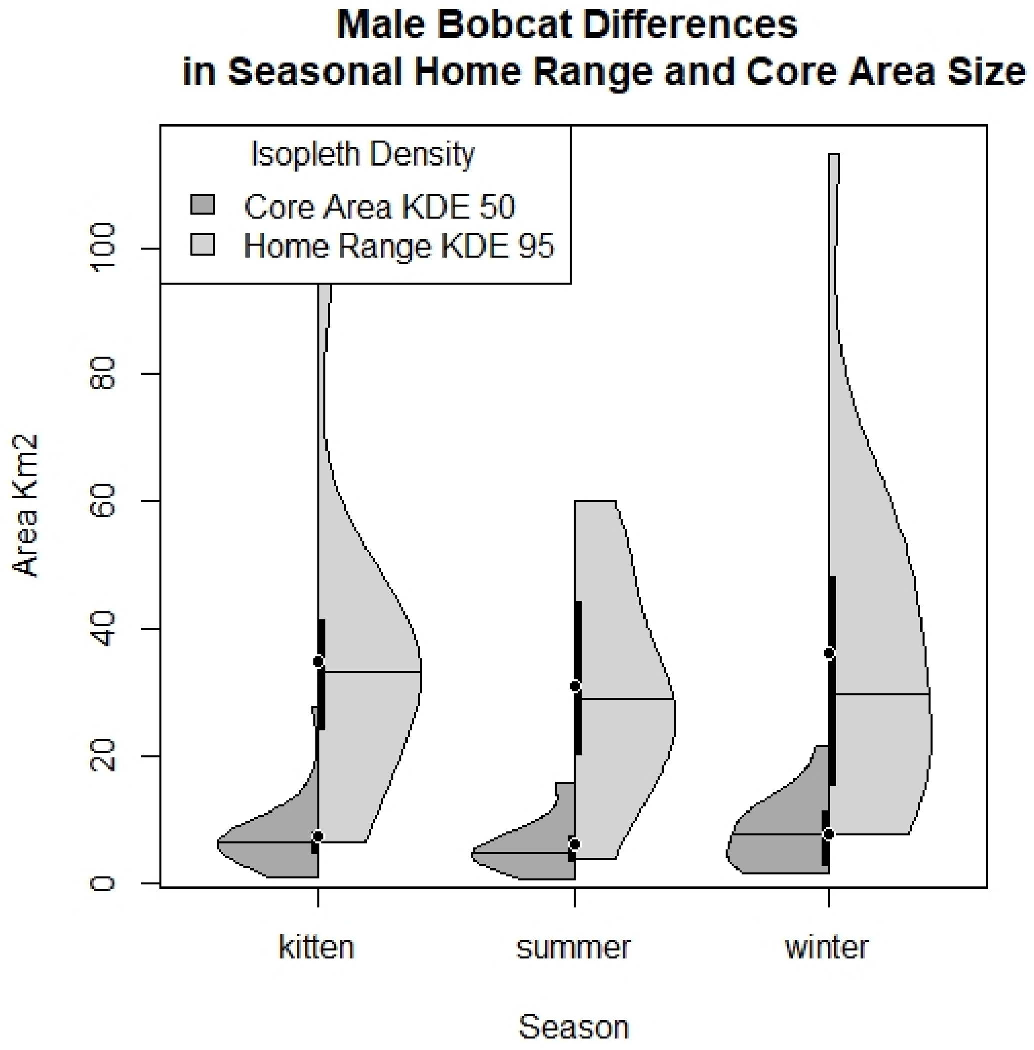


Figure 2.3. Mean bobcat home range (95% KDE) and core area (50% KDE) size of male bobcats across winter, kitten-rearing, and summer seasons on the eastern slope of the Sierra Nevada Mountains in California.

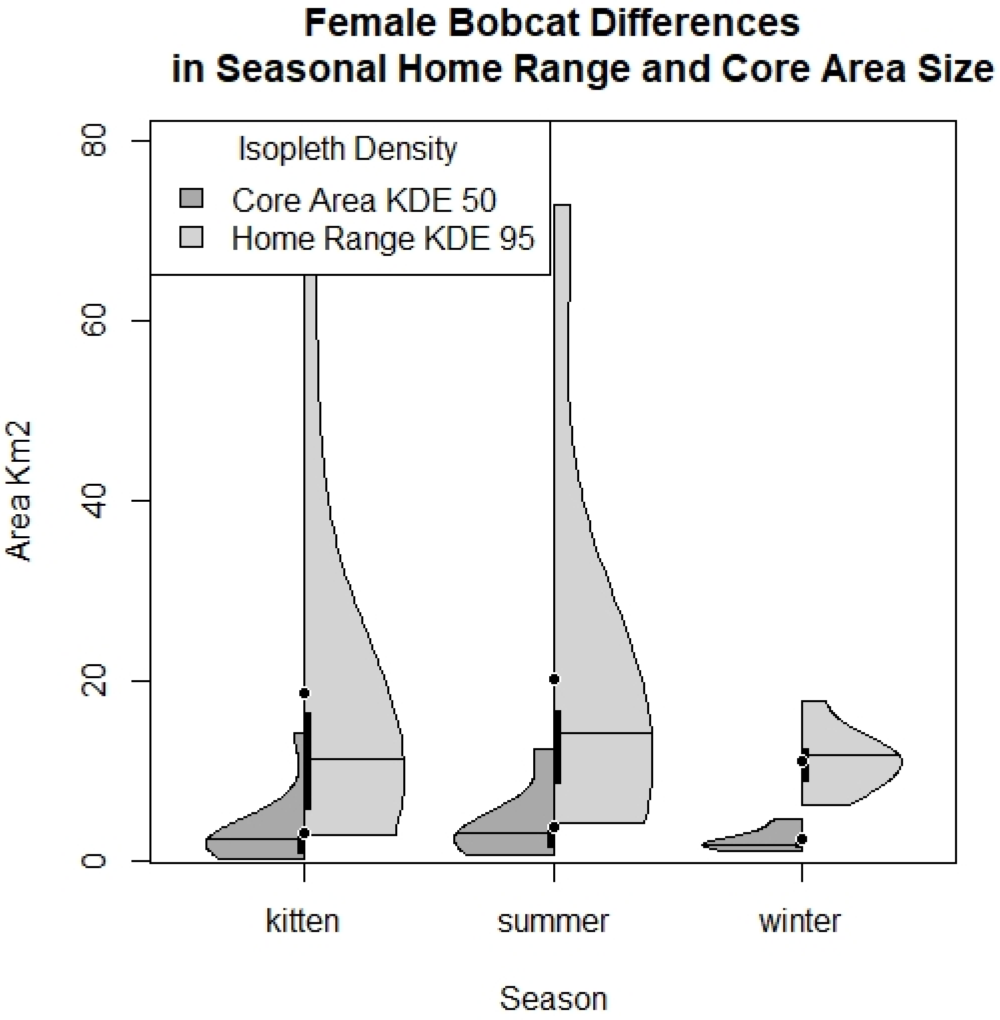
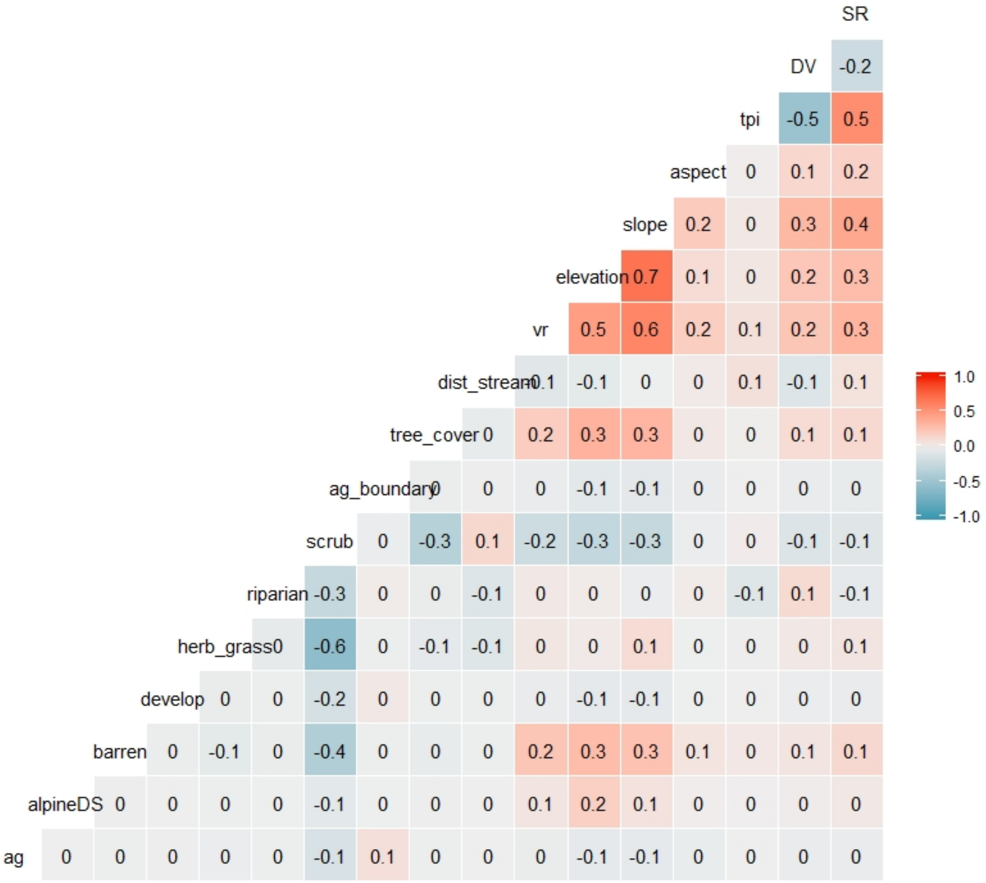


Figure 2.4. Mean bobcat home range (95% KDE) and core area (50% KDE) for female bobcats across winter, kitten-rearing, and summer seasons on the eastern slope of the Sierra Nevada Mountains in California.



	alpineDS	barren	develop	herb_grass	riparian	scrub	ag_boundary	tree_cover	dist_stream	vr	elevation	slope	aspect	tpi	DV	SR
DV																-0.2
tpi															-0.5	0.5
aspect														0	0.1	0.2
slope													0.2	0	0.3	0.4
elevation												0.7	0.1	0	0.2	0.3
vr											0.5	0.6	0.2	0.1	0.2	0.3
dist_stream										-0.1	-0.1	0	0	0.1	-0.1	0.1
tree_cover									0	0.2	0.3	0.3	0	0	0.1	0.1
ag_boundary								0	0	0	-0.1	-0.1	0	0	0	0
scrub							0	-0.3	0.1	-0.2	-0.3	-0.3	0	0	-0.1	-0.1
riparian						-0.3	0	0	-0.1	0	0	0	0	-0.1	0.1	-0.1
herb_grass					0	-0.6	0	-0.1	-0.1	0	0	0.1	0	0	0	0.1
develop				0	0	-0.2	0	0	0	0	-0.1	-0.1	0	0	0	0
barren			0	-0.1	0	-0.4	0	0	0	0.2	0.3	0.3	0.1	0	0.1	0.1
alpineDS		0	0	0	0	-0.1	0	0	0	0.1	0.2	0.1	0	0	0	0
ag	0	0	0	0	0	-0.1	0.1	0	0	0	-0.1	-0.1	0	0	0	0

Figure 2.5. Correlational analysis of associations between habitat variables used in resource selection functions for bobcat data on the eastern slope of the Sierra Nevada Mountains in California.

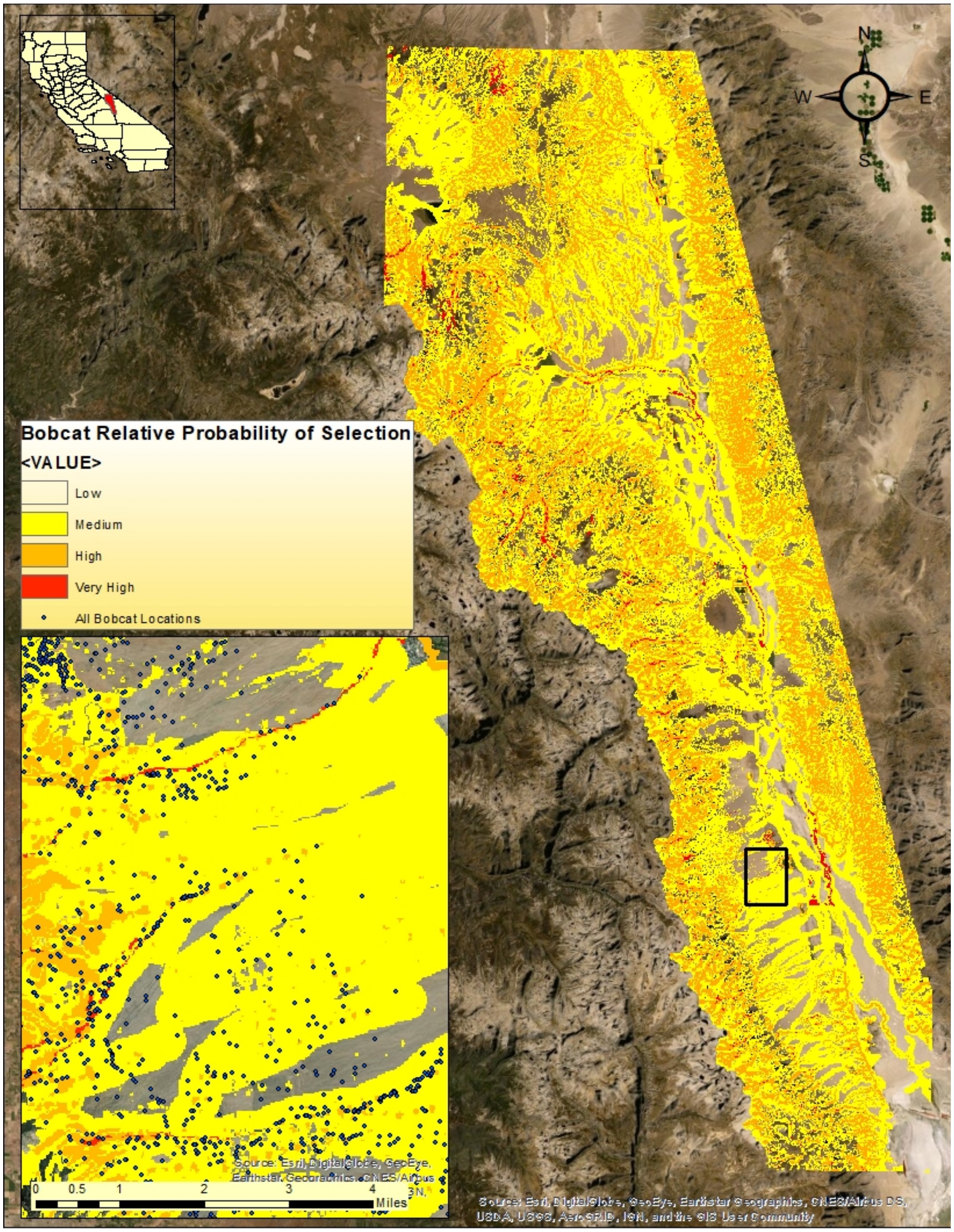


Figure 2.6. Predictive map displaying the relative probability of habitat selection of all collared bobcats on the eastern slope of the Sierra Nevada Mountains in California. This map was developed from 38 individual bobcats between 2015 and 2018 from a used-available resource selection function.

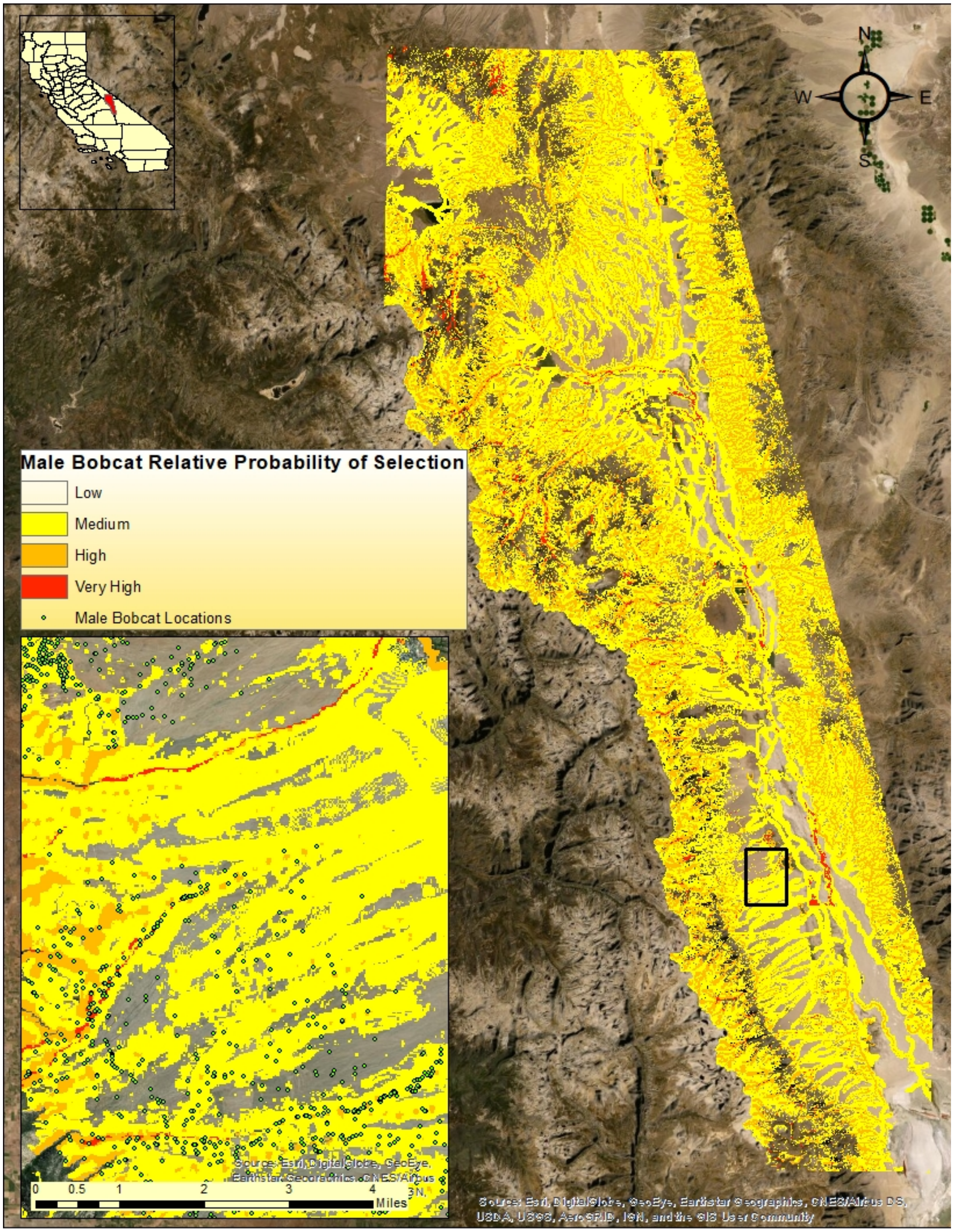


Figure 2.7. Predictive map displaying the relative probability of habitat selection of male bobcats on the eastern slope of the Sierra Nevada Mountains in California. This map was developed from 25 individual bobcats between 2015 and 2018 from a used-available resource selection function.

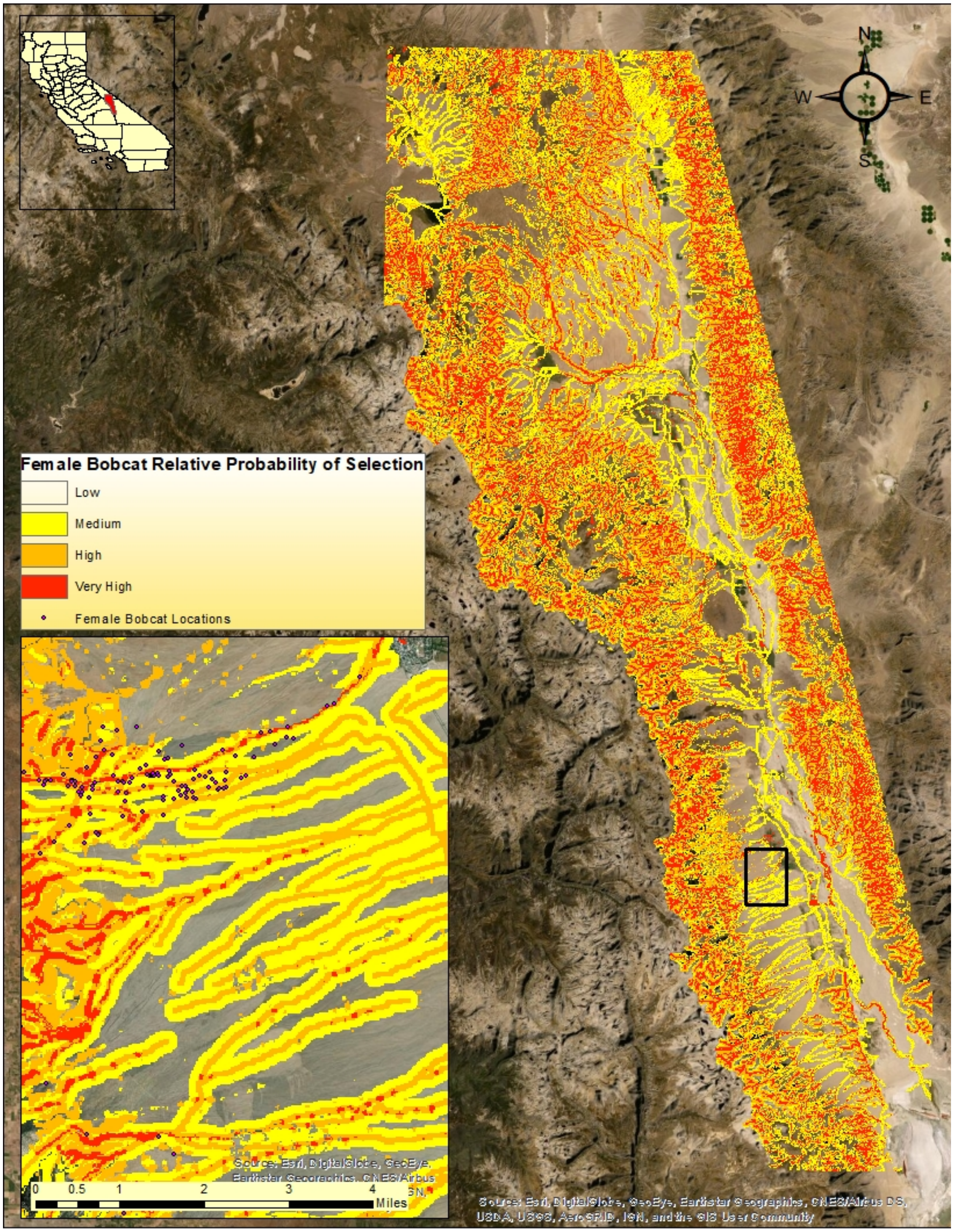
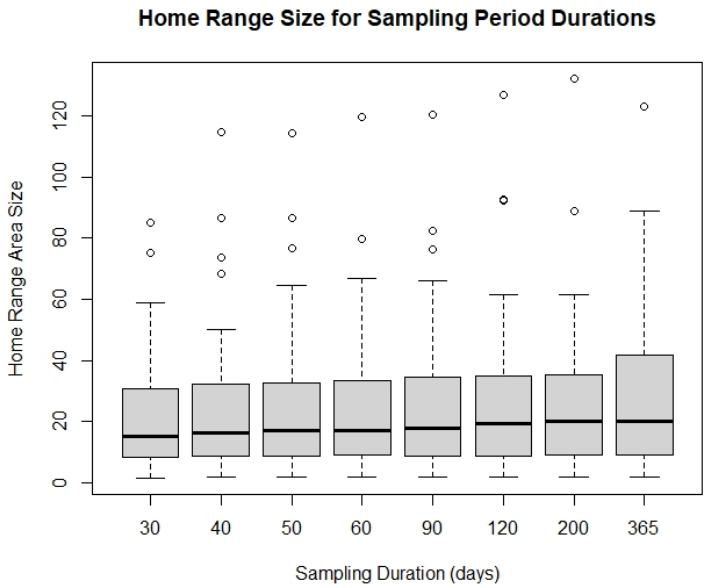


Figure 2.8. Predictive map displaying the relative probability of habitat selection of female bobcats on the eastern slope of the Sierra Nevada Mountains in California. This map was developed from 13 individual bobcats between 2015 and 2018 from a used-available resource selection function.



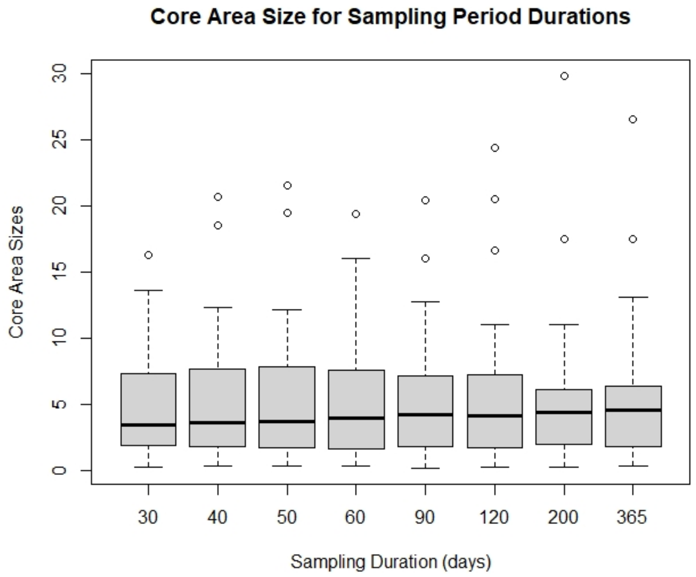
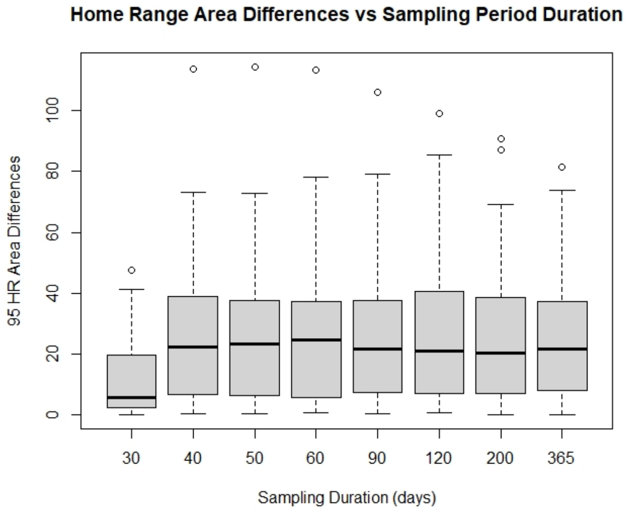


Figure 2.9. Home range and core area size estimates of bobcats for different sampling durations i.e. 30 days, 40 days, 50 days, 60 days, 90 days, 200 days and 365 days since initial capture. No significant difference existed in home range or core area size estimates over the sampling durations. Data was collected from 38 bobcats on the eastern slope of the Sierra Nevada Mountains in California.



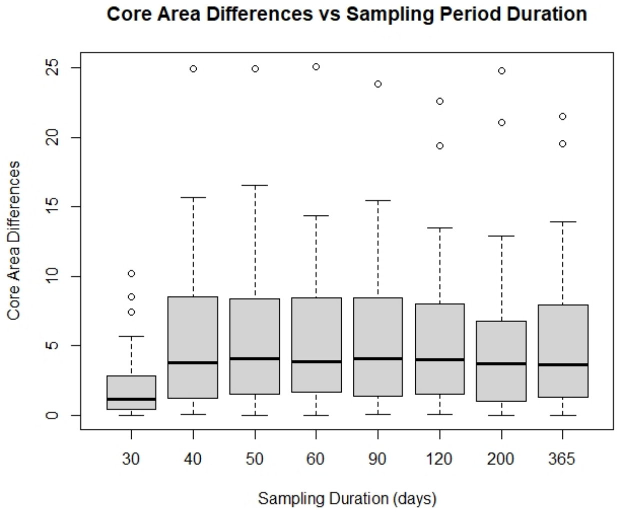
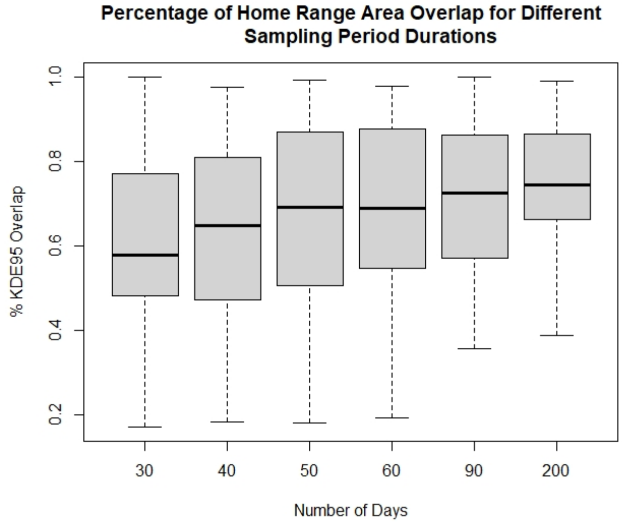


Figure 2.10. Size differences in estimates between bobcat home ranges (95% Kernel Density Estimators) and core areas (50% Kernel Density Estimators) calculated from all individual bobcat data and those calculated from a subset of data collected from different survey duration groups. A significant difference in home range and core area size differences, calculated from differing sampling durations, exists only between 30 and 40 sampling days. This suggests the minimum number of points used in home range and core area estimation should be no less than 40 days (168 points). Data was collected from 38 bobcats on the eastern slope of the Sierra Nevada Mountains in California.



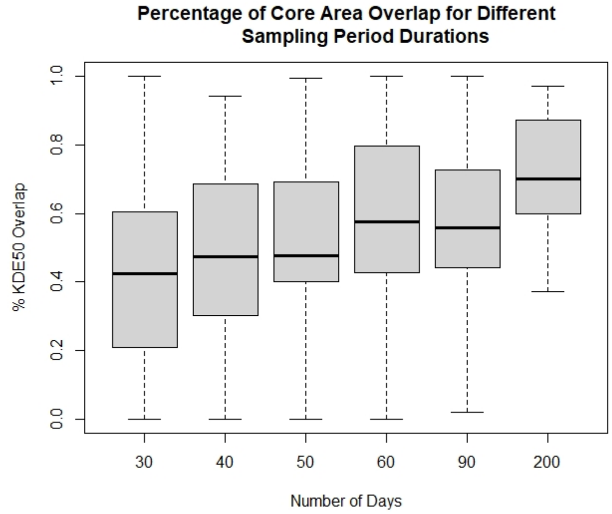


Figure 2.11. Degree of overlap between home ranges (95% Kernel Density Estimators) and core areas (50% Kernel Density Estimators) estimated using data from different durations of time since initial capture and total home range and core area size. No significant difference in overlap was detected for home range size, however there was a significant difference detected in core area size. This suggests that core areas can shift within a home range over time. Data was collected from 38 bobcats on the eastern slope of the Sierra Nevada Mountains in California.

CHAPTER 3

COMPARING CLOSED CAPTURE MARK-RECAPTURE TO SPATIALLY EXPLICIT CAPTURE RECAPTURE (SECR) TECHNIQUES FOR ESTIMATING BOBCAT DENSITY USING NON-INVASIVE CAMERA TRAPS

ABSTRACT

Effective monitoring and management of carnivore populations often requires obtaining accurate estimates of density and identifying reliable methods to estimate population parameters. However, due to their relatively low densities and wide-ranging elusive behavior, carnivores can be notoriously difficult to monitor. Historically, methods relied upon invasive physical capture of individuals which can be costly and inefficient. Recently, non-invasive methods such as camera traps have been utilized in mark-recapture frameworks for estimating carnivore abundance through identification of individuals via unique pelage patterns. Bobcats (*Lynx rufus*) are top-level medium sized carnivores that are distributed across much of North America. Our goal was to identify methods for obtaining accurate and non-invasive methods for obtaining density estimates of bobcats on the eastern slope of the Sierra Nevada Mountains of California, USA. Using camera trap data, we compare closed capture-recapture (CMR) and spatially explicit capture-recapture (SECR) methods for obtaining bobcat density estimates.

We collected data in April-May of 2018 in a study area on the eastern slope of the Sierra Nevada Mountains near Bishop, CA. Density estimates from CMR analysis was 17.9 bobcats/10km^2 (SE = 2.2, 95% CI = 14.0-22.8) compared to SECR estimates of 47.1 bobcats/10km^2 (SE = 16.6, 95% CI = 24.1-92.0). This discrepancy in density estimates between the two methods is likely due to a low rate of photographs meeting the criteria for individual identification (56% successful). We suggest that due to the low rate of successful individual

identification from camera traps, spatial scale parameters and home range size were underestimated using SECR methods resulting in inflated density estimates. In sparsely vegetated, open desert landscapes, perhaps photographic capture-recapture methods for monitoring bobcats are not as accurate as genetic capture-recapture or spatial mark resight methods of analysis.

INTRODUCTION

Carnivores play important ecological roles in ecosystems around the world and understanding population dynamics through estimating population abundance, density, size, and trends of these species can provide valuable insights into management and conservation efforts (Ray et al. 2005, Ruell et al. 2009, Thornton and Pekins, 2015). However, due to the relatively low densities, elusive behavior, solitary life histories, and large home ranges of terrestrial carnivores, populations can be difficult to monitor (Jackson et al. 2006, Balme et al. 2009, Ruell, et al. 2009, Blanc et al. 2013, Thornton and Pekins 2015).

Traditional methods used to estimate population parameters often involve invasive methods of physical capture or counts of individuals which can be inefficient or impossible (Blanc et al. 2013). Less invasive methods of obtaining population abundance and density estimates use detectors that identify individuals through genetic or photographic information using capture mark-recapture (CMR) methods (Heilbrun et al. 2006, Fusaro et al. 2017). However, traditionally these methods still require the need to obtain telemetry data through fitting animals with radio collars to estimate density (Dice 1938, Efford 2004). Recently, completely non-invasive spatially explicit capture-recapture (SECR) methods have been developed which eliminate the need for capturing animals because density is estimated directly from the data (Efford 2004). Here we compare closed-CMR and SECR methods of estimating population abundance and density of bobcats (*Lynx rufus*) using camera traps on the eastern slope of the Sierra Nevada Mountains of California.

Bobcats are solitary, medium-sized carnivores that occupy ranges across much of North America (Ferguson et al. 2009) including the eastern slope of the Sierra Nevada Mountains of California. Many studies have focused on CMR and SECR methods for estimating abundance and densities of bobcat populations across North America (Heilbrun et al. 2006, Thornton and Pekins 2015, Young et al. 2019). Yet, very little bobcat research has been conducted on the eastern slope of the Sierra Nevada Mountains of California to inform wildlife management and conservation.

Mesocarnivores can have important and variable impacts on ecosystem function, structure and dynamics (Roemer et al. 2009) through competition, predation and bottom-up impacts from fluctuations in prey populations. Densities of mesocarnivores such as coyotes can be influenced by prey populations (Clark 1972). Conversely, mesocarnivores can influence ecosystem structure through predation on prey (Wallach et al. 2015). Bobcats are prominent mesocarnivores in many ecosystems across North America (Ferguson et al. 2009). In the presence of large apex predators such as wolves (*Canis lupus*), grizzly bears (*Ursus arctos horribbilis*) and mountain lions (*Puma* concolor), mesocarnivores such as bobcats can be dominated by larger carnivores (Elbroch and Kusler 2018). For this reason, in areas in which they overlap with other large carnivore populations, bobcats likely act as mid-level trophic carnivores. Additionally, bobcats can be influenced by competitive pressures and be killed by other sympatric large carnivores (Koehler and Hornocker 1991, Hass 2009). However, it has been suggested that in the absence or decline of large carnivore species, mesocarnivores can act more like apex predators in an environment (Roemer et al. 2009). In ecosystems such as the Sierra Nevada Mountains which lack an abundance of these large carnivores, with the exception on mountain lions and black bear, it is possible that bobcats could hold roles in the ecosystem more akin to top-level predators in this area. Additionally, in the eastern Sierra Nevada there have been documented cases of bobcat predation on Sierra Nevada bighorn sheep, mule deer and kleptoparasitism of mountain lion kills by bobcats (CDFW unpublished data). Through the comparison of traditional CMR and modern SECR methods, this study aims to evaluate the efficacy of invasive (closed CMR) compared with non-invasive (SECR) methods for obtaining accurate abundance and density estimates of bobcat populations in this area.

CMR and SECR studies rely on the ability to uniquely identify individuals of a specific population to obtain abundance and density estimates (Rich et al. 2014). Remote camera trap surveys have been used to monitor elusive and widely dispersed carnivores by identifying individuals based on unique pelage and morphological patterns (Heilbrun et al. 2003, Jackson et al. 2006, Larrucea et al. 2007, Rich et al. 2014, Clare et al. 2015, Thornton and Pekins 2015). Bobcats exhibit distinct pelage and facial patterns that can be used for individual identification necessary for both CMR and SECR methods (Heilbrun et al. 2006, Mendoza et al. 2011). Furthermore, previous research has successfully used pelage pattern identification of unique individual bobcats to gain population abundance and density estimates (Thornton and Pekins 2015, Heilbrun et al. 2006, Alonso et al. 2015,). Unique pelage patterns and morphological features provide a non-invasive way of identifying individuals, a requisite for CMR and SECR methods of estimating population parameters.

Many researchers have used CMR survey methods in combination with non-invasive camera traps to obtain abundance and density estimates of wildlife populations (Huggins 1989, Huggins 1991, Silver et al. 2004, Ruell et al. 2009, Alonso et al. 2015,). Population density is commonly estimated by dividing the estimated population size from CMR by the effective trapping area referring to the spatial extent of the surveyed population (Efford 2004). However, closed CMR models assume both demographic and geographic closure of a population (Wilson and Anderson 1985). While demographic closure (i.e., no births, deaths, immigration, or emigration is occurring) can often be met, geographic closure can be more difficult (Wilson and Anderson 1985). When geographic closure is not met, edge effects arise that influence the actual effective trapping area (Wilson and Anderson 1985). Thus, CMR methods are highly susceptible to edge effects, which occur when individuals have the ability to move in and out of the study area and thus bias density estimates (Wilson and Anderson 1985, Balme et al. 2009, Obrien and Kinnaird 2011, Royle et al. 2011).

To attenuate biases from edge effects and obtain precise estimates of population density using a closed model CMR framework, the effective trapping area must be determined (Efford 2004, Balme et al. 2009, Thornton and Pekins 2015). Home range estimates and movement data derived from GPS data can be used to estimate the overall effective trapping area by placing a buffer area around the trapping grid (Wilson and Anderson 1985, Balme et al. 2009, Devens et al. 2018). In this study, CMR refers to the technique of using cameras traps used in a capture mark-recapture framework to identify individuals in combination with GPS collars.

However, these ad hoc determinations of the effective trapping area can be problematic. This is because they are subjective and can result in underestimating movements of individuals, thus biasing density estimates (Gardner et al. 2010, Thornton and Pekins 2015, Strampelli et al. 2020). Furthermore, fitting animals with GPS collars requires extensive resources (Pfeiler et al. 2020), is time intensive and highly invasive. Obtaining home range data relies on the successful capture of an appropriate sample size of individuals in a population which is difficult with species such as bobcat. Developing non-invasive CMR techniques that overcome edge effects without relying on invasive trapping and the associated biases has great potential for accurately and efficiently estimating wildlife population densities.

Over the last two decades, increased attention has been given to using SECR methods for estimating population densities. These methods incorporate spatial organization of detectors, movement, and space use. SECR methods combined with non-invasive detection techniques using cameras have been shown to be successful in estimating abundance and densities of elusive carnivores (Gardner et al. 2010, Blanc et al. 2013, Greenspan et al. 2020). SECR models incorporate the coordinate locations of traps to provide spatial information for individuals such as home range, movement patterns, and heterogeneity in the detection of individuals (Borches and Efford, 2008, Obrien and Kinnaird 2011, Royle et al. 2011, Sollman et al. 2012, Thornton and Pekins 2015, Devens et al. 2018, Efford 2004, Gardner et al. 2010). Through this process, SECR methods estimate the effective trapping area and population density directly from the data while eliminating the necessity of potentially problematic and ad hoc estimates of the effective trapping area (Gardner et al. 2010, Blanc et al. 2013, Efford 2004, Thornton and Pekins 2015, Strampelli et al. 2020). As non-invasive SECR methods provide the opportunity to estimate densities and the effective trapping area without the use of ad hoc analysis using telemetry data, the dependency on invasive and expensive physical capture animals could be negated.

Prior research has evaluated the efficacy of spatial methods such as SECR and non-spatial methods such as CMR for estimating densities of wildlife populations in large carnivore species (Obbard et al. 2010, Whittington and Sawaya 2015). Findings from such studies suggest that biases in density estimates can be avoided by using SECR methodology when edge effects are possible due to lack of geographic closure (Obbard et al. 2010).

Identifying accurate and effective methods of monitoring trends and dynamics of bobcat populations is important for effective monitoring and management. Very little research has been done comparing CMR to SECR with bobcat populations and we do not have accurate means of estimating bobcat abundance and densities in the eastern Sierra Nevada Mountains. As bobcats can act as high-level predators having varying impacts on the trophic system in which they exist, the ability to detect fluctuations in bobcat populations has important implications for management of not only bobcats, but other predators they compete with and sensitive prey species with which they overlap. Understanding population densities, abundance, and fluctuation of bobcat populations in this area will inform management regarding future bobcat harvest and protection decisions in this area. Management and monitoring of bobcat populations on the eastern slope of the Sierra Nevada Mountains has largely been based upon harvest records. Bobcats have been historically viewed as important furbearers (Garcia and Ypema 2015, Thornton and Pekins 2015) and have previously been legally harvested via fur trapping and sport hunting throughout California. Annual take estimates of up to 11,938 were documented in 1983-84 (Garcia and Ypema 2015). However, in 2015 California banned bobcat harvest via trapping and finally, in 2020 all harvest of bobcat was prohibited. Currently, monitoring bobcat populations on the eastern slope of the Sierra Nevada Mountains through harvest reports is not possible, requiring new methods to be adopted to monitor these populations.

Bobcats have been known to predate on a wide variety of prey species (Rose and Prange 2015) and thus can have important influences on ecosystems in which they inhabit through top-down predation pressures (Wallach et al. 2015). Increases in bobcat populations due to a lack of harvest pressure could have dramatic impacts on prey populations that have great recreational and economic value such as waterfowl and upland game species along with mule deer and Sierra Nevada bighorn sheep. Conversely, if harvest pressure has not had any significant influence on regulating bobcat populations, ongoing population trend estimates can inform future management and legislative decisions revolving around bobcat harvest in California. For this reason, continual monitoring of bobcat populations has important implications for the potential ecological impacts of bobcat population change. Prior research has also explored the relationship between urban areas and the presence of bobcats (Lombardi et al. 2017, Young et al. 2019). As urbanization increases in many areas, the occupancy of mesocarnivores such as bobcats in the urban interface provides increased opportunities for human-wildlife conflict issues to arise. Thus, in addition to the potential ecological consequences of an un-managed bobcat population that was historically under harvest pressure, possible wildlife conflict issues including depredation on pets and livestock from bobcats warrant further monitoring of the population trends of bobcats in this area.

In this study, we evaluated different analytical methodologies to develop effective monitoring strategies for bobcats on the eastern slope of the Sierra Nevada Mountains of California. To this end, our specific objectives were to: 1) Evaluate SECR methods of analysis to obtain density and abundance estimates of bobcats for the study area utilizing photo identification of bobcats, 2) Compare density and abundance estimates of bobcat populations from SECR methods with those obtained through a combination of closed-capture models and home range methods of analysis, and 3) Determine optimal methods for obtaining precise and accurate density and abundance estimations of bobcat populations throughout the eastern Sierra Nevada Mountains. Here we utilize both invasive methods using closed CMR in combination with telemetry data and non-invasive SECR methods of estimating bobcat population densities. By comparing the estimates from these two methods we aim to assess the necessity and usefulness of invasive and expensive sampling using GPS collars where non-invasive methods could provide comparable results. Findings from this study will inform management and conservation strategies, ultimately helping to assess and ensure the health of bobcat populations in this region. Furthermore, this study will help to determine the general usefulness of SECR methods for monitoring other carnivore populations in the eastern Sierra Nevada Mountains and in similar habitats.

STUDY AREA

The study area was located in the Owens Valley drainage between the towns of Big Pine and Independence in Inyo County, along the eastern slope of the Sierra Nevada Mountains of California (Fig. 3.1). The Owens valley is bordered on the west by the Sierra Nevada Mountains with peaks reaching upwards of 4,000 m above sea level (Hill 1975). To the east of the Owens valley are the White and Inyo mountain ranges. The Owens River runs north to south and is east of the study area from its source between Mammoth Lakes and June Lake, CA to the Owens Dry Lake near Olancha, CA (Fig. 3.1). Elevations in the Sierra Nevada range from approximately 1,200 m on the Owens Valley floor to Mount Whitney at 4,421 m above sea level.

The study area size was approximately 227.9 km^2 area and was split into 40 hexagonal 10.4km^2 cells. Survey locations ranged in elevation from 1,182 m to 1,960 m above sea level. These cell dimensions and cell size are based off of recommendations by CDFW mesocarnivore researchers in California (Zielinski and Kucera 1995).

The dominant vegetation present in the study area are bitter brush scrub and riparian communities such as water birch thicket and Fremont cottonwood forest and woodland along streams and drainages that flow to the Owens River from the Sierra Nevada Mountains (Sawyer Et al. 2009). Common fauna includes smaller bobcat prey such as California quail (*Callipepla californica*), mountain quail (*Oreortyx pictus*), desert cottontail rabbit (*Sylvilagus audubonii*), black-tailed jackrabbit (*Lepus* californicus) and various rodent species. Mule deer (*Odocoileus hemionus*), Tule elk (*Cervus canadensis nannodes*), feral ass (*Equus asinus*), and Federally Endangered Sierra Nevada bighorn sheep (*Ovis canadensis sierrae*) also occupy habitats within this study area. Prominent carnivore species within this study area include black bear (*Ursus americanus*), mountain lion (*Felis concolor*), gray fox (*Urocyon cinereoargenteus*), and coyote (*Canis latrins*) (California Wildlife Habitat Relationship database 2020).

METHODS

Field Methods

We sampled during April and May 2018. Individual bobcats were photographically captured using a 22-cell sampling grid composed of 2 double-camera sites per cell. Each of the 44 double-camera sites throughout the study area (Fig. 3.1) were placed at locations deemed to be good bobcat habitat based on evidence of bobcat activity (scat, latrines, or scent scrapes) such as defined trails or natural funnels in the landscape (Heilbrun et al. 2006). The spacing of camera sites averaged 1.67 km between locations. We chose this distance based minimum bobcat home range sizes from prior research (Ferguson et al. 2009, CDFW unpublished data), to minimize the likelihood of a bobcat's home range falling between cameras. Previous research suggests camera spacing should not allow holes between survey units that could completely encompass an animal's home range (Royle et al. 2011, Royle at al. 2014, Jacques et al. 2019).

At each camera site, we placed 2 Reconyx PC900 Hyperfire cameras on natural structures facing one another on opposite sides of the proposed focal point or trail to ensure both flanks of a bobcat would be photographed (Heilbrun et al. 2006, Alonso et al. 2015). Prior research suggests camera placement should be consistent with height and orientation across the grid (Heilbrun 2003). However, due to the open and sparsely vegetated nature of the study area and restrictions on using man-made materials such as fence t-posts, it was not always possible to maintain a consistent angle, height, and distance of the camera to the focal point.

We programmed cameras to capture rapid bursts of 10 photos on a motion-triggered sensor with <1 sec between each photo.

Each camera collected data over a 6-week study period. We placed a non-consumable scent lure between the cameras to draw bobcats in and increase detection probability of bobcats in the area (Garrote et al. 2012). We visited each camera site every 7-10 days to reapply an alternating scent lure and replace the secure digital card.

We collected photos on secure digital cards and organized them into bobcat and non-bobcat categories. We analyzed photos and assigned each bobcat an individual identification (ID) using the Colorado Department of Wildlife Photo Warehouse (CDWPW) access database (Ivan and Newkirk 2015). A single researcher with extensive experience analyzing bobcat pelage patterns manually identified and compared individuals from bobcat photographic data. Although bobcats are considered to be predominantly solitary and elusive carnivores (Ferguson et al. 2009), we documented occasions when multiple bobcats visited the same camera site simultaneously or in relatively short succession. For this reason, we considered a capture independent if a bobcat left the frame of view of the camera for a minimum duration of 1 minute.

Each individual bobcat was assigned a unique identification number or ID when strict criteria were met relating to pelage features (Heilbrun 2003). Unique pelage features were identified for each individual and classified into two categories: primary features and secondary features. Primary features were the most distinct feature on an individual, and secondary features were all other unique features that could be useful for determining an individual’s identity (Negroes et al. 2010). To successfully assign a unique bobcat ID and to differentiate between individuals, 3 unique features had to be defined (Heilbrun et al. 2006). We categorized bobcats as unknowns when identification criteria were not met. Bobcat pelage patterns remain stable throughout their life making individual identification possible. However, during the first year of life their pelage pattern changes dramatically (Heilbrun et al. 2003). This suggests that kittens may not be able to be reliably recaptured, so we did not include photos of kittens in the analyses. See Appendix C for details on photo recognition criteria.

Density Estimation

We created capture histories for each bobcat with a unique ID that was detected (i.e. captured) throughout the survey using the CDWPW access database. We used the same capture histories for the CMR and SECR analysis, although they were in different formats specific to the requirements of each method. For both methods, data were grouped into six 1-week sampling occasions to build capture histories.

Closed-Capture Mark Recapture

We analyzed capture histories in Program MARK to obtain abundance estimates. Individual bobcats were either detected (1) or not detected (0) in each of the 6 sampling occasions. Bobcats that were detected >1 time within a single sampling occasion were considered duplicates and a single detection of an individual was recorded for each sampling occasion. We used the Huggins formulation of closed capture-recapture models in Program MARK (White and Burnham 1999). We modelled initial capture (p) and recapture (c) probabilities. We used 8 *a priori* models to evaluate differences between p and c by occasion (time) or with no temporal component (constant or "." models), (Fig. 3.1). Furthermore, differences in space use pattern between individuals can produce detection (capture) heterogeneity, which if not accounted for, result in bias in estimates of abundance and density (D) (Pledger & Efford 1998, Pledger 2000). To test the importance of heterogeneity, we constructed a second set of models using the Huggins-Pledger full heterogeneity models, with a mixture of 2 capture probabilities in Program MARK (Pledger 2000). The heterogeneity models had the same structure as the non-heterogeneity models.

We ranked models on Akaike's Information Criteria (AIC) to determine the best fitting models. We then model-averaged estimates of population size ($\hat{N}$) and variance to calculate log-based confidence intervals (Burnham and Anderson 2002).

We estimated density by dividing the model-averaged population size estimate ($\hat{N}$) by the effective trapping area. A common method for estimating the effective trapping area for density estimation using capture mark-recapture techniques is to use spatial telemetry data relating to home range size of the study animal (Dice 1938, Fusaro et al. 2017). As spatial parameters such as home range size can vary within the same species in different study areas, obtaining home range estimates from animals within or close to the study area and during the same temporal window will ideally give the most accurate density estimates. To estimate the effective trapping area, we used bobcat home range size estimates from a local study (CDFW unpublished data) to estimate a buffer radius, and then added the buffer area to the minimum convex polygon area that encompassed all camera locations. Home range size was calculated from locations collected from GPS-collared bobcats within and around the study area over the duration of the camera survey (i.e., during April and May 2018). For this time period, we used the average home range size, which was estimated using a 95% Kernel Density Estimator (n=21). We estimated the buffer size based on the average radius for each bobcat home range size. That is, we calculated the radius that would result in the home range size if the home range were circular. These methods are similar to methods that estimate effective trapping areas by adding half the width of a circular home range or half the mean maximum distance moved to the trapping area (Williams et al. 2002, Fusaro et al. 2017). We used the Delta method to estimate the variance of density based on the variance of $\hat{N}$ and the buffer radius (i.e., variance of the mean home range radius) (Cooch and White 2002).

Spatially Explicit Capture Recapture (SECR)

We constructed SECR models in Program R (version 1.2.1335) using the secr.r package (Efford 2011) to estimate density of bobcats in the study area. To account for multiple detections of the same individual within an occasion we used a ‘count’ detector type for building our SECR capture histories. Bobcat ID, camera site location, and occasion were recorded for every time an identifiable individual was encountered at any of the 44 camera sites across the survey. We compiled these data into SECR capture histories using the Program R package ‘secr’ (Efford 2011).

SECR model input files included capture histories, trap locations, activity, and a grid of equally spaced potential home range centers referred to as the ‘mask’. To create this mask, a buffer distance around the trapping grid had to be large enough that the likelihood of encountering animals with home range centers outside this buffer zone was minimal (Jacques 2019, Efford 2011, Thornton and Pekins 2015). We determined the buffer distance by fitting a null model to the mask with all model parameters constant (“.”) and a large buffer size (10,000 m) to the SECR data. We used this null model to determine the buffer distance at which detection probability (p_r) drops to 0. Furthermore, we checked this distance by multiplying the upper confidence limit of the spatial parameter (sigma) by 4 (Efford and Boulanger 2019). We selected a hazard half-normal detection function to parameterize models in terms of cumulative hazard (i.e., expected number of detections) (Efford 2011, Young et al. 2019).

SECR models estimated by full maximum likelihood typically estimate 3 model parameters: density (*D*), detection function parameter (*g0* – probability of detection at the center of a home range), and a spatial scale parameter (sigma) describing how the detection probability declines with distance from home range centers (Thornton and Pekins 2015). We fitted several models and parameter combinations to evaluate the influence of time (sampling occasion - *t*), site, and behavioral response to sites and lures (*bk*) on density and detection probability parameter g0. We tested the importance of heterogeneity with a mixture of 2 detection probabilities in the SECR models. Models were ranked on AIC score (Table 3.1).

We calculated the effective trapping area from the model-averaged density estimate in Program R (version 1.2.1335) using the secr.r package (Efford 2011). Additionally, average home range size can be calculated from the spatial scale parameter sigma. We estimated the average circular home range size (95% bivariate home range) for all bobcats directly from sigma derived from the model averaging which we multiplied this value by 2.45. This value (2.45) denoting 95% activity within a circular area using a half normal detection function (Royle et al. 2014).

RESULTS

We documented a total of 250 independent captures of bobcats over the 55-day survey. This included recaptures of the same individuals at a given location within the same sampling period. The mean number of trap nights for camera stations was 49.9 nights. Of the 250 captures, 56% (*n* = 141) of captures were positively identified compared to 44% (*n* = 109) that we classified as bobcats but were not able to be identified. Of the 250 captures of bobcats, 128 independent capture events were detected. Closed CMR capture histories were built from 98 captures of 52 uniquely identifiable individuals. In contrast, because detectors in the SECR analysis were treated as ‘count’ detectors allowing multiple captures of the same individual at a given location within the same sampling occasion, SECR capture histories were built from 128 captures of the same 52 uniquely identifiable individuals.

We identified an average of 16.3 individual bobcats per one-week sampling occasion (Fig. 3.2). The mean number of bobcat captures per camera site was 6.3. The total number of recaptures at the same camera station (i.e. movement = 0 meters) was 82 (64%), compared to 46 (36%) recaptures at 29 different camera stations than initially captured at (spatial recaptures), (Fig. 3.3). Based on SECR count detectors and multiple captures within the same sampling period the mean maximum distance moved by positively identified bobcats, (i.e., movements between camera stations/detectors) was 0.93 km.

Closed Capture Mark-Recapture Models

The minimum convex polygon (MCP) area of the camera detector grid was 195.1 km^2. The mean 95% kernel density estimator (KDE) home range size estimated from telemetry data collected from GPS collared bobcats in the area during the survey duration period (4/10/2018 – 6/4/2018) was 22.9 km^2 (n = 21, SD = 3.73). The mean radius of bobcat home range size was 2.5 km, which produced an effective trapping area 365.2 km^2 (SE = 16.6). The average radius was calculated based on the radius for each bobcat's home range.

Closed-capture models that included heterogeneity in detection probability had the most support (W_i=0.97, Table 3.1). Thus, we only model averaged across models with heterogeneity. Using the effective trapping area, the estimated bobcat density was 17.9 bobcats per 10km^2 (SE = 2.2, 95% CI = 14.0-22.8).

Detection probabilities were different between groups in both initial capture (p) and recapture probability (c). Most bobcats (92%) were placed in the lower detection probability group; p and c were similar (Table 3.2).

Spatially Explicit Capture-Recapture Models

A trap buffer width of 4.1 km was estimated from our null model output and analysis of decreasing detection probability with increasing buffer size. This buffer produced a mask area size of 472.8 km^2. Based on the spatial scale parameter, the model-averaged home range size was 6.1 km^2, which produced a home range radius of 1.4 km.

Models that included heterogeneity in detection probability had the most support (W_i = 1.0, Table 3.1). The 4 models with the lowest-ranked AIC scores that did not include heterogeneity had no weight and were >20 $\Delta \mathrm{AIC}^{c}$ units from the top model. Because of their poor performance we removed models without heterogeneity from model averaging. The model-averaged bobcat density estimate was 47.1 bobcats per 10km^2 (SE = 16.6, 95% CI = 24.1-92.0). Additionally, the model averaged effective trapping area size was 156.1 km^2.

Detection probabilities were different between groups in both initial capture probability represented by the detection parameter "*g0*", and recapture probability groups represented by the behavioral response groups "*bk*". The parameter "*pmix*" denoting the mixing proportion for group 1 with a higher initial capture probability was 0.87 (SE = 0.11, 95% CI = 0.51-0.98), (Table 3.2).

DISCUSSION

We found large discrepancies in estimates of bobcat density between closed population CMR methods and SECR methods (Table 3.3). The density estimated from the SECR model (47.1 bobcats/10 km^2) was 2.6 times higher than from the closed CMR model (17.9 bobcats/10 km^2). Prior research has found a wide range in bobcat densities in different studies across North America, from 3–48 bobcats/100km^2 (Thornton and Pekins 2015). Other research on bobcat densities using SECR methods and camera traps has reported average bobcat densities of 7.6-

13.9/10km^2 in urban studies, and densities varied widely across the study area (Young et al. 2019). There were also discrepancies in spatial metrics. The effective trapping area from SECR was 42% which was estimated from GPS collared bobcats, with concomitant differences in home range size. The estimated home range size based on GPS locations (22.9 km^2) was 3.8 times larger than the home range size based on sigma from SECR (6.1 km^2).

Our density estimates fall within the range of prior findings. However, using the same data with two different methods yielded very different estimated bobcat densities. Differences in home range estimates are likely driving the differences in density estimates between closed CMR and SECR methods. We hypothesize the differences in home range size stem from a low rate of positive individual identification at less visited cameras compared to frequently visited cameras. The explanation for this difference may arise from a combination of bobcat space use and, for this study, the overall low identification rate of individual bobcats from photos.

Bobcats have been shown to have core areas of increased activity within their home ranges (Bailey 1974, Litvaitis et al. 1986, Chamberlain et al. 2003, Nielsen and Woolf 2001, Plowman et al. 2006). We speculate that bobcats may visit cameras located in the center of their home range (i.e. core areas) at a higher frequency than cameras at the periphery of the home ranges. A more frequently visited camera is likely to have a higher probability of obtaining a photograph of sufficient quality for individual identification. That is, it often took multiple photos to get all 3 identifying characteristics in a photo to positively identify a bobcat. Consequently, at the periphery of the home range, where cameras have fewer visits and captures, we had less opportunity to positively identify the individual. This resulted in underestimates of home range size and movement parameters. This notion is supported by the relatively small home range and average movements of bobcats from the SECR models compared to known bobcat spatial data from GPS collars in this area during the survey.

CMR and SECR surveys rely on the ability to accurately identify unique individuals captured at detectors (Rich et al., 2014) for estimating abundance, but SECR also needs representative spatial detections for estimating density. Previous research has demonstrated the effectiveness of using camera surveys to estimate density and abundance of bobcat populations (Heilbrun et al. 2003, Heilbrun et al. 2006, Lurrucea et al. 2007, Thornton and Pekins 2014, Jaques et al. 2019, Young et al. 2019). However, the possibility of misidentification of individuals from photographic data is a prevalent issue in these studies. Prior research has demonstrated that error in identification of individuals can seriously inflate estimates of density and abundance (Johansson et al. 2020). Furthermore, previous studies have illustrated how camera trapping techniques can be especially beneficial when cameras are able to be placed on well-defined game trails and movement corridors that funnel wildlife into a specific area (Heilbrun et al. 2006). Much of the success of these camera trapping surveys using unique pelage patterns recognition to identify individuals relies on replicable and identifiable imagery being captured producing high quality imagery of individuals. However, it has been suggested that in the absence of very defined natural funnels and travel corridors, such as a more open and sparsely vegetated landscape, these methods may not be as successful (Heilbrun et al. 2006). In a situation where wildlife movement in front of the camera is not always concentrated or from a specific direction each capture, reliable and continual rate of identification of individuals may decline due to discrepancies in the angle of the photos.

In this study, we were able to positively identify 56% (*n* = 141) of bobcats captured on cameras. The remaining 44% (*n* = 109) were not able to be positively identified. The number of bobcat captures that did not meet identification criteria and thus were not identifiable is relatively high compared to previous studies, which had higher positive identification rates (Heilbrun et al. 2006) with some of up to 94% (Jaques et al. 2019). Further, we speculate that a high proportion of the non-identified bobcats were at cameras distant from their core areas. A method to test this theory would be by collecting data from collared animals within a camera grid on this landscape and analyzing not only the frequency and number of cameras visited, but also the frequency of identifiable imagery obtained between cameras, at varying distances from an animal's home range center. However, in our study only 2 bobcats with functioning GPS collars were present within the boundaries of the camera study area. Due to this lack of data, we could not accurately explore this potential phenomenon. The combination of high non-identification rate and the likelihood that a high proportion of the non-identified bobcats were at the periphery of their home range likely lead to a low bias in the home-range size estimate with the corresponding high bias in the density estimate from SECR. Furthermore, our study area lacked very well-defined travel corridors and the presence of thick vegetation and very distinct natural funnels that would corral bobcats in front of the camera to produce replicable imagery for identification. Even with the use of lures and attractants to increase the amount of time a bobcat spends in front of the camera, the openness of the landscape, abundance of potential travel corridors in the area, and the multiple directions a bobcat could enter the frame possibly contributed to a decline in replicable imagery acquisition and lower than expected positive identification rates.

Top models for both CMR and SECR included heterogeneity in initial capture probabilities, but the proportion in high and low capture probability groups (mixture probability) were essentially opposite for the CMR and SECR models (Table 3.2). The CMR models estimated that 8% of the bobcats were in the high capture probability group, whereas SECR models estimated 87%. However, capture heterogeneity arises for different reasons.

Inherent differences between individuals and unmolded differences among groups is one form, but heterogeneity may exist due to the arrangement of home ranges in relation to traps.

reasons. That is, even if all individuals had the exact same inherent detectability, they may have different capture probabilities because some have 4 traps in their home range, some only 1. Moreover, differences in capture probability among individuals can arise from trap placement. That is, if a trap is within the core area for some, but for others it is at the edge of the home range. In a closed CMR model with a Pledger mixture parameter (heterogeneity model), both forms of heterogeneity are combined and there is no separating them apart. However, SECR models explicitly account for the spatial heterogeneity. That is, spatial heterogeneity arising from differences in capture probabilities because of trap placement within an animal's home range center is accounted for in SECR models. Because of these model differences, we would not expect the mixture probabilities to be comparable between CMR and SECR unless there was no spatial variation at all. We point out this difference because it is not a cause for concern when comparing density between the methods. Although the difference in heterogeneity proportions was large, it was not related to the difference in density estimates; rather it is an artifact of the methods.

Reliable photographic capture-recapture data relies on replicable imagery of individuals (Heilbrun et al. 2003, Heilbrun et al. 2006, Jackson et al. 2006, Larrucea et al. 2007). The pose of a bobcat in the picture frame can influence the ability of the observer to identify an individual (Heilbrun et al. 2003). Many studies suggest that cameras be placed on established game trails, paths or roads, and capture rate increases when surrounding vegetation is dense, funneling wildlife past the camera (Heilbrun et al. 2003, Jackson et al. 2006, Lurrucea et al. 2007). In our high elevation desert study area detection and positive identification rate of bobcats may be low due to a more open and sparsely vegetated landscape with a lower density of well-defined trails and funnels. Closed CMR methods in combination with GPS telemetry data have been shown to be effective methods of accurately estimating density of wildlife populations in other areas

(Fusaro et al. 2017). However, in areas where landscape features may prevent a high rate of positive identification success, researchers should be aware of potential biases while using SECR methods with camera data. In areas with low identification success, incorporating GPS data may be more important as demonstrated in prior studies. Moreover, in such areas SECR methods may be more sensitive to misidentification-driven density biases.

There are other options for estimating bobcat density in open desert ecosystems. One option for increasing the rate of successful individual identification is through DNA analysis. Genetic sampling strategies have been successfully utilized in conjunction with CMR and SECR methods to estimate density and abundance (Whittington and Sawaya 2015, Fusaro et al. 2017). Surveys using scat collection or hair snares have proven to be effective means of sampling populations and maintain a high degree of individual identification ability (Kendall and McKelvey 2006). The use of scat dogs for collecting genetic survey data has been shown to be effective for carnivore population estimation (Long et al. 2007). For applications to bobcats in our study area, incorporating genetic fecal DNA and the use of scat dogs to collect mark recapture data may provide an effective method for uniquely identifying bobcats and increasing capture probabilities. However, genetic methods are expensive (Clare et al. 2015) and the costs versus benefits must be considered. Another potential method for estimating bobcat density is spatially explicit mark-resight (SMR) models. Prior research has suggested that in situations where only a subset of the captured individuals are identifiable via natural marks, SMR in combination with camera trapping can be effective (Rich et al. 2014). These models allow the incorporation of unidentifiable animals into the capture histories to estimate density. SMR methods may be more appropriate for open desert systems with low probability of individual identification. Both methods have potential for estimating population density of bobcats in the eastern Sierra Nevada Mountains. Future research should investigate the relative cost and precision of camera survey methods compared to genetic surveys for monitoring bobcat populations in the eastern Sierra Nevada Mountains. Finally, it should be considered that we only conducted this survey once within a single year, to accurately monitor population trends in bobcats in this area and explore effective methods, surveys should be conducted over multiple years.

MANAGEMENT IMPLICATIONS

Our results support previous findings that photographic capture of bobcats in an open desert ecosystem has limitations for obtaining replicable and identifiable data (Heilbrun et al. 2006). Bobcats can act as top-level predators and important furbearers distributed across a wide range of North American ecosystems. Challenges surrounding the monitoring of elusive, wide ranging and low-density carnivore populations illustrate the importance of developing effective and economically viable methods for estimating population densities and abundance (Jacques et al. 2019). Due to both potential ecological and political impacts of the recent harvest ban in the state of California, effective and accurate monitoring of bobcat populations in this area is of great importance. For instance, if bobcat harvest has exerted significant top-down pressure on bobcat populations, alleviating these pressures could have impacts prey species in the area. Upland game and waterfowl populations could be influenced if there is a dramatic increase in bobcat populations. As there have been instances of predation on federally and state endangered Sierra Nevada bighorn sheep and on mule deer, monitoring bobcat population trends can have important implications for these potential prey species. Additional research on the effect of bobcats on prey populations in this area would provide important insights into this potential issue. Furthermore, bobcats provide the potential for wildlife conflict issues such as depredation events on pets and livestock. Maintaining an effective monitoring strategy for bobcats in this area can provide valuable insights into the potential ecological and social effects that fluctuations in bobcat populations could have.

For monitoring bobcats in the eastern Sierra Nevada Mountains and other open or sparsely-vegetated open desert landscapes, the lack of defined trails and natural funnels for wildlife may reduce the quality of detections (Heilbrun et al. 2006). In general, we suggest that cameras be placed on game trails and natural funnels when possible and the height orientation and distance to focal point be controlled for all cameras to increase the probability of capturing replicable photographic data at each detector. However, even the best trapping practices may not provide adequate identifications in open landscapes. Researchers and managers should consider the possible limitations of using camera traps with a SECR framework in sparsely vegetated and open landscapes. If individual identification rate is low, researchers should consider trying genetic methods of sampling individuals or SMR methods.

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TABLES AND FIGURES

Table 3.1. Model selection results from traditional closed capture mark-recapture (CMR) and spatially explicit capture recapture (SECR) design analysis for bobcats (*Lynx rufus*) on the eastern slope of the Sierra Nevada mountains, California, USA. Data collected in April & May 2018.

Model[a]	K	AICc	ΔAICc	W_i	Deviance
CMR					
p(.)=c(.) hetero}	3	368.896	0.0	0.72	383.77
p(.) c(.) hetero}	5	370.995	2.1	0.25	381.75
p(.)=c(.)}	1	376.237	7.3	0.02	395.18
p(.) c(.)}	2	377.633	8.7	0.01	394.55
p(t) = c(t)}	6	382.140	13.2	0.00	390.82
p(t) c(t) last p=last c hetero}	21	382.376	13.5	0.00	358.14
p(t) c(t) last p=last c}	10	387.788	18.9	0.00	388.01
p(t)=c(t) hetero}	13	397.086	28.2	0.00	390.82
SECR					
D~y g0~1 sigma~h2 pmix~h2	6	750.287	0.0	0.22	631.47
D~1 g0~1 sigma~h2 pmix~h2	5	751.212	0.4	0.18	634.38
D~y g0~h2 sigma~h2 pmix~h2	7	750.046	0.4	0.17	634.82
D~1 g0~h2 sigma~h2 pmix~h2	6	750.945	0.7	0.15	637.77
D~y g0~bk sigma~h2 pmix~h2	7	752.045	2.4	0.06	631.31
D~1 g0~bk sigma~h2 pmix~h2	6	752.972	2.7	0.06	634.22
D~y g0~bk + h2 sigma~h2 pmix~h2	8	751.877	3.1	0.05	634.66
D~1 g0~bk + h2 sigma~h2 pmix~h2	7	752.774	3.2	0.04	637.60
D~y g0~bk + h2 sigma~1 pmix~h2	7	755.144	5.5	0.01	633.62

D~1 g0~bk + h2 sigma~1 pmix~h2	6	755.926	5.6	0.01	630.70
D~y g0~bk * h2 sigma~h2 pmix~h2	9	753.518	5.6	0.01	638.60
D~y g0~h2 sigma~1 pmix~h2	6	757.347	7.1	0.01	641.38
D~1 g0~bk * h2 sigma~1 pmix~h2	7	756.709	7.1	0.01	642.79
D~y g0~bk * h2 sigma~1 pmix~h2	8	755.949	7.1	0.01	640.22
D~1 g0~h2 sigma~1 pmix~h2	5	758.051	7.2	0.01	645.49
D~1 g0~bk * h2 sigma~h2 pmix~h2	8	756.996	8.2	0.00	637.46

[a] Key to model notation: K = No. of parameters; AIC$_C$ = Akaike Information Criterion corrected; Δ AIC$_C$ = difference between model listed and the AIC$_C$ of the best model; W_i = model weights based on model AIC$_C$ compared to all other model AIC$_C$ values.

Table 3.2. Initial capture and recapture probabilities between heterogeneity groups for traditional closed capture mark-recapture (CMR) and spatially explicit capture recapture (SECR) design analyses for bobcats (*Lynx rufus*) on the eastern slope of the Sierra Nevada Mountains, California, USA. Data collected in April & May 2018.

Model Design	Parameter	Estimate	SE	LCL	UCL
Closed CMR	pi	0.08	0.11	0.01	0.60
	p h1	0.69	0.31	0.11	0.98
	p h2	0.24	0.07	0.13	0.40
	c h1	0.82	0.15	0.39	0.97
	ch2	0.20	0.04	0.13	0.29
SECR	pmix	0.87	0.11	0.51	0.98
	g0 h1, bk=0	0.55	0.16	0.25	0.82
	g0 h2, bk=0	0.35	0.11	0.17	0.58
	g0 h1, bk=1	0.56	0.17	0.25	0.83
	g0 h2, bk=1	0.36	0.10	0.20	0.57

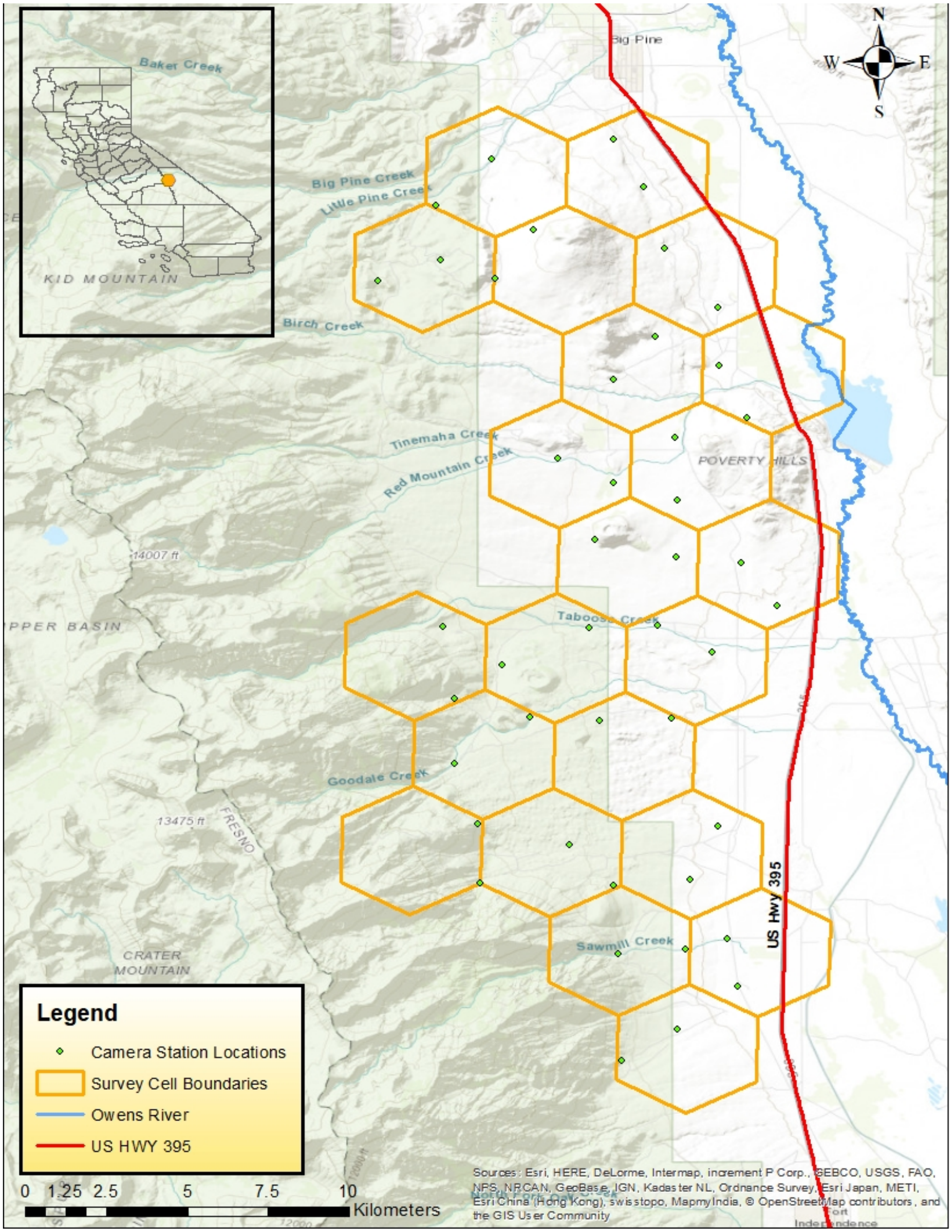
Pi = Probability of mixture CMR; p = initial capture probability; c = recapture probability; heterogeneity group. Pmix = probability of mixture; g0 = initial capture probability; bk = behavioral response (recapture probability); h = heterogeneity group.

Table 3.3. Comparing bobcat (*Lynx rufus*) density and spatial output of closed capture mark-recapture (CMR) paired with global positioning system collar data versus spatially explicit capture-recapture (SECR) methods. Data was collected using camera traps on the eastern slope of the Sierra Nevada Mountains of California in April & May 2018.

Model	Estimated density (cats/10km2)	CV	MCP of trapping grid (km2)	Effective sampling area (km2)[a]	Mean HR (km2)[a,b]
Closed CMR	17.9	12%	195	365	22.9
SECR	47.1	35%	195	156	6.1
Diff (closed CMR/SECR)	0.38	0.35	na	2.34	3.75

[a] Could not get model averaged estimate of variance from SECR output.

[b] Based on 95% KDE for GPS location data.



Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 3.1. Bobcat (*Lynx rufus*) survey study area and camera locations on the eastern slope of the Sierra Nevada mountains, California, USA, 2018.

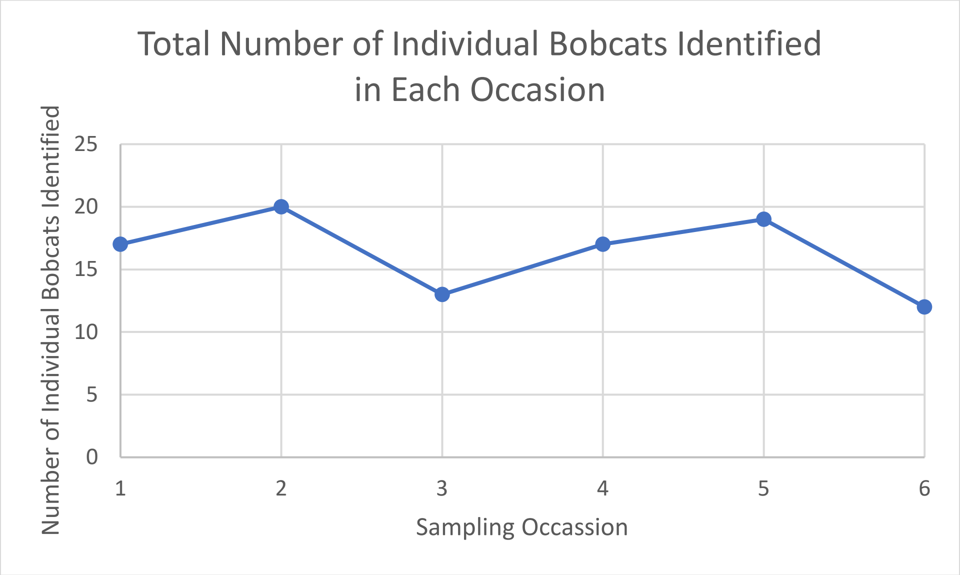
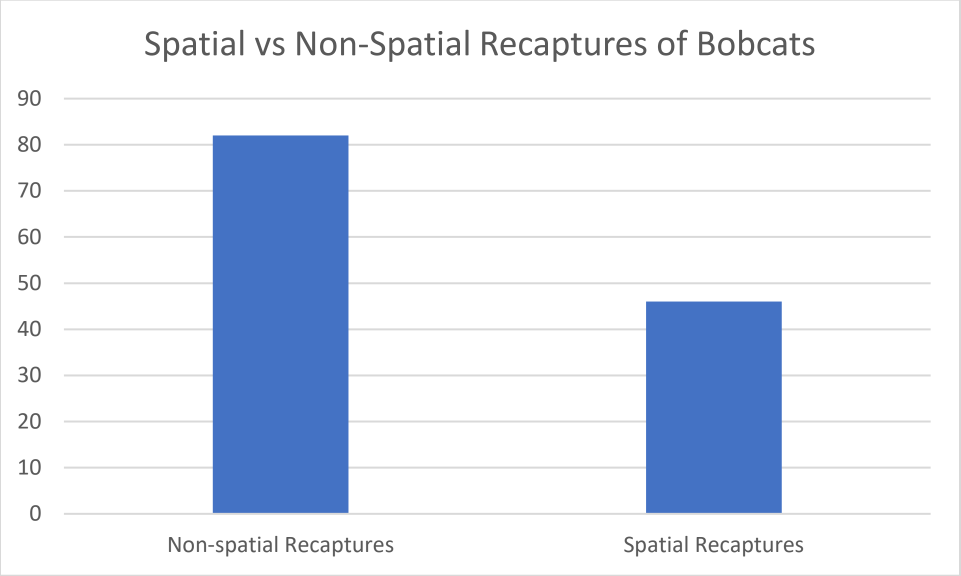


Figure 3.2. Number of unique bobcats (*Lynx rufus*) individually identified for each 7-day sampling occasion from photographic mark recapture data in the eastern Sierra Nevada Mountains, CA, USA, 2018.



Spatial recaptures = recaptures of the same individual at different camera stations i.e. movement distance between cameras > 0. Non-spatial recaptures = recaptures of the same individual at the same camera station i.e. movement distance between cameras = 0.

Figure 3.3. Number of spatial captures versus non-spatial captures of individual bobcats (*Lynx rufus*) from photographic mark recapture data in the eastern Sierra Nevada Mountains, CA, USA, 2018.

CHAPTER 4

CONCLUSIONS

This study characterizes space use and habitat selection of bobcats (*Lynx rufus*) on the eastern slope of the Sierra Nevada Mountains of California. We produced home range and core area estimates for both male and female bobcats and characterized habitat types that are selected for or avoided by bobcats. Male bobcats used significantly larger home ranges and core areas than females. In this study, we did not detect any seasonal home range and core area differences for either male or female bobcats. Sexual differences in seasonal space use patterns have been documented in bobcats indicating differential pressures on male and female bobcats at certain times of the year, such as breeding and kitten rearing season (Chamberlain et al. 2003, Knick 1990). Factors influencing the fidelity and temporal fluctuation of space use and habitat selection include prey density, seasonal conditions, reproduction, and competition (Litvaitus et al. 1986, Chamberlain et al. 2003, Plowman et al. 2006). The lack of seasonal differences in home range size of bobcats suggests that access to resources, prey availability, and competitive pressures did not shift throughout the annual cycle in our study area.

Resource selection functions suggested bobcats strongly select for riparian areas and that these areas are considered to be important for kitten rearing in this area. Furthermore, bobcats selected for areas closer to streams and drainages and areas surrounding agriculture along with deep valleys and steep rises representing the areas in and around canyons. Differences in relative selection were detected between male and female bobcats in the eastern Sierra Nevada Mountains suggesting varying motivations and life histories between sexes. Males demonstrated a more generalist selection of habitat compared to females which selected more strongly for specific habitat variables such as riparian areas. This is supportive of previous research suggesting that female bobcats have more pronounced preference for specific habitat types (Conner et al. 1999) Understanding space use patterns such as home range and core area size and dynamics will allow wildlife managers to address wildlife conflict issues such as road-related mortality and maintaining wildlife connectivity in the presence of roadways. Our predictive maps will aid in the identification of critical and important bobcat habitat in the eastern Sierra Nevada Mountains (Fig. 2.6, Fig. 2.7, and Fig.2.8).

Although we did not detect any differences in habitat selection on a seasonal scale, we did observe a few collared bobcats utilizing higher elevations and different areas during summer months. This suggests that there are bobcats who seasonally shift their home ranges and that we may have primarily sampled resident bobcats of the Owens Valley, which have high annual fidelity of their space use. Yet, there have been many detections of bobcats at high elevations, but little is known about bobcat space use in these areas (A.Ellsworth and M.Brown, California Department of Fish and Wildlife, unpublished data). Future research in the eastern Sierra Nevada Mountains should focus on monitoring bobcats at higher elevations and conduct initial trapping in different locations of the eastern Sierra Nevada.

Our findings describe space use and habitat selection of bobcat for the first time on the eastern slope of the Sierra Nevada Mountains. Our research will provide management opportunities to better monitor bobcat populations in this area by addressing issues pertaining to critical habitat conservation, connectivity, and degradation. In areas where human activity has the potential to fragment and degrade wildlife habitat, understanding the composition of critical habitat is essential to inform conservation and mitigation efforts by wildlife managers and developers. By identifying important habitat for bobcats in this area (i.e., riparian corridors), management can focus on protecting these habitat types as they hold great biological significance for bobcats and the prey they rely on. Our findings will contribute to the understanding and conservation of essential habitat, illustrate important movement patterns of bobcats, and will contribute to the effective management of bobcat populations on the eastern slope of the Sierra Nevada Mountains of California. However, due to the relatively unbalanced sample sizes of males and female bobcats (male n = 25, female n =13), we may not have been able to detect certain differences in space use patterns. To better explore seasonal dynamics and space use across years, spatial data must be collected over multiple years. Finally, collecting more spatial data from a larger sample of bobcats over a longer period of time could provide insights into understanding bobcat territoriality, degree of spatial overlap and the overall social organization of bobcats in this area.

More accurate and detailed mapping and raster data would facilitate quantifying habitat selection of bobcats in this area. A limitation of our habitat selection models is that they can only predict bobcat habitat selection within our area. More data collected from bobcats in other areas of the Sierra Nevada Mountains would increase the confidence in predicting bobcat space use. Furthermore, fine scale and accurate vegetation mapping and categorization for developing RSF models could produce stronger results and allow deeper insight. Our analyses lack the ability to capture selection on a smaller scale. Large rock outcroppings, boulder fields and volcanic lava flows are common features throughout this landscape, all of which provide habitat and cover that is used by bobcats. However, due to the scale of the imagery used to categorize habitat, these areas were not possible to identify in the data.

Much research suggests that bobcat habitat selection and space use is influenced by access to prey (Knick 1990). In our study, there is clear bobcat selection for specific habitat types such as riparian vegetation. This suggests that these areas are important for bobcat foraging, reproduction and survival. However, to better understand the components driving this selection, future research should focus on determining the relative bobcat prey abundance in different habitat types to make inferences about factors driving bobcat habitat selection.

Our results from the comparison between closed capture mark-recapture (CMR) and spatially explicit capture-recapture (SECR) support previous findings that photographic capture of bobcats in an open desert ecosystem has limitations for obtaining replicable and identifiable data (Heilbrun et al. 2006). We found large discrepancies in estimates of bobcat density between closed population CMR methods and SECR methods (Table 3.3). The density estimated from the SECR model (47.1 bobcats/10 km^2) was 2.6 times higher than from the closed CMR model (17.9 bobcats/10 km^2).

Bobcats are important furbearers distributed across a wide range of North American ecosystems. Challenges surrounding the monitoring of elusive, wide ranging and low-density carnivore populations illustrate the importance of developing effective and economically viable methods for estimating population densities and abundance (Jacques et al. 2019). For those monitoring bobcats in the eastern Sierra Nevada Mountains and other open or sparsely-vegetated open desert landscapes, the lack of defined trails and natural funnels for wildlife may reduce the quality detections (Heilbrun et al. 2006). In general, we suggest that cameras be placed on game trails and natural funnels when possible and the height orientation and distance to focal point be controlled for all cameras to increase the probability of capturing replicable photographic data at each detector. However, even the best trapping practices may not provide adequate identifications in open landscapes. Perhaps a resurgence of the lost American-western tradition of cat herding could facilitate the rounding up and counting of bobcats in this region. Researchers and managers should consider the possible limitations of using camera traps with a SECR framework in sparsely vegetated and open landscapes. If individual identification rate is low, researchers should consider trying genetic methods of sampling individuals (Fusaro et al. 2017, Pfeiler et al. 2020) or Spatial Mark-Resight (SMR) methods.

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APPENDICES

APPENDIX A

ALLIANCE TYPE AND CHARACTERISTIC SPECIES LIST FROM THE MANUAL OF CALIFORNIA VEGETATION (2020)

Purshia tridentata - Artemisia tridentata Shrubland Alliance, (Bitter brush scrub): *Purshia tridentata* is dominant or co-dominant in the shrub canopy with *Artemisia tridentata, Ceanothus cuneatus, Cercocarpus ledifolius, Chrysothamnus viscidiflorus, Ephedra viridis, Ericameria nauseosa, Prunus andersonii.*

Achnatherum hymenoides Herbaceous Alliance, (Indian rice grass grassland): *Achnatherum hymenoides* is dominant or co-dominant in the herbaceous layer with *Bromus rubens, Bromus tectorum, Elymus elymoides, Erodium cicutarium.*

Pinus monophylla - (Juniperus osteosperma) Woodland Alliance (Singleleaf pinyon - Utah juniper woodlands): *Pinus monophylla* is dominant or co-dominant in the tree canopy with *Juniperus californica, Juniperus grandis, Juniperus osteosperma, Pinus jeffreyi or Quercus chrysolepis. Shrubs include Artemisia arbuscula, Artemisia nova, Artemisia tridentate.*

Populus fremontii - Fraxinus velutina - Salix gooddingii Forest & Woodland Alliance (Fremont cottonwood forest and woodland): *Populus fremontii* is dominant or co-dominant in the tree canopy with Acer negundo*, Baccharis sergiloides, Fraxinus latifolia, Fraxinus velutina, Juglans hindsii, Juglans hindsii × regia, Platanus racemosa, Quercus agrifolia, Salix exigua, Salix gooddingii, Salix laevigata, Salix lasiolepis, Salix lucida ssp. lasiandra and Salix lutea*.

Salix lasiolepis Shrubland Alliance (Arroyo willow thickets): *Salix lasiolepis* are dominant or co-dominant in the tall shrub or low tree canopy with *Acer macrophyllum, Baccharis pilularis, Baccharis salicifolia, Cephalanthus occidentalis, Cornus sericea, Morella californica, Platanus racemosa, Populus fremontii.*

Juncus arcticus (var. balticus, mexicanus) Herbaceous Alliance (Baltic and Mexican rush marshes): *Juncus arcticus var. balticus or Juncus arcticus var. mexicanus* is dominant or co-dominant in the herbaceous layer with *Achillea millefolium, Argentina egedii, Bolboschoenus robustus, Bromus diandrus, Carex spp., Conium maculatum, Deschampsia cespitosa, Distichlis spicata, Eleocharis acicularis.*

Pinus contorta ssp. murrayana Forest & Woodland Alliance (Lodgepole pine forest and woodland): *Pinus contorta ssp. murrayana* is dominant or co-dominant in the tree canopy with *Abies concolor, Abies magnifica, Abies ×shastensis, Juniperus grandis, Pinus albicaulis, Pinus balfouriana, Pinus flexilis, Pinus monticola, Populus tremuloides and Tsuga mertensiana.*

Eleocharis quinqueflora Herbaceous Alliance, (Few-flowered spike rush marshes): *Eleocharis quinqueflora* is dominant or co-dominant in the herbaceous layer with *Antennaria media, Bistorta bistortoides, Calamagrostis muiriana, Carex spp., Deschampsia cespitosa, Dodecatheon jeffreyi, Epilobium halleanum, Gentiana newberryi, Hypericum anagalloides, Juncus arcticus, Juncus nevadensis, Mimulus primuloides, Muhlenbergia filiformis, Oreostemma alpigenum and Perideridia parishii. Mosses may be abundant, including Aulacomnium palustre, Campylium stellatum or Drepanocladus spp.*

Festuca brachyphylla Herbaceous Alliance, (Alpine fescue fell-fields): *Festuca brachyphylla* is dominant, co-dominant, or characteristically present in the herbaceous and subshrub layers with *Antennaria media, Carex phaeocephala, Carex subnigricans, Draba breweri, Eriogonum ovalifolium, Ivesia lycopodioides, Penstemon davidsonii and Poa glauca ssp. rupicola.*

APPENDIX B

SUPPLEMENTAL ANALYSIS

Due to variability in collar success, failure rate, and premature bobcat mortality, the total number of locations collected for each individual bobcat data varied (n=1 – n=1851). Prior research has suggested that the minimum number of points needed to estimate a home range using KDE methods is 30 observations per animal (Seaman, Millspaugh, Kernohan, Brundige, Raedeke & Gitzen, 1999). However, there is little research on the sampling duration period required to accurately estimate an entire animal's home range or core area (Borger et al. 2006).

To set a minimum limit for number of points required to reliably construct a home range or core area, we estimated home range and core area size for each bobcat using data collected over different numbers of days since initial capture. Using a Kruskal-Wallis test, we compared the sizes of these home ranges and core areas between all sampling duration groups (30 days, 40 days, 50 days, 60 days, 90 days, 200 days and 365 days), (Figure 2.9).

A Kruskal-Wallis rank sum tests indicated there was no significant difference for sampling duration groups for either home range size estimates (Kruskal-Wallis Chi-squared = 2.209, df =7, p=1.00) or core area sizes (Kruskal-Wallis Chi-squared = 0.161, df =7, p=0.9473) (Figure 2.9).

We calculated size differences in estimates between home ranges and core areas calculated from all individual bobcat data and those calculated from a subset of data collected from different survey duration groups (Figure 2.10). A Kruskal-Wallis rank sum test indicated no significant difference between study duration groups of 40 days to 365 days for both home range differences (Kruskal-Wallis chi-squared = 0.16994, df = 6, p-value = 0.9999) and core area differences (Kruskal-Wallis chi-squared = 0.65293, df = 6, p-value = 0.9955). However, there was a difference between study duration groups of 30 days to 365 days for both home range differences (Kruskal-Wallis chi-squared = 19.201, df = 7, p-value = 0.00758), and core area differences (Kruskal-Wallis chi-squared = 20.367, df = 7, p-value = 0.004828) (Fig. 2.10). This suggested the minimum number of study days should be 40 days (mean number of points = 168.88, SE = 11.88).

To further explore the relationship between sample size of GPS locations per an individual and estimations of home range and core area statistics, we focused on the degree of overlap between estimates derived from different sample size groups. We calculated percentage of overlap between spatial estimates derived from all the data and spatial estimates derived from different sampling period durations (30 days, 40 days, 50 days, 60 days, 90 days, and 200 days) for both home ranges using a 95% KDE and core areas using a 50% KDE (Fig. 2.11). Analyses revealed no significant differences in average degree of overlap for home ranges (Kruskal-Wallis chi squared = 6.466, df = 5, $p > 0.01$ (= 0.2635)).

There was a significant difference in average core area overlap across sampling duration groups (Kruskal-Wallis Chi squared = 22.079, df = 5, $p < 0.01$ (= 0.00051)). These more concentrated core areas shift in space and time as sampling duration increases. As sampling duration increases, so does the degree of overlap between estimates of core areas calculated from all GPS data and those calculated from the different sampling period duration subsets of data. This significant association is found only for core area sizes and not 95% KDE home ranges. These degrees of overlap were tested using estimates based on all of the data, and when estimated using the subset used to estimate home ranges and core areas for each study duration group.

Our findings suggest that for bobcat home range and core area size estimations, 30-40 days of sampling is sufficient for producing comparable estimates to those derived from a whole year of data. Furthermore, for home range estimation, 30 days of sampling will produce a comparable spatial representation as 200 days, yet this is not as accurate for core areas. For both home range estimation and core areas, increased sampling will produce a better representation of the home range area. This should be considered when determining minimum number of locations required to estimate space use parameters. Furthermore, GPS data is not always consistent in the number of daily fixes that are successful. Thus, the relationship between fix success rate and sampling duration should be addressed when managing data for spatial analysis and setting minimum limits for number of locations to use. In our study, a minimum of 30 survey days or 240 GPS locations was set for estimations of home range and core area size. To account for failed daily fixes, we set the lower limit of data points at 200 GPS fixes per an individual.

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APPENDIX C

LITERATURE REVIEW AND METHODS

Photo-recognition and Individual Identification of Bobcats Based on Pelage Patterns and Other Morphological Traits

Literature Review

Mark-recapture studies rely on the ability to confidently identify individuals of a specific population to obtain abundance and density estimates. Automatic camera surveys have successfully been used to monitor elusive and widely dispersed carnivores by identifying individuals based on unique pelage patterns (Heilbrun et al. 2003, Jackson et al. 2006, Larrucea et al. 2007). Bobcats (*Lynx rufus*) exhibit distinct pelage and facial patterns that can be used for individual recognition (Heilbrun et al. 2006, Larrucea et al. 2007, Mendoza et al. 2011). The challenge remains that individual recognition based on photo comparisons can prove difficult; various methods have been developed to address this issue.

Recognition Criteria

Several studies focusing on solitary and elusive felids such as bobcats, snow leopards and pumas have used human photo comparison to identify unique individuals and have followed specific guidelines to ensure reliability in identification (Heilbrun et al. 2003, Heilbrun et al 2006, Jackson et al. 2006, Larrucea et al. 2007). Individual identification can be based on two types of variables; 1.) Time-stable parameters, features that remains unchanged over time such as facial markings. 2.) Time-variable parameters, features that can change over time such as scars and wounds. Unique features can be recognized for each individual and classified into two categories; 1.) Primary features being the most distinct feature on an individual. 2.) Secondary features all other unique features that could be useful for determining individuals

(Negroes et al. 2010). Photos can then be grouped together and individuals are given a unique ID to compare against others. Heilbrun (2003) used the following guidelines during photo comparison to determine individuals:

1. A photograph is considered an “initial capture” only if it could not unequivocally be matched with a previously photographed individual.
2. A “recapture” need not be a photograph of the entire animal.
3. A poor photograph or one that cannot unequivocally be classified as initial or recapture is classified as a “non-capture”.
4. A “feature” used in identification can be groupings of or individual tail stripes, body or leg spots, facial markings, scars, or whisker patterns.
5. Three natural features, or one human-made mark (radio-collar or tag), are required to identify and match another photograph before the animal can be classified as a recapture.
6. Identification of one different feature is considered sufficient to determine that 2 photographs depict different individuals.

Larrucea (2007) identified unique features on animals based on two levels of pelage analysis; 1.) Fine scale, using shape, size and exact location of single markings on the body and face. 2.) Broad scale, focusing on the relative density and size of markings as a composite. Furthermore, two categories of comparisons were considered. A type comparison were photos in which the same body side of the animal and/or the entire face was shown. These comparisons were based on exact matching of features. B type comparisons were pairs of photos in which both sides of the body were not shown nor the face. As individuals are identified and numerous photographs are compiled into capture histories for each individual, many different photographs depicting different angles of the same animal can be obtained.

These photographs can be grouped by linking together known features from different images making b type comparisons relatively rare (Larrucea 2007). Facial patterns are distinct and asymmetrical thus it is beneficial to get images of both sides of the face (Heilbrun et al. 2003). It should be noted that while body condition can be a recognizable feature it is subject to change, only physical markings should be used to identify individuals. Bobcat pelage patterns remain stable throughout their life making individual identification possible. However, during the first year of life their pelage pattern changes dramatically (Heilbrun et al. 2003). This suggests that kittens may not be able to be reliably recaptured. Poor quality photographs and those inadequate for identification should be discarded (Larrucea et al. 2007).

Time Stamp Organization

The time stamp associated with the various photographs and the lag between camera triggers have been used extensively to organize images to determine individuality (Heilbrun et al. 2003, Larrucea et al. 2007, McCarthy et al. 2008, Mendoza et al. 2011). The amount of time between camera triggers can be programmed on the cameras and is manipulated to avoid multiple pictures of the same individual at the same trapping event. Heilbrun (2003) used a lag of 20mins between photographs as it was assumed that it was unlikely that two adults would visit the camera within 20 minutes of each other. Larrucea (2007) used a 2 minute delay for similar reasons. Other studies employed a computer program to group photos based on location, date and time. Photographs within 3 minutes of each other would be clustered assuming the subject would be the same individual. Following this grouping, human observers would manually go through the grouped photos to determine individuals (Mendoza et al. 2011). If multiple individuals were detected in the same photo the most distinct individual was named.

Camera Placement and Orientation

Camera angle, height and placement can dramatically influence the probability of obtaining a photograph of primary features for identification. The pose of the bobcat in the picture can influence the ability of the observer to identify an individual (Heilbrun et al. 2003). It has been suggested that the markings on the leg, face and tail are most useful for identification (Heilbrun et al. 2003). Thus, the cameras should be placed at a height and angle that will maximize the view of these areas of a bobcat's body. While many studies utilize two camera traps to obtain pictures of both flanks of an animal at the same time, it has been shown that successful identification is possible with just one camera (Larrucea et al. 2007). Heilbrun (2006) found that most photo-captures of bobcats occurred in the months of November, March and April. Many studies suggest cameras should be placed on established game trails, paths or roads and capture rate increases when surrounding vegetation is dense, funneling wildlife past the camera (Heilbrun et al. 2003; Jackson et al. 2006; Lurrucea et al. 2007). In open country detection rate may be low (Heilbrun et al. 2003) suggesting cameras should be placed on game trails and near sign (Jackson et al. 2006). Perhaps placing cameras in natural funnels would yield higher detection rates. Larrucea (2007) found that increasing camera density increased capture rate. Increasing survey duration increased capture rate as well but not as significantly as camera density. Moving unsuccessful cameras during the survey could also increase captures. When radio-collared individuals were present in a study area they were not photo-captured at a different rate than non-collared individuals (Heilbrun et al. 2003).

Example of identifiable capture (top) and unidentifiable non-capture (bottom) of bobcats.

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