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Environmental Biology Masters Capstone

Antonio Gonzalez-Pita

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MS ENVIRONMENTAL BIOLOGY
CAPSTONE PROJECT

by

Antonio M. Gonzalez-Pita

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CAPSTONE PROJECT

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Antonio M. Gonzalez-Pita

has been approved

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APPROVED:

_____________________________________, John Sakulich, Ph.D. (Faculty Advisor)

_____________________________________, Daniela Rivarola, Ph.D. (Chapters 1 & 2)

_____________________________________, Tyler Imfeld, Ph.D. (Chapter 3)

_____________________________________, Mike Ghedotti, Ph.D. (Chapter 4)

_____________________________________, Ariel Wooldridge, M.S

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CHAPTER 1
LITERATURE REVIEW

Introduction

The alpine treeline ecotone is the zone between subalpine forests and alpine tundra where environmental constraints begin to limit tree growth and establishment (Körner et al., 2012). The treeline environment is characterized by a shift in species composition, distinct vegetal arrangement and densities, and the beginning of unique individual tree morphology characteristic of harsh environments. This area of abrupt shift in vegetation type is an important bioindicator of response to climate change due to the sensitivity of local species to climactic conditions (Harsch et al., 2011). A localized shift in environmental conditions which diverge from the historical norms have shown to have outsized effects on the treeline ecotones of the Southern Rockies (Feurdean et al., 2016).

Research aimed at determining future species establishment potential, tree growth patterns, density, climate resilience, and species composition is important to developing land management practices and will continue to provide insight into the anthropogenic impact on ecosystem response to global climate system alteration. Because these environments provide ecosystems services such as water retention and filtration, formation of soils and natural erosion control, climate regulation, and recreation (Perera et al., 2018; Orsi et al., 2020), their conservation and an understanding of the unique dynamics such as growth rates and climactic response is necessary.

The current literature on factors that affect treeline dynamics provides baseline conditions for monitoring. However, knowledge regarding how the changing climate will influence future treeline characteristics under anthropogenic influence is limited. In this literature review, I will summarize the influence of these factors on treeline dynamics, then identify knowledge gaps and recommend further areas of study for treeline areas located in the Southern Rocky Mountains to better understand the complex relationships of treeline dynamics. The influence of geomorphology, climate, species composition, and anthropogenic management practices will be the main focal points in this review. Because anthropogenic influence will continue to play a role in the alteration of treeline dynamics, continued monitoring and further site/region specific studies will inform future management and persistence of these dynamic ecotones.

The Southern Rocky Mountains, which encompass Colorado, Northern New Mexico, Wyoming, and Eastern Utah, provide a well-suited outdoor laboratory for scientific study due to the number of high elevation mountainous areas, aridity, climactic record availability, and long-term ecological research stations (LTERs) present for current monitoring efforts. A portion of these areas are also located near urban centers with large populations and provide ecosystem services for many communities dispersed throughout the region.

Treeline geomorphology and optics

Ecosystems found at high elevations and latitudes are disproportionally affected by anthropogenic climate change (Feurdean et al., 2016). The life stages, growth rates, and size of trees at high elevations can be markedly different from slightly lower elevations, maturing through their germling-seedling-sapling-tree life stages at different temporal scales than their lower neighbors. (Korner et al., 2012). Individuals, and clusters of trees, often exhibit stunted growth and compact statures under harsh conditions and shorter growing seasons – a phenomenon known as Krummholz (Aitken et al., 2008).

This size and structure gradient in these ecotones is rarely a sharp line or small band of a few meters depending on the spatial resolution used and scope of the observer; often occurring in fragmented sections across linear areas of tens or hundreds of meters, due to local geography and environmental characteristics. What may seem like a gradual gradient for the ground-based observer, when seen from satellite imagery or aerial vantage points, a distinct visual linear separation is often apparent (Kummel et al., 2021). Highly variable densities and overall structural habits form diffuse or stable groupings along the treeline highly dependent on precise location and influenced by factors such as slope, aspect, elevation, local weather patterns, and species.

Climate

Anthropogenic climate change is altering environmental conditions in the Southern Rockies, with unforeseen and often counterintuitive effects on local species. A decoupling of the seasonal water supply and type of precipitation historically evident in the region has profound effects on species inhabiting high elevation forested areas. Precipitation that used to fall as snow and slowly melt throughout the spring providing regular moisture, instead now falls as rain providing quick and inconsistent intervals of available moisture at the beginning of the growing season. A short-term water limitation may decrease leaf display and photosynthetic capability, meanwhile a longer and warming growing season may increase total growth capability and overall carbon sequestration in the ecosystem (Dong et al., 2019).

Studies that have recently quantified effects of climate change found significant alterations to local environmental conditions in the context of their respective historical range of variability. These changes have been documented in the Southern Rockies and quantified across other similar high elevation forest transitional zones across the world. Research of Australian treelines indicate that as the climate has warmed, precipitation regime change and snow cover has declined leading to densification and upslope migration of trees (Verral et al., 2023). Similarly, some forests in California's Sierra Nevada range have displayed a 69% increase in coniferous forest density within the last century (Dolanc et al., 2014). Recent climactic alteration in the Carpathian Mountain range of Romania also displayed a nonuniform, or inconsistent and noncontinuous, upslope migration pattern due to climate warming (Feurdean et al., 2016).

Current climactic projections and continued scientific research of environmental conditions will provide accurate data for the determination of future actions that will greatly affect the landscape. Predicting treeline dynamics based on current forest structure is a complicated and difficult process. Using treeline form, species compositional change, and elevational gradient as a proxy, however, has limitations. Because change in this ecotone is multifaceted, a nonlinear response to individual climactic interactions viewed from a single variable becomes highly complex (Harsch et al., 2011). Altered environmental variables, such as increased temperature and decreasing precipitation, may present responses that are incongruent with current climate prediction models which proposes continuously changing challenges for land managers (Dong et al., 2019; Maori et al., 2023). Species, even select individuals, oftentimes display unusual vigor due to distinct beneficial microhabitat and site-specific location rather than regional drivers in climate.

Species Composition

Certain tree species found at treeline in the Southern Rockies, such as bristlecone pine (*Pinus aristata*) and limber pine (*Pinus flexilis*), are especially sensitive to climactic factors over their millennial-long lifespan. By analyzing tree ring growth rates, a glimpse into historical environmental conditions is possible, offering unique perspectives of the past environmental conditions and species compositions by examining the rate and intensity of environmental change in these ecotones (Arnold et al., 1951, Brunstein et al., 1992, Woodhouse 2011). These analyses give rise to future projections of potential habitat structure and species composition at treeline. Historical conditions, site specific densities, and evidence of previous species habituation from downed wood or stumps, offers additional evidence of historical structure and the historical range of variability in these high elevation mountainous environments.

Other tree species found in this ecotone throughout the Southern Rockies include Engelman spruce (*Picea engelmannii*), subalpine fir (*Abies lasiocarpa*), and lodgepole pine (*Pinus contorta*). Although cohabitants in many areas, they face differing natural disturbance regimes such as wildfire and pathogens, and indirect anthropogenic threats such as climate change and air pollution (Dandan et al., 2022; Zou et al., 2022). Further study into how these variables continue to affect local species is key to understanding treeline dynamics and future response to altered climate and disturbance regimes.

Recent outbreaks of pine blister rust (*Cronartium ribicola*) and mountain pine beetle (*Dendroctonus ponderosae*) have been compounded by human alterations such as fire suppression, grazing, logging, and climate change (Ye et al., 2021). The direct effects of human influence may alter establishment rates in the case of livestock grazing, while establishment and species compositional change due to clear cuts may restrict spread of seedlings and availability of seed cast from nearby parent trees. Bridging the present knowledge gap of how and why these high elevation species are able to respond to these disturbances will determine the potential courses of action in management activities and the future of the structure and composition in these ecosystems.

Limiting Factors

The extreme environmental conditions faced by these species are the main limiting factors of their growth, development, and continued presence on the landscape. Research produced by Elliot (2011) found that on the regional scale, climactic variables such as seasonal moisture availability, precipitation, temperature, and growing season length drive the distribution of species. By examining regime-shift changes in snowfall and temperature over the last ~350 years in the Southern Rockies, a strong demographic change was apparent in the upper treeline communities, corroborating previous evidence of abrupt changes in community structure due to bioclimatic thresholds being exceeded.

A recent study by Dyderski & Pawlik (2020) found that the fine scale geomorphological influences such as slope, aspect, elevation, and moisture availability are a major driver of species presence in microhabitats. Using random forest models and forest inventory data from undisturbed national parks in central Europe, the researchers were able to separate the effects of different variables and identify sites that were either more or less vulnerable to climate change. In particular, the topography and site-specific soil characteristics in the study sites showed a high influence in species distribution and composition.

Prior research has focused on specific physiological responses of mature and established high elevation individuals to altered climactic regimes and environmental variabilities (Salzer et al., 2014). This has allowed researchers to better understand and quantify growth rates, nutrient cycling and requirements, neighbor response, regeneration rates and optimal environmental conditions of treeline species. Although these environmental variables do not follow a uniform exclusion or inclusion pattern for species composition, they offer a useful metric for habitat suitability models and potential migration adaptability efforts (Gazda et al., 2019).

More recent research has focused on seedling establishment rates (Andrus et al., 2018), species compositional shifts (Kummel et al., 2021), and the upward elevational range shifts in habitat currently underway due to anthropogenic climate alteration (Davis et al., 2020). Knowledge of past climactic effects on species capabilities to withstand specific environmental conditions has provided a strong knowledge base of species adaptability and environmental suitability thresholds for recruitment and perseverance in established habitats to quickly changing climate fluctuations.

A recent study by Andrus & Harvey (2020) correlated the role increased summer temperatures and larger moisture deficits had on seedling establishment. The researchers obtained data on forest cone abundance and stand basal areas overall influence on seedling establishment. Their multi decadal study (1975-2010) showed that Engelmann spruce and subalpine fir established in large pulses during favorable years with larger soil moisture availability under cooler and wetter growing season temperatures. Because increased temperatures are associated with stronger and more prolonged drought conditions at high elevation treeline, continued detrimental climate shifts will affect the establishment of new individuals and habitat availability. Studies such as these have opened the recent discourse for potential human intervention and the efforts to abate the effects of anthropogenic climate change via a variety of assisted management techniques.

Management

Human assisted species migration, the deliberate movement and placement of species into currently uninhabited but favorable areas (Maori et al., 2023), has recently become an increasingly popular management tool for continued forest regeneration and species resilience projects. Many government and private agencies, such as the United States Forest Service and The Nature Conservancy, are conducting large scale assisted migration operations. These intervention efforts are broken into three strategies: assisted population expansion, assisted range expansion, and assisted species migration (Williams et al., 2013).

These management strategies have the potential for implementation at treeline locations and may be an essential, albeit controversial, method of ensuring future establishment and resilience under the new anthropogenic climate regime. New favorable seedling establishment sites may need to be exploited on a shorter timescale. Human interference into these naturally occurring species migrations will have direct effects on species composition, density, and age structure which will heavily influence future treeline dynamics.

Conclusion

The general physical, biological, temporal, and spatial dynamics inherent in the complex treeline ecotone exemplifies the need for further systematic review and research across multiple scales and scientific disciplines. This literature review has highlighted recent evidence that anthropogenic climate change is rapidly altering these sensitive areas on an increasing intensity and scale; furthering the uncertainty of where, when, and how these ecosystems will be shaped into the future. The ethical considerations with direct implication to disturbance intervention, species migration, land protection policies, and scope of human involvement necessary remain to be decided. Continued fact driven discourse with practical impacts will be instrumental for future treeline ecosystem health and prosperity. Foundational knowledge of the natural drivers and complexities inherent in established treeline ecosystems is necessary for future research, beneficial policy decisions, and active land management which incorporates the current best practices and protocols for intervention or passive management.

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CHAPTER 2
GRANT PROPOSAL

Abstract

Mitigating wildfire risks and improving overall forest health is becoming increasingly important for forest management in the Denver Mountain Parks system and surrounding communities. The major focus of management efforts is to establish conditions that align with the historical range of variability (HRV), or past environmental conditions and species composition previously present in the landscape. The HRV of natural disturbance varies greatly along elevational gradients, slope, and aspect in the forest of the Front Range of Colorado. Fire suppression over the last century has increased density, biomass, and fuel load of forested areas in the Front Range, preventing natural disturbance cycles from clearing understory vegetation, reducing fuel accumulation, and inhibiting natural nutrient cycling. An increase in canopy cover associated with fire suppression has decreased understory vegetation, prevented seedling establishment, and has influenced the presence of non-native and invasive vegetation over native, fire adapted species. Quantifying the effects that forest biomass reduction and thinning efforts have in mimicking these natural processes is necessary to determine trajectories of forest structure and composition. In addition to statistically quantifying models of tree regeneration and forest biomass, I will conduct a forest inventory in Stanley Park to determine if manual thinning can be used as a surrogate for fire in alignment with DMP restoration goals. The findings of this study will provide important information for future management practices and the structural dynamics of forest ecosystems in the Front Range.

Objectives, Hypotheses, Anticipated Value, Literature Review

Objectives

This research will evaluate the effect of forest thinning techniques on overall species richness, species composition, total forest biomass, and seedling recruitment. These comparisons will determine whether thinning techniques benefit forest management restoration efforts and provide comprehensive review of management goals for the area. The goal of this study will be to compare areas that will be thinned to unmanaged areas that will remain un-thinned. Comparison in the pre-thinning to post-thinning areas, as well as nearby untreated areas as a control zone, will generate data and insight into the effectiveness of these management techniques.

Hypotheses

This proposed research aims to answer two questions:

Q1 - Do forest thinning techniques increase species evenness of trees and large woody vegetation in treated areas?
H1 - Thinning the forested areas of Stanley Park will increase species evenness of tree species compared to areas that have not been thinned.

Q2 - Do thinned areas have higher spatial heterogeneity, increased age stand diversity, and more seedling recruitment?
H2 - Areas that have been thinned (treatment) will display higher spatial heterogeneity, increased diversity of age structure, and higher levels of seedling establishment.

Anticipated Value

While thinning techniques have been widely implemented in Front Range forests as surrogate fire to remove fuel loads and high intensity wildfire risks, there remains a need for empirical data which quantifies impacts of these management techniques on forest structure, biomass, and regeneration. This research will quantify if thinning can replace fire as an ecological process. Surveys of representative samples of Denver Mountain Park (DMP) properties, such as Stanley Park, will provide area-specific information enabling a targeted approach in DMP management efforts. DMP conducts forest thinning operations to reduce fuels and lower wildfire risk, however, the effectiveness of these treatments on spatial distribution, species composition, and regeneration rates are largely unknown.

Measurement of biomass, species richness, evenness, and species abundance after forest thinning efforts will be conducted to understand how these practices influence ecosystem function and wildfire risk. The results of this research will assist land managers by assessing the overall influence and effectiveness of forest management techniques.

There is limited information about the extent to which forest thinning will influence potential wildfire risk, species regeneration, and species evenness in the areas managed by DMP. To adequately manage and monitor forest biomass, fuel loads, levels of species recruitment, and species evenness, this valuable data must be obtained and assessed by DMP. The overall purpose of this study is to evaluate the effectiveness of forest management strategies.

Literature Review

Current land management policies on public forest lands in the United States mandate wildfire suppression. The exclusion of fire from fire-prone environments has altered forest structure, leading to large changes in environmental conditions such as increased stand density, increased biomass, increased fuel loads, and the alteration of species distributions (Battaglia et al., 2018). This policy has led to a departure from the historic range of variability (HRV) of forest densities, and species composition historically found in Colorado dry conifer forests (Sherriff et al., 2006). These policy changes have also led to forest tree stand homogenization, a higher level of wildfire risk from higher severity fires with increased potential of crown fire, and increased susceptibility of local human communities to wildfire risk (Battaglia et al., 2018; Cannon et al., 2018).

Increases in tree density over the last century in the Front Range have been limited to south-facing slopes at lower elevations (Platt et al., 2009). Because the site conditions can vary greatly with aspect, slope, temperature, precipitation, and elevation within forested stands, a large variation in overall structure and species composition is present within each specific forest mosaic landscape.

Fuel-reduction treatments, or thinning, have become an increasingly common forest management technique, especially in the Wildland Urban Interface (WUI). However, fire suppression favors non-native and invasive vegetation over native, fire adapted species (Addington, 2018). This leads to an alteration of species composition, species evenness, and species richness of the landscape (Sherriff et al., 2018).

The rates of tree species recruitment are highly dependent on the type of disturbance and severity (Carter et al., 2022). Disturbances such as fire (prescribed or natural), beetle outbreak, avalanches, drought, flood, and unseasonal frost events have large influences on what species are able to establish and survive. Depending on severity and the frequency of these disturbances, the trajectory of future forest structure and species composition is highly variable (Cannon et al., 2018)

Methods, Sampling, Data Analysis

Sampling Methods

First, I will partition Stanley Park into equal sections of North and South-facing areas allowing for a delineation of thinning treatment areas - one in the northern and one in the southern zone. Secondly, randomly place ten, 10m radial plots in both the northern and southern areas with five plots in both thinned and pre-thinned areas, using ArcGIS to randomly select center points of radial plots. Then, discard randomly selected plots with zero vegetation (rock outcrops) or otherwise inaccessible plots and substitute additional plots as needed. An estimate of canopy cover will be taken from ArcGIS. Plots will be sampled before and after the first growing season pre- and post-treatment, and subsequent growing seasons as needed.

To test the hypothesis that thinning will increase levels of species heterogeneity, I will begin by performing a standardized forest inventory. Within each 10m radial plot, individual tree species will be recorded. Recording life stage as: 1 being alive, 2 dead and standing, 3 dead and fallen, 4 stump. Diameter at Breast Height (DBH) will be recorded at 1.3 meters above ground level for every tree over 2 meters in height or greater than 2.5cm DBH. Age class recorded as: 1 being full canopy, 2 mid canopy, 3 adolescent, 4 understory, 5 sapling, and 6 seedling.

To quantify seedling regeneration post thinning, I will establish five randomly located 1m quadrats within each 10m plot for subplot sampling. Using compass orientation in degrees, specific location of specimens below 2.5cm DBH within plots will be marked on paper layout of micro plot. Overall percentage cover of seedlings in quadrats will be measured and seedlings species recorded.

Data Analysis Techniques:

-Compare overall basal cover, canopy cover, and species richness of tree species across northern and southern areas pre-treatment and post-treatment using t-tests

-Compare basal cover, canopy cover, and species richness of tree species across treated and untreated areas, and between areas pre- and post-treatment using t-tests

-Compare species richness in overall 10m plots across northern and southern areas, and pre- and post-treatment areas using t-tests

-Compare species richness, Simpsons Diversity Index, litter percent, and bare ground in sub plots in northern and southern areas, and pre- and post-treatment using t-tests

Project Schedule, Budget, Negative Impacts

Table 1: Schedule

Dates	Activities	Deliverables
May 2024	Literature review Initial GIS referencing (NDVI / Delineation) Historical map/ Image analysis	Annotated bibliography Spatial records / Overlay Species suitability map
June 2024	GIS location selection / layer input Coordinate sampling locations with DMP	GIS layout of treatment and control sites Final approval from DMP
June 2024- July 2024	Conduct vegetation surveys Begin draft report writing	Raw data in excel spreadsheet
August 2024- Sept 2024	Data Analysis Conduct statistical analysis of initial data	Draft Report
October 2024	Finish report and presentation for DMP	Final Written Report Report Presentation

Table 2: Budget

Item	Justification	Cost	Quantity	Total Cost
GIS Stipend	Graduate student to complete GIS mapping and delineation	$250	1	$250
Field Survey Technician Stipend	Undergraduate students to complete field sampling	$25/hour	160	$4000
Researcher Stipend	Field sampling and report writing	$30/hour	120	$3600
DMP Staff Stipend	Assistance with field data survey collection and final report writing	$1200/week	1	$1200
Gas	10 commutes to Stanley Park from Regis Campus	$0.62/Mile	310	$192.20
Field Equipment	DBH tape, quadrat, flagging	$150	1	$150
GPS Units	Garmin 65 Series	$300	2	$600
Total Proposal Request				$9992.20

Negative Impacts

Impacts will be minimal during the initial surveying phase and limited to light foot traffic and minimal impact on small vegetation and soils in second survey phase. The thinning operations are planned, and this study will have minimal physical structural impact before or after major physical alteration incurred in thinning procedures.

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FIGURE LIST

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CHAPTER 3
JOURNAL MANUSCRIPT

Abstract

Human wildlife interactions (HWI) pose a complex challenge for wildlife managers. Human encroachment into wildlife habitat and the growing number of outdoor recreationists are increasing the frequency of contact and conflict, especially in regions such as the Front Range of Colorado. Geographic information systems (GIS), which use a combination of remote sensing and environmental survey data, allow for predictive spatial analyses of where human wildlife interactions are likely to occur. I used publicly reported observations of moose to create spatial predictive maps in a species distribution model framework. Slope and elevation were shown to be the strongest predictors of HWI, and additional environmental variables added modest predictive power to the SDM. Additionally, a parsimonious model is presented here for a streamlined and practical framework for future monitoring and analysis. Investigation of suitable habitats based on recent observations provides land managers information to identify the likely locations of human-moose encounters. This study identifies the spatial distribution of moose in the wildland urban interface, the potential for increasing populations in nearby suitable habitats, and subsequent implications for wildlife managers.

Introduction

Human Wildlife Interactions (HWI) are of concern for public land managers, conservation biologists, and recreational users of public lands (Ditchkoff et al., 2006). HWI include a broad variety of encounters ranging from violent attacks to distant observations. The continued human encroachment on wildlife habitat in the Western U.S. is leading to a rise in

HWI and an increasing need for effective management strategies to mitigate these conflicts (Dussault et al., 2006). Increased understanding of anthropogenic social forces and wildlife ecology has primed the field for advances in best management approaches and land management strategies (Hull et al., 2023).

Geospatial techniques can be used to develop management strategies focused on the safety of humans, wildlife populations, and local ecosystems. The development of effective management strategies requires quantitative data of visitor use and documented interactions (Dickman, 2010). Remote sensing technologies and geographic information systems (GIS) allow for tracking and quantitative spatial data analysis (Dussault et al., 2006). Remote sensing techniques have become a commonly used method for monitoring habitat, species presence / absence, aiding officials in public land use planning, and development of management strategies (Blouin et al., 2021). Methods incorporating GIS technologies have been used to quantify variables related to habitat trends and HWI for species such as moose (*Alces alces*), bighorn sheep (*Ovis canadensis*), white-tailed deer (*Odocoileus virginianus*), and elk (*Cervus canadensis*; Jensen et al., 2018; Gagnon et al., 2022; Van Deelen et al., 1997). These studies incorporate environmental data with population data to better understand preferred habitats and spatial distribution patterns.

Habitat suitability analyses are an effective method for discerning appropriate focal areas for protected areas such as seasonal closures and restoration zones and are able to provide a quantitative method for bolstering appropriate land management strategies with data driven decision making (Dussault et al., 2006; Olson et al., 2020). Habitat suitability models provide estimates of the spatial distribution of target species based on the environmental conditions in locations where the species has been observed (Rathore et al., 2023). These models may be customized to examine trends of currently inhabited areas and to address potential range expansion for highly mobile animals.

A large and highly charismatic species, moose were originally introduced by Colorado Parks and Wildlife (CPW) to Park County, CO in 1978, and have since increased in range and population numbers to an estimated 3,460 individuals in 2023 (Nadeau et al., 2024; CPW., 2013; CPW., 2023), colonizing areas in the Front Range wildland urban interface (WUI), and becoming a species of concern for HWI with minimal amounts of current location data. Understanding which areas have potential for increased moose presence in the near future is crucial for guiding future natural resource management decisions (Griffin et al., 2022, Ditchkoff et al., 2006, Dickman et al., 2010). The recently observed location of moose, when compared to the potential habitat of moose, will allow land management officials to prepare for wildlife movement, educate the public for responsible recreation, and implement timely safety precautions for humans and wildlife alike (Tendeng et al., 2016).

These practices are especially important in Jefferson County, a populous county in the Colorado Front Range that contains many heavily trafficked public recreation and open space lands. The Jefferson County Open Space (JCOS) department is tasked with wildlife management, recreational area operation, and safety of its constituents within and surrounding 29 properties consisting of over 56,000 acres. In this study, I examined historical open space HWI reports on JCOS properties and environmental data collected from the JCOS natural resources department to predict moose HWI in JCOS lands using an SDM framework. The research framework established here will continue to provide up to date knowledge for land managers and the ever-evolving best management practices in successful implementation of JCOS goals. The results of this investigation will guide HWI best practice and management protocols for Jefferson County and aid in continued species monitoring efforts.

Methods

Study Area

I used data collected in JCOS management units and the surrounding lands managed by Jefferson County, Colorado, USA. Jefferson County has three distinct geographic areas: the plains, the foothills, and mountainous areas (Prague et al., 1993). This study examined subsets of the foothills and mountainous areas where moose have been recently observed. A total of 29 open space areas and parks totaling an area over 56,000 acres across the foothills and mountainous region were included in the study.

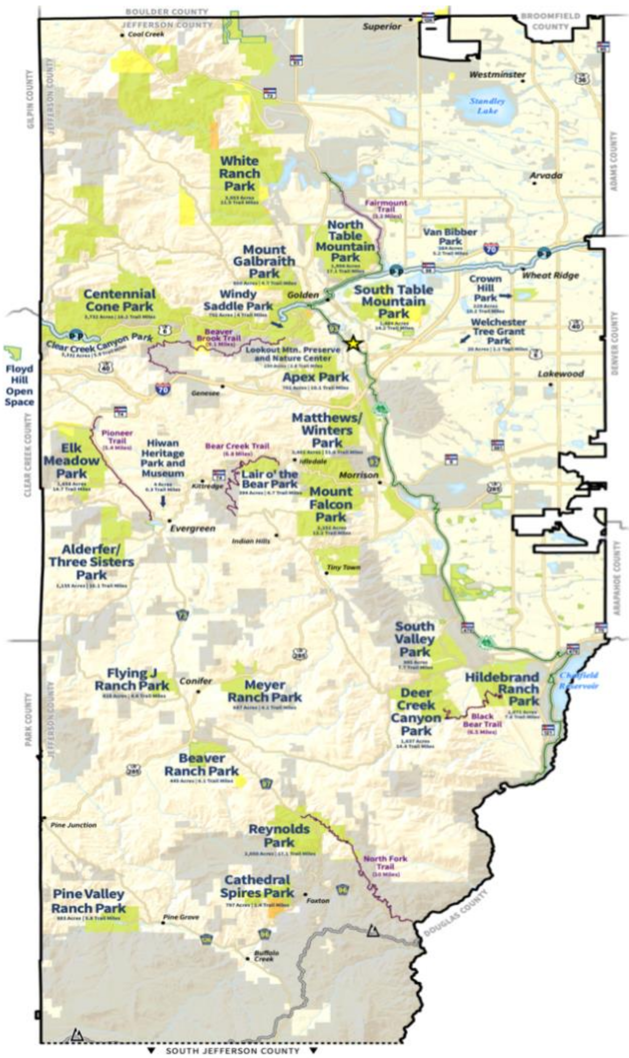

Figure 1 - JCOS map of parks, open spaces, and trails included in the present study. Map credit: Jefferson County Open Space Department.

HWI Data Collection

I used existing data for moose occurrence from publicly reported observations of wildlife. These observations were submitted to the Jefferson County Open Space department's online Human Wildlife Interaction Portal (JCOS, 2023). Location point data were input via GPS point location of where the encounters occurred. The types of interactions were reported as: an observation - act of noticing or taking note of tracks, scat or vocalizations, a sighting - visual observation of a wild animal(s), an encounter - direct meeting between a human and a wild animal without incident (to human), an incident - conflict between a human and a wild animal where the animal exhibited behavior creating an unsafe situation for the human, and attack - when a human is bodily injured or killed by a wild animal.

Environmental Data Collection

I obtained environmental data (cover type, slope, aspect, elevation, latitude, and longitude) for JCOS lands from the United States Geological Survey (USGS) Digital Elevation Models (DEM) and the United States Department of Agriculture (USDA) National Agricultural Imagery Program (NAIP) datasets. Next, I overlaid all observations of moose from HWI incident data onto raster-based environmental data sets and extracted the values of environmental conditions. The cover types were demarcated as a series of classes: structures, impervious surfaces, surface water, grassland / prairie, observable tree canopy, irrigated lands / turf, barren rock outcroppings, cropland, and scrubland / shrubland. Slope was measured as degree, aspect as degrees from north, and elevation in meters.

A set of 100 random locations were randomly plotted in the study area to serve as a set of control data points with no recent observations of moose. The locations were buffered to have a minimum distance of 2,000 feet from the nearest location of a recorded observation to avoid duplication and over representation of specific favorable areas. Cell size of predicted moose probability raster was set as 400 using nearest neighbor pyramids in a NAD 1983 StatePlane Colorado Central FIPS 0502 projected coordinate system.

Statistical Analysis

I used generalized additive models (GAMs) to investigate the relationship between moose occurrence and environmental variables. GAM was chosen as a flexible modeling scheme where the relationships between the dependent and independent variables of this study were not assumed to be linear and would thus be able to follow smoothed patterns of potentially nonlinear data. I then used two different metrics for selection of the best two models.

To identify variables that best explain HWI point data given available environmental variable data, I fit binomial GAM models to perform logistic regressions which included all environmental variables for maximum predictive power (R^2). I also used multi model inference to obtain the most parsimonious models maximizing fit· while minimizing variables for inclusion by comparing AIC values was performed. Models displaying Δ AIC > 4 were selected. I used the most predictive two models, as determined by maximum R^2 , and minimum Δ AIC values, as separate SDMs and generated log odds of moose presence for 13,787 points to predict the probability of moose HWI across the entire JCOS system. The predicted log odds values were backtransformed to probability for a final range of 0 to 1. Lastly, I compared the probabilities of moose HWI predicted by the two separate SDMs by plotting the difference in predicted probabilities for each point across the entire JCOS region. The MGCV package in R (V1.8-34; Wood, 2011; R Core Team, 2023) and predict function was used for model predictions.

Results

Slope, elevation, aspect, and cover type had significant effects on moose presence in Jefferson County. A model containing all environmental variables tested had the highest goodness of fit (adj. $R^2 = 0.413$, AIC = 146.4) with slope being the most significant variable ($P = 0.005$), along with elevation ($P = 0.011$), and aspect ($P = 0.723$). A simpler model, including only elevation, slope, and land use, had the second highest goodness of fit (adj. $R^2 = 0.411$) with slope being the most significant variable ($P = 0.005$, AIC = 146.4). The much simpler model, including only elevation and slope, had similarly strong values and the lowest AIC score out of 20 models fit (adj. $R^2 = 0.409$, AIC = 142.7) with slope being the most significant variable ($P= 0.005$).

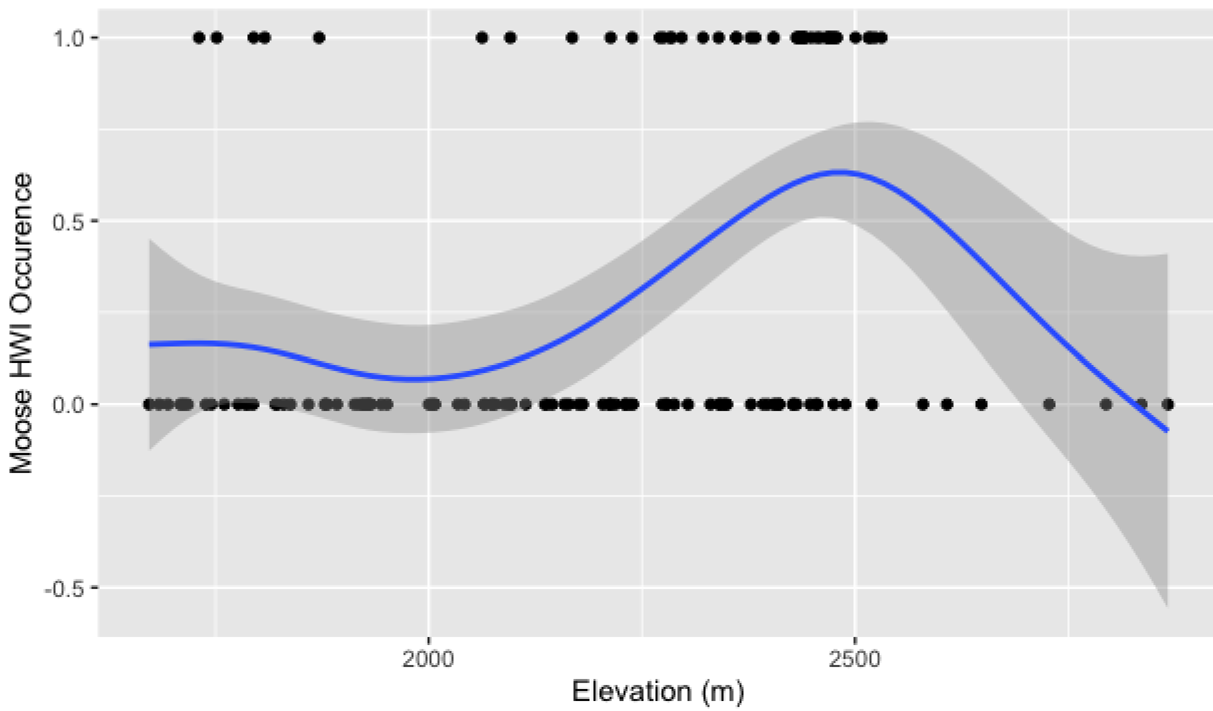

Figure 2 - The odds of moose HWI peak around 2500 meters. Black points represent either HWI observations (1) or randomly generated points (0). Blue line indicates the line of best fit in the non-linear relationship between occurrence and elevation. Shaded gray area represent confidence bands.

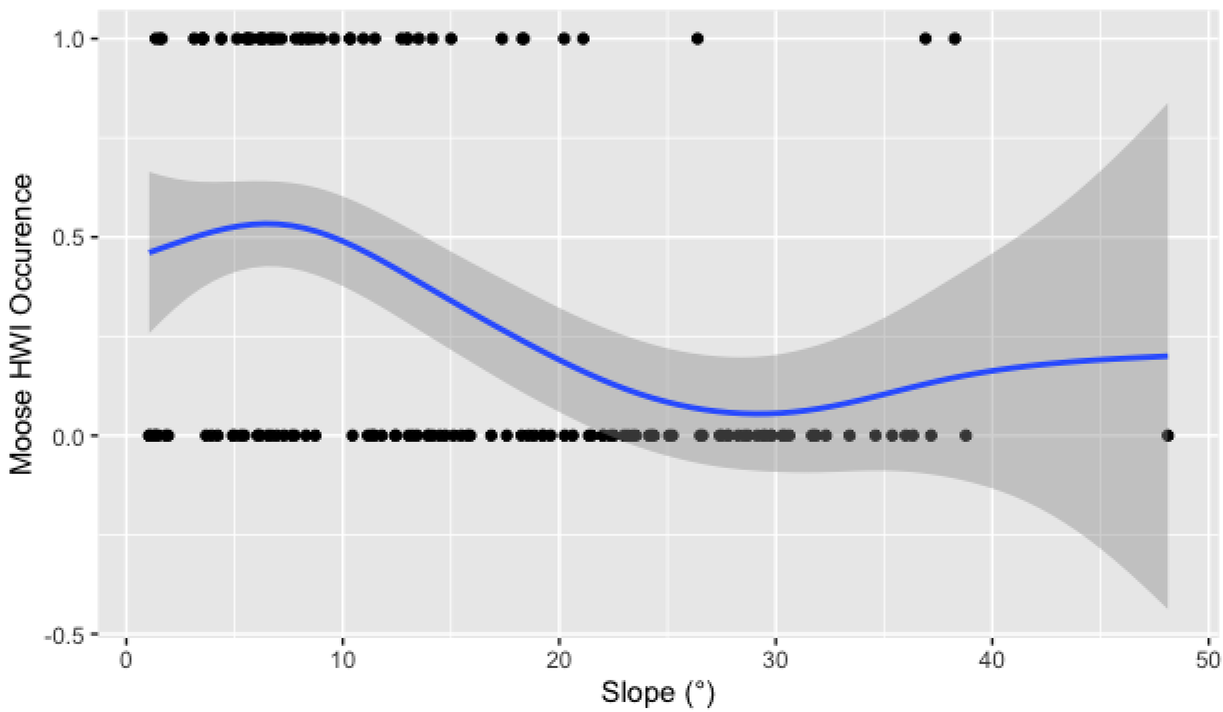

Figure 3 - The odds of moose HWI decrease as slope increases. Black points represent either HWI observations (1) or randomly generated points (0). Blue line indicates the line of best fit in the non-linear relationship between occurrence and slope. Shaded gray area represent confidence bands.

The two final predictive maps display a high degree of similarity in projected distributions of moose. The predictive map which also included land use and aspect (Fig. 4) displayed a minimal amount of higher resolution and discernment between the projected cells in comparison to the map which only considered elevation and slope (Fig. 5). The final map (Fig 6) displays the range of values observed in the difference raster of the two selected models with a 5% deviance in probability between Fig. 4 and Fig. 5.

Flying J Ranch, Meyer Ranch, and Beaver Ranch Parks were the most likely to have future moose observations and potential HWIs. This is consistent with the original observational data which displayed a high concentration of moose observations in these areas. Additionally, three other large parks: Elk Meadows park, Alderfer/Three Sisters park, and the eastern Golden Gate Canyon area showed very high habitat suitability, with only 3 total sightings over the entirety of the three regions. Unsurprisingly, the areas displaying the lowest predictions of suitability were the lowest elevation parks in the southeastern part of the study area closest to high human population density, development, and a high degree of relief (e.g. slope) over smaller acreage. The greatest difference in predicted probabilities between the two models was shown to be in the western and northern sections of the Golden Gate Canyon regions, where no HWI have been reported.

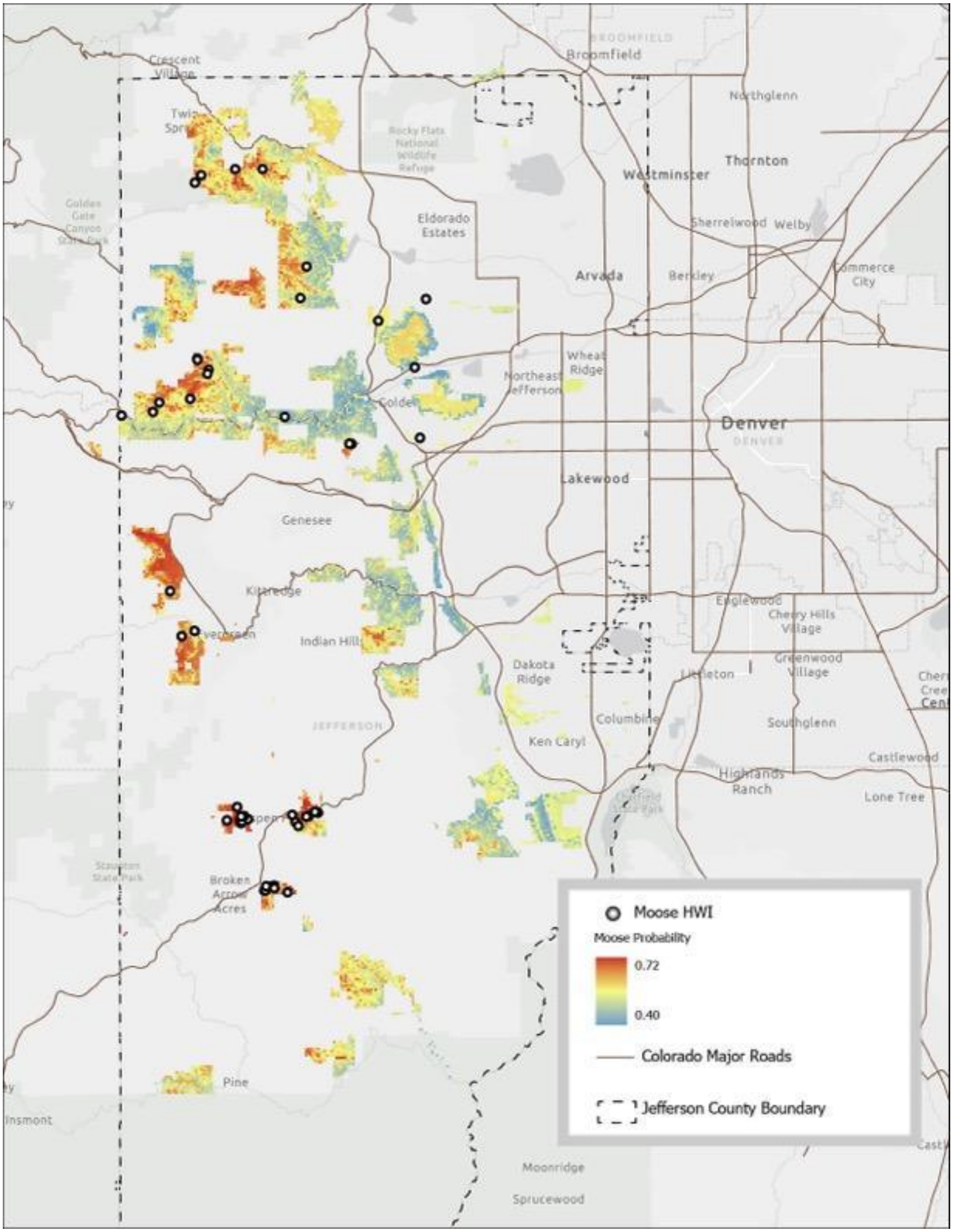

Figure 4 (Above)- Probability of moose occurrence on JCOS properties based on the SDM with maximum R^2. Colored areas display raster of fullest model in JCOS properties. Points represent the recent 49 observations of moose.

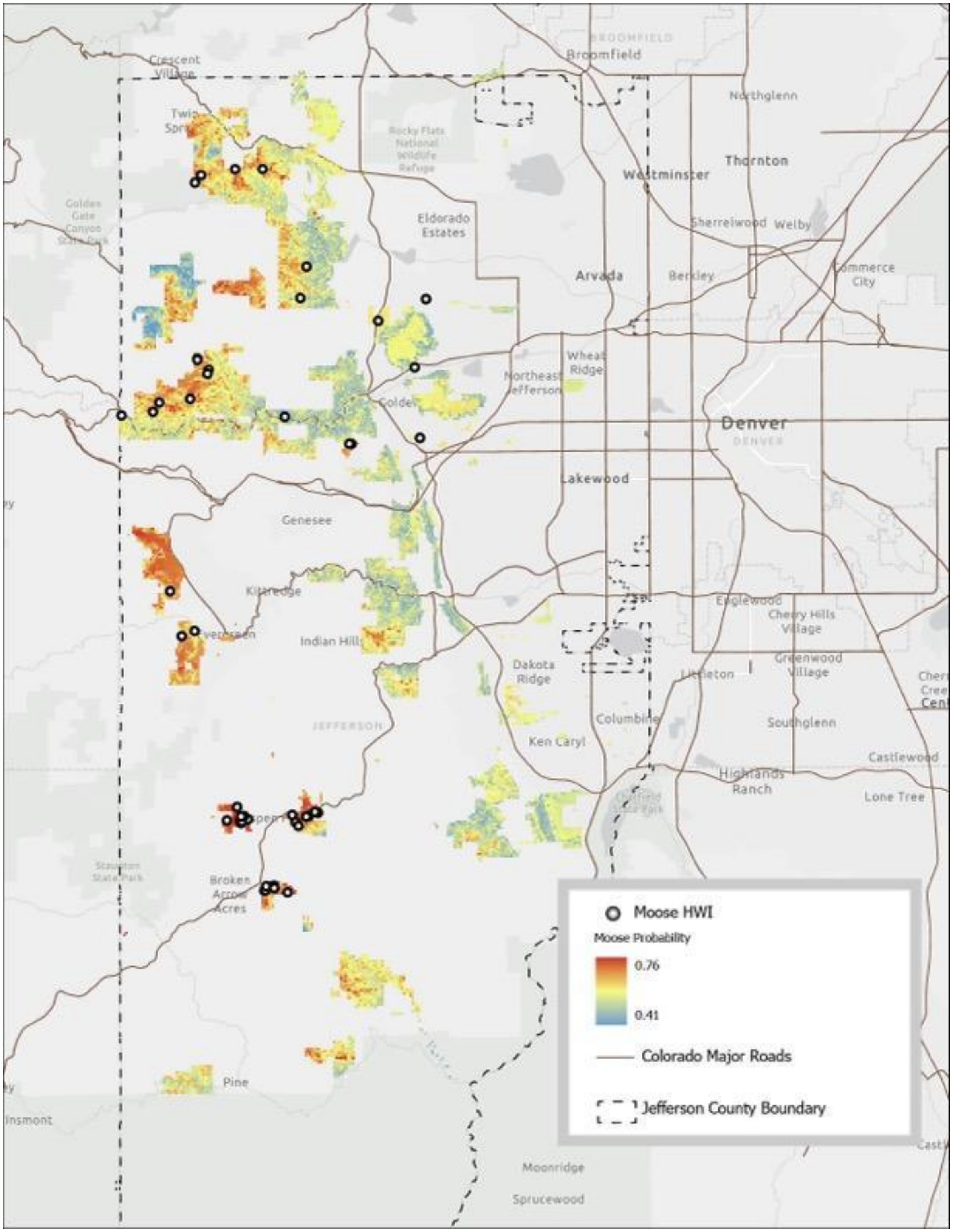

Figure 5 (Above) - Probability of moose occurrence on JCOS properties based on the simpler parsimonious SDM. Colored areas display raster of reduced model in JCOS properties. Points represent the recent 49 observations of moose.

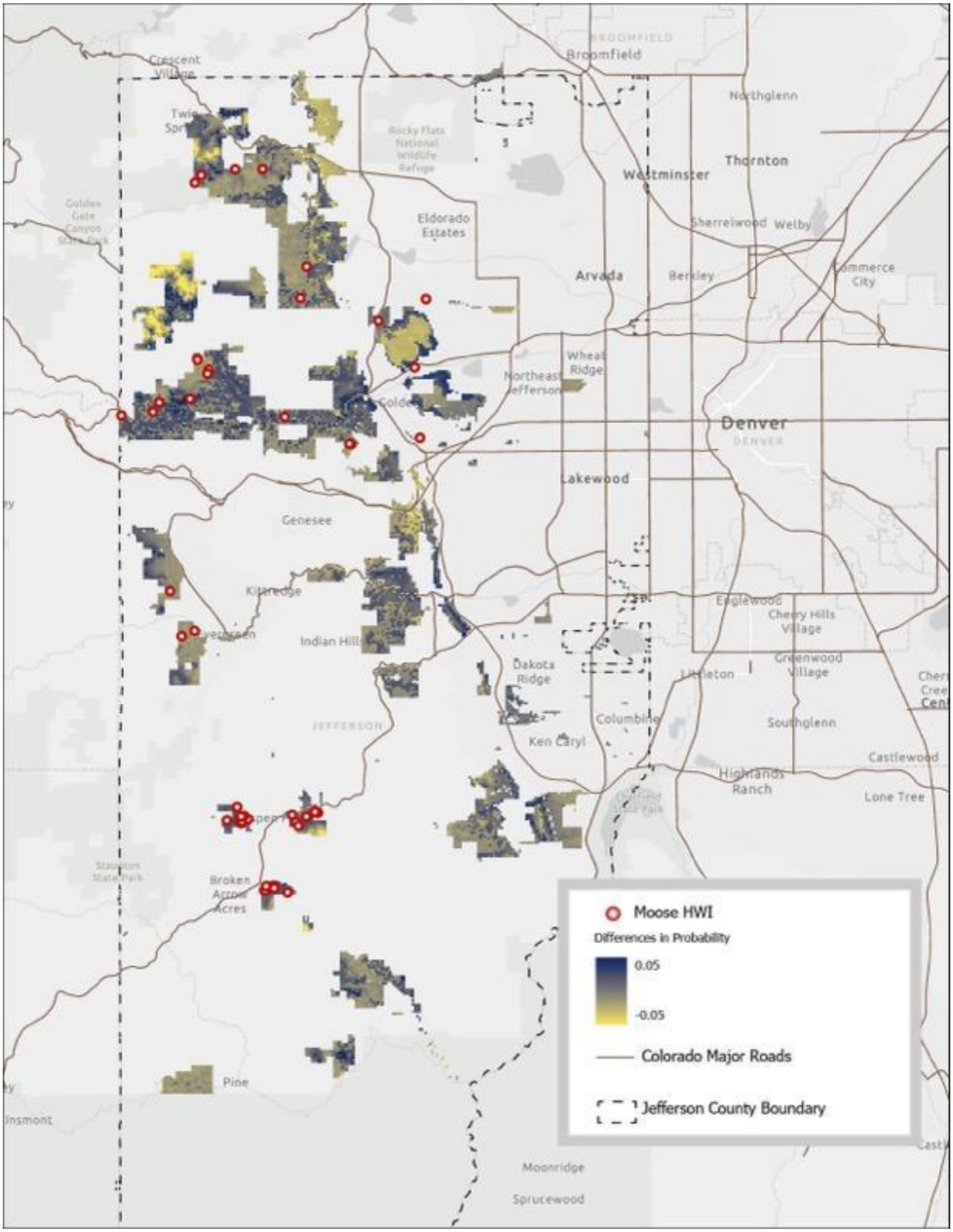

Figure 6 (Above) - Colored areas display raster of differences in predicted probabilities between the fullest and most parsimonious SDMs. Points represent the recent 49 observations of moose.

Discussion

This study aimed to visualize where moose have recently been observed in Jefferson County and to predict where viable moose habitat is located in areas managed by the JCOS department's land management system. The interplay of populations and ultimately the safety of wildlife and humans in the WUI may be better realized in response to adequate knowledge of potential areas of conflict. The paucity of live location data coupled with a lack of SDMs for moose in the Front Range, encourages the practical use of SDMs employed here in future studies. This study shows that by incorporating readily available data, the quantified relative moose risk may be incorporated as a novel metric for decision making processes.

The models presented here predict high suitability of moose habitat in areas of ~2,500 meters in elevation with gradual to low angle slopes between 0-30°. The management implications for the 56,000 acres administered by JCOS, as determined by my analysis, will allow managers to adequately prepare for potential moose distribution into areas that are currently sparsely populated, or altogether currently unoccupied. Flying J Ranch, Meyer Ranch, and Beaver Ranch Parks (Fig. 4 & Fig. 5 - southernmost observational data points) were the most likely to have future moose observations and potential HWIs. This is consistent with the original observational data which displayed a high concentration of moose observations in these areas.

Species distribution models allow for the quantification of environmental variables and species preferred habitat. My simplest model (Fig. 5) was incorporated to show the similarities and maintained overall effectiveness of modeling capacity in a more streamlined, accessible, and less time-consuming method for practical application of this framework. The ability to predict movements and potential available habitats on public lands is essential in establishing a quantifiable approach to best appropriate resources and bolster knowledge of wildlife patterns for public officials (Olson et al., 2020). Importantly, for moose, my results show that easily accessible data (e.g. elevation and slope) can be used as a powerful tool in achieving these goals.

This analysis provides a model of suitable habitat only, based on observational data and the corresponding environment from observational points. SDMs are not intended for use as a predictive method for areas where populations are expected to establish in the future. Different methods incorporating seasonality and timing to create dynamic models, such as agent-based models, are necessary for accurate predictive capacities of expected future establishment of a species. Wildlife corridors conducive to movement and seasonal migrations, such as highway wildlife crossings and conversely, physical barriers to movement, were not included in this study. Models that incorporate flexibility for movement and accessibility are necessary to understand adequate pathways for potential population movement and habitat establishment.

The magnitude in the difference of respective model performance (Fig 6), displays a minimal departure of model performance as a 5% change in probability of occurrence. The small degree of difference between the two models suggests that the model's performances in predicting moose habitat are most strongly correlated with slope and elevation, and minimally influenced by the addition of cover type and or aspect. Although slightly higher resolution and specificity are displayed, the results here demonstrate the value of using a parsimonious, less selective, and less data intensive predictive framework.

GIS and remote sensing technologies have proven to be a successful tool for land managers and wildlife scientists (Blouin et al., 2021, Dussault et al., 2006). Continued use of these technologies as a publicly available tracking system in combination with improving spatial environmental data will continue to be a useful tool in land management planning directives and the JCOS department's objectives. Additional monitoring efforts incorporating citizen science and informed management decisions will provide a framework for the best practice approach to methods of responsible stewardship of natural resources and cohabitation of increasing moose and human populations in the WUI. By identifying areas where contact between humans and moose are likely, JCOS can better allocate resources for public education. A combination of GIS analysis and current environmental survey data is essential in creating the best data driven methods for monitoring efforts and management strategy (Heard et al., 2008, Nadeau et al., 2017).

This species distribution model will allow management officials to better understand potential moose habitat in relation to current populations, and therefore the ability to appropriately prepare resources and efforts to minimize dangerous human wildlife interactions. Here, I conducted the first SDM for moose specific to Jefferson County, Colorado, to address the gap in current knowledge of moose distributions and species data available for wildlife managers and land planning officials. I began with the aim of using current species data and the most appropriate environmental data using remote sensing technology in order to better understand the implications of moose population spread. The results of this study provide a framework for species monitoring efforts and a vital method for predicting areas of potential HWI in Colorado's expanding Front Range WUI.

Acknowledgements

I thank the many citizen scientists who reported HWIs, Mary Ann Bonnell and Lauren Hendricks of Jefferson County Open Space, and the faculty of the Regis University Biology Department who assisted with study conception, data analysis, and the writing of this manuscript.

Conflict of Interest

The authors declare that they have no conflicts of interest.

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CHAPTER 4
STAKEHOLDER REVIEW

Introduction

The increasing Wildland Urban Interface (WUI) and the associated increased fire risk in the Jefferson County foothills poses a set of complex governmental planning efforts requiring community stakeholder engagement because of substantial new development of high-income housing (McGrath Novak et al., 2020). Here, I present straightforward and practical measures for a collaboration among a diverse group of stakeholders in order to develop a comprehensive community wildfire protection plan (CWPP). I am recommending measures to reduce potential negative impacts of naturally ignited or unintentional fires, and do not recommend prescribed fires at this time. To meet these goals, I propose a set of guidelines to implement property wildfire buffer zones that include requiring advanced fire-resistant building materials for new construction, mechanical thinning of the nearby forests and creating buffer zones adjacent to grassland areas. These efforts should diminish financial impacts and decrease potential loss of property and life through preventative fire mitigation strategies.

A complex framework surrounding considerations of prescribed fire and best management practices, such as the implementation of natural fire regimes that have historically occurred in the landscape, has led to a charged regional debate on course of action. Areas that are now in the WUI have experienced naturally occurring fire events in the past, which are essential to the life history and regular natural disturbance regimes of the local environment (Schoennagel et al., 2011). Commonly found species in the Jefferson County foothills, such as Ponderosa Pine (*Pinus ponderosa*), require frequent low intensity fires for dispersal, germination, and nutrient acquisition from the landscape (Keith et al., 2010). Continued fire suppression, along with a warming climate and the aridification of the region, will continue to increase fuel load (Van Mantgem et al., 2016; Ritter et al., 2023). Fuel load accumulation primes the landscape for larger, more uncontrollable fire events in the future (Addington et al., 2018; Hunter et al, 2020). Proximity to the recent Marshall fire, that destroyed 1,084 residences and has been estimated at $513,212,589 of damages to residences alone, in the neighboring community of Superior in Boulder County, has exacerbated community concerns about uncontrolled fire and the necessity of undertaking preventative measures such as vegetation thinning techniques (Thomas et al., 1999; Yoder et al., 2003; Boulder County, 2022).

Stakeholders:

Home Owner Association Stakeholders

The Home Owners Associations (HOAs) Candelas, Layden, and Quaker Acres are interested in a Community Wildfire Proposed Plan (CWPP) which contains minimal restrictions for continued development and the least financial burden due to construction and maintenance costs. Developers and their HOAs have invested large sums of money and time into new housing developments and pre-planned communities. They don't want their properties to be put under unnecessary risk or potential harm if prescribed fires were to be performed and mismanaged (McGrath Novak et al., 2020; Yoder et al., 2003). Nearby community members and the public are similarly afraid of prescribed fires getting out of control and spreading outside of the targeted areas to damage their property, the smoke and negative air quality produced from these prescription fires, and the diminished aesthetic value of their broader community in the short term after a burn. These economic, aesthetic, and safety concerns are the main drivers of their engagement (McGrath Novak et al., 2020). Burnt houses and damaged infrastructure are expensive to rebuild or repair. A delay in development due to increased construction time and costs from requirements of additional preventative infrastructure, forestry and mowing operations, and code regulation compliance, may decrease profits for developers. This in turn may cause decreased sales tax and property tax for municipal governments.

Land Managers

Jefferson County Open Space (JCOS), Colorado State Forest Service (CSFS), and the U.S. Fish and Wildlife Service (USFWS) are primarily invested in environmental management, restoration practices, preservation of native ecosystems and wildlife, the responsible stewardship of natural resources, and safety of the general public (Jefferson County, n.d.; USFWS, n.d.). These agencies are also the officials charged with the responsibility of proper land management and serve as the ultimate bureaucratic authority for environmental planning and course of action. Their aims for appropriate techniques and best practice principles must align with current scientific understanding for the general health of the ecosystem in the nearby open space areas and jointly managed public lands. Economic implications, ecological consideration, public safety, and visual aesthetics of the landscape are values of concern within the respective agencies.

Fire Departments

The City of Arvada's Fire Department (AF) and the Colorado Division of Fire Prevention & Control (CDFPC) are primarily invested in the health and safety of their constituents and general public. Their primary responsibilities are the protection of life and property of their districts. These Fire Departments are charged with approval of proper city planning and maintenance of infrastructure such as water lines, fire main access points, and evacuation routes. They are also responsible for the management programs including administration, preparedness, funding, and wildfire response operations and collaboration (AF, n.d.; CDFPC, n.d.). Because fire districts are the ultimate authorities responsible for holding parties accountable, such as in cases of negligence, knowledge about property lines and specific residential/commercial/public zones are necessary.

Conservationists and Scientists

Conservationists and scientists involved in land management and the various governmental public safety divisions advocate for the return of the historic natural range of variability and reintegration of the historically active fire regime (Addington et al., 2018; USFS, 2021). They understand that a frequent fire regime is a part of the natural history of this landscape and advocate for implementing prescribed fire for current ecological health and the continuance of this practice as supplement for naturally occurring historical disturbance regimes. There are, however, some scientists and professionals who emphasize the nuances and caveats on prescribed fire, such as in areas with threatened species and areas with variances in the natural fire history of specific locations. Prescription fire is seen as a valuable method for restoration and future conservation methods and framework for the ecological integrity of the Front Range (Francos et al., 2021; Manfredo et al., 1990).

Local environmental conservation groups and interagency collaborative partnerships, such as the National Forest Foundation (NFF) and Northern Colorado Fireshed Collaborative (NCFC), aim to involve the public through community engagement and outreach. These types of projects and groups have been developed to educate the public on the beneficial effects of prescribed fire, while at the same time providing strategic plans and management strategies across jurisdictional boundaries (NFF n.d.; NCFC, n.d.)

Knowing that lack of action will only continue to amplify these threats in the long term, these stakeholders advocate for buffer zones and adequate measures taken to ensure prescription and naturally ignited fires do not threaten life or property (Addington et al., 2018; Ryan et al., 2013). Minimizing risk, regardless of ignition type, is understood to be a sensible approach when proactive and preventative measures are implemented.

There is potential opportunity for scientific researchers and land management officials to study burn sites and the effects of vegetative thinning on outcomes of prescribed fire (Addintgon et al., 2020). Having a proactive framework, that has mindful intention for gaining ecological knowledge while minimizing risk, will continue to advance wildland fire ecology and adaptive management strategies for communities and infrastructure. A unique opportunity for social scientists and planning officials to study community restoration and community adaptation/resilience efforts may also be taken advantage of (Francos et al., 2021; Kaval et al., 2007).

Conclusion

Prescribed fire of any size should be viewed as a serious land management operation with inherent risks to life and property if not carefully managed and monitored. Past prescribed fires that were performed in the region which were mismanaged and quickly got out of control and threatened property, livelihoods, and neighborhoods (Manfredo et al., 1990; Taylor et al., 1984), remain a deterrent for select public officials and the community members impacted. As a result of the difficulty in properly employing and managing prescribed fire operations, I do not recommend prescribed fires for these specific areas.

Safety of human life and property is an important concern and remains at the forefront for land management, government officials, private developers, property owners, and public citizens.

Human health threats from compromised air quality and displaced wildlife with a potential for increased negative Human Wildlife Interactions (HWI) are additional risks that must be addressed during these conversations. These concerns fall onto both sides of the coin, with inaction increasing potential long-term risks and action increasing acute short-term risk (Francos et al., 2021).

I recommend a diligently planned and cooperative interagency operation to mitigate wildfire risk. A Community Wildfire Protection Plan, along with future small scale prescription fires, modernized construction requirements, and broad consensus among stakeholders for community safety and course of action, is an essential framework for living in the WUI. Small steps towards the achievement of these objectives, such as regular vegetation thinning, maintaining buffer zones for high-risk areas, and firewise construction, may be undertaken over extended periods of time to meet long term goals. Overall effectiveness and bolstered safety will continue to accumulate as each goal is met, compounding overall effectiveness, and decreasing the risk of larger and more destructive future fires.

Although size and scope of these management efforts will vary on a case by case, seasonal, and annual basis, well planned and implemented strategies will by necessity require stakeholder collaboration and education for proactive and beneficial preventative measures to be taken.

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