THESIS

HOME RANGE ESTIMATES, HABITAT SELECTION, AND NESTING BEHAVIOR OF FERRUGINOUS HAWKS (*BUTEO REGALIS*) IN WESTERN WYOMING

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ABSTRACT

HOME RANGE ESTIMATES, HABITAT SELECTION, AND NESTING BEHAVIOR OF FERRUGINOUS HAWKS (*BUTEO REGALIS*) IN WESTERN WYOMING

Oil and gas development has the potential to negatively impact wildlife, but the consequences for some raptor species are less well understood. Ferruginous Hawks could be particularly susceptible to negative effects due to their large habitat requirements and sensitivity to anthropogenic disturbance. Given the rapid expansion of oil and gas development in many parts of the range of Ferruginous Hawks, it is critical to evaluate habitat use in both a pre-construction and post-construction environment. Understanding selection of habitat resources and nest sites, as well as the factors that contribute to home range estimates, nest success and nest productivity could help inform efforts to mitigate against potential negative effects of land use change.

In my first chapter, I aimed to investigate factors associated with breeding Ferruginous Hawk home range estimates and habitat selection in a landscape slated for energy development. In a sagebrush-steppe study site in western Wyoming, I captured breeding hawks and used radio and satellite-telemetry to collect location data, estimate home range estimates, and model habitat selection. Home range estimates were smaller for females and hawks with egg-laying breeding status, and larger with increasing numbers of producing wells. Ferruginous Hawks selected habitat with high terrain ruggedness, low shrub cover, and areas closer to primary prey, and avoided areas with high density of wells. The relationship between lagomorph density and distance to development was dependent on scale. My findings show that home range estimates are smaller in my study relative to other parts of the species' range, and that future energy development is likely to reduce habitat quality and availability for Ferruginous Hawks.

In my second chapter, I investigated the factors associated with nest site selection, success, and productivity in the same study site in western Wyoming. I used an existing dataset on nest site locations, nest success, and productivity, and collected new data on these response variables between 2019 and 2023. I used a resource selection function model (RSF) to evaluate nest site selection and used generalized linear mixed models (GLMMs) to evaluate nest success and productivity. Ferruginous Hawks selected nest sites in developed-open space landcover (e.g., areas cleared of vegetation with little or no infrastructure), higher topographic position index (TPI), and in closer proximity to producing wells (km). In contrast, breeding hawks avoided nest sites in areas with higher densities of producing wells (per km^2) and more shrub cover (%). Nest success and productivity of egg-laying pairs was positively associated with artificial nesting platforms (ANPs) and negatively associated with anthropogenic structures and rocky outcrops, developed-open space landcover, TPI and year. These findings suggest that Ferruginous Hawks may be subject to an ecological trap when they nest on anthropogenic structures, but that ANPs are a potentially viable tool for mitigation.

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PREFACE

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TABLE OF CONTENTS

Chapter 1: Home range and habitat selection of Ferruginous Hawks in a landscape slated for energy development

Introduction

Energy extraction and associated infrastructure results in habitat loss and fragmentation, and other forms of disturbance (e.g., noise and light pollution), which can negatively affect bird species (Chalfoun, 2021; Northrup & Wittemyer, 2013). Oil and natural gas development can directly and indirectly reduce the abundance of various passerines (Davis et al., 2023; Hethcoat & Chalfoun, 2015; Nenninger & Koper, 2018), lower nest success of killdeer (*Charadrius vociferus*) (Atuo et al., 2018) and has negative effects on greater sage-grouse (*Centrocercus urophasianus*) population dynamics (Coates et al., 2023). Even so, there remains an urgent need to understand and mitigate the effects of oil and natural gas development on other less well-understood taxa, such as raptors (Carlisle et al., 2018; Chalfoun, 2021; Diffendorfer et al., 2021; Wiggins et al., 2017).

Relative to passerine species, raptor species are potentially at even higher risk from energy development projects because of slower life histories (Buechley et al., 2019; Diffendorfer et al., 2021), lower reproductive rates (Diffendorfer et al., 2021; Ng et al., 2022) and larger area requirements (Kocina & Aagaard, 2021; Watson et al., 2023). In wind energy fields, direct mortalities from turbine collisions occur at rates that for some raptor species have the potential to result in population-level declines (Diffendorfer et al., 2021; Smallwood & Thelander 2008). Some raptor species avoid nesting in areas with coalbed natural gas development (Carlisle et al., 2018) and other raptors have lost nest sites or stopped nesting in areas with an increase in oil and gas development (Smith et al., 2010; Wiggins et al., 2017). When nest sites are limited, raptors may utilize energy development infrastructure, and are thus exposed to elevated levels of disturbance (Wallace, 2014).

Ferruginous Hawks (*Buteo regalis*) may be particularly vulnerable to development due to their relatively large habitat requirements (Isted et al., 2023; Watson, 2020; Watson et al., 2023) and sensitivity to human disturbance (White & Thurow, 1985; Nordell et al., 2017). This species is designated a species of concern in numerous states across its range largely as a result of habitat loss (Ng et al., 2020; USFWS, 2021) and is listed as threatened in Canada (COSEWIC, 2021). The effects of the extraction of oil and gas on Ferruginous Hawks are poorly understood and at times conflicting (Wallace et al., 2016; Wiggins et al., 2017), likely because of the difficulties of conducting pre-treatment research in areas slated for development (Northrup & Wittemyer, 2013). Breeding Ferruginous Hawks have shown lower rates of nest re-use after oil and gas development increased in North Dakota (Wiggins et al., 2017). Other studies have found that the density of active (eggs laid) nests increased as proximity to active wells (i.e., those operational at time of study) decreased, potentially due to increases in nest site availability through artificial nesting platforms as a mitigation tool (Smith et al., 2010) or improved habitat quality at edges, including improved habitat for prey or determent of predator species (Keough & Conover, 2012). Conversely, studies have also found oil and gas development was not avoided by breeding Ferruginous Hawks (Squires et al., 2020) and distance to active wells had no significant relationship on nesting success (Wallace et al., 2016). Yet, these relationships were investigated in landscapes post-development and therefore may be biased toward more tolerant hawks. A vital step towards understanding the relationship between Ferruginous Hawks and oil and gas development rests in evaluating habitat use of this species in both a pre-construction and post-construction environment (Smith et al., 2010; Wallace et al., 2016).

Understanding how species utilize habitat is crucial for both understanding and mitigating negative effects of anthropogenic development. Biological factors such as sex and breeding status have known effects on breeding home range estimates in raptor species, largely due to separation of responsibilities during the breeding season. Female breeding Ferruginous Hawks are expected to have smaller home ranges because they spend more time incubating eggs and defending chicks at the nest site, whereas males are mainly responsible for hunting and retrieving prey over larger areas (Keeley & Bechard, 2017; Ng et al., 2020). Additionally, breeding adults with egg caring responsibilities (egg-laying pairs) are expected to stay close to the nest site during the breeding season relative to non-laying pairs (Isted et al., 2023; Ng et al., 2020). Beyond intrinsic factors, home range estimates can also be affected by extrinsic factors. Home range estimates can indicate habitat quality, as larger home ranges require traveling greater distances to obtain resources, resulting in greater energy expenditure, and likely more risk to both the individual and a pair's reproductive success (Fattebert et al., 2018; Moss et al., 2014; Watson, 2020). Anthropogenic disturbance can alter resources that results in lower habitat quality and larger home range estimates, both from avoidance or direct habitat loss (Doherty et al., 2021; Perona et al., 2019). Estimating home ranges for Ferruginous Hawks on working lands (i.e., energy extraction, agricultural activities) also has conservation implications, informing appropriate buffer distances for anthropogenic development to minimize negative effects on nesting pairs (Kocina & Aagaard, 2021; Watson et al., 2023). Furthermore, identifying resources that are selected by breeding hawks through habitat selection can identify crucial resources to focus conservation strategies (Kocina & Aagaard, 2021; Tapia et al., 2007).

A new energy development project in the western U.S. provides an ideal opportunity for evaluating the impacts of energy development on Ferruginous Hawks in a pre-development setting. The Normally Pressured Lance Natural Gas Development Project (NPL) was approved by the Bureau of Land Management in 2018 for construction in southwestern Wyoming in an area that also supports a breeding population of Ferruginous Hawks. This development is projected to add 3,500 directionally-drilled well pads across 140,859 acres, over a period of 10 years (Bureau of Land Management, 2018) Several large existing oil and gas developments (e.g., Jonah Infill Drilling Project, Pinedale Anticline Natural Gas Field) are outside of, but adjacent to, this new planned field. Because Wyoming likely supports the largest portion of the global population of Ferruginous Hawks (NatureServe 2023; Travsky & Beauvais, 2005; Ziolkowski et al., 2023) the NPL could be particularly impactful for this species of concern.

The objectives of my study were to investigate abiotic and biotic factors associated with Ferruginous Hawk home range estimates and habitat selection in a landscape about to undergo energy development. I expected biological factors, such as sex and breeding status, to influence home range estimates, as adults have different nest responsibilities during the breeding season (Ng et al., 2020). Therefore, I expected females and egg-laying pairs to have smaller home range estimates compared to males and non-laying pairs. I hypothesized that Ferruginous Hawks would select habitats that may provide better hunting opportunities, such as areas with higher prey abundance and lower shrub cover. Anthropogenic development and associated disturbance is likely to diminish breeding habitat quality and quantity, and result in larger home range estimates (Doherty et al., 2021). Therefore, in edge areas adjacent to development, I expected Ferruginous Hawks to avoid development and producing wells, resulting in larger home ranges in areas with high densities of oil and gas wells. My study provides crucial pre-development data, which is often lacking, for comparison to future studies in the NPL. Further, understanding space-use behavior in Ferruginous Hawks pre-development could help inform mitigation measures, such as informing buffer distances or prioritizing management of crucial habitat resources, to minimize the potential harmful impacts of energy extraction in this landscape and others.

Methods

Study Area

This study took place within and around the Normally Pressured Lance Natural Gas Development Project (NPL), located approximately 56 km south of Pinedale, Wyoming (Bureau of Land Management, 2018; Figure 1.1). The study area is directly adjacent to two existing natural gas development projects, including the Jonah Infill Development Project to the northeast and the Pinedale Anticline Project to the north (Bureau of Land Management, 2018). The study site is comprised of 96.3% Bureau of Land Management (BLM) land, as well as both state (3.6%) and private (0.06%) lands (Bureau of Land Management, 2018). This area's anthropogenic uses include natural gas energy extraction, agricultural grazing, off-highway vehicle use, antler collecting, wildlife viewing, hunting, and trapping. About 1.1% of the study site has existing development, including 55 producing natural gas wells, 19 dry/junked/abandoned wells, one Class II Underground Injection Control well, 10 water supply wells (for oil and gas operations), 31 stock water wells, and related infrastructure such as roads and transmission towers (Bureau of Land Management, 2018). The elevation of the study site is between 2079 and 2139m, the topography is characterized by low rolling hills, rock outcrops and large draws, and the land cover is predominately Wyoming big sagebrush (*Artemisia tridentata*) in a shrub-steppe habitat (Bureau of Land Management, 2018). The site also includes erosional sandstone, other sagebrush species (*Artemisia spp.)*, rabbitbrush (*Chrysothamnus spp.*), saltbush (*Atriplex spp.*), and forb and grass species (Bureau of Land Management, 2018). The study area includes an established breeding population of Ferruginous Hawks which has been monitored by the BLM since 2011. The number of nesting Ferruginous Hawks in the study area ranges from 5 – 20 breeding pairs in any single breeding season.

Radiotelemetry

To quantify home ranges and habitat selection of Ferruginous Hawks, I deployed GPS transmitters on breeding adults. The following methods adhere to standard protocols (Bloom et al., 2007; Fair et al., 2010) and received IACUC approval from Colorado State University (IACUC protocol #1871). Between 2019 and 2022, I worked in tandem with BLM and Teton Raptor Center to survey the study site and locate nesting attempts of Ferruginous Hawks. To find nests, nest surveys were conducted by ground and air both within and adjacent to the field site at the beginning of the breeding season. I monitored nests weekly until eggs were successfully hatched and began trapping when nestlings were approximately 10 days old. At this age, nestlings can independently thermoregulate, and adults are most invested in protecting their young, leading to better trapping success (Leary et al., 1998; Watson, 2020). I used an established technique for capturing breeding raptor species, which involved using two dho-gaza nets setup in a “V” formation and a mechanical Great Horned Owl (*Bubo virginianus)* set at the base of the nest (Bloom et al., 1992; Bloom et al., 2007; Jensen et al., 2019). I aimed to capture one breeding adult per egg-laying pair and recorded standard ornithological morphometric measurements (i.e. mass, wing chord, hallux length) to confirm sex in the field (Travsky & Beauvais, 2005). Each individual was banded with a single metal USGS band.

I equipped hawks with one of three different GPS transmitters – either a GPS-UHF logger long rang link (LRD) (20g) with an attached VHF transmitter (5g; 25g in total), or a GPS-GSM (20g), both KITE-H models manufactured by Ecotone Telemetry (Gdynia, Poland), or a refurbished Argos/GPS Platform Transmitter Terminals (PTTs) (22g) manufactured by

Microwave Telemetry, Inc. (Columbia, MD, USA). All units were powered with solar panels and equipped on hawks using a teflon-coated ribbon backpack harness (Bedrosian & Craighead, 2007; Buehler et al., 1995). Total weight of the transmitters was no more than 1.5% of total body weight, well below USGS requirements that transmitters be less than 3% of a bird's body mass (Bird Banding Laboratory, 2018). In 2019, I exclusively deployed Ecotone GPS-UHF logger units. Location data was remotely downloaded from a range of 0.8km or more, depending on surrounding topography, and converted into a Microsoft Excel file using an Ecotone provided decoding program. In 2020 and 2021, I also utilized Ecotone GPS-GSM units and Microwave Argos/GPS PTT units. The GSM transmitter data was downloaded remotely via a digital cellular network, while the Argos transmitters were downloaded remotely via Argos satellites data servers. The Ecotone UHF loggers gathered location points every 30-min, and the GSM units collected a location every 1-hr during daylight hours. The Microwave Argos/GPS PTT transmitters were refurbished units that collected locations at 2-hour intervals. Location data for all tagged individuals were routinely downloaded at least once every week through the breeding season.

Home Range Estimates

To quantify home ranges during the breeding season for this study site, I analyzed location data for each tagged individual captured between 2019 and 2022. For hawks newly captured, I used location data collected between the time of capture in early June until an individual left the study site for fall migration, which was usually between late July and early August. For tagged individuals who returned for another breeding season, location data was used from date of arrival on the breeding grounds in late March until initiation of fall migration. GPS points were filtered to exclude any erroneous locations, as indicated by negative speed values or sudden longitude/latitude values out of the country. I used program R (Version 3.3 for Windows) (R Core Team, 2021) to calculate home ranges with an autocorrelated kernel density estimation (AKDE) approach using the *ctmm* package (Fleming et al., 2022), which includes a temporal component when estimating home ranges. Including time into home range estimation allowed us to compare estimates more confidently across individuals equipped with different types of transmitters with different fix rates (Isted et al., 2023). I also evaluated home range estimates using a minimum convex polygons (MCP) and kernel density estimation (KDE) approach with the *adehabitatHR* R package (Calenge, 2006) for comparative purposes, because most previous studies on Ferruginous Hawks used these home range estimators (Leary et al., 1998; Watson, 2020; Watson et al., 2023). I calculated home range and core area estimates using a 95% and 50% Utilization Distribution (UD), respectively (Isted et al., 2023; Leary et al., 1998; Watson, 2020; Watson et al., 2023).

Variables Associated with Home Range Estimates

I investigated how biological factors, such as sex and breeding status may relate to size of a breeding home range (Table S1.3). Sex was determined in the field using mass (g) (Gossett, 1993). I followed Steenhof et al.'s (2017) definition for breeding status and defined a pair that laid eggs in a nest as an "egg-laying pair" and a "non-laying pair" as an individual or pair that displayed breeding behavior and/or was territorial of a nest site but ultimately was confirmed to have not laid at least one egg. I also considered the effect of the number of producing natural gas wells and mean shrub cover percentage on home range estimates (Table S1.3). I additionally considered landcover type as a covariate, but this was ultimately removed from the final model as home ranges were uniformly dominated by scrubland/shrubland (home range estimates average 95% ± 4.76%). To quantify oil and natural gas wells within a home range, location data of wells were extracted from the Wyoming Oil and Gas Conservation Commission (retrieved 28 April 2022 from http://wogcc.state.wy.us). I used ArcGIS Pro software (Version 10.1) and the "Intersect" function of the Spatial Analyst tools to calculate the number of wells within a respective bird's home range and core area (ESRI, 2013).

The percent shrub cover raster was built by utilizing LANDFIRE's Existing Vegetation Cover layer (LANDFIRE, 2020). The categories of vegetative cover (%) present in this study were barren (<1% vegetative cover), sparse vegetation canopy (1-9% vegetative cover) and shrub cover. Shrub cover was the most dominant class and ranged from 10– 68% for this field site. Barren and sparse vegetation was defined by LANDFIRE as unidentified vegetation with less than 1% or between 1 and 9% cover, respectively. These classes do not specify the vegetation type, but they are most likely shrub-type vegetation for this field site and were treated as such in the final shrub cover layer. I treated these ranges as discrete values of 1% and 5%, respectively, in order to include them in the final model. I extracted the mean shrub cover percentage within each bird's home range using the *exactextractr* package in R (Baston & ISciences LLC, 2023).

I modeled the relationship between home range and core area size against covariates using a Generalized Linear Mixed Model (GLMM) model with a Gamma family with a log function. Individual ID and year were included as random effects, and the model was fitted using the *lme4* R package (Bates et al., 2015). I considered a p-value (P) < 0.05 to be statistically significant. The home range and core area scale were determined utilizing individuals' 95% and 50% AKDE measurements, respectively. Tagged individuals who returned for multiple breeding seasons were considered independent for each year (Leary et al., 1998; Watson, 2020). I confirmed sampling frequency did not have a significant effect on calculated ranges with a linear mixed model before moving forward with analysis (Table S1.4).

Habitat Selection

In building the habitat selection model, I considered the habitat characteristics of this field site and the life history of the Ferruginous Hawk in selecting covariates (Table S1.7) (Ng et al., 2020) and considered covariates both within home ranges and at the study site scale. I included landcover type, shrub cover, shrub height, topographic position index (TPI), elevation (m), terrain ruggedness index (TRI), distance to producing well (km), distance to highway (km), and distance to developed landcover (km). I also included individual by year as a random effect to account for individual variability. Landcover data was extracted from the National Landcover Database (NLCD) (Dewitz & U.S. Geological Survey, 2021) and included scrub/shrub, barren, grassland, pasture/hay, and developed landcover. I aggregated the different intensities of developed landcover, including open space, low intensity, medium intensity, and high intensity into one general developed landcover class due to its overall low density in this field site (~1.1%). I also manually digitized major roadways (i.e., highways, two-lane gravel roads) via ArcGIS Pro and added these areas into the developed landcover raster for a more accurate layer. From the LANDFIRE database I extracted datasets on shrub cover (%), shrub height (m), elevation (m), terrain ruggedness index (TRI), and topographic position index (TPI) (LANDFIRE, 2020). I compiled all covariates into 30m-resolution raster layers. As with the home range analysis, I extracted the location of oil and natural gas wells from the Wyoming Oil and Gas Conservation Committee (retrieved 28 April 2022 from http://wogcc.state.wy.us) and specifically filtered out wells designated as “Producing” to analyze the relationship specifically with wells associated with noise, light, and other anthropogenic disturbance. I created a raster layer of well density in ArcGIS Pro using the Spatial Analyst tool *Point to Raster* at 30m-resolution. Distance to producing well, highway, and developed landcover was calculated in ArcGIS Pro using the Spatial Analyst tool *Near* to calculate the distance from a location point to the nearest respective pixel.

I collected or collated data on Wyoming ground squirrels (*Urocitellus elegans elegans*), white-tailed prairie dogs (*Cynomys leucurus*), and lagomorph species, including white-tailed jackrabbits (*Lepus townsendii*), mountain cottontails (*Sylvilagus nuttallii*), and pygmy rabbits (*Brachylagus idahoensis*) as a proxy for prey availability. Mammals within these orders have been documented as prey items for Ferruginous Hawks (Cartron et al., 2021; Keough & Conover, 2012; Ng et al., 2020; Watson et al., 2023) and were observed being fed to adult or nestling birds by trail cameras, or found in pellets within Ferruginous Hawk nests, at this field site (Ramirez unpub. 2023). To document the extent of white-tailed prairie dog colonies, I walked transect lines within the estimated average home range (3 km radius) for all egg-laying and non-laying pairs within a given year. Once a colony with prairie dogs was found, I followed the mapping protocol as described by BLM by marking the edges with a GPS location of a burrow on the edge of a colony, and then searching within 30m for the next burrow on the edge. This process continued until returning to the starting burrow (Bureau of Land Management, 2011). I excluded collapsed burrows but included unoccupied burrows. These points formed polygons through the *Aggregate Points* tool in ArcGIS Pro. I then utilized the *Near* tool to calculate the distance (km) from each point to the nearest white-tailed prairie dog colony.

To assess lagomorph species abundance at the home range and study site scale, I conducted nocturnal spotlight surveys in 2020 and 2021. At least two observers drove along the survey route at night with a spotlight and lagomorph species were located via reflected eyeshine.

Observers recorded species of lagomorph detected, if possible, location, and distance to the road. These surveys involved surveying at least 5km of road (two-track or main gravel) within the estimated home range (3 km radius) of each pair in each year of the study as well as random transects outside the home range for comparison. I used the *Create Random Points* tool in ArcGIS Pro to select the same number of random transects as actual home range transects to capture abundance at the full extent of the study area. Lagomorph species were not found in large numbers in this field site, so to achieve a sufficient sample size for modeling, I combined white-tailed jackrabbits (*Lepus townsendii*), mountain cottontails (*Sylvilagus nuttallii*), and pygmy rabbits (*Brachylagus idahoensis*) and unknown lagomorph species into a single ‘lagomorph’ group. I defined “presence” points as locations where a lagomorph species was found and “absence” points as random points along all transects where lagomorphs were not observed. I extracted information on elevation, percent shrub cover, and topographic position index (TPI) at all points with the *extract* function in the *terra* package in R (Hijmans et al., 2022). Covariates used to describe lagomorph density were decided based on previous rabbit distribution literature (Olson et al., 2017). I then used the presence-absence points to create a species distribution map by running a generalized linear model (GLM) with a binomial family and a logit link function, evaluating lagomorph presence as a function of elevation, percent shrub cover, and TPI (Table S1.8). I used the *glm* function of the *lme4* R package to run the GLM model (Bates et al., 2015). I used the model results to create a predictive distribution map for combined lagomorph species for this study site using the *predict* function in the *dismo* package in R (Hijmans et al., 2023). Finally, because collecting field data on ground squirrel distribution and abundance was beyond the scope of this project but this species was delivered to nestlings documented by trail cameras (Ramirez unpub., 2023), I utilized a United State Geological

Survey (USGS) Gap Analysis Project (GAP) habitat suitability map for the Wyoming ground squirrel (USGS - GAP, 2018) within this study area.

To evaluate the factors associated with habitat selection, I produced three resource selection probability function (RSF) models using a design III approach (Manly et al., 1993). Habitat selection was investigated at two spatial scales, at the home ranges of tagged Ferruginous Hawks, and at the study site scale, defined by the full extent of all location data points. Due to high annual variability in white-tailed prairie dog occupancy values (Clark 1973, Menkens 1987), I ran a separate third RSF model for prairie dog colonies for the years I conducted prairie dog colony surveys (2020-2021). I only ran this model against location data from those specific years within home range scale, given that I did not collect data at the study site scale. For the home range scale, I randomized "available" points within a 99% MCP for each individual home range estimate. At the study site scale, "available" points were drawn from a 99% MCP boundary of all collected location points, essentially drawing a boundary around the entirety of this field site. I defined "used" points from acquired location data points. I extracted covariate details at each point using the *extract* function in the *terra* R package (Hijmans et al., 2022).

I tested for correlation among covariates using Pearson's correlation ($-0.7 < r > 0.7$) and removed single covariates that were considered highly correlated with another (Table S1.9). Final covariates from highly correlated options were chosen based on significant covariates in previous publications (Ng et al., 2022; Squires et al., 2020; Wallace et al., 2016; Watson, 2020) or based on what might be more relevant for management decisions in this particular field site. I also checked for potential collinearity using the *performance* package in R (Lüdecke et al., 2023) and removed covariates with a VIF value >3. For the RSF model, I ran GLMMs with a binomial family and logit link function. Selection ratios were considered the response variable and I evaluated both categorical and continuous covariates as predictor variables (Table S1.7). GLMMs were fitted using the *glmer* function of the *lme4* R package (Bates et al., 2015) and used a backward step-wise selection approach using Akaike's information criterion (AIC) values to select the most parsimonious model. To determine the appropriate ratio of available points for the resource selection function, I repeated the model with increased available points until the model produced the same results regardless of ratio number. This determined that an available-to-use ratio of 5:1 to be sufficient at both scales. Variables with $P < 0.05$ were considered statistically significant. I included individual and year as random effects. I used a *k*-fold cross-validation approach based on Spearman-rank correlation to validate the final model (Boyce et al., 2002).

Results

Home Range

Between 2019 and 2022, I captured and equipped 15 breeding Ferruginous Hawks with GPS transmitters, consisting of nine males and six females (Table S1.1). Of the 15 tagged hawks, I tracked seven individuals for one season, three individuals for two seasons, two individuals for three seasons, and two individuals for four seasons. One hawk with a GPS-UHF logger left the field site on fall migration shortly after it was trapped and was not relocated the following spring with remote-download equipment. In 2021, one tagged female moved territories halfway through the nesting season after a failed nesting attempt. Given how far she moved (8 km), and the consistency of her location points in this area in subsequent years (2021 and 2022), I considered this new territory as a new individual home range within the same year. In total, this resulted in 27 home ranges that were included in the analysis. I collected a total of 44,347 GPS locations and home range estimates had an average of 1,642 ± 1238 location points over an average of 78 ± 34 days (Table S1.2).

In egg-laying pairs, average home ranges at 95% AKDE for males was 25.67 km^2 (± 10.76 SD, n=11) and for females was 11.36 km^2 (± 9.15 SD, n=10). Additionally for egg-laying pairs, mean core area based on 50% AKDE for males was 2.75 km^2 (± 1.27 SD, n=11) and for females was 1.03 km^2 (± 0.58 SD, n=10). For non-laying pairs, average home ranges for males was 58.09 km^2 (± 23.28 SD, n=3) and 13.81 km^2 (± 1.20 SD, n=3) for females. Additionally, for non-laying pairs, mean core area for males 3.33 km^2 (± 0.44 SD, n=3) and for females was 1.65 km^2 (± 0.44 SD, n=3) (Table 1.1). Home ranges estimated using other approaches (MCP and KDE) were similar to AKDE values (Table S1.5).

Variables Associated with Home Range Estimates

Home range and core area sizes were associated with sex and breeding status. Males and birds with a non-laying status (no eggs in nest) had larger home ranges and core areas (Figure 1.2, Table S1.6). Home range estimates were positively associated with number of producing wells, although this relationship was not statistically significant at the core area scale (Figure 1.2, Table S1.6). Twelve of the 27 home ranges contained producing wells within a 95% AKDE boundary, ranging from 1 to 545 (mean = 150.42 ± 180.36). Conversely, 96% of core areas (n=26) had no producing wells within a 50% AKDE boundary. . Percent shrub cover trended towards being positively associated with home range estimates, but this relationship was not significant (Figure 1.2, Table S1.6). Within home range, mean percent of shrub cover averaged 27.46% ± 4.94%, and within core area averaged 26.14% ± 6.18%.

Habitat Selection

At both the home range and study site scale, Ferruginous Hawks exhibited strongest selection for areas with high TRI values (Figure 1.3, Table S1.10). At the home range scale, breeding Ferruginous Hawks showed the strongest avoidance of areas with a high percentage of shrub cover (Figure 1.3, Table S1.10). Grassland landcover was slightly selected for at both scales, while barren landcover was slightly avoided at the home range scale and slightly selected for in the study site scale. For the anthropogenic covariates at the home range scale, hawks selected for larger distances from developed landcover and avoided areas with higher densities of wells (Figure 1.3, Table S1.10). However, at the study site scale, breeding Ferruginous Hawks selected habitat closer to development landcover, although they still strongly avoided areas with higher densities of wells (Figure 1.3, Table S1.10). Ferruginous Hawks selected areas with predicted presence of Wyoming ground squirrel at both the home range and study site scale (Figure 1.3, Table S1.10). At the home range scale, hawks avoided areas with predicted higher densities of lagomorph species but at the study site scale they selected areas with higher predicted densities of lagomorphs (Figure 1.3). Mean Spearman's rank coefficients for k-fold cross validation averaged 0.93 (± 0.05) at the home range scale and 0.93 (± 0.04) at the study site scale. In the subset RSF model for prairie dog colonies, Ferruginous Hawks selected habitat closer to colonies at the home range scale (Figure 1.3, Table S1.11) and k-fold cross validation averaged 0.90 (± 0.02).

Discussion

Ferruginous Hawks are a species of concern across their North American range (COSEWIC, 2021; Ng et al., 2020; USFWS, 2021) and may be more sensitive to human disturbance relative to other birds of prey (White & Thurow, 1985). I evaluated the factors associated with breeding Ferruginous Hawk home range estimates and habitat selection in the core of their range in a relatively undisturbed landscape approved for future large-scale energy development. In this study site in western Wyoming, Ferruginous Hawks had the smallest home range estimates yet reported for this species, potentially due to higher quality habitat in this landscape. This study is also the first to report major differences in home range estimates by sex and breeding status. Ferruginous Hawks selected habitat with high terrain ruggedness (i.e., pillars and rocky outcrops), low shrub cover, and areas closer to white-tailed prairie dog colonies and areas predicted for Wyoming ground squirrels. Areas with higher lagomorph density were avoided at the home range scale, potentially due to a correlated relationship with closer distance to producing well at this scale. My findings further suggest that producing wells decrease habitat suitability for breeding Ferruginous Hawks, resulting in larger home range estimates and avoidance of these areas.

Home range estimates for both male and female Ferruginous Hawks in this study site are the smallest yet to be reported for the species among studies that used GPS transmitters (Isted et al., 2023; Watson, 2020; Watson et al., 2023). Additionally, sex and breeding status were determining factors in a hawk's home range estimate, with females and an egg-laying breeding status being associated with a smaller home range estimate. In contrast, other recent studies found no significant differences in home range estimates according to sex or breeding status for this species (Isted et al., 2023; Watson et al., 2023). The differences detected both in average home ranges, and among sex and breeding status in this study site, could indicate higher quality habitat in this region in western Wyoming relative to other parts of this species' range (Fattebert et al., 2018; Moss et al., 2014; Watson, 2020). This site is remote, is primarily comprised of natural land cover (e.g., no cropland, sparse energy development, and relatively minimal human infrastructure) with only 1.1% of this study site containing development, and is located in what is considered one of the most intact sagebrush steppe landscapes remaining within the overall range of Ferruginous Hawks (Squires et al., 2020). This study site specifically may have critical resources, such as more hunting opportunities or low anthropogenic activity, in closer proximity to each other leading to smaller home range estimates that support breeding pairs. Populations with larger average home range estimates may need to compensate for poorer habitat quality and additionally may shift from expected behavioral roles (i.e., females matching home range estimates to males, egg-laying breeders utilizing similarly sized areas as a non-egg laying pair would use) to obtain sufficient resources for survival and reproduction. Previous work has shown female Ferruginous Hawk nest attendance increased with the amount of prey biomass delivered by the male (Keeley & Bechard, 2017) suggesting that if males are able to deliver a sufficient amount of prey, females respond by spending more time at the nest, and likely would result in a smaller home range estimate compared to males.

Habitat selection in raptors is often explained by their relationship with prey availability, including landcover types and topographic elements that affect prey type, abundance, and visibility (Bühler et al., 2023; Domenech et al., 2015). The preference for areas with higher terrain ruggedness (i.e., ridges and pillars) and low shrub cover may indicate that these landscape characteristics are suitable for finding prey, either through higher prey abundance or improved visibility (Andersson et al., 2009). Perch height can be important for improved foraging success in raptors (Jenkins, 2000), and likely explains the preference for areas of higher terrain ruggedness. Although these proxies for prey availability are useful, direct measures of prey can be even more informative. Ferruginous Hawks in this study area preferred areas with a predicted presence of Wyoming ground squirrels at both the home range and study site scale, closer proximity to white-tailed prairie dog colonies at the home range scale, and higher lagomorph density only at the study site scale. These results are consistent with other studies on Ferruginous Hawk primary prey species (Keeley et al., 2016; MacLaren et al., 1988). Wyoming ground squirrels and white-tailed prairie dogs in particular tend to avoid areas with high shrub/sagebrush cover (Olson et al., 2017) which could additionally explain why hawks in this study site selected against these areas. Surprisingly, at the home range scale Ferruginous Hawks avoided areas with higher lagomorph density. At the finer home range scale, lagomorph density was positively correlated with closer proximity to producing wells (Table S1.9). Given the avoidance of development at the same home range scale (i.e., selecting farther distances from developed landcover, avoidance of higher density of producing wells), breeding hawks may avoid areas with increased lagomorph density at this scale due to increased disturbance or human activity that is associated with producing wells. The relationship between lagomorph density and proximity to producing well was not correlated at the study site scale, which could further explain why hawks at this coarser scale were more likely to select for areas with higher densities of lagomorphs. Given the cyclic nature of lagomorph abundance (Bartel et al., 2008; Preston et al., 2017) it is possible a longer-term study would better define the relationship between Ferruginous Hawks and lagomorph species in this study site.

Ferruginous Hawks largely avoided oil and gas development in places where overlap occurred. Relatively high densities of oil and gas development are located on the edges of the study area (e.g., Jonah Infill Drilling Project and Pinedale Anticline Project Area). Although the Jonah field specifically is associated with higher small-mammal abundance (Hethcoat and Chalfoun, 2015) and anthropogenic development may provide infrastructure for hunting perches (Ng et al., 2020; Watson, 2020), I found that Ferruginous Hawks avoided areas associated with higher densities of producing wells, and when overlap between hawks and development did occur, higher densities of producing wells resulted in larger home range estimates. Additionally, most core area estimates (96%) overlapped with no producing wells, suggesting that Ferruginous Hawks avoid areas with wells in the most critical portion of their breeding habitat (Samuel et al., 1985). Producing wells are associated with more noise and vehicle traffic (Adgate et al., 2014; Davis et al., 2023; Hays et al., 2017), which likely deter hawks from both habitat itself and/or possible resources in these areas. Furthermore, at the home range scale, breeding hawks avoided developed landcover, which included producing and abandoned wells, highways and dirt roads, and other anthropogenic infrastructure. The avoidance of both producing wells and other types of development indicates a consistently negative response to anthropogenic activities and infrastructure related to energy development within the home range scale.

Habitat selection decisions at the study site scale for a breeding raptor may be driven more by placement of breeding territories and nest site options and could explain why breeding Ferruginous Hawks at the coarser study site scale selected habitat near developed landcover. Indeed, Ferruginous Hawks in this field site selected nest sites on anthropogenic structures in developed landcover where terrain was relatively flat (see Chapter 2, Ramirez). Developed areas provide infrastructure that may introduce new height on landscapes (Ng et al., 2020; Watson, 2020) which may be attractive to nesting hawks. Additionally in this field site, artificial nesting platforms placed near neighboring energy development were also used by nesting hawks, potentially influencing placement of territories to be closer to developed landcover than natural sites (Smith et al., 2010). Breeding Ferruginous Hawks can be limited by nest site availability (Parayko et al., 2021) and artificial height on a landscape, through artificial nesting platforms or anthropogenic structures, could influence nesting both near and directly on development.

Concerningly, research has also shown nest sites in developed landcover on anthropogenic structures experience lower nest success and productivity (see Chapter 2, Ramirez) and lower nest re-use rates as development increases (Wiggins et al., 2017) posing a risk to breeding populations. Although artificial nesting platforms may offer height in areas with limited nest site options, they should be thoughtfully placed to avoid attracting breeding pairs to poor quality habitat.

This study provides important baseline data on Ferruginous Hawk home range estimates and habitat selection in a largely undisturbed landscape slated for oil and gas development. Currently, home range estimates vary widely for Ferruginous Hawks between populations across North America, and a comparison study may highlight specifics on habitat quality differences, such as density of development or diversity of landcover types. Additionally, home range estimates for breeding females are currently underreported for Ferruginous Hawks, and more published estimates would further understanding of female space use, especially when faced with diminishing habitat quality. Furthermore, there is likely a threshold at which Ferruginous Hawks cannot tolerate energy development, but more research is needed to understand this limit (Keough & Conover, 2012; Schmutz, 1989; Squires et al., 2020) and the dynamics that result in tolerance versus avoidance. Direct measurements of disturbance (e.g., noise, light) were beyond the scope of this study, but may expand understanding of Ferruginous Hawk space use. In this study site, nests located closest to development were positioned in terrain that potentially shielded them from direct noise and light pollution as well as daily anthropogenic activities. Future work should focus specifically on how Ferruginous Hawks respond to a gradient of anthropogenic development and disturbance, as well as how terrain and nest site placement may affect exposure to disturbance. Lastly, most research on wildlife and energy development occurs post-construction (Parayko et al., 2021) leaving a vital gap in pre-construction data. Repeating this study after oil and gas development is complete, and while it is underway, would provide valuable information on the effects of development on this sensitive raptor species.

This study provides new insight on the relationship between breeding Ferruginous Hawks and key habitat and resources in a relatively undisturbed landscape. My home range estimates and habitat selection findings can be used by land managers to prioritize resources that are important to breeding Ferruginous Hawks, including areas that support prey abundance and visibility. Home range estimates vary by both sex and breeding status, and land managers should be aware of how documenting these differences could be an indicator of habitat quality. This study also suggests that Ferruginous Hawks avoid energy development, and their avoidance of nearby high-density natural gas fields suggests these fields are not suitable habitat for Ferruginous Hawks. Land managers may consider minimizing the density of development or excluding it altogether within existing home ranges to preserve habitat quality for breeding populations of Ferruginous Hawks.

TABLES

Table 1.1 - Average home range estimates (km^2) for Ferruginous Hawks in a breeding population in southwestern Wyoming (n=27). Autocorrelated Kernel Density Estimation is reported at both the home range (95%) and core area (50%) utilization. "Egg-laying" is defined as hawks with eggs in a nest, and "non-laying" defined as hawks courting, defending, and occupying a territory but never laid eggs during the season. See Supplemental Materials (Table S1.4) for values derived from other estimation approaches (MCP and KDE), which were similar to those presented here.

	Males			
	Egg-laying (n=11)		**Non-laying (n=3)**	
METHOD	**MEAN**	**SD**	**MEAN**	**SD**
AKDE 95%	25.67	± 10.76	58.09	± 23.28
AKDE 50%	2.75	± 1.27	3.33	± 0.47
	Females			
	Egg-laying (n=10)		**Non-laying (n=3)**	
METHOD	**MEAN**	**SD**	**MEAN**	**SD**
AKDE 95%	11.36	± 9.15	13.81	± 1.20
AKDE 50%	1.03	± 0.58	1.65	± 0.44

FIGURES

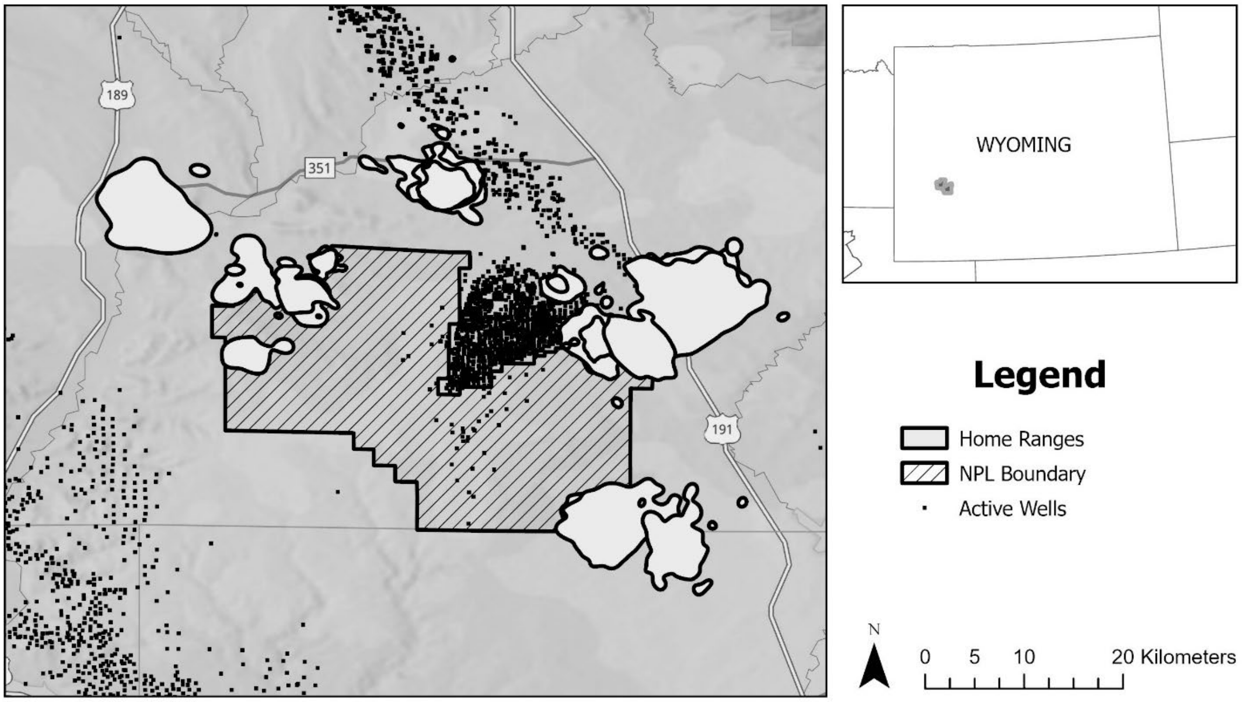
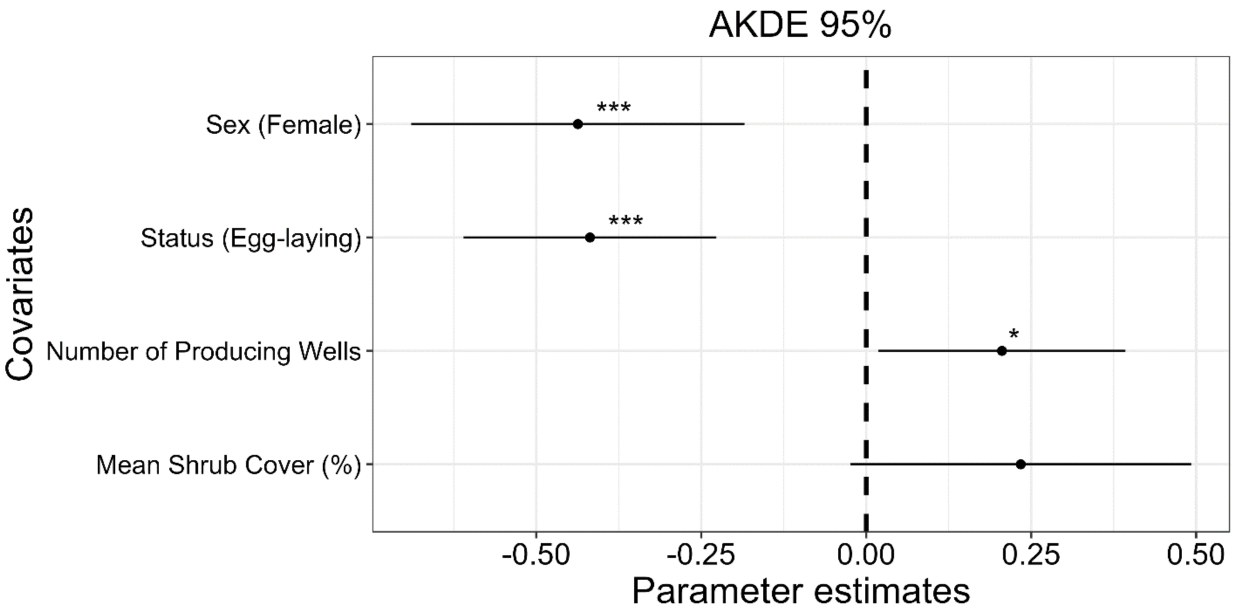


Figure 1.1 - The study site for evaluating home range estimates and habitat selection of Ferruginous Hawks in western Wyoming. The planned Naturally Pressured Lance Natural Gas Development area (NPL) is shown with dashed lines. Ferruginous Hawk breeding home ranges (n=27), which were calculated using the Autocorrelated Kernel Density Estimation method, are shown in white.



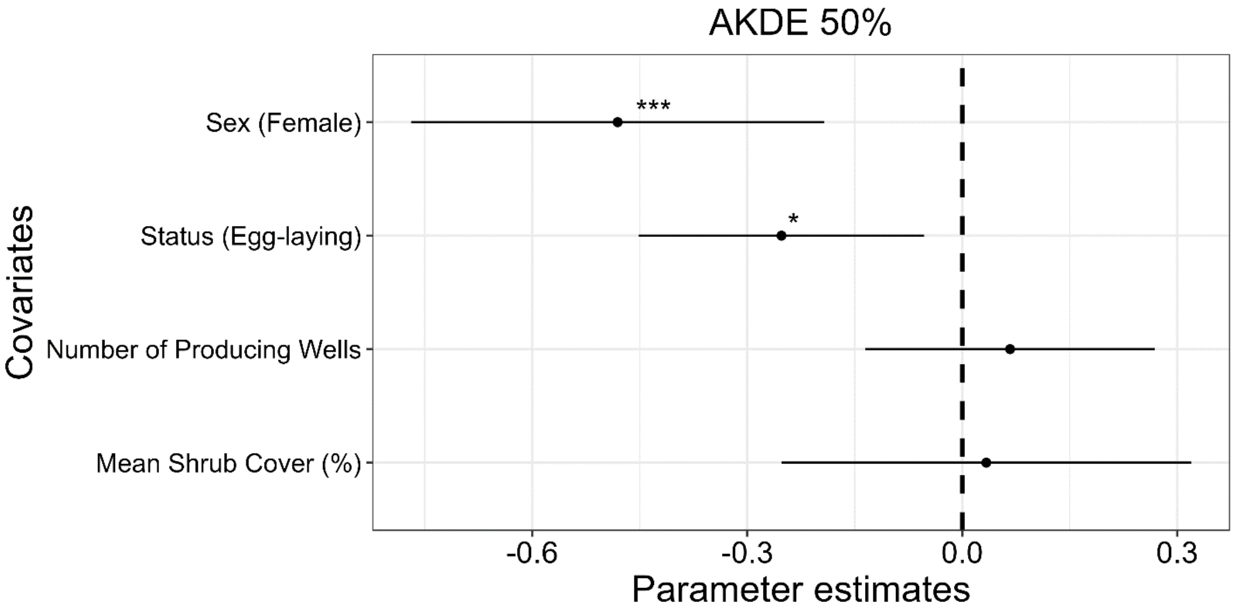


Figure 1.2 - Results of the model (GLMM) evaluating the relationship between sex, status, number of oil and gas wells and mean shrub cover (%) on Ferruginous Hawk home range (95%) and core area (50%) defined by AKDE. Asterisk indicates level of statistical significance as defined by p-value ($p^* < 0.05$, $p^{***} < 0.001$) (Table S1.4). Smaller home range estimates are associated with being female and having an egg-laying breeding status. Larger home range estimates are positively associated with the number of producing wells.

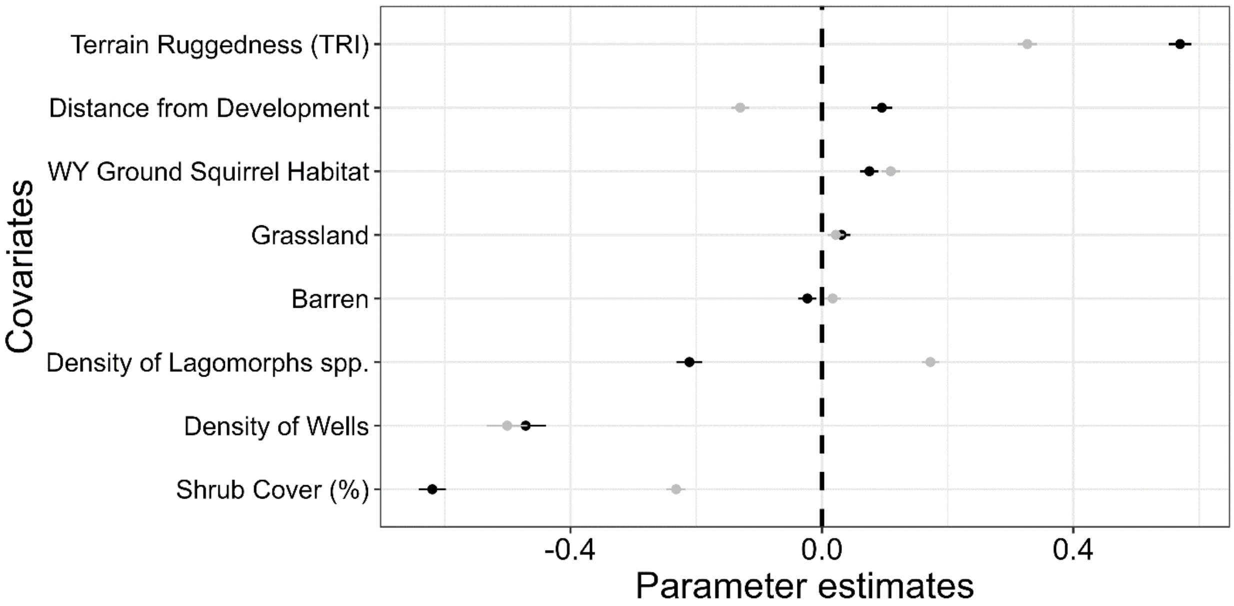


Figure 1.3 - Results of Resource Selection Function model of breeding Ferruginous Hawks (n=27) in Wyoming between 2019 and 2022 at two scales, within home-range scale (black dot) compared to study site scale (grey dot). Covariates are scaled with a mean of 0 and standard deviation of 1 (Table S1.5). Positive values indicate covariates that were selected, and negative values indicate covariates that were avoided.

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Chapter 2: Ferruginous Hawk nest site selection, success, and productivity: implications for mitigating the effects of energy development

Introduction

Energy extraction projects pose a threat to wildlife globally causing direct habitat degradation and loss along with increased human activities with associated noise and light pollution (Walker et al, 2007; Kociolek et. al, 2011; Oretega 2012; Northrup & Wittemyer, 2013). Anthropogenic disturbance associated with energy development reduces bird abundance of various species (Davis et al., 2023; Hethcoat & Chalfoun, 2015; Nenninger & Koper, 2018), disrupts mate pairing, and reduces nesting success (Francis et al., 2012) and birds can experience direct mortality from wastewater ponds and ingesting toxins (Gurney et al., 2005; Ramirez, 2010). The negative effects of energy extraction on wildlife can be mitigated with a variety of approaches (Chalfoun, 2021; Northrup & Wittemyer, 2013). For example, to reduce anthropogenic noise associated with energy development, methods include utilizing natural noise barriers, constructing artificial barriers, installing noise suppression devices, or using fewer compressors (Bayne et al., 2008; Francis et al., 2011). Similarly, deterrents and netting ponds can be effective in preventing birds from landing on toxic wastewater ponds (Ronconi & Cassady St. Clair, 2006; Ramirez, 2010). Mitigation can also take the form of habitat management, including enhancing habitat for target species by restoring native vegetation to help offset nutritional stress (Northrup & Wittemyer, 2013).

Increasing the number and quality of nest sites is another promising mitigation strategy for many avian taxa (Tapia & Zuberogoitia, 2018; Watchorn et al., 2022). Artificial nesting structures, such as nest boxes and platforms, have been widely used for a diversity of species, including raptors (Reynolds et al., 2019). Artificial nesting platforms (ANPs) have been installed to encourage relocation of nests away from dangerous substrates, such as powerlines (Kemper et al., 2020), utility poles and large light fixtures (Guill & Forys, 2020) without affecting productivity at nest sites. Nesting platforms were found to have a longer lifespan compared to natural nest sites for some forest-dwelling raptor species, which could benefit species with high nest fidelity (Jiménez-Franco et al., 2014). ANPs can also increase nesting opportunities in landscapes where raptors are nest-site limited (Tigner et al., 1996; Kemper et al., 2020).

Previous researchers have suggested that installing ANPs could benefit Ferruginous Hawks (*Buteo regalis*) exposed to anthropogenic disturbance (Tigner et al., 1996; Kemper et al., 2020; Squires et al., 2020). Although Ferruginous Hawks have historically nested on the ground (Ng et al., 2020), nest site selection may be changing with a rapid increase in human development across their range, including more elevated anthropogenic structures (Watson, 2020). Ferruginous Hawks found nesting on ANPs tolerate oil and natural gas wells at a closer distance (Keough & Conover, 2012), and these structures have been used to encourage raptors to nest away from hazardous conditions (Kemper et al., 2020). ANPs may be beneficial to nesting adults during the breeding season within developed areas, providing a more stable nesting substrate, and protection from ground predators and other forms of disturbance (Nordell et al., 2017; Tigner et al., 1996).

The effectiveness of ANPs must be evaluated prior to energy development before this mitigation tool is adopted (Reynolds et al., 2019; Robertson & Hutto, 2006; Wallace et al., 2016). Human placement of ANPs may not mimic the nest selection process of Ferruginous Hawks and may result in an ecological trap (e.g., environmental cues attracting nesting birds with but negative consequences for nest success, productivity, and survival) (Squires et al., 2020;

Wallace et al., 2016). Raptors may alter their behavior in an attempt to compensate for suboptimal nest sites, by increasing nest attendance (Henderson et al., 2021) or increasing home range estimates (See Chapter 1), which may increase the cost of reproduction for breeders without increasing reproductive success (Henderson et al., 2021). It is therefore critical that ANPs be placed in known areas of high habitat quality (Henderson et al., 2021).

A host of local and landscape-scale factors could be associated with Ferruginous Hawk nest site selection, and these may vary across the species range. Ferruginous Hawks in Wyoming have been found to nest on a variety of substrates, including cottonwood (*Populus spp.*) and juniper (*Juniperus spp.*) trees, rock outcrops, erosional pillars, ground/hillsides, and artificial nesting structures (Squires et al., 2020). In Utah, Ferruginous Hawk nest sites were most closely associated with elevation, slope, vegetation type, and distance to the nearest oil and gas well (Hopkins, 2019). Factors such as nesting substrate, vegetation composition within a territory, disturbance rates, and prey availability may also interact and affect nest site selection or demographics. For example, during years with poor prey abundance, disturbance events can lead to a higher rate of nest abandonment compared to years with high prey abundance (White & Thurow, 1985). In another study, depredation of Ferruginous Hawk juveniles by avian predators, mainly Golden Eagles (*Aquila chrysaetos*), increased as lagomorph abundance decreased (Keough et al., 2015).

Nest sites likely vary in success and productivity based both on parental care (Byholm et al., 2011) and resource availability (Schmutz & Hungle 1989; Keeley et al., 2016). Ferruginous Hawk nest success and productivity has been strongly linked to prey abundance (Schmutz & Hungle 1989; Keeley et al., 2016). Daily nest success and nest productivity of Ferruginous Hawks have been found to be higher for nests with greater shrub cover, in areas with fewer severe storms, and on anthropogenic structures rather than natural substrates (Wallace et al., 2016). Previous work has not found that nest site selection was negatively associated with energy infrastructure post-development (Squires et al. 2020), but less is known about these relationships in largely undisturbed landscapes.

The objective of this study was to identify factors associated with nest site selection, success, and productivity of Ferruginous Hawks in a landscape slated for energy development, with the goal of informing future mitigation efforts, including the possible placement of artificial nesting platforms. To explore which factors are most strongly associated with Ferruginous Hawk nest site selection, success, and productivity, I posed the following hypotheses. In this largely intact sagebrush ecosystem, I expected nest sites to be selected at greater distances from producing wells and developed landcover, as these areas are likely associated with higher rates of disturbance. I also hypothesized that selected nest sites, nest success, and productivity would be positively associated with topographic position (TPI) because nest height can be associated with higher tolerance to disturbance (Nordell et al., 2017).

Methods

Study Site

Southwestern Wyoming is an ideal region to evaluate the impacts of energy development on Ferruginous Hawks and to explore the effectiveness of ANPs for mitigating those impacts. Wyoming is considered to have one of the most intact sagebrush steppe ecosystems remaining within the range of this species (Squires et al., 2020) and is thought to support the highest numbers of the entire population (NatureServe 2023; Travsky & Beauvais, 2005; Ziolkowski et al., 2023). This study occurred in a sagebrush steppe ecosystem between 2079 and 2139 m elevation in an area bordered by Big Piney and Boulder, Wyoming. The area is largely owned and managed by the Bureau of Land Management (BLM), with anthropogenic land uses including natural gas energy extraction, agricultural grazing, off-highway vehicle use, and hunting (Bureau of Land Management, 2018). A large portion of this study area (56,983 hectares) is slated for development as part of the Naturally Lance Pressured (NPL) Natural Gas Development Project, which plans to install 3,500 directionally drilled natural gas wells over a 10-year period (Bureau of Land Management, 2018). For more detailed information on the study site, see Chapter 1 (Ramirez et al. in prep).

Nest Surveys

BLM has been monitoring raptor nests in this study site in western Wyoming since 2009. I extracted the Ferruginous Hawk nests from this dataset that were monitored between 2009 and 2017, excluding data that had missing or conflicting entries (i.e. nests deemed unsuccessful but that also had fledgling data). Between 2018 and 2023, I worked in tandem with BLM and Teton Raptor Center to survey the study site and locate nesting attempts of Ferruginous Hawks, defined by nests with eggs or an incubating adult. Nests that met these criteria are henceforth termed "nesting attempt" (Steenhof et al., 2017). Nest surveys were conducted by ground and air both within and adjacent to the field site at the beginning of each breeding season. The field site was split into 10-km^2 hexagonal grids which is approximately equivalent to a Ferruginous Hawk's nesting territory (Olson et al., 2015; Wallace et al., 2016). Surveys occurred at the beginning of the breeding season in early May and involved visually searching all potential habitat within each grid. Ground surveys, which involved driving every two-track road available within a grid and hiking to areas otherwise not accessible by vehicle, were conducted in 2018-2020. If a hawk was spotted within a grid, I observed the bird and looked for signs of nest building or incubation activity for a maximum of 4 hours. Aerial surveys, which included flights over all grids, were conducted in 2021-2023. At each nest observed using either type of survey I recorded the location (UTM coordinates), nest site substrate type (Figure 2.1), and height of the nest from the ground using a rangefinder. Nest site substrates included artificial nesting platforms (ANPs), ground/hillside, erosional formation (i.e. pillar or hill), rocky outcropping, anthropogenic structures (e.g., water towers or sheds), and natural gas structures (Figure 2.1). I combined anthropogenic structures and natural gas structures into a single category, henceforth termed "anthropogenic structures" due to the small sample size of nests on natural gas structures (n=3; Figure 2.1). Between 2009 and 2018 nests were visited by BLM staff twice per breeding season to determine nesting status and fledgling count. I visited nests once per week during the 2019-2023 breeding seasons to determine nest success and productivity.

Covariates

I considered covariates that reflected both the ecology of Ferruginous Hawks and the landscape characteristics of the study area that could be associated with nest site selection, success, and productivity. For all three models, I considered the same list of covariates, including landcover type, shrub cover (%), shrub height (m), elevation, topographic roughness index (TPI), terrain ruggedness index (TRI), distance to nearest producing well (km), distance to nearest highway (km), density of wells at nest site (per km^2), and number of producing wells within 1 km^2 and 3 km^2 of nest site. These distances were selected based on the average core area size of male and female Ferruginous Hawks for this study site (see Chapter 1). I used landcover data from the National Landcover Database (NLCD) (Dewitz & U.S. Geological Survey, 2021) and included scrub/shrub, barren, grassland, developed–open space (cleared vegetation with < 20% constructed materials), developed–low intensity, developed – medium intensity and developed-high intensity landcover types. I created an additional covariate for all developed landcover and aggregated the different intensities of developed landcover into one metric. I extracted datasets on shrub cover (%), shrub height (m), elevation (m), terrain ruggedness index (TRI), and topographic position index (TPI) from the LANDFIRE database (LANDFIRE, 2020). I extracted the location of "producing" oil and natural gas wells from the Wyoming Oil and Gas Conservation Committee (retrieved 28 April 2022 from http://wogcc.state.wy.us). I created a raster layer of well density in ArcGIS Pro using the Spatial Analyst tool *Point to Raster*. I manually mapped nearby highways via ArcGIS Pro (ESRI, 2013). All covariates were structured into 30m-resolution raster layers. I calculated distance to nearest producing well, nearest highway, and nearest Ferruginous Hawk nesting attempt in ArcGIS Pro using the Spatial Analyst tool *Near* to calculate the distance from a location point to the nearest respective pixel.

Nest Site Selection

To assess nest site selection, I ran a generalized linear mixed model (GLMM) with a binomial family and logit link function for nests to create a resource selection function (RSF) using a design III approach (Manly et al., 1993). "Used" points were defined by the location of nests, while "available" points were random points from within a boundary defined by the full extent of the "used" nest locations. I extracted covariate values from both "used" and "available" nest site locations using the *extract* function in the *terra* R package (Hijmans et al., 2022). I determined a 1:10 ratio of used-to-available points was sufficient for the RSF model by repeating the model with various ratios until the model outcome remained the same. For the nest site selection model, I included Year as a random effect. I used a *k*-fold cross-validation approach to validate the final model (Boyce et al., 2002) using the *kfold* function in the *IndRSA* package in R (Bastille-Rousseau, 2021).

Nest success and productivity

To assess nest success and productivity, I ran three separate generalized linear mixed models (GLMMs). I defined nest success as the number of nesting attempts that raised at least one chick to 80% of fledgling age, an accepted standard for raptor species (Steenhof & Newton, 2007). I defined a "successful" nest as a binary parameter, with a "yes" being a nest with at least 1 young that reached fledgling age and a "no" being a nest that did not successfully produce fledglings (i.e. eggs did not hatch, or young chicks did not survive). I ran a GLMM with binomial family and logit link function to evaluate the associations among covariates and nest success. A nest's productivity was considered a continuous parameter and was defined by the number of chicks that reached 80% of fledgling age (Steenhof & Newton, 2007). I ran GLMMs with Poisson family with log link function to evaluate nest productivity per nesting attempts (nests with eggs) and nest productivity per successful pairs (nests that fledged at least 1 young).

Modeling

All modeling was conducted using R (Version 3.3 for Windows) (R Core Team, 2021). For all models, covariates were first checked for correlation via Pearson's coefficient values ($-0.7 < r > 0.7$). When covariates were correlated, I selected between covariates based on variables associated with nesting behavior in previous literature, or variables most relevant to management decisions within this study area (Table S2.2). For all models, I ran preliminary models and further checked for collinearity between covariates using the *check_collinearity* function in the *performance* package in R (Lüdecke et al., 2023) and removed select covariates (VIF > 2.5). For all models, I used a backward stepwise selection approach based on Akaike's Information Criterion (AIC) to identify the most parsimonious model. Significant variables were defined as a p-value < 0.05.

Results

Nest Site Selection

Between 2009 and 2023, there were 111 Ferruginous Hawk nesting attempts documented in the study area. Many of these nests were reused between years, with 22 containing eggs for 1 year, 11 for 2 years, three for 3 years, one for 4 years, two for 5 years, two for 6 years, one for 13 years, and one for 15 years, resulting in 43 unique nest sites. Of those, 32 nest sites were on natural substrates, including 15 erosional formations (i.e. pillar or mound), 12 rocky outcrops, and 5 on ground/hillside substrates. Nest sites on natural substrates were reused 1 – 6 times within the 15-year study period. Eight nest sites were on anthropogenic structures (i.e. water wells, transmission towers, storage structure, producing and non-producing natural gas wells) and these sites were reused from 1 – 4 times. Lastly, three nest sites were on artificial nest platforms (ANPs) and were reused 4, 13, and 15 times.

The number of nesting attempts varied among years from as few as two to as many as 15 (Figure S2.1), and covariates differed among nest sites (Table S2.1). Ferruginous hawks selected nest sites with increased TPI and developed-open space landcover (Figure 2.4; Table S2.3). Ferruginous Hawks picked nest sites in closer proximity to nearest producing wells (km) but avoided placing nest sites in higher density of producing wells and shrub cover (%) (Figure 2.4; Table S2.3). Cross validation results indicated the model predicted nest site selection well as mean Spearman's rank coefficients for k-fold cross validation averaged 0.96 (± 0.04).

Nest Success and Productivity

Of the 111 nesting attempts, data on fledglings was recorded for 98 nests (Figure 2.2). Of those 98 nesting attempts, 134 fledglings were produced. On average per year there were 6.53 (± 4.26) nesting attempts, 66.77% (± 47.41%) were successful (n = 4.36 ± 2.02), producing an average of 1.37 (± 1.23) fledglings per nesting attempt (nests with eggs) and 2.19 (± 0.77) fledglings per successful pairs (nests that fledged at least 1 young).

Nest success varied between nest substrates (Figure 2.3; Table S2.4). Nest success was positively associated with artificial nesting platforms and negatively associated with rocky outcrops and anthropogenic structures (Table 2.1). Nest success was also negatively associated with developed-open space landcover, TPI, and year (i.e., lower nest success in later years). Nest productivity per nesting attempt was positively associated with artificial nesting platforms and negatively associated with rocky outcrops, anthropogenic structures, TPI, and developed-open space landcover (Table 2.1). Nest productivity for successful pairs (nests that fledged at least 1 young) was not associated with any covariate.

Discussion

Understanding the relationship between raptor nesting behavior and landscape characteristics is essential to mitigating anthropogenic disturbance. This study investigated factors associated with Ferruginous Hawk nest site selection, success, and productivity in an area on the cusp of large-scale energy development. Ferruginous Hawks selected nest sites in anthropogenically disturbed areas in developed–open space landcover and used anthropogenic substrates (such as water towers and gas wells), yet these nest sites were also associated with lower nest success. In contrast, artificial nesting platforms (ANPs) in this study area were associated with higher nest success and productivity, suggesting that ANPs may be a promising mitigation strategy, especially in areas of high-quality habitat. Nest success decreased over this 15-year study, which is a concerning trend and highlights the importance of long-term datasets on raptor populations. These findings are valuable for informing measures to mitigate the effects of development on reproductive success for a species of conservation concern.

Ferruginous Hawks experienced lower nest success and productivity when nest sites were on anthropogenic structures compared to other types of nest sites in the study area. These anthropogenic structures were exclusively found in developed-open space landcover (i.e., areas of cleared vegetation for gravel roads, agricultural water wells, transmission towers, and powerlines), which was a covariate positively associated with nest site selection. The finding that Ferruginous Hawks are both selecting for nest sites in these developed areas but experiencing lower reproductive success is concerning and could constitute an ecological trap (Robertson & Hutto, 2006). In the NPL study site, anthropogenic substrates that served as nest sites were generally single structures, such as water towers or storage shacks, in otherwise relatively flat terrain. Since Ferruginous Hawks also selected nest sites with higher topographic position index (TPI), breeding hawks may select anthropogenic structures to position nests high on the landscape in the absence of natural pillars or buttes. In areas with limited nest site options, anthropogenic structures may unintentionally attract breeding Ferruginous Hawks to suboptimal breeding sites.

Ferruginous Hawks also selected nest sites in close proximity to producing wells but avoided producing wells at high densities, though neither of these energy development metrics were associated with nest success or productivity. ANPs and ground/hillside nests were on average closer to producing wells compared to other nest substrates (avg. 1.60 km and 2.31 km respectively, compared to > 7 km for all other substrates) and compared to random points (avg. 5.02 km). ANPs in Wyoming, including the ANPs placed in this field site, are often placed near energy extraction fields as a mitigation measure, and may bring nesting Ferruginous Hawks closer to natural gas wells as a result (Smith et al., 2010). Habitat selection work has shown an avoidance of habitat close to developed landcover within home ranges (see Chapter 1, Ramirez) so these nest sites may be chosen despite their proximity to producing wells and instead due to the appeal of the nest site option itself (i.e. substrate offers more stability than other options).

Providing more nest site options through strategic placement of ANPs may be a promising mitigation strategy for breeding Ferruginous Hawks facing encroaching development. ANPs were positively associated with nest success and productivity compared to some other nest site substrates in this study area. ANPs may offer more stability for nests in weather events (Nordell et al., 2017; Tigner et al., 1996) and be less susceptible to nest predation (Squires et al., 2020; Wallace et al., 2016) compared to anthropogenic structures and rocky outcrops. ANPs were reused the most in this study area compared to other nest sites, suggesting that previous nesting experience may also play a role in nest success (Byholm et al., 2011; Wittig et al., 2024). When considering the placement of ANPs, maintaining or improving habitat quality for breeding Ferruginous Hawks should be prioritized. ANPs in this study area were intentionally placed by Bureau of Land Management near historically successful nest sites (D. Woolwine, personal comm.) and therefore likely located in habitat capable of sustaining a breeding pair of Ferruginous Hawks. Future efforts should similarly consider environmental variables positively associated with nest site selection and without negative consequences for nest success and productivity. For example, platforms could mimic the preference of Ferruginous Hawk nest sites in higher TPI, lower shrub cover (%) and lower density of producing wells (per km^2). However, TPI was also negatively associated with nest success. Nest sites at higher TPI (i.e., rocky outcrops) may be more exposed to wind or severe storms that could affect nest stability and/or egg and chick survival, so further work to define these relationships is warranted before ANPs mimic this nest site preference.

I found that some covariates (nest site substrate, year, developed-open space landcover, and TPI) were associated with nest success and productivity per nesting attempt, and no covariates were significantly associated with nest productivity for successful pairs (nests with at least 1 chick fledged). Additionally, it is concerning that nest success decreased over the course of this 15-year study. Nest success and productivity may also be affected by parental behaviors (Laux et al., 2016), prey (Ng et al., 2022; Wallace, 2014), predator dynamics (Keough, 2006; Wallace et al., 2016), disturbance rates (White & Thurow 1985; Nordell et al., 2017), or inter-annual variations in climate (Laux et al., 2016; Wallace et al., 2016), all of which were beyond the scope of this study. Future efforts should evaluate whether these factors are associated with Ferruginous Hawk nest success and productivity. Long-term studies on raptor populations, including research on primary prey, will be vital for understanding the consequences of land use and climate change on a longer temporal scale, as well as assessing the impacts of development rigorously (e.g., using a before-after-control-impact design; Parayko et al., 2021). Additionally, although my findings indicated lower nest success and productivity for nest sites on anthropogenic structures and rocky outcrops, and higher nest success and productivity for ANPs, more research is warranted on the mechanisms that explain these relationships. Lastly, aerial surveys were more time-efficient than ground surveys in this study. Aerial surveys were completed annually in 2-3 days compared to the month-long ground surveys required to cover the same area. Future studies should consider investing in aerial surveys to monitor Ferruginous Hawks, which tend to nest at low densities and in areas that are sometimes remote and difficult to access (Ng et al., 2020).

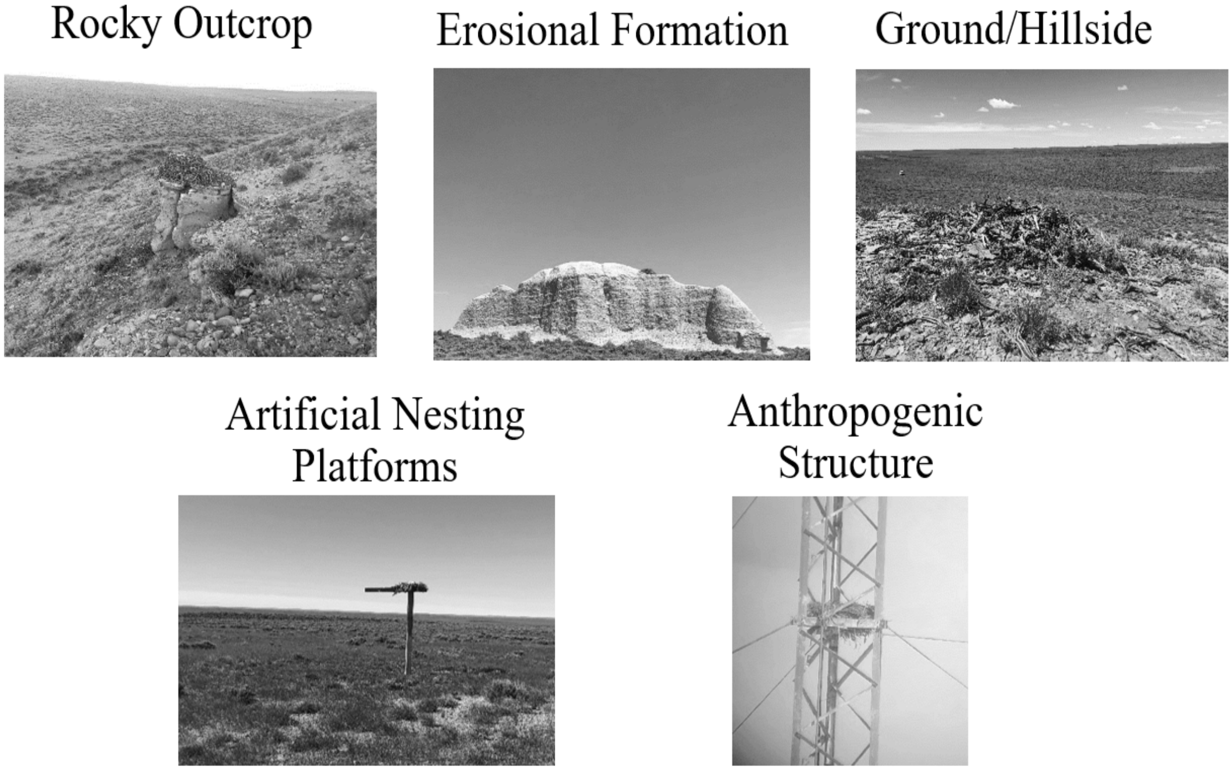
Land managers should be aware that anthropogenic structures can play a complex role in Ferruginous Hawk nest success and productivity. On the one hand, ANPs show promise as a mitigation strategy for Ferruginous Hawks in a landscape facing anthropogenic change. Identifying areas of high habitat quality for Ferruginous Hawks will be important when considering ANP placement. On the other hand, Ferruginous Hawks may face population-level consequences if they continue to select nest sites on anthropogenic structures in low density development. Because these structures and habitats resulted in lower nest success and productivity, managers could consider actively restoring habitat quality in these areas. Long-term monitoring and well-designed impact studies in areas planned for major land use change are likely to be critical for the long-term conservation of Ferruginous Hawk populations.

TABLES

Table 2.1: The results of four generalized linear mixed model (GLMMs) evaluating the relationship between nest success and productivity per nesting attempt of Ferruginous Hawks, nest substrates, and environmental covariates. Nest success was defined as nests that fledged at least one chick (n=98) during the study period. Nest productivity was defined as number of chicks that fledged during the study period.

Model	Covariates	Estimate	p-value	SE	95% CI	
Nest Success	(Intercept) Artificial Nesting Platform	1.6	<0.01**	0.6	0.4	2.79
	Anthropogenic Structures	-2.09	<0.05*	0.9	-3.83	-0.36
	Erosional Pillar/Hill	-0.89	0.23	0.74	-2.36	0.59
	Ground/Hillside	-1.6	0.5	1.24	-4.08	0.89
	Rocky Outcrop	-2.1	<0.01**	0.8	-3.69	-0.51
	(Intercept)	0.62	<0.05*	0.27	0.09	1.15
	Year	-0.72	<0.05*	0.29	-1.29	-0.16
	Developed – Open space	-0.56	<0.05*	0.26	-1.09	-0.04
	TPI	-0.75	<0.01**	0.29	-1.33	-0.17
Nest Productivity	(Intercept) Artificial Nesting Platform	0.71	<0.001***	0.13	0.45	0.97
	Anthropogenic Structures	-1.08	<0.01**	0.36	-1.79	-0.36
	Erosional Pillar/Hill	-0.38	0.055	0.2	-0.78	0.02
	Ground/Hillside	-0.71	0.17	0.52	-1.74	0.32
	Rocky Outcrop	-0.87	<0.01**	0.27	-1.42	-0.32
	(Intercept)	0.22	<0.05*	0.09	0.03	0.41
	TPI	-0.26	<0.01**	0.1	-0.45	-0.06
	Year	-0.15	0.07	0.09	-0.33	0.02
	Developed – Open space	-0.27	<0.05*	0.13	-0.52	-0.01
	Distance to nearest Ferruginous Hawk nesting attempt	-0.23	0.06	0.12	-0.47	0.02

FIGURES



Rocky Outcrop

Erosional Formation

Ground/Hillside

Artificial Nesting Platforms

Anthropogenic Structure

Figure 2.1: Major types of nest site substrates used by breeding Ferruginous Hawks in a western Wyoming population from 2009 and 2023.

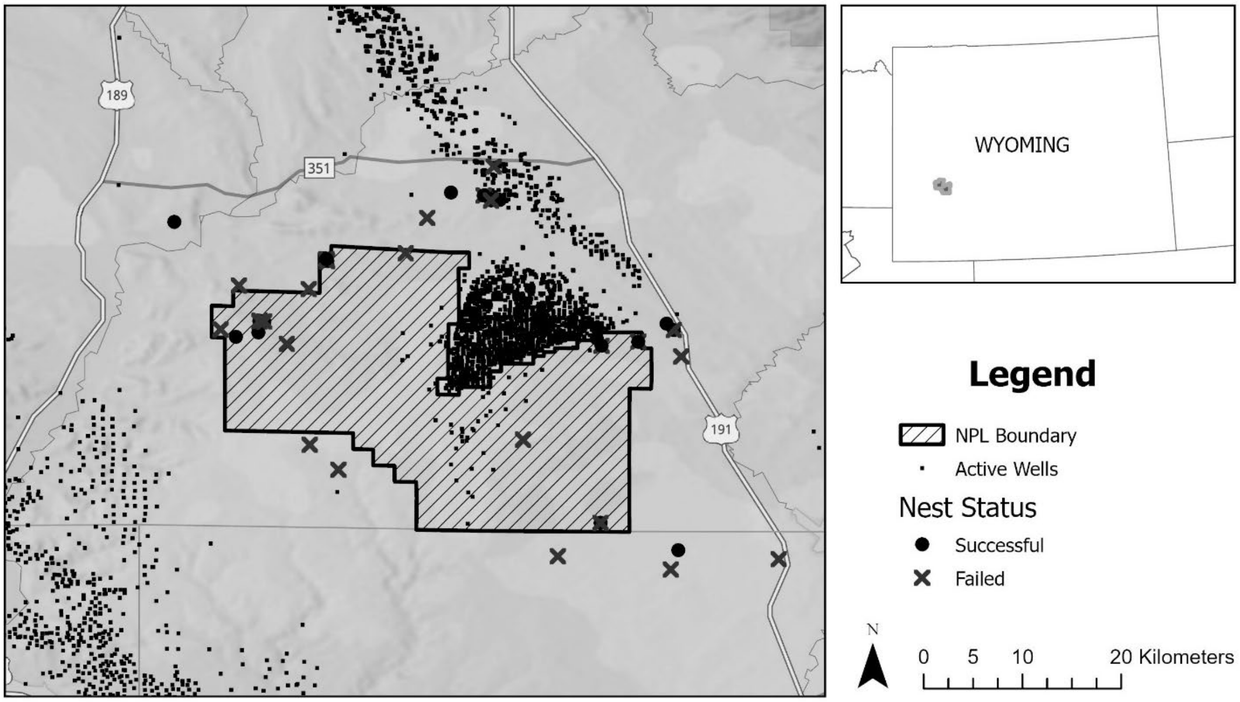


Figure 2.2: Study site for evaluating nest site selection, success and productivity of Ferruginous Hawks in western Wyoming between 2009 and 2023. The proposed Naturally Lance Pressured (NPL) Natural Gas Development Area is shown with dashed lines. Nest site locations of Ferruginous Hawk nests are show with dots (successful nests) and crosses (failed nests).

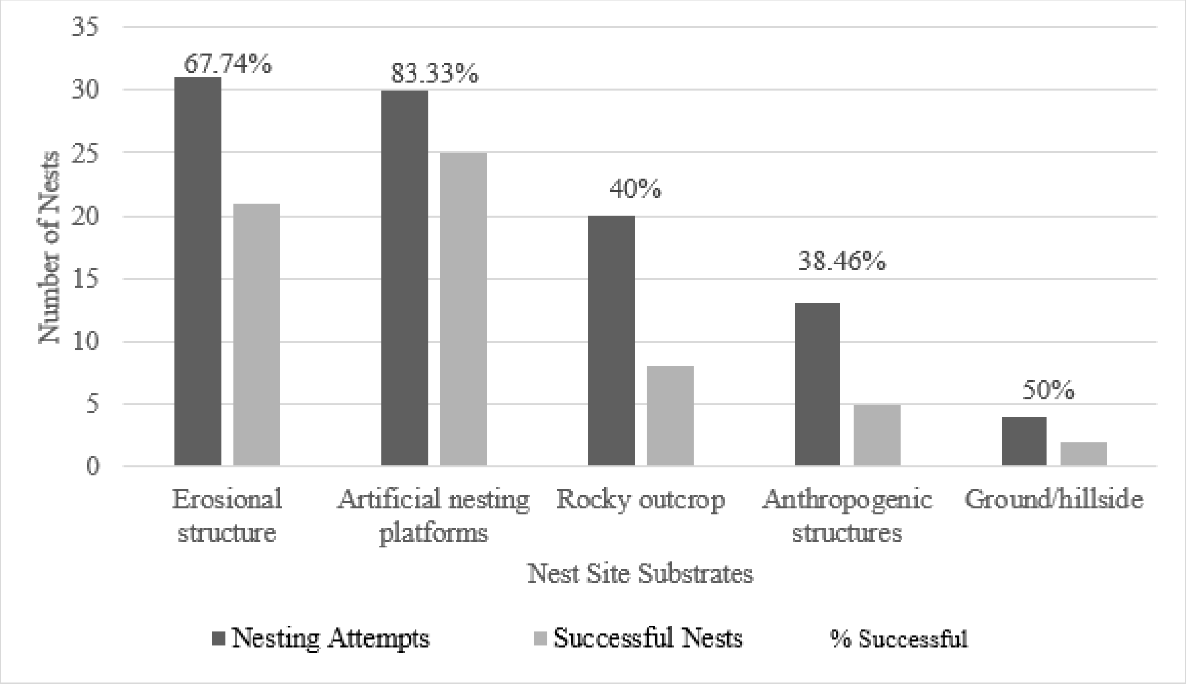


Figure 2.3: Total number of nesting attempts (dark grey bars) and successful nests (light grey bars), and the percent of nests on each substrate type that were successful for a western Wyoming population of Ferruginous Hawks (2009-2023). Nesting attempts are defined as a nest with eggs, and successful nests are defined as a nest where at least one chick fledged. Additional details reported in Table S2.4.

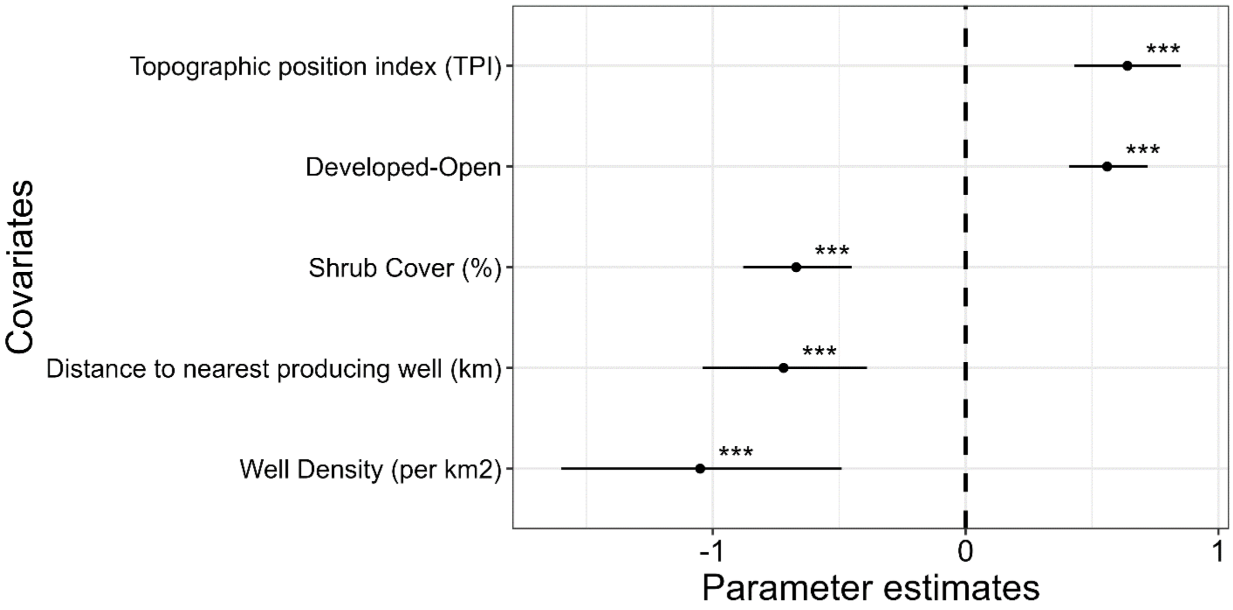


Figure 2.4: Nest site selection for Ferruginous Hawks in a western Wyoming population in 2009-2023. Resource selection function (RSF) results are reported at the study site scale. Asterisks reference significance of p-values ($p < 0.001$ ***). A positive parameter estimate indicates a covariate selected compared to what was randomly available on the landscape and a negative estimate indicates avoidance.

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SUPPLEMENTAL MATERIALS

Chapter 1

Trapping Information

Table S1.1 - Morphometrics for 15 adult breeding Ferruginous Hawks (9 males and 6 females) captured between 2019 and 2022 in Southwestern Wyoming. Across all measurements, females were larger, on average, compared to males.

	Males (n=9)		**Females (n=6)**	
Measurement (mm)	**Average**	**± SD**	**Average**	**± SD**
Toe Pad	75.04	2.09	87.03	1.81
Hallux	26.09	1.09	33.08	1.14
Wing Chord	423.63	7.63	454.50	8.20
Tail Length	220.38	14.97	235.50	8.56
Cranium	88.21	2.51	97.43	4.02
Culmen Length	26.68	1.25	29.90	0.51
Culmen Depth	18.64	2.06	21.95	1.84
Mass (g)	1112.50	33.45	1722.50	69.06

Table S1.2 – Summary information on days tracked and number of locations for 15 breeding Ferruginous Hawks (28 home ranges) outfitted with GPS transmitters between 2019 and 2022 in Southwestern Wyoming.

	Mean	**SD**	**Minimum**	**Maximum**
Days Tracked	78.70	33.59	28	171
Number of Locations	1,642.48	1214.86	78	3,528

Home Range Analysis

Table S1.3 – Covariates included in the model evaluating the factors associated with home range (95%) and core area (50%) size for Ferruginous Hawks during the breeding season in southwestern Wyoming.

Predictor Covariate	Description	Source
Sex	Female or male based on body mass (g) measured in the field	Collected in the field
Nesting Status	Nesting status of tagged adult, either egg-laying (an adult with eggs in a nest) or non-laying (an adult claiming a territory but no eggs laid)	Collected in the field
Shrub Cover (%)	Mean percent cover of shrub cover. Layer comprised of classes shrub cover (>10%) as well as barren (<1%) and sparse vegetation canopy (1-9%). Barren and sparse vegetation canopy classes represent cover of unidentifiable vegetation, but likely is shrub-type for this study area.	LANDFIRE (2020)
Number of Producing Wells	Number of producing wells within a home range	Wyoming Oil and Gas Conservation Commission (2023) for location of producing wells

Table S1.4 – Results of a linear mixed model evaluating the relationship between home range estimates (defined by Autocorrelated Kernel Density Estimation (AKDE) method), and number of points and days of data collection for breeding Ferruginous Hawks wearing GPS transmitters with different sampling rates. Variation in point frequency and number of sampling days did not have a statistically significant (p<0.01) effect on estimated home range or core area sizes.

Response	Predictor	Estimate	p-value	SE	95% CI	
Home-range size (95%)	Intercept	3.090	<0.001	0.130	2.835	3.344
	Number of Points	0.220	0.268	0.191	-0.154	0.594
	Number of Days	0.250	0.211	0.191	-0.124	0.624
Core area size (50%)	Intercept	0.765	<0.001	0.134	0.502	1.028
	Number of Points	0.040	0.841	0.197	-0.345	0.426
	Number of Days	0.121	0.544	0.197	-0.265	0.507

Table S1.5 - Average home range estimates (km^2) for Ferruginous Hawks in a breeding population in southwestern Wyoming (n=27). Minimum Convex Polygon (MCP), Kernel Density Estimation (KDE) and Autocorrelated Kernel Density Estimation (AKDE) reported at both the home range (95%) and core area (50%) utilization. "Egg-laying" is defined as hawks with eggs laid, and "non-laying" is defined as hawks courting, defending and occupying a territory, but failing to lay an egg anytime during the breeding season.

	Males			
	Egg-laying pairs (n=11)		**Non-laying pairs (n=3)**	
METHOD	**MEAN**	**SD**	**MEAN**	**SD**
MCP 95%	26.58	± 12.15	74.91	± 36.09
KDE 95%	27.63	± 11.63	62.24	± 24.44
AKDE 95%	25.67	± 10.76	58.09	± 23.28
MCP 50%	2.55	± 1.24	3.90	± 0.89
KDE 50%	2.58	± 1.25	3.23	± 0.12
AKDE 50%	2.75	± 1.27	3.33	± 0.47

	Females			
	Egg-laying pairs (n=10)		**Non-laying pairs (n=3)**	
METHOD	**MEAN**	**SD**	**MEAN**	**SD**
MCP 95%	21.09	± 32.83	17.29	± 5.19
KDE 95%	11.79	± 9.58	15.59	± 1.27
AKDE 95%	11.36	± 9.15	13.81	± 1.20
MCP 50%	0.65	± 0.37	0.68	± 0.26
KDE 50%	0.86	± 0.45	1.69	± 0.50
AKDE 50%	1.03	± 0.58	1.65	± 0.44

Table S1.6 - Results of the Generalized Linear Mixed Models (GLMM) evaluating the relationship between sex, status, number of oil and gas wells, shrub cover and Ferruginous Hawk home range and core area estimates in western Wyoming.

Response	Predictor	Estimate	p-value	SE	95% CI	
Home Range Size (95%)	Intercept	2.840	<0.001***	0.089	2.666	3.014
	Sex (Female)	-0.437	<0.001***	0.126	-0.684	-0.190
	Status (Egg-laying)	-0.419	<0.001***	0.096	-0.607	-0.231
	Number of Producing Wells	0.206	0.027*	0.094	0.022	0.390
	Mean Shrub Cover	0.234	0.069	0.129	-0.019	0.487
Core Area Size (50%)	Intercept	0.523	<0.001***	0.095	0.337	0.709
	Sex (Female)	-0.480	<0.001***	0.144	-0.762	-0.198
	Status (Egg-laying)	-0.252	0.011*	0.099	-0.446	-0.058
	Number of Producing Wells	0.067	0.509	0.101	-0.131	0.265
	Mean Shrub Cover	0.034	0.814	0.143	-0.246	0.314

Habitat Selection

Table S1.7 – Covariates considered in the habitat selection model for a population of Ferruginous Hawks in southwestern Wyoming, at a resolution of 30m (raster).

Predictor	**Description**	**Value**	**Source**	**Included in final model**
Landcover Type	Landcover types, including shrub/scrub, barren, grassland/herbaceous, pasture/hay, and developed. Developed landcover was further supplemented with manually mapped roadways via ArcGIS Pro	Discrete	National Land Cover Database (2019)	Barren and Grassland
Shrub Cover	Percent cover of shrub (%)	Continuous	LANDFIRE (2020)	√
Shrub Height	Height of dominant shrub (m)	Continuous	LANDFIRE (2020)	
Elevation	Elevation in degrees (°)	Continuous	LANDFIRE (2020)	
Terrain Ruggedness Index (TRI)	Average difference between value of cell and its 8 surrounding cells	Continuous	Calculated from elevation layer	√
Topographic Position Index (TPI)	Difference between value of a cell and the mean value of its 8 surrounding cells	Continuous	Calculated from elevation layer	
Well Density	Number of producing wells per 30m pixel	Continuous	Wyoming Oil and Gas Conservation Commission (2023) for location of wells Density layer created in ArcGis Pro	√

Distance to well	Distance to nearest producing well (km)	Continuous	Wyoming Oil and Gas Conservation Commission (2023) for location of wells Distance calculated in ArcGISPro	
Distance to Development	Distance from point to nearest development (km)	Continuous	Developed landcover from National Land Cover Database (2019) with additionally manually mapped roadways via ArcGis PRO Distance calculated in ArcGISPro	√
Lagomorph Distribution	Distribution of three lagomorph species at varying probabilities of occurrence. Lagomorph species include White-tailed Jackrabbits (*Lepus townsendii*), Mountain Cottontail (*Sylvilagus nuttallii*), and Pygmy Rabbit (*Brachylagus idahoensis*)	Continuous	Distribution map built in R studio – see methods section	√
Distance to Prairie Dog Colony	Distance to nearest White-tailed Prairie Dog (*Cynomys leucurus*) colony (km)	Continuous	White-tailed praririe dog colonies mapped in the field Distance calculated in ArcGISn Pro	√
Wyoming Ground Squirrel Predicted Habitat	Location point within or outside predicted habitat for Wyoming Ground Squirrel (*Urocitellus elegans elegans*)	Discrete	USGS - GAP (2018)	√

Table S1.8 - Generalized linear model results for known location of spotted lagomorph species. These results were then used to create a predicted distribution map for this taxa across the the NPL study site in Wyoming. The resulting AIC value was 111.

Predictor	**Estimate**	**p-value**	**SE**	**95% CI**	
Intercept	-25.46	0.054	13.23	-51.39	0.47
Shrub Cover %	-0.03	0.48	0.04	-0.11	0.05
Elevation	0.01	<0.05*	0.01	-0.01	0.03
TPI	-0.15	0.21	0.12	-0.39	0.09

Table S1.9 - Correlation among covariates considered for a Ferruginous Hawk habitat selection model using Pearson's correlation (-0.5 < r > 0.5). Covariates in bold were selected for the final Resource Selection Function (RSF) model. Final covariates were selected based on literature or management implications for this study area.

Correlated Covariates		Rho value
Home Range Scale		
Shrub Cover (%)	Shrub Height (m)	0.749
Terrain Ruggedness Index (TRI)	Topographic Position Index (TPI)	0.775
Lagomorph Density	Elevation	0.765
Elevation	Distance to Producing Well	-0.698
Grassland Landcover	Scrub/Shrub Landcover	-0.608
Lagomorph Density	Distance to Producing Well	-0.651
Distance to Development (km)	Distance to Producing Well	0.572
Distance to Main Highway (km)	Distance to Producing Well	0.563
Study Site Scale		
Shrub Cover (%)	Shrub Height (m)	0.748
Terrain Ruggedness Index (TRI)	Topographic Position Index (TPI)	0.795
Lagomorph Density	Elevation	0.731
Grassland Landcover	Scrub/Shrub Landcover	-0.511

Table S1.10 - Results of the Resource Selection Function models for breeding Ferruginous Hawks (n=27) in Wyoming, at two spatial scales.

Scale	Predictor	Estimate	p-value	SE	95% CI	
HOME RANGE	Intercept	-2.392	<0.001***	0.218	-2.82	-1.96
	Shrub Cover (%)	-0.460	<0.001 ***	0.007	-0.47	-0.45
	Barren	-0.021	<0.001 ***	0.005	-0.03	-0.01
	Grassland	0.040	<0.001***	0.005	0.08	0.11
	Terrain Ruggedness (TRI)	0.474	<0.001***	0.006	-0.18	-0.15
	Density of Wells	-0.536	<0.001***	0.017	-0.57	-0.50
	Distance from Development (km)	0.096	<0.001***	0.007	0.08	0.11
	Density of Lagomorph spp.	-0.161	<0.001***	0.008	-0.18	-0.15
	WY Ground Squirrel Habitat	0.099	<0.001***	0.007	0.09	0.11
STUDY SITE	(Intercept)	-1.646	<0.001***	0.027	-1.70	-1.60
	Shrub Cover (%)	-0.260	<0.001***	0.006	-0.27	-0.25
	Barren	0.020	<0.001***	0.005	0.01	0.03
	Grassland	0.020	<0.001***	0.005	0.01	0.03
	Terrain Ruggedness (TRI)	0.254	<0.001***	0.006	0.24	0.27
	Density of Wells	-0.375	<0.001***	0.014	-0.35	-0.10
	Distance from Development (km)	-0.212	<0.001***	-0.212	-0.63	0.20
	Density of Lagomorph spp.	0.159	<0.001***	0.006	0.15	0.17
	WY Ground Squirrel Habitat	0.124	<0.001***	0.007	0.11	0.14

Table S1.11 - Results of the prairie dog Resource Selection Function model for breeding Ferruginous Hawks (n=14) in Wyoming at the home range scale. This model used a subset of data to match the year white-tailed prairie dog colonies to location data from the same year.

Scale	Predictor	Estimate	SE	p-value
HOME RANGE	(Intercept)	1.607e-01	1.700e-01	0.345
	Distance to White-tailed Prairie Dog Colony (km)	-6.608e-04	5.974e-06	<0.001***

Chapter 2

Table S2.1: Nest site covariates (mean and range) for Ferruginous Hawk nesting attempt in western Wyoming between 2009 and 2023.

Covariate	**Mean ± SD**	**Range**
Height of nest substrate	77.92 ± 92.24	0 - 300
Shrub cover (%)	18.22 ± 12.46	0 – 33.55
Shrub height (m)	0.44 ± 0.33	0 – 0.87
Elevation (m)	2157 ± 39.35	2033 – 2246
Topographic position index (TPI)	7.14 ± 5.25	0.23 – 17.05
Terrain ruggedness index (TRI)	2.79 ± 2.45	0 – 7.65
Slope	6.52 ± 5.54	0 – 16.88
Distance to producing well (km)	5.42 ± 4.48	0 – 15.94
Well density (per km^2)	0.06 ± 0.27	0 – 1.42
Number of producing wells within 1 km^2	1.12 ± 4.82	0 – 99
Number of producing wells within 3 km^2	4.84 ± 17.73	0 - 39
Distance to nearest highway (km)	7.14 ± 4.56	0.28 – 22.38
Distance to nearest Ferruginous Hawk nesting attempt (km)	5.06 ± 4.89	0.54 – 27.17

Table S2.2: Covariates considered for inclusion in nest site selection, nest success and productivity models for a population of Ferruginous Hawks in western Wyoming, at a resolution of 30m (raster), including explanations where covariates were ultimately excluded.

Covariate	**Description**	**Nest Site Selection**	**Nest Success**	**Nest Productivity per nesting attempt**
Topographic Position Index (TPI)	Difference between value of a cell and the mean value of its 8 surrounding cells	**In final model**	**In final model**	**In final model**
LANDCOVER: Developed – Open space	Landcover type, defined by NLCD (2021)	**In final model**	**In final model**	**In final model**
Shrub Cover (%)	Percent cover of shrub (%)	**In final model**	Removed- highly correlated to TPI (-0.832)	Removed- highly correlated to TPI (-0.832)
Distance to nearest producing well (km)	Distance to nearest producing well (km), defined by WOGCC (2022) as "Producing"	**In final model**	Removed- statistically insignificant	Removed- statistically insignificant
Density of producing wells (per m^2)	Number of producing wells per 30m pixel	**In final model**	Removed- statistically insignificant	Removed- statistically insignificant
Year	2009 – 2023	NA	**In final model**	**In final model**
Nest Substrate	Nest substrate type, including artificial nesting platforms (ANPs), anthropogenic structures, erosional formations (pillars or hills), ground/hillside, and rocky outcrops	NA	**In subset model**	**In subset model**
Shrub Height (m)	Height of dominant shrub (m)	Removed- highly correlated to shrub cover (%) (+0.871)	Removed- highly correlated to TPI (-0.793)	Removed- highly correlated to TPI (-0.793)
Terrain Ruggedness Index (TRI)	Average difference between value of cell and its 8 surrounding cells	Removed- highly correlated to TPI (+0.823)	Removed- highly correlated to TPI (-0.766)	Removed- highly correlated to TPI (-0.766)

Slope	The change of elevation over 30m pixel	Removed- highly correlated to TPI (+ 0.833)	Removed- highly correlated to TPI (+0.880)	Removed- highly correlated to TPI (+0.880)
Nest Height (m)	Height from ground to bottom of nest (m)	NA	Removed- highly correlated to TPI (+0.805)	Removed- highly correlated to TPI (+0.805)
Elevation	Elevation in degrees (°)	Removed- statistically insignificant	Removed- statistically insignificant	Removed- statistically insignificant
LANDCOVER: Developed	Landcover type, defined by NLCD (2021)	Removed- highly correlated to Developed – Open Space (+0.792)	Removed- highly correlated to Developed – Open Space (+1.00)	Removed- highly correlated to Developed – Open Space (+1.00)
LANDCOVER: Developed – High Intensity	Landcover type, defined by NLCD (2021)	Removed- no data	Removed- no data	Removed- no data
LANDCOVER: Scrub/Shrub	Landcover type, defined by NLCD (2021)	Removed- high collinearity (VIF > 2.5)	Removed- high collinearity (VIF > 2.5)	Removed- high collinearity (VIF > 2.5)
LANDCOVER: Developed – Low intensity Developed – Medium intensity	Landcover type, defined by NLCD (2021)	Removed- statistically insignificant	Removed- no data	Removed- no data
LANDCOVER: Barren Grassland	Landcover type, defined by NLCD (2021)	Removed- statistically insignificant	Removed- statistically insignificant	Removed- statistically insignificant
Distance to nearest Developed landcover (km)	Distance from point to nearest development (km)	Removed- statistically insignificant	Removed- statistically insignificant	Removed- statistically insignificant
Distance to nearest highway (km)	Distance to nearest highway (km)	Removed- improved AIC once removed	Removed- statistically insignificant	Removed- statistically insignificant

Table S2.3: Nest site selection model results for a Ferruginous Hawk population in western Wyoming (2009-2023).

Predictor	Estimate	p-value	Std. Error	95% CI	
(Intercept)	-3.03	<0.001***	0.16	-3.36	-2.70
Shrub Cover (%)	-0.67	<0.001***	0.12	-0.88	-0.45
Topographic position index (TPI)	0.64	<0.001***	0.12	0.43	0.85
Developed – Open Space	0.56	<0.001***	0.08	0.41	0.72
Well Density (per km^2)	-1.05	<0.001***	0.28	-1.60	-0.49
Distance to nearest producing well (km)	-0.72	<0.001***	0.16	-1.04	-0.39

Table S2.4: Nest success and productivity for Ferruginous Hawks in a western Wyoming population between 2009 and 2023. Nesting attempts are defined as a nest with eggs laid, and successful nests are defined as a nest where at least one chick fledged.

Nest Site Substrate	Nesting Attempts	Nest success	Number of Fledglings	Productivity per egg-laying pair	Productivity per successful pairs
Artificial nesting platforms	30	83.33% (n=25)	61	2.03	2.44
Erosional structure	31	67.74% (n=21)	43	1.39	2.05
Ground/hillside	4	50% (n=2)	4	1	2
Rocky outcrop	20	40% (n=8)	17	0.85	2.13
Anthropogenic structures	13	38.46% (n=5)	9	0.69	1.8

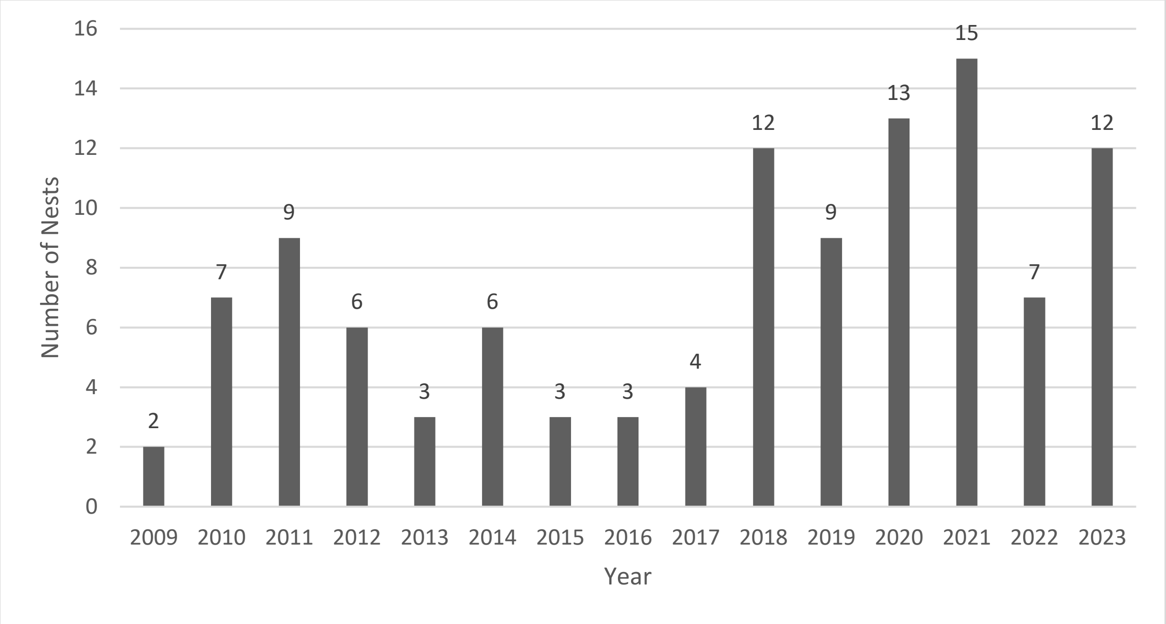

Figure S2.1: Total number of Ferruginous Hawk nesting attempts by year in a western Wyoming population.