# Ferruginous Hawk (*Buteo regalis*) response to energy development and inclement weather in southern Alberta

by

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# Abstract

Growing global energy demand is projected to increase by nearly 30% in coming decades. As such, wildlife is increasingly required to persist in altered landscapes resulting from energy-related changes and development. In breeding birds, anthropogenic structures are often used as perches and, in many cases, are depended upon as nest supports. I investigated (1) the influence of temporary habitat alterations for energy development on a population of provincially *Endangered* Ferruginous Hawks (*Buteo regalis*), and (2) if artificial nest platforms (ANP) can mitigate the negative effects of extreme weather events on Ferruginous Hawk reproduction in southern Alberta, Canada. First, I applied a robust Before-During-After Control-Impact study design between 2013 and 2019 to assess the influence of three phases of transmission line development on the nesting density of the local study population, and examine whether temporary habitat alterations could result in a sink population or ecological trap. Using generalized linear and logistic mixed models, I found no differences in nest success, nest productivity, nest site reoccupancy, or community composition between or among treatment types. However, I reported a significant change in Ferruginous Hawk nest density following construction activities (tower addition or removal). Nest densities fluctuated positively with the number of transmission line towers present on the landscape. Though I found no evidence of an ecological trap, the influence of temporary alterations to nesting and perching substrates significantly influenced Ferruginous Hawk nest density. In addition to following existing industrial protocols for mitigation measures and post-construction monitoring, I recommend that future projects are proactive and begin monitoring activities at least 2 years prior to scheduled developments. Next, I investigated the effects of inclement weather during the Ferruginous Hawk breeding season and the importance of nest substrate on nest persistence, productivity, and the daily survival rate of nestlings (DSR). Variation in both timing and severity of extreme weather (wind, precipitation, and temperature) are predicted to increase under future climate scenarios. I used data from 8 years (2010–2017) of weekly nest monitoring to examine the influence of weather on 973 nesting attempts by pairs at 507 nests. Extreme wind events strongly influenced nest persistence rates, and DSR was significantly lower at sites with higher daily average wind speeds. Nest substrate type was also an important predictor of both nest persistence and DSR. Nests in ANPs had significantly higher survival rates where days with high average wind speeds and extreme wind events were more frequent. My results provide new insights and additional support for the use of ANPs as a practical and cost-effective management tool for open grassland raptors. I recommend that areas with both high daily average and extreme wind speeds receive higher priority when selecting sites for ANP installation.

# Preface

This thesis is an original work by Nick Parayko and no part of this thesis has been previously published. Chapter 2 is currently under review in Avian Conservation and Ecology and Chapter 3 is being prepared for journal submission. Research for this thesis was conducted with the Raptor Ecology and Conservation Team (REACT), a collection of graduate students and post-doctoral fellows working to generate a comprehensive dataset of Ferruginous Hawk biology to inform conservation efforts for the species. This group is supervised by Dr. Erin Bayne at the University of Alberta and Dr. Troy Wellicome with the Canadian Wildlife Service (and University of Alberta Adjunct Professor).

This project was approved by University of Alberta Animal Care (#724) and conducted under permit AUP00000018: "Foraging and Reproduction of Wild Ferruginous Hawks" from the Research Ethics Board at the University of Alberta, Alberta Environment and Sustainable Resource Development (#55483 and #55482), Alberta SARA permit #SARA-PNR-2013-0231, and the federal banding office (#10796H and #10277Z).

“[A] splendid hawk, the largest, most powerful, and grandest of our buteos, a truly regal bird.”
- *Arthur Cleveland Bent (1937)*

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# Table of Contents

# List of Figures

# List of Tables

## CHAPTER 1: Introduction

Temperate grasslands are among the most altered and least protected biomes world-wide (Hoekstra et al. 2005). Approximately 70% of native grassland in the Great Plains of North America has disappeared or become fragmented by cropland conversion and increased agricultural or industrial development (Samson and Knopf 1994, Askins et al. 2007), with additional pressures from intensive grazing and human recreational activities (White et al. 2000, Brennan and Kuvlesky 2005). Between 1982 and 1997, 93 000 km$^2$ of native grasslands in the United States were converted for agricultural purposes (Samson et al. 2004). The Canadian prairie ecozone, across southern between Alberta, Saskatchewan, and Manitoba, has had 70–75% of its native grassland converted to cultivated cropland (Gauthier and Wiken 2003, Samson et al. 2004). Within the Alberta portion of the prairie ecozone, 43% of native prairie remains, which is more than any other province (Nernberg and Ingstrup 2005), but habitat loss continues in the province, albeit at a slower rate (Watmough and Schmoll 2007).

Homesteading and conversion of grassland to cropland began as early as 1830 in eastern North America, with European settlement (Samson and Knopf 1994). Native wildlife in the Great Plains were hunted or displaced, and many species and subspecies of large mammals (e.g., plains grizzly bear [*Ursus arctos*] and Great Plains wolf [*Canis lupus nubilus*]) were hunted to extinction. Plains bison (*Bison bison bison*) and prairie dogs (*Cynomys* spp.) have undergone significant reductions in their populations (Samson and Knopf 1994), with up to 98% reductions in prairie dog populations (Marsh 1984). At least one third of mammals and birds listed by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) have been associated with native grassland regions (World Wildlife Fund 1992). Grassland birds have experienced steeper declines than any other taxonomic group in North America (Knopf 1994), with 74% of grassland species in decline since 1970 (Rosenburg et al. 2019). In Alberta, there are 14 avian grassland specialists currently listed by Alberta Environment and Parks as *May Be at Risk* or higher (AEP 2017). As agricultural practices continued to intensify from the early 20th century, an increasing amount of land conversion has degraded prairie habitat and significantly affected native prairie species, resulting in one of the world's most thoroughly developed landscapes (Ostlie et al. 1997, White et al. 2000, Samson et al. 2004). Additional anthropogenic alteration to native prairie stems from increased energy demand from growing populations, leading to rapid development by oil and gas and renewable resource industries (International Energy Agency 2009, Walters et al. 2014).

Energy-related development and infrastructure is expected to increase substantially within the next 20 years, with global demand projected to increase by up to 40% (International Energy Agency 2009). Development to meet increased energy demands can have large-scale impacts for wildlife across ecosystems by contributing to habitat loss, conversion, and fragmentation (Leu et al. 2008, McDonald et al. 2009). Future projections anticipate temperate grasslands to be among the most impacted of the biomes under all energy development scenarios (McDonald et al. 2009). Threats to wildlife include exposure to oil and gas products in waste pits (Trail 2006), collision with wind turbines (e.g., bird [Katzner et al. 2016] and bat [Kunz et al. 2007] collisions), and electrocution from powerlines (Guil et al. 2011, Rioux et al. 2013).

Anthropogenic disturbance and development can have varying effects on local avifauna (Nelson 1982, APLIC 2006). For example, Common Ravens (*Corvus corax*) have undergone substantial range expansion related to anthropogenic resources including increased food, perch, and nest site availability (Marzluff and Neatherlin 2006, Kristan and Boarman 2007). For species that suffer from nest depredation by ravens, such as the Greater Sage-Grouse (*Centrocercus* *urophasianus*), increases in raven densities can lower habitat quality and potentially cause population declines (Bui et al. 2010; Table 1). For raptors and ravens, elevated perches such as trees, fence lines, distribution poles, and transmission towers play an important role in hunting, resting, perching, and nesting (APLIC 2006). The importance of elevated perches is amplified in landscapes where nesting and perching substrates are limited, such as those in tundra, desert, and grassland ecosystems (Restani et al. 2001, Boarman et al. 2006). Electrical utility rights-of-way are strongly correlated with elevated raptor densities and provide millions of kilometers of perching and nesting habitat. On elevated perches, the visual search area is enhanced while foraging energy is simultaneously conserved compared to foraging in flight (APLIC 2006). Transmission towers provide suitable nesting sites and perches for raptors and ravens in areas where relic trees are the only other suitable structures on the landscape. Improved perching and nesting locations can also increase densities of raptors and ravens nesting within the general vicinity of transmission towers (Stahlecker 1978, Williams and Colson 1989). For example, a 138–425% increase in raptors per km$^2$ (from 4–13 raptors/ km$^2$ to 21–32 raptors/km$^2$) was observed following the construction of a transmission line in 1974 (Stahlecker 1978). Additional studies suggest that raptors will disproportionately select transmission lines for perches over other available perches (APLIC 2006, Watson 2020). Due to the attractiveness of elevated perches to raptors, the installation or augmentation of vertical structures (installation of artificial nest platforms [ANPs] or fortification of transmission towers) has also been used as a passive conservation technique for raptors by opening habitat to hunting and nesting in areas otherwise void of suitable nesting substrates (Olendorff et al. 1980, Reinert 1984).

Energy infrastructure – oil and gas wells, windfarms, and transmission lines – has become common in native grasslands and, in the case of transmission lines, their indirect impacts on wildlife are relatively understudied (Walters et al. 2014). Current avian literature focuses primarily on direct effects, such as the potential for collision and electrocution (Smith and Dwyer 2016), or on the range expansion of ravens and the resulting indirect impacts on native species of conservation concern such as Greater Sage-Grouse (Coates et al. 2014) and Desert Tortoise (*Gopherus agassizii*; Boarman 2003). Few studies have assessed the response of raptors to transmission lines or other elevated structures. Previous studies assessed the influence of recently constructed transmission lines on raptor nesting densities and the attraction of towers as nest sites (Knight and Kawashima 1993, Steenhof et al. 1993). With projected increases in energy demand, existing transmission lines will require replacement or upgrading to accommodate new energy developments or increased voltage transmission from existing energy-generation sites (i.e., wind and solar farms). Upgrades to transmission infrastructure may include the construction of new transmission line towers along an existing utility corridor. In such cases, two transmission lines may exist during the construction process and could ultimately result in either the twinning of lines or removal of the old line. Implementing Before-After Control-Impact (BACI) designs from pre-construction through to post-construction has been recommended to improve our understanding of anthropogenic alterations on wildlife (Walters et al. 2014, Smith and Dwyer 2016, Richardson et al. 2017). The magnitude of impact from development is difficult to measure and is often a result of regulatory processes where project approval occurs before pre-construction baseline data can be collected (Northrup and Wittemyer 2012, Richardson et al. 2017). To my knowledge, there are no studies that investigate the response of raptors to temporary upgrades to existing energy transmission infrastructure from pre-construction through to post-construction.

Temporary habitat alterations from transmission line development or upgrading have the potential to influence local populations through the creation of ecological traps. Ecological traps can occur following habitat alterations that shift individual habitat preference where reproductive success is poor (Battin 2004). This phenomenon can occur when novel conditions uncouple the link between fitness and habitat selection (Dwernychuk and Boag 1972). Investigating the response of different components of fitness is recommended when assessing a potential ecological trap. Recommended parameters to assess include the survival rates of young and adults, nest success and productivity, and nest-site reoccupancy (Donovan and Thompson 2001). Few studies have investigated potential ecological traps in birds breeding near anthropogenic disturbances; however, there is evidence for the presence of ecological traps for nesting songbirds near oil and gas developments (Yoo and Koper 2017) and reduced fledging rates in preferentially selected edge patches by Indigo Buntings (*Passerina cyanea*; Weldon and Haddad 2005). Where nesting substrates are limited, alterations to existing energy-related projects have the potential to impact reproductive parameters of breeding birds nesting on associated vertical infrastructure. Raptors could be particularly vulnerable to temporary alterations to elevated nesting substrates because of their high nest-site fidelity as adult breeders. For instance, temporarily inflating the number of attractants such as elevated nesting substrates, and possibly increasing density of breeding hawks, and then removing these artificial structures in a subsequent year may lead to high densities of potential breeders where there are too few nesting structures. A potential outcome is increased local floater-to-breeder ratios after removal of nesting structures. Floaters are reproductively mature individuals unable to settle on a breeding territory (Hunt 1998), and may occur in greater numbers where nesting opportunities were once present (from previous years nesting in a given region) but have since been removed. These non-breeding individuals often return to areas near their previous home range and can hold territories up to five times larger than those of breeding individuals (Rohner 1997, Tapia and Zuberogoitia 2018). Some evidence suggests that floaters can interfere with breeding individuals in the area (Tapia and Zuberogoitia 2018), though some studies indicate that their influence on the nest success and productivity of nearby nests is limited (see Ferrer et al. 2015). Further, raptors may engage in physical altercations to win access to limited nesting structures (Ensign 1983) and the productivity of territorial breeding raptors may decrease with increases to the breeding population density (Sergio and Newton 2003).

Extreme weather events (i.e., storms and high wind) are predicted to increase in severity and frequency (Easterling et al. 2000, Meehl and Tebaldi 2004) in the Canadian prairies. Inclement weather such as storms and droughts can impact breeding and migrating birds. For breeding birds, demographic parameters may be influenced by rapid changes to local climate and inclement weather patterns (Sergio 2003, Mallory et al. 2009, Fisher et al. 2015). In the Canadian prairies, some long-term climate models predict that wind gusts will increase 10–30% during key breeding months (Cheng et al. 2014). Increases in the mean and variance of extreme wind events is of importance to nesting success for raptors breeding in open habitats. Exposed stick nests in trees or in tall anthropogenic structures are at risk of damage and destruction by windstorms (hereafter, ‘blow out’ or ‘blowing out’; Lokemoen and Duebbert 1976, Gilmer and Wiehe 1977). Further, increased exposure to windstorms could damage or destroy isolated prairie trees (Hogg and Hurdle 1995) creating a need for nest-site substitution. ANPs are often used to supplement nest-sites in areas of good habitat with limited nest substrate availability (Postupalsky 1978, Houston 1982). In some cases, ANPs are constructed with anchored nesting material to promote nest use, which could also mitigate potential nest blow out (Steenhof et al. 1993, Tigner et al.

1996). Similarly, heavy steel lattice used to construct transmission towers likely offers some shelter and support from wind (APLIC 2006) compared to the flexible or sometimes brittle branches in trees. Previous literature has shown that inclement weather can reduce raptor productivity in various nesting substrates (Dawson and Bortolotti 2000, Anctil et al. 2014, Wallace et al. 2016), and provided anecdotal reports of the direct effects of severe weather on nests in transmission towers (Gilmer and Wiehe 1977, Steenhof et al. 1993). However, few studies have considered the impacts of high wind events on breeding raptors.

### *Study Area*

This study was conducted within the four ecoregions of the prairie ecozone in southern Alberta (Ecological Stratification Working Group 1996). The study area stretched from the southwest, near Pincher Creek (49.49° N, 113.95° W) in the Rocky Mountain foothills, north to Calgary (51.05° N, 114.07° W), and east to the moist-mixed grasslands near Medicine Hat (49.66° N, 103.85° W). The overall study area was 97,237 km$^2$ (Figure 1). The area is predominantly flat grasslands in the east, with an elevation gain in the west towards the southern Alberta foothills. Dominant soil types in the prairie ecozone are black chernozems (fescue grassland), brown chernozems (mixed grassland), and dark brown chernozems (moist mixed grassland), with a significant presence of solonetzic soils in certain areas (Ecological Stratification Working Group 1996). The most commonly occurring tree species in the ecozone are Balsam Poplar (*Populus balsamifera*), Trembling Aspen (*Populus tremuloides*), Narrow-leaved Cottonwood (*Populus angustifolia*), Plains Cottonwood (*Populus deltoides*), and willows (*Salix* spp.). The dominant vegetation the fescue grasslands in the west includes Foothills Rough Fescue (*Fescuta campestris Rydberg*), Parry's Oat Grass (*Danthonia parryi*), Prairie Junegrass (*Koeleria macrantha*), and wheat grasses (*Agropyron* spp.) (Ecological Stratification Working

Group 1996, ASRD 2010). Further east, the dominant ecoregions are mixed grasslands and moist mixed grasslands in the eastern prairies where the common vegetation includes, sagebrush (*Artemisia* spp.), Spear Grass (*Heteropogon contortus*), Needle–and–Thread Grass (*Stipa comata*), wheat grasses, and Blue Grama (*Bouteloua gracilis*; Ecological Stratification Working Group 1996). Average summer temperature is 14°C in the foothills and 16°C in the mixed grasslands. Average precipitation in the Canadian prairies is 454 mm (McGinn and Shepherd 2003), with 395 mm in Saskatchewan and 482 mm in Alberta (Shepherd and McGinn 2003). Annual average surface wind is highly variable in the Canadian prairies (14 to 22 km/h) with extreme maximums reached in Lethbridge, Alberta of 171 km/h. Wind speed averages are highest in the spring and fall and moves west-to-east from low-pressure systems stemming from the Rocky Mountains (McGinn 2010).

Chapter 2 focused on a subsection of the overall study area to control for potential spatial and landscape effects and was located from the foothills fescue grasslands west of Pincher Creek, north to the southern outskirts of the Calgary city limits, and east to the moist-mixed grasslands of Lethbridge. Chapter 3 used nesting data throughout the aforementioned study area (Figure 1).

### *Study Species*

The Ferruginous Hawk (*Buteo regalis*) is North America’s largest soaring hawk (*Buteo* sp.) and endemic to the grassland and shrubsteppe regions of the United States and Canada (Bechard and Schmutz 1995). They range from southern Alberta, Saskatchewan, and Manitoba in Canada, throughout the west-central grasslands of the United States and south-western USA and into desert portions of northern Mexico during the winter months. They are found in flat or rolling, open-country habitat, often where there are elevated features on the landscape (cliffs and rocky outcrops) or isolated trees (Bechard and Schmutz 1995). These topographic features, in addition to sparse trees, provide ideal natural nesting habitat for breeding Ferruginous Hawks (Smith and Murphy 1973). Nesting density tends to have a negative correlation where cultivation is high (Stepnisky et al. 2002). Densities increase significantly in heterogenous landscapes with approximately equal amounts of cropland and native grassland (Schmutz 1993, Ng 2019). Two Ferruginous Hawk subpopulations are bisected by the continental divide (Rocky Mountains) and depend on different prey types (Ng et al. 2020). Leporids (cottontails *Sylvilagus* spp. and jackrabbits *Lepus* spp.) are preferred in the West and sciurids (ground squirrels *Urocitellus richardsonii* and prairie dogs) are the most common mammalian prey in the East. Olendorff (1993) found that 66% of Ferruginous Hawk diet (by biomass) consisted of leporids, but Canadian populations of Ferruginous Hawks rely on ground squirrels as prey (Schmutz et al. 1980). Additional prey includes Thirteen-lined Ground Squirrel (*Ictidomys tridecemlineatus*), amphibians, reptiles (Schmutz et al. 1980), and birds (Nordell et al. 2017).

The Canadian breeding range of the Ferruginous Hawk is approximately 12% of the present-day North American range (Schmutz et al. 1980). Ferruginous Hawk populations in Canada have been declining since the mid-1980s and between 1992 and 2005 experienced a range contraction of 52% and an estimated 64% population decline (COSEWIC 2008). In Alberta, the population declined by approximately half between 1992 and 2005 to an estimated 618 +/- 162 pairs. In 2006, Ferruginous Hawks were listed as provincially *Endangered* in Alberta under the *Alberta Wildlife Act* (AFHRT 2009) and, in 2008, were listed in Canada as *Threatened* under Schedule 1 of the *Species At Risk Act* (Government of Canada 2019). Ferruginous Hawks were also designated as *Threatened* in Manitoba since 1994 (Manitoba 2018) and listed as a species of conservation concern in several US Fish and Wildlife Service regions

(US Fish and Wildlife Service 2008). Recent declines in Ferruginous Hawk are attributed to anthropogenic disturbance including habitat loss (industrial development, conversion for agriculture, fragmentation, and farming) and the loss of nesting structures (AFHRT 2009).

In Alberta, transmission lines are projected to increase by a total of 4000 km over the next 21 years to meet the energy demands of a growing population and increasing industrial development (Alberta Utilities Commission 2013). To support additional energy requirements, there is a need to upgrade or construct new energy infrastructure (i.e., new transmission lines or upgrades to pre-existing lines) to support a non-renewable or renewable energy source. When available, Ferruginous Hawks frequently use transmission towers and nearby landscape features for nesting, perching and foraging (Bechard and Schmutz 1995, Watson 2020). Though Ferruginous Hawks have been observed nesting along transmission line corridors and on the cross arms of transmission towers (Steenhof et al. 1993, Ng et al. 2020), outside of electrocution and collision literature (i.e., direct mortality), there are few studies on the indirect effects of transmission lines on raptors, such as how nest densities may be affected or if ecological traps may occur.

### *Objectives*

My thesis objectives were to assess the effects of temporary habitat change and the influence of severe weather events on Ferruginous Hawks in southern Alberta. Specifically, in Chapter 2, my primary objective was to quantify how the temporary addition of transmission lines to a landscape (essentially doubling the density of elevated artificial nesting substrates) influenced Ferruginous Hawks compared to areas with similar landscape characteristics and no transmission line change. Using a Before-During-After Control-Impact study design, I estimated four Ferruginous Hawk nesting parameters, and the composition of the raptor and raven community, to compare change between sites impacted by transmission line alterations and unaltered sites. Data were collected in southwestern Alberta over 7 years, between 2013 and 2019. In Chapter 3, I examined how Ferruginous Hawk nest persistence (defined as the time during the monitoring period that the nest remained elevated and intact), productivity (number of young fledged per successful nest), and the daily survival rates of nestlings are affected by inclement weather during the breeding season, and explored the importance of nest substrate in mitigating negative effects of extreme weather. Data were collected between 2010 and 2017 in southern Alberta, and weather data were provided by the Government of Alberta. Finally, in Chapter 4, I summarize my key findings and provide management suggestions and implications.

## TABLES AND FIGURES

**Table 1.1.** Costs and benefits of power and transmission lines on nesting birds (derived from Mainwaring 2015).

| Benefits | Costs |
|---|---|
| Increases in nest site availability (Balmori 2005, Tryjanowski et al. 2014), particularly in areas with limited available nesting substrate such as agricultural or prairie landscapes (Howe et al. 2014) | Elevated levels of mortality form electrocution or collisions with powerlines (e.g., Ferrer et al. 1991, Bevanger 1998; Martin and Shaw 2010, Jenkins et al. 2010, Kaługa et al. 2011) |
| Higher number of available perches and access to locations previously unused by “perch foraging” birds (e.g., Phipps et al. 2013) | Increases in exposure to electric fields resulting in lower levels of breeding success for nests on (Tryjanowski et al. 2014) or near towers (Balmori 2005) |
| | Attraction to poorer habitat/ possible ecological trap (e.g., Schlaepfer et al. 2002) |
| | Increased susceptibility to stick nest blow out versus natural substrates (Steenhof et al. 1993) |
| | Indirect effects of increased predation on At Risk species (e.g., Raven predation on Greater Sage-Grouse [Howe et al. 2014]) |
| | No associated costs to nesting species (e.g., Tryjanowski et al. 2014, Howe et al. 2014) |

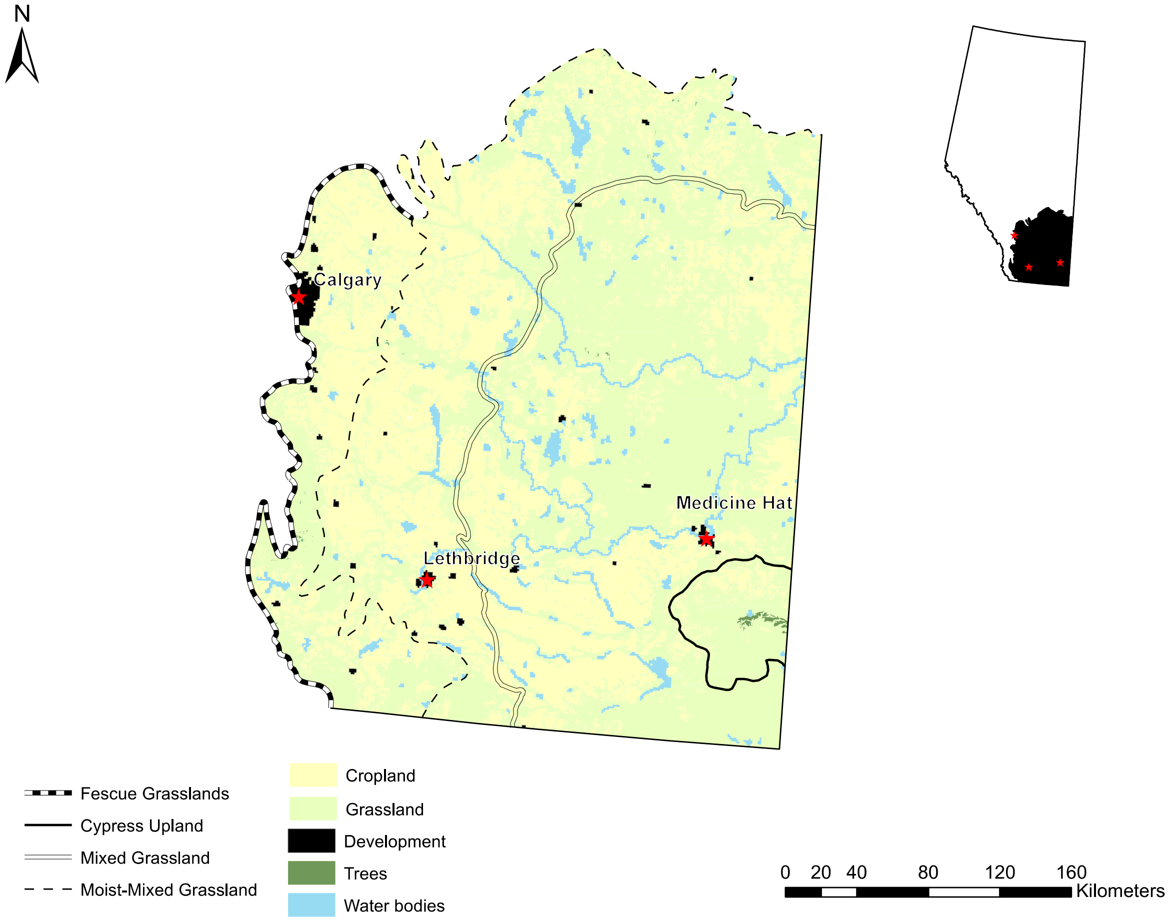

**Figure 1.1.** The project study area was located within all four ecoregions in the prairie ecozone in southern Alberta (Ecological Stratification Working Group 1996).

# CHAPTER 2: Response of Ferruginous Hawks to temporary habitat alterations for energy development in southwestern Alberta

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## ABSTRACT

Temperate grasslands are among the most altered biomes worldwide, largely through anthropogenic modification. The rapid construction of renewable energy projects is necessary to accommodate for growing energy demands and, when existing projects are upgraded, alterations to associated infrastructure are necessary. The direct effects of these developments on wildlife are relatively well understood (e.g., mortality risk), but there is little understanding of indirect impacts on wildlife breeding near developments. We applied a robust Before-During-After Control-Impact (BDACI) design to determine the influence of high-voltage transmission line alterations on an *Endangered* population of Ferruginous Hawk (*Buteo regalis*), in southern Alberta, Canada. Using data collected between 2013–2019, we compared the response of breeding hawks to three phases of development between control and impact sites to determine if the number of transmission towers on the landscape could influence this local population, and if alterations could result in a sink population or ecological trap. Generalized linear mixed models were used to test for five responses: (1) Ferruginous Hawk nest density, (2) nest success, (3) productivity, (4) nest site reoccupancy, and (5) changes to nesting raptor and raven community composition. We found no effect of phase and site on nest success, productivity, or reoccupancy. However, nest densities increased significantly by >37% after towers were added but returned to pre-construction levels after tower removal. Additionally, community composition changed significantly with high variability near impact sites. Our study is the first to test for population-level effects of energy development on an At Risk raptor using a robust BDACI design. Our experimental design demonstrates that the availability of nesting structures limits the size of this Endangered population, providing evidence that this population can be increased by adding nesting structures to the landscape. This suggests that adding nesting substrates (e.g., trees or nest platforms) to this landscape could increase the population.

**Keywords:** Ferruginous Hawk, human development, BACI, nest density, ecological trap, *Buteo regalis*, energy infrastructure

## INTRODUCTION

Habitat loss and degradation by anthropogenic activities is a leading cause of global biodiversity decline (Pimm and Raven 2000). Changes to landscapes are increasingly caused by energy development (McDonald et al. 2009). Once a non-renewable or renewable energy source is developed, maintenance and upgrading of infrastructure becomes increasingly common. A 28% increase in global energy demand is projected over the next 22 years (USEIA 2017). To meet this demand, the greatest proportional increase in energy production is predicted to come from renewable energy. In the United States, over 200,000 $km^2$ of new land is expected to be developed for energy-related projects by 2035 (MacDonald et al. 2009). With these energy projects, associated infrastructure such as transmission lines often require updating to support higher capacities. In addition to the well documented risks of collision to birds (APLIC 2006, Smith and Dwyer 2016), transmission lines can cause habitat fragmentation (Hanowski et al. 2013) and spread of invasive and exotic species (Goosem and Marsh 1997). However, most studies assess impacts at the individual level by monitoring mortality rates of individual birds or breeding pairs on or near transmission lines, but fewer studies demonstrate population level effects or address any indirect effects of transmission line development (Lovich and Ennen 2011, Smith and Dwyer 2016).

Most monitoring of the impacts of energy development are retrospective and control-impact designs are the most common way of assessing effects. In North America, fewer than 20% of studies assessing the impacts of energy development include a before and after component (Kuvlesky et al. 2007, Northrup and Wittemyer 2012). Additionally, pre-construction data is typically from a single year, increasing the uncertainty about natural variability (Richardson et al. 2017). BACI study designs are important to control for natural variation and drawing robust conclusions about the causal mechanisms driving observed changes (Walters et al. 2014).

Raptors and ravens readily use transmission towers for perching, nesting, and hunting in open landscapes (Steenhof et al. 1993). Thus, they often exhibit a positive response to transmission lines (Boarman 1993, Knight and Kawashima 1993). By perching on elevated structures, avian predators are thought to gain a visual advantage by expanding their search area while using less energy than from flight-hunting (APLIC 2006). For example, Common Raven (*Corvus corax*) and Red-tailed Hawk (*Buteo jamaicensis*) abundance increased along transmission line right-of-ways (Knight and Kawashima 1993, Coates et al. 2014) and ravens prefer nesting at sites near transmission lines (Howe et al. 2014). The effect of transmission line development on local raptor and corvid densities is particularly high in areas where alternative vertical structures (e.g.., trees and cliffs) are limited (Coates et al. 2014, Walters et al. 2014). Whether this concentration of different raptor and corvid species near transmission lines causes changes in ecological processes like competition or predation between species, and whether these interactions may create an ecological trap, is poorly understood (Richardson et al. 2017). Importantly, it is not always known whether these birds are altering behaviours by using these perching or nesting structures, thereby biasing observer detection, or whether these structures are leading to an increase in population size for these species within the broader landscape dissected by transmission lines.

Ecological traps occur when an organism selects relatively poor habitat over other available habitat despite reduced fitness while using this habitat (Dwernychuk and Boag 1972). This uncoupling of environmental cues and reproductive consequences is often triggered by habitat alterations and is exacerbated by rapid anthropogenic change (Robertson, Rehage, and

Sih 2013). Further, when populations occur at low densities, the negative consequences of ecological traps are heightened because of their exposure to local demographic stochasticity (Kokko and Sutherland 2001). In raptors that are long-lived and have high nest-site fidelity, attraction to transmission lines caused by increasing nest site availability may increase density but result in an overall decrease in habitat quality because of fewer resources per individual (i.e., greater competition for prey). In the extreme, this could result in inflated floater-to-breeder ratios (Hunt 1998) where floaters encroach on breeding pairs leading to inflated population densities where limited breeding opportunities typically exist (Kokko and Sutherland 1998). Recommended parameters for identifying ecological traps include the survival of young or adults, nesting success, nesting productivity, and in some situations re-nesting attempts (Donovan and Thompson 2001).

Ferruginous Hawk (*Buteo regalis*) populations in Canada have been declining since the 1980s (COSEWIC 2008) and are listed as nationally *Threatened* under the federal *Species At Risk Act* (Government of Canada 2019) and provincially *Endangered* in Alberta under the *Alberta Wildlife Act* (AFHRT 2009). Recent population declines are attributed to the loss of habitat (e.g., industrial development and conversion for agriculture) and loss of suitable nesting structures from tree senescence (Ng 2019). Of the *Buteo* species, some studies suggest Ferruginous Hawks are the most likely *Buteo* species to nest on transmission towers (MacLaren 1986), but trees seem to be preferred when available (Hansen 1994, Coates et al. 2014). Ferruginous Hawks may benefit from additional nest substrates, such as transmission towers, in grassland landscapes, which in turn may result in higher use of areas with greater development (Keough and Conover 2012, Wallace et al. 2016). However, turnover rates are often higher for species nesting on or near transmission lines (Steenhof et al. 1993), possibly because of increased mortality risk for adult birds with transmission lines in their home range (Manosa and Real 2001). In addition, nests on transmission towers may be more susceptible to wind and weather damage than nests at lower heights in natural structures (Steenhof et al. 1993, APLIC 2006), potentially impacting the recovery of Ferruginous Hawk populations.

With a growing population and energy sector, the amount of transmission lines in Alberta is projected to increase by a total of 4000 km over the next 21 years with approximately 50% of all lines in southern Alberta (Alberta Utilities Commission 2013). Our study provides a unique opportunity to assess the response of a local population of Ferruginous Hawks to temporary alterations to nest substrate availability via transmission line construction and decommissioning using a Before-During-After Control-Impact (BDACI) study design. We used two fitness parameters – nest success and productivity – in addition to nest density and nest reoccupancy rates to assess for the potential of an ecological trap or sink population near sites undergoing transmission line development. Based on previous literature, we predicted that nest density would increase near impact sites after new tower construction, but that rates would decrease in the final construction phase (old tower removal). We also predicted increased nesting densities for ravens and raptors near impacted sites after tower construction with a shift to generalist species (e.g., Common Raven) after tower removal.

## METHODS

### Ethics Statement

Our data collection methods were designed to limit harm or stress to individual adult and nestling hawks. This study complied with the Ethical Treatment of Animals Guidelines under the University of Alberta Animal Care #724, Permit AUP00000018. Before approaching nests on private land, access permissions were acquired from landowners. Nests were not approached or checked while it was raining or on cold (<10 ºC) or windy days (wind >30 km/h). During vulnerable stages early in the breeding season (nest building and incubation) for Ferruginous Hawks or other species, observers limited the time spent near nests to minimize the risk of nest abandonment.

## Study Area

Our study was conducted in a 3982 km$^2$ area of the Ferruginous Hawk breeding range in southwestern Alberta, crossing into three subregions in the Canadian prairie ecozone in southern Alberta: the Rocky Mountain foothills fescue in the West, and mixed-grass and dry mixed-grass prairie in the East. The western portion of the study area is located between Fort MacLeod (49.72° N, -113.40° W) and Calgary (51.05° N, -114.07° W). The regions' climate is semi-arid, with greater precipitation and lower average summer temperatures in the Rocky Mountain foothills fescue subregion. The dominant natural nesting substrates throughout the study area are old cottonwood trees (*Populus angustifolia*) and natural south facing cliffs.

Transmission line activities occurred at impacted sites in the western region of our study area (Figure 1) to accommodate for additional power generated from wind farm development near Fort MacLeod (AltaLink 2014). Construction activity occurred over three stages between 2014 and 2018 whereby a single circuit 240-kV line constructed in 1969 was replaced by a larger double circuit 240-kV transmission line. The original line was comprised of steel-lattice transmission towers spaced approximately 350 m apart and 25–30 m tall. The parallel replacement double circuit 240-kV transmission line towers were separated by the same distance, but new towers were 50–100% taller (45–50 m). The steel-lattice of the original towers consisted of a single, relatively dense horizonal piece, whereas the new towers have three horizontal pieces (two small, one large) with reduced latticework densities which could limit nesting opportunities (Steenhof et al. 1993). Construction began in the winter of 2014 and was completed before the 2015 breeding season. In 2015, the line was decommissioned and most (96%) towers were removed in the winter of 2016 and 2017. Towers with Ferruginous Hawk nests defined as active under provincial guidelines (i.e., at least once in the previous three breeding seasons) were not removed until the mitigation protocol was met (AFHRT 2009). To mitigate nest removal from towers, one or two nest platforms were installed between 300 and 1000 m away from the tower and, if two nest platforms were installed, a minimum distance of 800 m was maintained between platforms. Further, platforms were attached to the base of six new towers in an effort to dissuade nesting in the steel-lattice support structures while providing artificial nesting opportunities within the home range (<2.5 km) from historical tower nests. The remaining towers were removed in the winters of 2017 and 2018 following the implementation of the above mitigation measures. Both transmission lines travel from Fort MacLeod to south of Calgary (AltaLink 2014). The construction of a taller replacement line provided an opportunity to investigate how landscape alterations to the regions' primary nesting and perching substrates influenced Ferruginous Hawk nesting behavior near impacted sites.

### Sampling Design

We selected survey sites using a BDACI study design (Roedenbeck et al. 2007) with paired treatment-control blocks. Impacted sites were bisected by the original transmission line, while control blocks were distributed in the moist-mixed and mixed grasslands of southern Alberta (Figure 1). Control blocks were selected based on similar landscape characteristics of corresponding impact sites (i.e., % grassland, cropland, and human footprint (i.e., human development features that result in change in land cover such as roads, oil and gas wells). Each block was 9.6 km by 9.6 km, the dimensions of a township. Control block placement was limited west of the transmission line by foothills of the eastern slopes of the Rocky Mountains (Figure 1).

## Survey Protocol

Stick nest surveys were conducted between mid-April and early May to ensure Ferruginous Hawks were present either on or near their nests. Sticks nests used by raptors can persist for years on the landscape after abandonment and Ferruginous Hawks will often re-enforce a pre-existing nest (Ng et al. 2020). Therefore, all stick nests suitable for Ferruginous Hawks, regardless of occupancy status, were noted. Survey routes ranging from 20 km to 30 km were randomly selected in each block based on the following guidelines: i) only roads (hard or loose surface) in a block would be driven, ii) all land cover types in each block would be surveyed, and iii) when a transmission line was present, the survey route was selected both parallel and perpendicular to the line to ensure habitat both near and far from the line was surveyed. Stick nest detection rates were maximized by surveying before spring leaf-out and surveys were conducted at driving speeds of 30–50 km/h. Surveys were conducted from 4x4 trucks on public roads (paved, gravel, or dirt). When possible, we returned to previously surveyed blocks to drive unsurveyed roads in a second pass, however this depended on spring leaf-out after the completion of all surveys. Surveys ceased when spring leaf-out obscured nests in trees and negatively affected nest detection. We surveyed during daylight hours after sunrise and before sunset and in fair to good weather conditions. Surveys were not conducted when environmental conditions negatively impacted visibility (i.e., high wind [≥ 30 km/h] or heavy precipitation events). At each nest, status (active or empty), date, and occupancy status (species, number of adults) were recorded. Nests were considered occupied when an individual was sitting in a nest or a breeding pair was perched near an available nest (Steenhof and Newton 2007). We assumed a nest detection radius of 800 m from roads, which is conservative in open grasslands where large stick nests in trees are easily detected from far distances, to calculate the area surveyed in a block (Figure 2). When possible, exact nest locations were recorded using a Global Positioning System (GPS). If land access was not possible or permitted, we used triangulation methods using the ACCRU Toolbox (Neilson 2010) in ArcGIS v10.5. For nests in distinct structures (e.g., lone trees, transmission towers) where land access was not granted, we estimated locations from satellite imagery on Google Maps. We compared the accuracy of known nest locations on Google Maps and found estimates were similar to GPS location errors ($n = 24$, $\mu = 9.4$ m, median = 2.8 m).

### Nest Visits

Nests were visited weekly by a single observer to record nest stage, the number of nestlings, fledglings, and adults present until all fledglings had left the nest (~45–50 days from hatching). Nests were checked from afar using a spotting scope was mounted to a truck window from the nearest access point to the nest to view nestlings once visible. Binoculars were also used to observe hawk nests and behaviour. When approaching the nest was possible (depending on landowner permission and nest height), nest contents were viewed using a digital camera mounted on an extendable pole for accurate monitoring of nest contents (i.e., number of eggs, number of nestlings, age of nestlings, prey content). Before approaching a nest, mean temperature (ºC) and wind speed (km/h) were recorded using Kestrel hand-held devices (www.kestrelmeters.com). We could not access nests in transmission towers, therefore these nests were only viewed with a spotting scope and nestlings were aged and counted once visible in the nest. Nest occupancy criteria was (i) an adult was incubating or nest building, (ii) a pair of adults were observed on the nesting structure, or (iii) young were observed in a nest if adults were absent. Nests previously occupied by Ferruginous Hawks (for ≥ 1 year) were checked to determine occupancy status and nest status (empty or occupied by a Ferruginous Hawk or other species) was checked the following year.

## Statistical Analysis

To test for change after transmission towers were first erected and following tower removal with the BDACI study design, our models were fit with a Site (Impact and Control) and Phase (timing of construction) interaction term. A significant interaction indicates an effect of impacted sites on the response variable (Osenberg and Schmitt 1996, Morrison et al. 2008). We fit Generalized Linear Mixed Models (GLMM) with a Conway-Maxwell-Poisson error family (Brooks et al. 2019) to examine continuous response variables (i.e., productivity and density) and logistic regression with a binomial error family to analyze binary and proportion response variables (i.e., nest success and reoccupancy). See below for rationale of this distribution. A random effect for BlockID (nest density model) or NestID (success, productivity, and reoccupancy models) was included to account for non-independence of repeated measures. If random effects were overfitting the model (SD and variance near 0), then they were dropped from the final model (Pasch et al. 2013). We used a Likelihood Ratio Test (LRT) to test the significance of the random effects structure in our final models.

Models were built using a forward step-wise process where covariates were added to a base model and compared using $AIC_c$ (Burnham and Anderson 2002). Our base model was first developed to control for nuisance variables not related to study objectives (i.e., intrinsic variables). Continuous variables were first compared using a LRT to determine if linear or quadratic term was more suitable. Where appropriate, we binned categorical covariates with many levels to simplify our analysis and compared the original and binned covariate using a LRT (e.g., we binned nest substrate to anthropogenic vs. natural). For each analysis, we developed the base model by adding variables in three steps. If the addition of a covariate improved our base model, then it was advanced to the next step to create a final model. Covariates considered for each step are listed in Appendix 1, Table 1. Statistically significant covariates improving model performance were added to the base model until there were no further improvements to model performance. Models were further simplified by removing variables that were not significant ($P > 0.10$) in the final model via a backward stepwise approach, whereby the least significant variables were dropped one at a time by order of significance. If $AIC_c$ was not lowered, then variables were not retained (Arnold 2010). All models within $\Delta AIC_c < 2$ of the top model were selected, whereby the most parsimonious model (i.e., with the fewest parameters) was selected as our top model (Arnold 2010).

To calculate and model nest densities, we converted count values to a rate (nests per area surveyed) by including a model offset (log[Area]) that assumed the chance of locating a nest increased with area surveyed. Phase and site were included as factors in the model. Phase refers to the time of transmission line construction and included three levels: Before, During, and After. The two levels were included for Site were Impact and Control.

Nest success, productivity, and reoccupancy models were not limited to nests observed in blocks and also included active known and incidental nests in the study area. To account for these additional nests and maintain a BDACI design, we developed binned treatment zones based on distance from transmission line construction. We first developed an Impact Zone (IZ) around nests 2.5 km from the transmission line. The buffer distance was selected based on the core Ferruginous Hawk home range size (3.54 km$^2$; J. Watson, *personal communication*) and is where we predicted Ferruginous Hawk response to the development would occur. Previous studies recommend including an intermediate zone between the Impact and a Control Zone (e.g., Bro et al., 2004; Torres et al. 2011). Therefore, two Control Zones (CZ) were established with zone edges at medium (CZ1; 2.5 km to 10 km) and high (CZ2; >10 km) distances from the transmission line. Reoccupancy was limited to n-1 years to account for the first year of nest monitoring, therefore a single year (2013) was included in the Before phase of this analysis. Sample sizes and the number of unique nests in each analysis varied because additional areas and fewer constraints were included in these analyses. Further, the number of nests available for each model was affected by a nests success (e.g., historical nests that failed early could be used in reoccupancy models, but not in success or productivity analyses) and observer confidence in our ability to estimate productivity.

Before each analysis, a visual inspection was conducted to assess for outliers, normality, and correlation among covariates (Zuur et al. 2010). Null models were first fit and assessed using log-likelihood and $AIC_c$ scores between Poisson, Conway-Maxwell-Poisson, negative binomial, zero-inflated Poisson, and zero-inflated negative binomial error family. Count data is often modelled with Poisson or negative binomial distributions; however, these error families assume overdispersion is present and can be conservative, thereby impeding our ability to detect significance. Our count-based models (nest density and productivity) were under-dispersed, thus we fit them with a Conway-Maxwell-Poisson distribution (Lynch et al. 2014, Brooks et al. 2019) to account for under-dispersion and improve final model fit. Where multiple covariates were highly correlated ($r > 0.7$), the covariate with the lowest $AIC_c$ of univariate models or the most significant covariate was considered in our base model. Model fit was assessed for zero-inflation, overdispersion, multicollinearity (VIF <3; Zuur et al. 2010), outliers, residual homogeneity, and normality of residuals using the DHARMa package (version 0.2.7; Hartig 2017). For logistic models, fit was assessed by inspecting binned residual plots where data is binned based on fitted values and the average residual is plotted against the average fitted value for each bin (Gelman and Hill 2006) using the arm package (version 1.10–1; Gelman et al. 2013). All continuous covariates were centered and rescaled to allow for direct comparison of results and account for different scales among covariates. Analyses were performed in RStudio v1.0.143 (RStudio Team 2015) and results were considered significant at $\alpha < 0.05$.

### Raptor and Raven Community Analysis

To detect patterns in our community dataset, we used multivariate analyses with the ManyGLM function of the mvabund package (version 4.0.1) in RStudio, which provides more power to detect patterns among a given community than separately analyzing each species (Wang et al. 2012). Model assumptions and fit were assessed by checking the mean-variance relationship of the species abundance data, whereby a strong linear relationship suggests overdispersion. Thus, the community assemblage was modelled with a negative binomial error distribution. We visually assessed Dunn-Smyth residuals against fitted values and found no evidence of any pattern when using a negative binomial distribution (Warton et al. 2015). To account for non-independence in our repeated measures block design, we permuted the species abundance within each replicate (BlockID). PIT-trap residual bootstrapping was selected for resampling, which returns dependable Type I error rates (Warton et al. 2017). This model-based approach to handling multivariate data tests the response of the community assemblage as whole and then separately for each species with univariate tests. Similar to our GLMM models, we included raw abundance data for each species as our response variable and specified an offset of the logarithm of area surveyed to account for variation in block survey sampling intensity. To test the BDACI study design, Wald tests were used in a hypothesis-testing framework for comparison of Phase-only and Phase x Site interaction models (Wang et al. 2012).

To visualize the community composition between phases and in each site, we used non-metric multidimensional scaling (NMDS) from the R-package vegan (version 2.5–6; Oksanen et al. 2015). Dissimilarity indices of our community matrix were compared and the highest-ranking index (Gower; 0.099) was used to ordinate our NMDS plots. Centroid ellipses were added to observe the difference between block types using a 70% standard deviation ellipse size. Ordination dimensions and stress were determined using an iterative approach and we determined the optimal setting for minimizing stress to be a 3-dimensional ordination with 50 iterations (stress = 0.121). Variation in Gower distances between species at each site type and all phases was also visualized to help interpret discrepancies between NMDS plots and ManyGLM results. This process calculates the multivariate homogeneity of group variances from a distance matrix using the "vegdist" and "betadisper" functions in vegan.

Occasionally, we were unable to identify the occupant of a nest for various reasons (e.g., distance, heat haze, backlighting, and poor angle to nest). When possible, we would return to the nest location to confirm the identity of an occupant, though this was not always feasible for logistical reasons. Only nests with confirmed species identification were used in this analysis.

## RESULTS

### Nest Density

Between 2013–2019, 1,441.9 km$^2$/ year were surveyed at impact blocks (n = 19) and 1,295.6 km$^2$/ year at control blocks (n = 19) on average. Annually, we found an average of 0.56 Ferruginous Hawk nests/ block totalling 150 unique nest sites in all 38 blocks during our 7-year study (103 in impact blocks and 47 in control blocks). Across all years, Ferruginous Hawk nests were observed at least once in 52.6% of blocks (20/38 – 8 impact and 12 control). Controlling for area, we found 0.010 Ferruginous Hawk nests/km$^2$ in impact blocks and 0.005 nests/km$^2$ in control blocks. Across all years, impact block nest densities ranged from 0.00 to 0.092 nests/km$^2$ and 0.00 to 0.050 nests/km$^2$ in control blocks (Figure 3, Table 1).

The subregion ($\chi^2 = 16.94$, $P < 0.001$) and proportion of grassland ($\chi^2 = 6.84$, $P = 0.009$) in a block were included as significant variables in our final model. We observed a significant interaction between Phase and Site ($\chi^2 = 5.98$, $P = 0.050$; Table 2). Means in the impacted blocks for both During ($\beta = 0.967$, $P = 0.029$) and After ($\beta = 0.703$, $P = 0.044$; Appendix 1, Table 2) phases were significantly higher than for control blocks for nest density in the Before phase. A significant amount of the residual variance was explained by the random effects structure (LRT, $P < 0.001$).

**Success and Productivity**

We monitored 465 nesting attempts (Impact Zone: 150, Control Zone 1: 68, Control Zone 2: 144) between 2013–2019 from 216 unique nests. On average, nests were monitored for 2.15 nesting attempts per nest (range = 1–6 years, median = 2). Pooled across all phases, mean nesting success and productivity was highest in IZ nests (73.3%, 1.95 fledglings/ nest) and lowest in CZ1 nests (65.4%, 1.62 fledglings/ nest). The highest nest success and productivity for any treatment and phase was IZ, During (84.6%, 2.48 fledglings/ nest; Figure 4, Table 3), which had 6.83% higher success and produced 0.47 fledglings/ nest more than the next highest Treatment-Phase combination (CZ2, During). However, after controlling for intrinsic and landscape variables, we did not find a significant interaction between Phase and Treatment for either nest success ($\chi^2 = 0.51$, df = 4, $P = 0.973$) or productivity ($\chi^2 = 5.37$, df = 4, $P = 0.252$; Table 2) models. A significant effect of Impact Zones was observed ($\chi^2 = 9.05$, df = 2, $P = 0.011$) with a large increase in successful IZ nests ($\beta = 2.39$, $P = 0.074$; Table 2). Random effects in both models overfit the model (SD and variance <0.001) and were dropped from final models.

### Reoccupancy

We completed 437 reoccupancy surveys (IZ: 140, CZ1: 101, CZ2: 196 nests) conducted between 2013–2019, from 192 unique nests in our analysis. During our study, each nest was visited 2.28 times on average (range = 1–5 years, median = 2). Six species (including Ferruginous Hawks) were observed using nests occupied by Ferruginous Hawks the year before: Ferruginous Hawk (64.57%), Red-tailed Hawk (2.10%), Great Horned Owl (*Bubo virginianus*; 2.62%), Swainson's Hawk (*Buteo swainsoni*; 1.31%), Canada Goose (*Branta canadensis*; 1.05%), and Common Raven (0.52%). There were an additional 7 (1.84%) occupied nests with unidentified species and 58 (15.22%) unoccupied nests.

The previous year's nest occupant (Ferruginous Hawk, Other, or Unoccupied), first year monitored, and loose road density (quadratic) within 2.5 km of the nest site were included as intrinsic and land use controls in the final model (Appendix 1; Table 5). After controlling for these variables, we found no significant interaction between Phase and Treatment ($\chi^2 = 0.62$, df = 4, $P = 0.960$; Table 2). A significant effect of phase was observed ($\chi^2 = 9.95$, df = 2, $P = 0.007$) with a low reoccupancy rates before construction ($\beta = -1.35$, $P = 0.011$). Random effects overfit the model (SD and variance <0.001) and were dropped from final models.

### Community Analysis

Four raptors and ravens were observed in each Phase and Site: Common Raven, Ferruginous Hawk, Great Horned Owl, Red-tailed Hawk, and Swainson's Hawk. Impact sites varied substantially relative to control sites (Figure 5) with Ferruginous Hawks and Common

Ravens most strongly associating with impact blocks. Though species richness was unchanged, nest densities and species site affiliation varied largely (Table 4, Figure 6).

We used ANOVA tests to compare Phase-only and Phase x Site models. We found significant change in community composition between sites and construction phases ($\chi^2$= 6.34, *P* = 0.030); Table 5). However, univariate tests indicated that no species contributed significantly to community change between sites and phases. Ferruginous Hawks (27.5%), Common Ravens (24.9%), and Red-tailed Hawks (21.3%) contributed the most to community changes, though none contributed significantly (Table 6).

## DISCUSSION

Relative to direct effects, the indirect impacts of energy development on breeding raptors are understudied. The collective results of our 7-year study suggest a limited influence of transmission line changes to Ferruginous Hawk nesting structures on nest density, success, productivity, and reoccupancy. Only nest density change was significant with an increase following the construction of new transmission towers. Thus, we did not find significant evidence suggesting the presence of an ecological trap on Ferruginous Hawks breeding success following temporary alterations to suitable nesting structures in the form of transmission tower construction and subsequent removal.

Ferruginous Hawk nest densities increased near impact blocks when more transmission towers were present on the landscape. Our results suggest that the doubling of transmission towers on the landscape contributed to a 37.2% increase in Ferruginous Hawk nesting density between phases before old towers were removed. On average, impact block nest densities were 47.9% higher (range: 14.5 – 91.5%) than average pre-construction (Phase 1) nest densities. Nest densities in this study varied between sites (Impact: 0.0076 – 0.0121 nests/ km$^2$; Control: 0.0036 – 0.0072 nests/ km$^2$), but both sites were similar to those observed in previous studies (0.003 – 0.063 nests/ km$^2$ [Olendorff 1973; Lokemoen and Duebbert 1976; Blair and Schitoskey 1982; Gilmer and Stewart 1983]). Mean nest densities were low relative to previous studies in this area (0.100 – 0.150 nests/ km$^2$ [Schmutz et al. 1984; Schmutz and Hungle 1989]). This could be because the study area is on the northwestern limits of the current Ferruginous Hawk range (Ng et al. 2020), particularly along the northern half of the transmission line. Stahlecker (1978) reported a 138–425% increase in raptors per km$^2$ after new transmission line construction. Additionally, Steenhof et al. (1993) found that transmission tower nests of five species (including Ferruginous Hawks) increased annually for eight of nine years after new transmission line construction. They also observed a 2-year lag period for Ferruginous Hawks before they colonized the line in higher numbers. The presence of an existing line in our study area likely limited a possible lag effect by creating available nest-sites decades earlier at the time of construction. However, the steady increase in post-construction nest densities with limited effects on breeding success suggest the area can support a larger population of Ferruginous Hawks, if other factors important for breeding remain static or increased. However, nest-sites are not the only limiting factor for Ferruginous Hawks so whether increasing transmission line density will increase local nesting densities will vary in different areas. The introduction of new structures likely has the greatest impact on breeding corvids and raptors in areas of attractive habitat with limited nesting substrates (Smith and Murphy 1978). Our results demonstrate the importance of available nest-sites in limiting breeding population densities even in areas where the number of nest-sites was already inflated substantially.

Mature raptors unable to hold a breeding territory may persist in a landscape as a "floater" until breeding space becomes available (Hunt 1998). Areas where available nest substrates are occupied can limit nesting densities resulting from a lack of breeding space. In high nest-site fidelity breeders such as Ferruginous Hawks (Ng et al. 2020), returning to an occupied breeding area could result in non-nesting years or, alternatively, force individuals to breed in suboptimal space. The presence of floaters has been reported in some Ferruginous Hawks populations (Ayers et al. 2009) but are absent from others (Schmutz et al. 2008). A temporary inflation of available breeding sites could lead to an influx in floaters returning to previously substrate-rich landscapes, though little is known about floaters and their impact on existing populations in Ferruginous Hawks. In other raptor species, studies suggest that floaters returning to their natal territory may occupy large home ranges and interfere with breeding pairs in the area (Tapia and Zuberogoitia 2018), though their influence may be limited (Ferrer et al. 2015). Though we found no significant effect of transmission line alterations on breeding success, we recommend monitoring impacted areas for the possible presence of floaters where declines in the nesting success of the breeding populations have been observed as an indirect consequence of temporary transmission line alterations.

Our results provide evidence that the doubling of towers increased nest densities followed by a decrease to pre-construction levels after old towers were removed. Impact sites had higher densities than control blocks in six of seven years including all years post-construction. After transmission line removal, nest densities decreased 40.3% to near pre-construction levels. Raptors will disproportionately use transmission towers for perching and will consistently perch on a few towers within their core home range (Watson 2020). Utility rights-of-way are often strongly correlated with high raptor densities, particularly in open habitats and grassland biomes

(Restani et al. 2001, Boarman et al. 2006) where the visual search area is amplified, and energy can be conserved while hunting from a perch (APLIC 2006). Hunting from a perch is likely higher for Ferruginous Hawks and other raptors that use perches more often than soaring (Plumpton and Anderson 1998).

Breeding success and nest productivity of raptors is increased with additional food provisioning opportunities (Newton 1998, Tapia and Zuberogoitia 2018). We predicted high nest success and productivity near Impact Zones with an increase after initial tower construction, but found no support for these predictions after controlling for intrinsic and biological parameters. Mean nest productivity for all nests (1.82 fledglings; range = 1.49 – 2.48) was comparable to the mean nest productivity (1.83 fledglings; range = 0.80 – 3.38) of 11 studies summarized by Wallace et al. (2016). Impact Zone nests fledged more young on average (1.95 fledglings) and had higher success rates (73.3%) than those in either Control Zone. Nest success (78.8%) and productivity (2.10 fledglings/ nest) were highest after tower construction. However, overall nest success rates (68.97%; range = 58.50 – 84.61) were similar to rates reported across the Canadian breeding range (69%; range = 62 – 74% [Ng 2019]). Steenhof et al. (1993) reported slightly higher success rates for nests on transmission towers (83% and 77.27%, respectively). Previous research has reported increased success of Ferruginous Hawks and other raptors nesting along transmission lines which may result from nest inaccessibility by mammalian predators, cooler temperatures from higher wind speeds, and additional shelter for nests in towers (Steenhof et al. 1993). Prey abundance and availability has often been suggested as a limiting factor for Ferruginous Hawk breeding success (Smith et al. 1981, Schmutz and Hungle 1989, Zelenak and Rotella 1997); however, research in our study area did not find support for this (Ng 2019). We were not able to control for prey availability in our models, which could have been a primary driver of nest success and productivity and more important than additional elevated perches on the landscape.

Early in the breeding season, Ferruginous Hawks are sensitive to anthropogenic disturbance near nest sites (White and Thurow 1985, Keeley and Bechard 2011). An important caveat to our study is that major construction activities (i.e., tower construction and removal) were planned outside the Ferruginous Hawk breeding season with work commencing between breeding seasons (November to February). Any work scheduled during the breeding season (e.g., line flights) was restricted to a 1000 m buffer as required by provincial (Government of Alberta 2011) and federal (Environment Canada 2009) guidelines. Nordell et al. (2017) also found that the recommended setback distances are overly conservative for low and medium disturbances, therefore we are confident that nest success and productivity were not impacted by construction activities 1000 m away.

Ferruginous Hawks often have high rates of nest reoccupancy (>70%; Woffinden and Murphy 1989, Schmutz et al. 2008). Reoccupancy rates of nests occupied by Ferruginous Hawks the previous year were lower on average (64.57%, range = 48.00 – 75.71) than those reported by previous research (>70%; White and Thurow 1985, Bechard and Schmutz 1995, Lehman et al. 1998, Bayne et al. 2016). High reoccupancy rates for Ferruginous Hawks have been documented in our study area for successful nests (i.e., nests producing ≥ 1 young; 72%), but decreased substantially (57%) when all nests were considered regardless of success rates (Bayne et al. 2016). We found similar reoccupancy rates between transmission tower construction and removal (64.6% and 59.5%, respectively), but there was no effect on reoccupancy from either disturbance. High reoccupancy rates have also been reported for birds returning to within two towers of a previous nest (82.4%). Slightly lower reoccupancy rates (66.9%) were reported for all raptors and ravens reoccupying the same tower along a transmission line in Idaho and Oregon (Steenhof et al. 1993). Reoccupancy was lowest in transmission towers (57.6%) and a disproportionate number of nests failed from wind damage or destruction (43.8%, n = 16) relative to trees (18.3%, n = 120). Similarly, several studies have included wind damage and destruction as the great cause of nest failure from transmission towers (Gilmer and Wiehe 1977, Steenhof et al. 1993). Despite the apparent risk of nest destruction and failure in transmission towers, Ferruginous Hawks do not appear to be deterred from nesting in towers. Perhaps the enhanced perch availability for hunting and higher nest success in towers is enough to offset the risk of failure.

Raptor and raven abundance has been linked to the presence of transmission towers because of the superiority of perching and nesting substrates provided relative to other elevated structures (Knight and Kawashima 1993, Steenhof et al. 1993). We found a shift in the raptor and raven nesting communities during our study, but the result was subtle because we could find no single species driving community change. After the removal of rare species, breeding raptor and raven diversity was low and unchanged for all sites (n = 5; Ferruginous Hawk, Red-tailed Hawk, Swainson’s Hawk, Great Horned Owl, and Common Raven). We predicted densities would increase following the construction of new towers, but pooled community density revealed the opposite. Raptors and ravens will colonize new transmission line corridors following development in suitable habitat, particularly when nesting substrates were previously limited (Steenhof et al 1993). In altered sagebrush steppe habitats, community composition has shifted in favor of generalist species, such as ravens and Red-tailed Hawks (Coates et al. 2014). Ferruginous Hawks are known to occupy a wide variety of nest substrates (Bechard and Schmutz 1995) including an affinity for elevated anthropogenic substrates and perches (Steenhof et al.

1993, Watson 2020). Ravens also exhibit a strong attraction to nearby transmission lines and elevated structures (Howe et al. 2014) and are known to exploit altered habitats more than coexisting *Buteo* species (Coates et al. 2014). In our study, ravens, though abundant, did not exhibit the same dominance reported in previous studies near transmission lines and were observed nesting in similar densities as Ferruginous Hawks with a low overall influence on community change. Raven nest densities near transmission lines were substantially lower than those reported in previous studies (Steenhof et al. 1993, Coates et al. 2014). After every breeding season, all nests (except for those of Ferruginous Hawks) were removed from transmission towers. Steenhof et al. (1993) suggested that raptors and ravens will not be deterred from nesting after nest removal, but that nest removal or low scavenging opportunities near the transmission line contributed to lower densities. We were unable to collect data for nest success, productivity, or reoccupancy of raptors and ravens in the community and recommend future studies consider collecting these data to make broader inferences on community change following landscape alterations.

## Management Implications and Conclusion

We did not find strong evidence supporting negative effects of transmission line construction and removal on Ferruginous Hawk reproductive performance (nest success and productivity) or nest reoccupancy. However, nest densities were significantly affected by temporary transmission line alterations. Importantly, some responses were not measured, such as post-fledging survival and the continued monitoring of mitigation measures (i.e., success of nest platform installation) implemented to offset nest site removal after decommissioning. Similar spatial and temporal breeding parameter and reoccupancy rates reported in previous research suggest that an ecological trap or potential sink population was not present for Ferruginous

Hawks in our study area. Yet, a temporary increase in suitable nest substrates (i.e., transmission towers) may present the risk of inflating the floater-to-breeder ratio (Hunt 1998), thereby subjecting non-breeding individuals to interfere with occupied territories (Tapia and Zuberogoitia 2018), or force their breeding efforts to suboptimal locations (Kokko and Sutherland 1998). Ferruginous Hawks will readily nest on artificial nest platforms (ANPs; Schmutz et al. 1984, Migaj et al. 2011) and the installation of ANPs as required mitigation for nest substrate removal are expected to stabilize local populations. The presence of artificial nest structures has also been suggested as a solution to address floaters in a given population and support higher breeding densities in suitable habitat (Village 1983, Newton 1994). However, in the years after tower removal, 18 ANPs were installed (6 on towers in 2016; 10 platforms in 2018) and had a 37.5% occupancy rate in 2019. Schmutz et al. (1984) reported a 2-year lag-period following initial ANP installation before a near two-fold increase in platform use. Without prolonged monitoring, the low occupancy rates warrant some concern and support the need for longer-term post-tower removal monitoring in similar nest removal or habitat alteration programs.

Continued human population growth and growing energy demand will necessitate the development or upgrading of energy projects and their associated infrastructure. Our study provides a first assessment of a novel situation for an established At Risk raptor population. The indirect impacts of transmission line development are understudied and poorly understood, with potential to influence local populations of nesting species dependent on associated infrastructure for breeding and provisioning. Larger projects (both spatially and temporally) can provide the opportunity for increased sample sizes and greater power to detect impacts and support conservation recommendations for nesting raptors. We recommend that future studies continue working in collaboration with energy companies ahead of future development to implement robust Before-After Control-Impact or BDACI designs.

## TABLES AND FIGURES

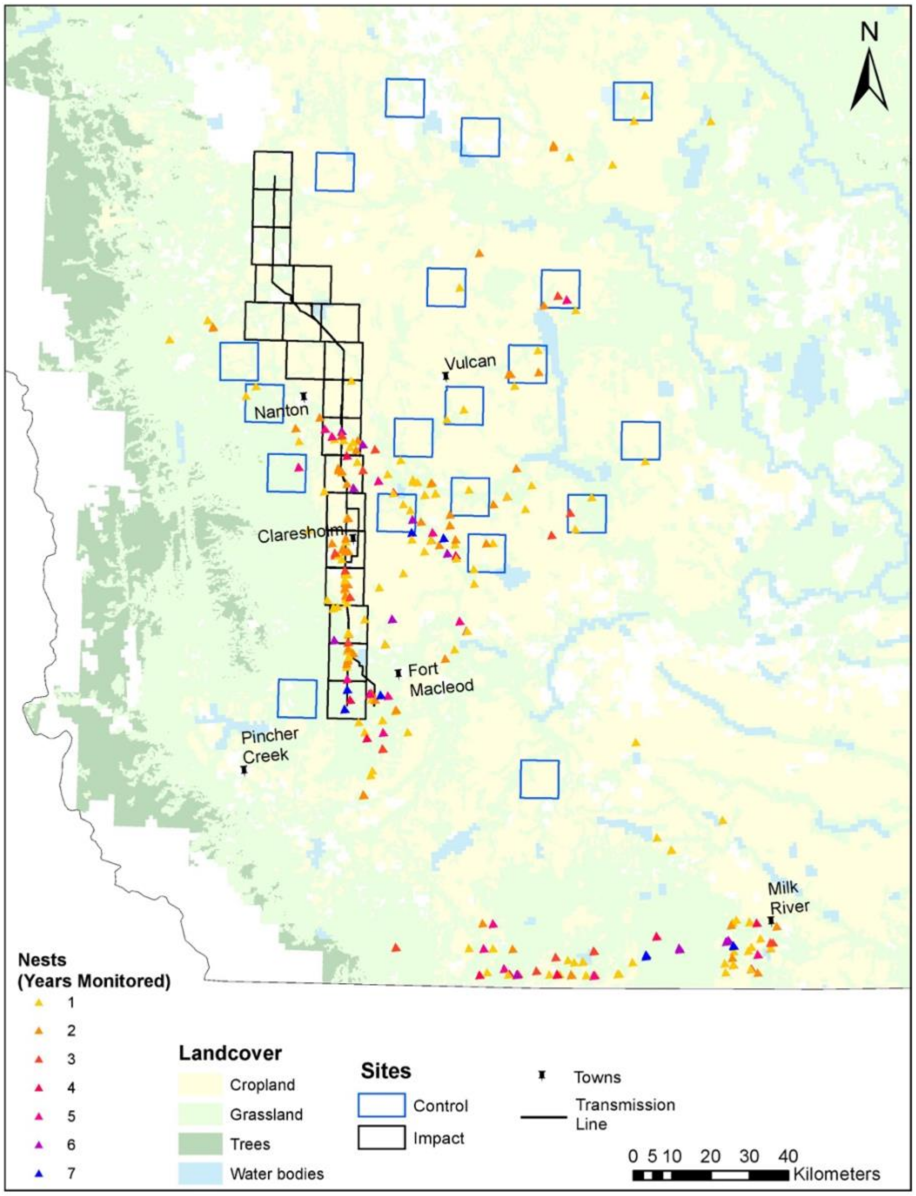
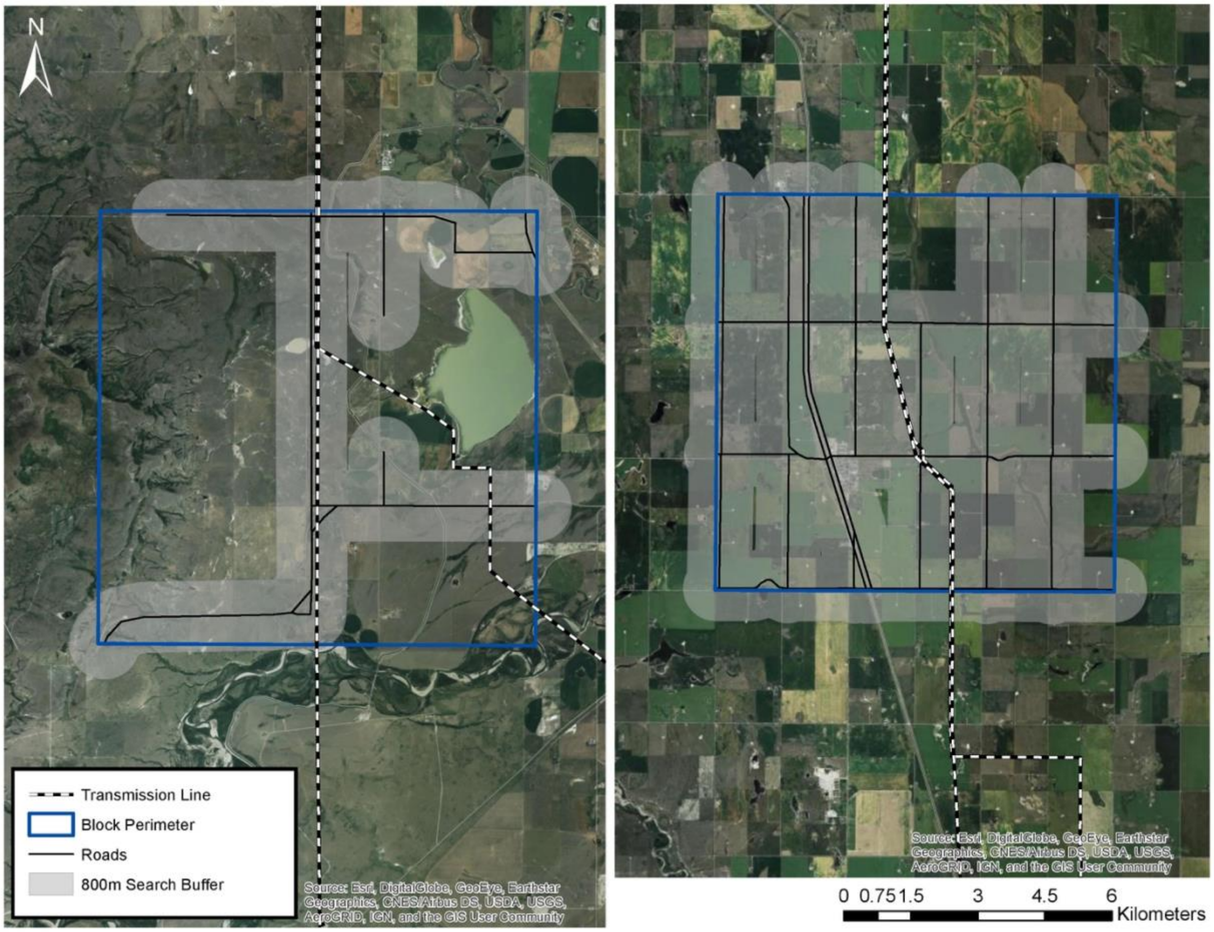


**Figure 2.1.** Overview of the study area in southern Alberta, showing both the impact and control survey blocks surveyed between 2013–2019. Impact blocks (n=19) were placed to represent areas within 5 km of transmission line development. Control blocks (n=19) were selected based on similar landscape characteristics of impact sites.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

**Figure 2.2.** Comparison of block surveys efforts between low and high road density impact blocks. Nest density was calculated by dividing the number of active nests found by the total area surveyed (km$^2$; 800m buffer around roads driven).

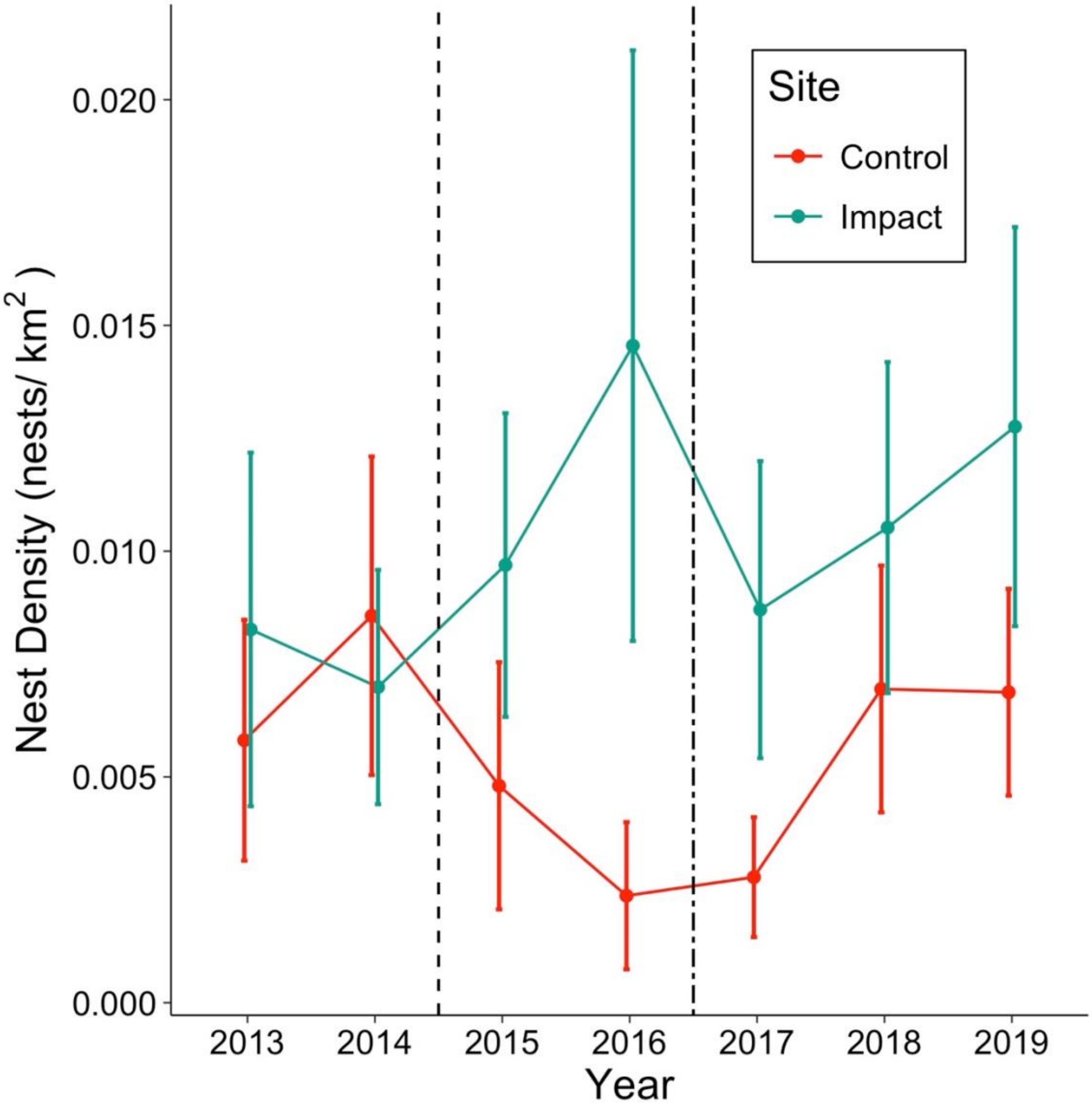


**Figure 2.3.** Mean Ferruginous Hawk nest densities during the 7-year (2013–2019) transmission line construction project in southern Alberta, Canada. The tower construction event is represented by the dashed line and old tower removal is indicated by the dotted line. Error bars represent the standard error of the mean.

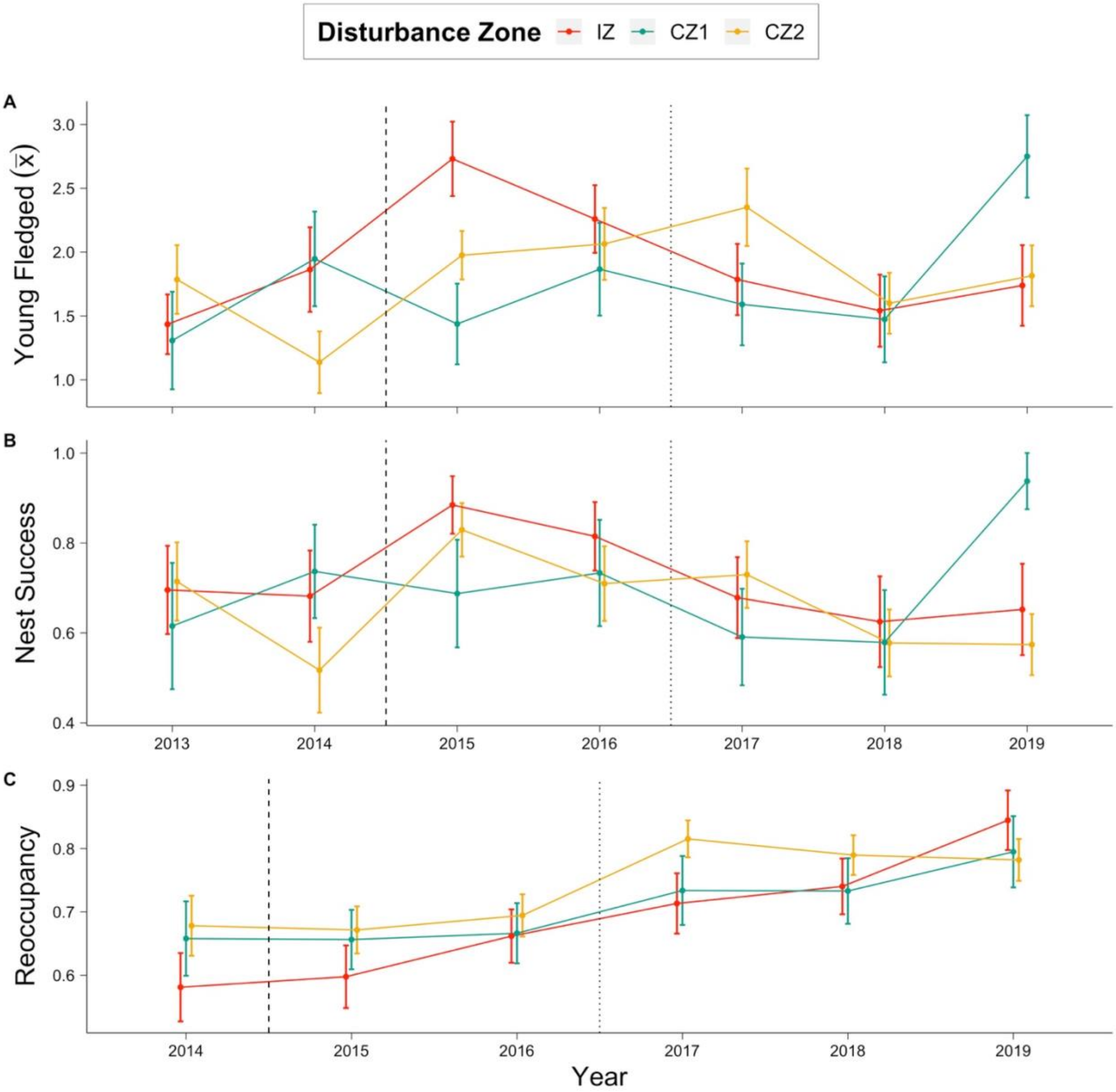


**Figure 2.4.** Mean Ferruginous Hawk nest young fledged (A), nest success (B), and reoccupancy rates (C) at varying distances from transmission lines Before (2013–2014), During (2015–2016), and After (2017–2018) transmission line construction activity. Nests were separated across three disturbance zones: Impact Zone (IZ), Control Zone 1 (CZ1), and Control Zone 2 (CZ2). The tower construction event is represented by the dashed line and old tower removal is indicated by the dotted line. Error bars represent the standard error of the mean.

**Table 2.1.** Summary table of block surveys for impact (n=19) and control blocks (n=19) between 2013–2019. Nest density values represent the total Ferruginous Hawk nest density pooled across all blocks and years of a given phase. Total area surveyed values were inflated after transmission line decommissioning because of an additional year of surveys and later spring leaf out which allowed surveys to continue until late May.

| Time | Site | Total Area Surveyed ($km^2$) | Nest Density ($nests/km^2$) (*n*) | SE |
|---|---|---|---|---|
| Before | Impact | 2947.50 | 0.0076 (26) | 0.0023 |
| | Control | 2093.59 | 0.0072 (15) | 0.0022 |
| During | Impact | 2169.16 | 0.0121 (27) | 0.0036 |
| | Control | 2014.52 | 0.0036 (8) | 0.0016 |
| After | Impact | 4976.72 | 0.0107 (50) | 0.0022 |
| | Control | 4961.22 | 0.0055 (24) | 0.0013 |

**Table 2.2.** Summary statistics (Wald's $\chi^2$ and *P*-values) of fixed effects from the Ferruginous Hawk response to habitat change models. Significant values ($\alpha < 0.05$) are bolded.

| **Model** | **Predictor** | **DF** | $\chi^2$ | ***P*** |
|---|---|---|---|---|
| *Nest Density* | | | | |
| | Region | 2 | 16.94 | **<0.001** |
| | Grass100 | 1 | 6.84 | **0.009** |
| | Site | 1 | 1.91 | 0.167 |
| | Phase | 1 | 0.54 | 0.764 |
| | Site x Phase | 2 | 5.98 | **0.050** |
| *Success* | | | | |
| | $\text{OutcomeDate}^2$ | 1 | 12.22 | **<0.001** |
| | OutcomeDate | 1 | 49.80 | **<0.001** |
| | HatchDate | 1 | 37.35 | **<0.001** |
| | DZ[†] | 2 | 12.90 | **0.002** |
| | Phase | 2 | 2.25 | 0.324 |
| | DZ x Phase | 4 | 0.52 | 0.971 |
| *Productivity* | | | | |
| | $\text{OutcomeDate}^2$ | 1 | 59.99 | **<0.001** |
| | OutcomeDate | 1 | 136.54 | **<0.001** |
| | HatchDate | 1 | 93.26 | **<0.001** |
| | DZ | 2 | 2.27 | 0.322 |
| | Phase | 2 | 4.45 | 0.108 |
| | DZ x Phase | 4 | 6.39 | 0.172 |
| *Reoccupancy* | | | | |
| | PrevYearOcc | 2 | 18.91 | **<0.001** |
| | YearsMonitored | 1 | 23.55 | **<0.001** |
| | LooseRd | 1 | 3.43 | 0.064 |
| | DZ | 2 | 0.02 | 0.989 |
| | Phase | 2 | 7.25 | **0.023** |
| | DZ x Phase | 4 | 0.04 | 0.999 |

[†] Disturbance Zone

**Table 2.3.** Summary of reproductive metrics (productivity and nest success) and reoccupancy in Ferruginous Hawk nests monitored between 2013–2019.

| **Time** | **Site**[†] | **Nest Productivity (*n*)**[‡] | **% Nests Successful (*n*)**[§] | **% Reoccupied (*n*)** |
|---|---|---|---|---|
| Before | IZ | 1.62 (37) | 67.57 (37) | 48.00 (25) |
| | CZ1 | 1.60 (30) | 66.67 (30) | 68.75 (16) |
| | CZ2 | 1.49 (51) | 60.78 (51) | 57.58 (33) |
| During | IZ | 2.48 (52) | 84.61 (52) | 52.38 (63) |
| | CZ1 | 1.65 (31) | 70.97 (31) | 48.98 (49) |
| | CZ2 | 2.01 (72) | 77.78 (72) | 58.06 (93) |
| After | IZ | 1.69 (75) | 65.33 (75) | 66.67 (114) |
| | CZ1 | 1.88 (57) | 68.42 (57) | 60.00 (55) |
| | CZ2 | 1.89 (136) | 61.76 (136) | 61.54 (78) |

[†] Categorical variable defining distance of nest to transmission line (Impact Zone [IZ] <2.5 km; Control Zone 1 [CZ1] >2.5 km <10 km; Control Zone 2 [CZ2] >10 km).

[‡] Young defined as fledglings when ≥40 days old.

[§] Nest success defined by ≥1 fledgling observed in nest.

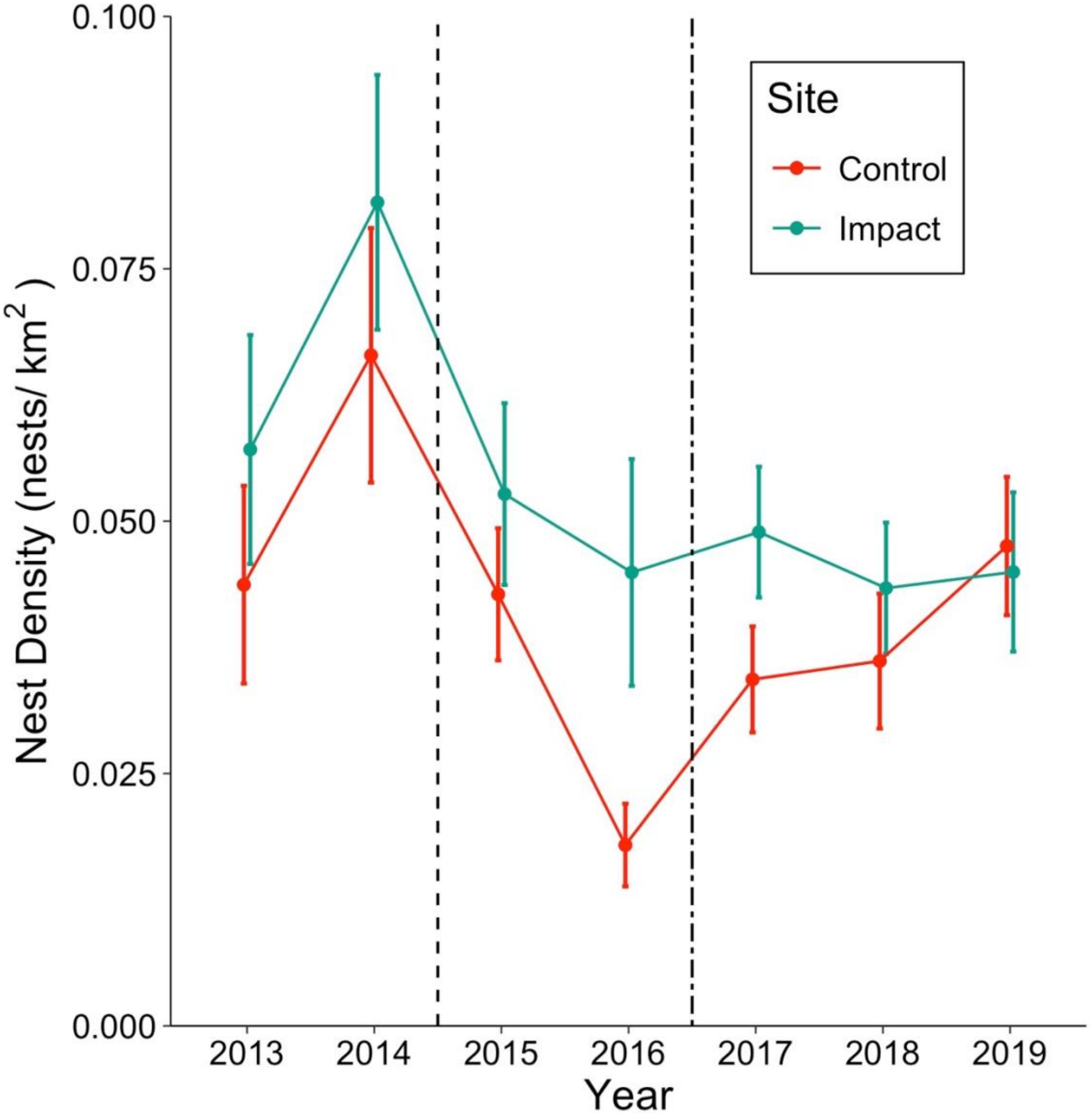


**Figure 2.5.** Mean nest densities of all occupied nests during the 7-year (2013–2019) transmission line construction project in southern Alberta, Canada. The tower construction (Winter 2015) and removal (Winter 2017) events are represented by the dashed line and the dotted line, respectively. Error bars represent the standard error of the mean.

**Table 2.4.** Block survey abundance and nest density values of nest site competitors observed during the 7-year (2013–2019) transmission line construction project in southern Alberta, Canada. New transmission line towers were construction between the Before and During (Winter 2015) phase and old transmission line towers were removed between the During and After phase (Winter 2017).

| | **Before** *(2013–14)* | | | | | | **During** *(2015–16)* | | | | | | **After** *(2017–19)* | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Control** | | | **Impact** | | | **Control** | | | **Impact** | | | **Control** | | | **Impact** | | |
| | ***n*** | **D†** | **%** | ***n*** | **D** | **%** | ***n*** | **D** | **%** | ***n*** | **D** | **%** | ***n*** | **D** | **%** | ***n*** | **D** | **%** |
| Common Raven | 12 | 3.15 | 10.7 | 50 | 6.73 | 24.8 | 5 | 1.96 | 7.5 | 20 | 5.05 | 19.4 | 36 | 3.79 | 19.0 | 34 | 3.29 | 15.2 |
| Ferruginous Hawk | 15 | 3.94 | 13.4 | 28 | 3.77 | 13.9 | 8 | 3.13 | 11.9 | 27 | 6.82 | 26.2 | 26 | 2.74 | 13.8 | 49 | 4.74 | 21.9 |
| Great Horned Owl | 18 | 4.73 | 16.1 | 24 | 3.23 | 11.9 | 6 | 2.35 | 9.0 | 10 | 2.53 | 9.7 | 33 | 3.48 | 17.5 | 29 | 2.81 | 12.9 |
| Red-tailed Hawk | 56 | 14.5 | 50.0 | 61 | 8.21 | 30.2 | 34 | 13.3 | 50.8 | 34 | 8.59 | 33.0 | 81 | 8.53 | 42.9 | 101 | 9.77 | 45.1 |
| Swainson's Hawk | 11 | 2.89 | 9.82 | 39 | 5.25 | 19.3 | 14 | 5.48 | 20.9 | 12 | 3.03 | 11.7 | 13 | 1.37 | 6.9 | 11 | 1.06 | 4.9 |

† $10^{-3}$

*n* = Raw abundance

D = Density (nests/ $km^2$)

% = percentage among nest competitors in the community

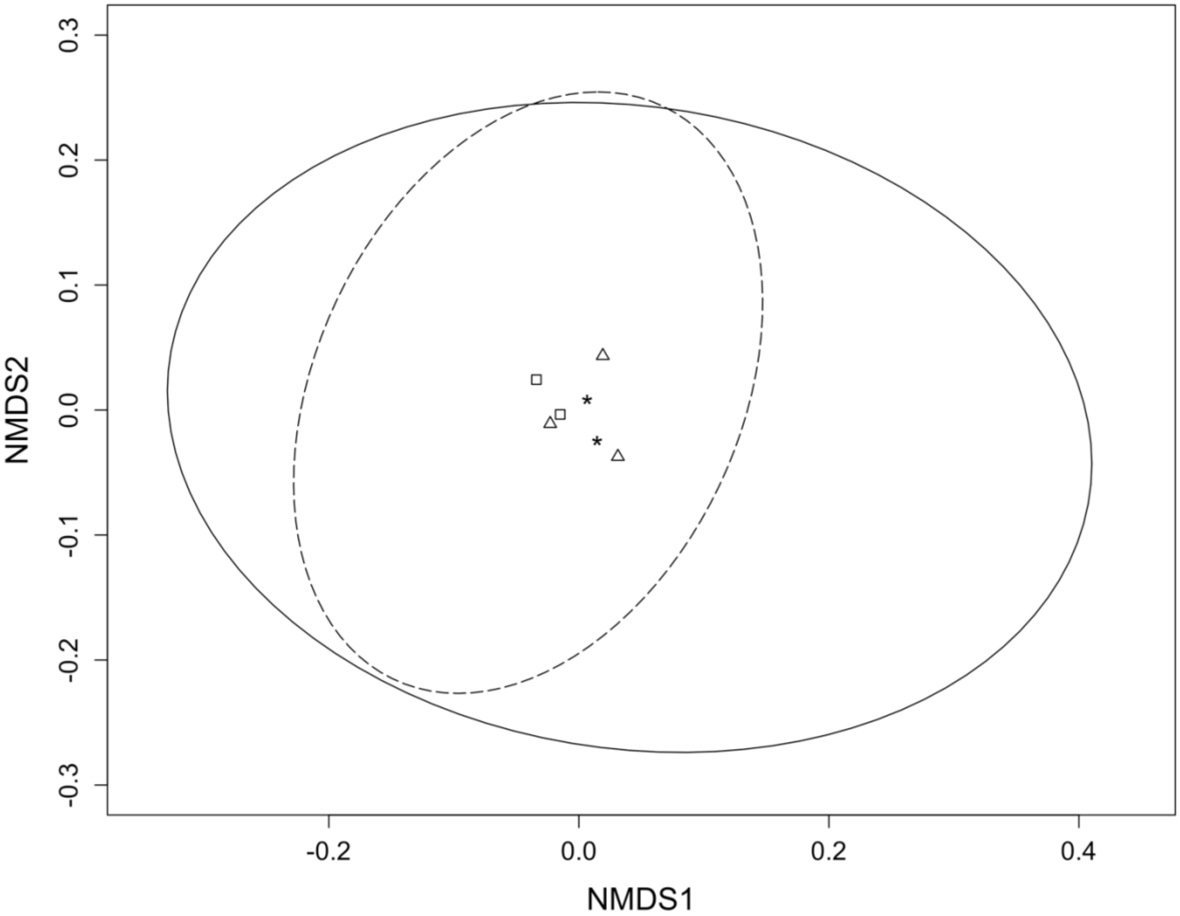


**Figure 2.6.** Non-metric multidimensional scaling (NMDS) scores for the competitive nesting bird community structure at control and impact sites between 2013–2019. The solid ellipse represents the 0.7 standard deviation around the ellipse centroid of impact sites, whereas the dashed ellipse represents the 0.7 standard deviation around the ellipse centroid of control sites. The stars indicate years "Before"; hollow squares represent years "During"; and, hollow triangles represent years "After".

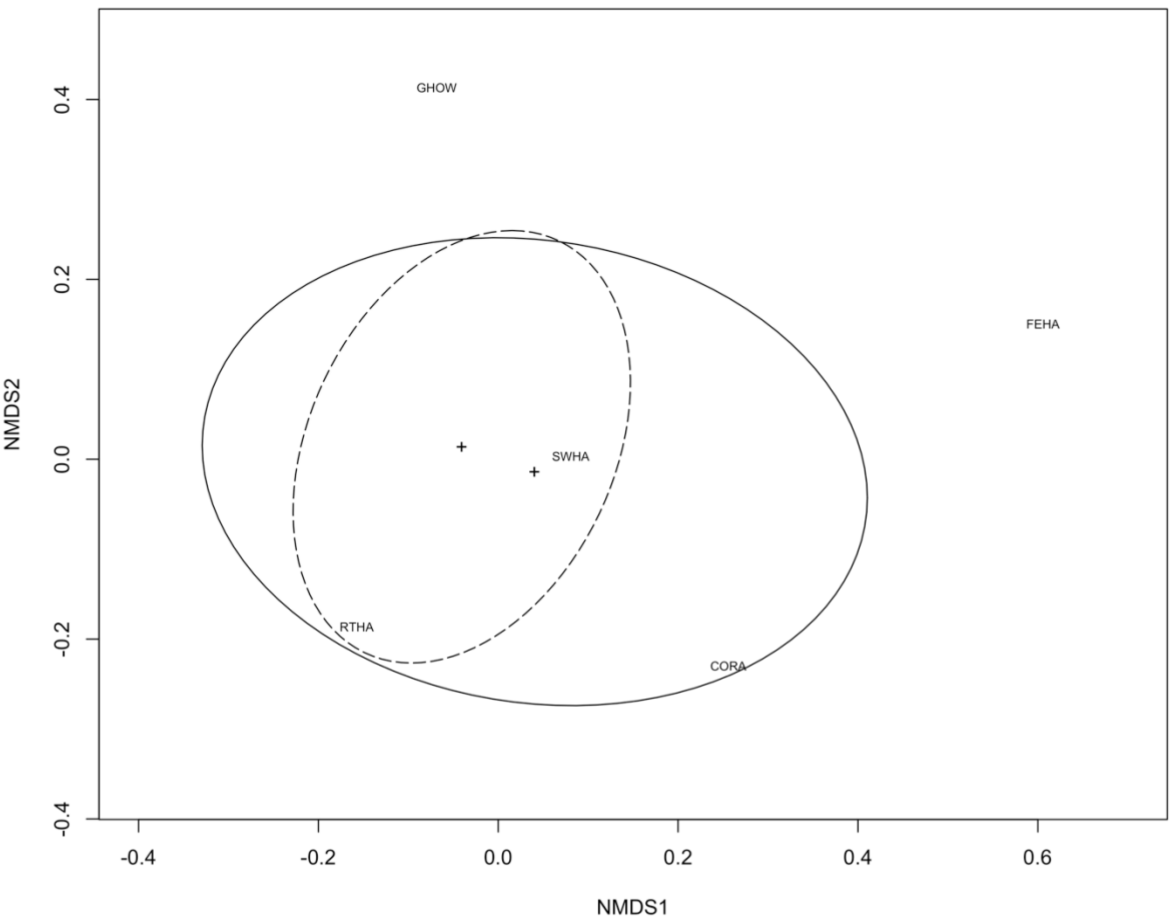


**Figure 2.7.** NMDS scores for the competitive nesting bird community structure at control and impact sites between 2013–2019. "+" symbols indicate centroid ellipses. The solid ellipse represents the 0.7 standard deviation around the ellipse centroid of impact sites, whereas the dashed ellipse represents the 0.7 standard deviation around the ellipse centroid of control sites. All species included in the ordination are overlaid by their American Ornithologists' Union codes.

**Table 2.5.** Results of multivariate and univariate test assessing species assemblage change following transmission line construction and decommission during our 7-year study. Only univariate tests with a significant Site x Phase interaction are included in the results.

| | **Res. Df** | **Df. Diff** | $\chi^2$ | ***P*** |
|---|---|---|---|---|
| *Multivariate* | | | | |
| Phase-only | 255 | | | |
| Site x Phase | 252 | 3 | 6.34 | **0.030** |
| *Univariate* | | | | |
| No species significant | | | 1.15 – 3.58 | 0.095 – 0.710 |

**Table 2.6.** Percent of species contribution to changes in the nesting raptor and raven community composition based on the individual contribution of each species (LR) to the summed community-level likelihood ratio.

| **Species** | **LR** | **Contribution (%)** | ***P*** |
|---|---|---|---|
| Common Raven | 3.24 | 24.87 | 0.120 |
| Ferruginous Hawk | 3.58 | 27.47 | 0.095 |
| Great Horned Owl | 1.15 | 8.79 | 0.710 |
| Red-tailed Hawk | 2.78 | 21.33 | 0.240 |
| Swainson’s Hawk | 2.29 | 17.54 | 0.260 |

# CHAPTER 3: The importance of nest substrate and effects of local weather events on Ferruginous Hawk nest persistence and breeding parameters

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## ABSTRACT

Future climate scenarios predict that variation in the timing and severity of weather events will increase, but knowledge of the effects of extreme weather on breeding birds is limited, particularly the impacts of wind. We assessed the effects of weather events during the Ferruginous Hawk (*Buteo regalis*) breeding season on nest persistence, fledgling productivity, and daily survival rates to determine the importance of nesting substrate in mitigating inclement weather. We monitored 507 individual nests across the Grassland Natural Region in southern Alberta, Canada between 2010–2017. We used Kaplan-Meier survival estimates, and general linear and logistic models to analyze relationships between nest persistence, fledgling productivity, and survival of nestlings. Our results suggested that extreme wind events ($90^{th}$ percentile wind gusts) strongly influenced nest persistence rates and that DSR was strongly correlated with daily average wind speeds. The probability of persistence and DSR increased for nests on artificial nest platforms (ANPs) compared to tree nests. ANPs are often used as a conservation tool to improve raptor habitat and support population growth; however, the effectiveness of ANPs in mitigating for effects of extreme weather were unknown until now. Our study contributes insight on the use and importance of ANPs as a practical and cost-effective management tool for raptors.

### Keywords

Climate change, raptor, Ferruginous Hawk, *Buteo regalis*, extreme weather, nest survival, Kaplan-Meier

## INTRODUCTION

Many bird species experience extreme variation in weather conditions. How birds respond to weather varies by the duration, extremity, and type of weather event (Gorzo et al. 2016). Recent climate models predict higher average temperatures and increased risk of drought in many areas of the world (Easterling et al. 2000, Meehl and Tebaldi 2004, Intergovernmental Panel on Climate Change 2007). Concurrently, the duration and intensity of extreme weather events are expected to rise, which may have considerable impacts on breeding birds (Parmesan et al. 2000). Previously infrequent events are now exposing birds to inclement weather more regularly, and, for some species, local population sizes have undergone substantial reduction because of stochastic weather events (Parmesan et al. 2000, Deville et al. 2014, Latimer and Zuckerberg 2019). The impacts of extreme weather are heightened during the breeding season when nests and young are directly exposed to acute, severe weather conditions.

With expected increases in the variation of the timing and severity of weather events, it is important to understand how the success, failure, and overall productivity of breeding birds is affected and how to mitigate such effects. For instance, nest provisioning may be limited by decreased prey availability (Siikamäki 1996) and time to forage (Sergio 2003), while young birds may be unable to regulate their body temperatures in extreme heat (Evans 1984; Kirkley and Gessaman 1990). Further, cold weather before egg-laying negatively affected the clutch size of European White Storks (*Ciconia ciconia*; Sasvári and Hegyi 2001), and Northern Fulmars (*Fulmarus glacialis*) did not breed if environmental conditions were poor at the start of the nesting cycle (Mallory et al. 2009). There is some evidence that birds will alter their behaviors ahead of inclement weather to compensate for reduced feeding opportunities (Rodgers et al. 1988, Laux et al. 2015), but the impacts of increasingly severe weather require further investigation. In some instances, human intervention has helped alleviate potentially fatal effects of heavy rain on nestlings through supplemental feeding (Fisher et al. 2015) and improved nesting opportunities that reduce the impacts of inclement weather (e.g., nest boxes in Peregrine Falcons [*Falco peregrinus*]; Anctil et al. 2014).

Temperature and precipitation are the most common weather parameters studied in avian research, but the effects of wind can also be important. Periods of high wind can be detrimental to the nests of *Buteo* species nesting in both natural or anthropogenic substrates (De Smet and Conrad 1991) and, in some cases, can limit nest site availability (Schmutz et al. 1984). In southern Alberta, Canada recent weather trends have been stable with no clear pattern for either changes in temperature, precipitation, or wind. However, future climate scenarios predict temperatures in the Alberta prairies to rise substantially by upwards of 9°C by 2080 (Schneider 2013). Total annual precipitation is not expected to change dramatically, but extreme events are predicted to increase when precipitation falls because of alterations to evapotranspiration patterns in a warmer climate (Francis and Hengeveld 1998, Stone et al. 2000). In Alberta, long-term climate models have projected that severe daily and hourly wind gusts could intensify during key times in the avian breeding season by 2100 and that wind near Lethbridge could increase 15–20% by mid-century (Cheng et al. 2014).

Ferruginous Hawks are large, migratory raptors native to North America’s grasslands. Canadian populations have been declining since the 1980s and they are listed as federally *Threatened* (COSEWIC 2008) and provincially *Endangered* (AFHRT 2009). Recent declines are attributed to the loss of habitat and suitable nesting structures. Ferruginous Hawks often use or refurbish historical nests rather than constructing new nests (Bechard and Schmutz 1995) and the availability of nesting substrates can limit population densities (Steenhof et al. 1993). Previous research has found high nest reuse rates in Ferruginous Hawks over time, which is partially attributed to their affinity to use artificial nest platforms (ANPs) (Steenhof et al. 1993). When strategically placed, ANPs are often preferentially selected by Ferruginous Hawks relative to natural nest structures (Migaj et al. 2011). Erecting ANPs in areas with limited nesting substrates is linked to increased Ferruginous Hawk nest densities (Schmutz 1984, Parayko et al. 2020), success, and productivity (Steenhof et al. 1993). ANPs have also been suggested as a Ferruginous Hawk recovery tool to mitigate the loss of nest substrates (naturally or from human removal; AFHRT 2009).

Nest site availability and climate change are considered threats to Ferruginous Hawk populations in Alberta (AFHRT 2009). Strong winds in their southern Alberta range may increase nest vulnerability by directly or indirectly blowing nests out of trees, breaking tree branches, or blowing entire trees down. Bayne et al. (2016) found that 8% (n = 81) of all nests studied were damaged or destroyed by wind and, where nesting substrates were limited, nest-site availability was reduced following blow out events (Schmutz et al. 1984). The importance of nest blow outs relative to more indirect effects of inclement weather on other Ferruginous Hawk life stages is poorly understood and likely depends on when extreme weather events occur. For instance, during spring incubation, higher temperatures are likely to benefit nest productivity (Blair 1978, Sergio 2003). However, later in the season heat stress could be fatal to nestlings (Tomback and Murphy 1981, Kirkley and Gessaman 1990) that have been shown to seek shade as early as five days post-hatch (Powers 1981). Further, high wind is a potential threat to nest failure during all breeding stages and high wind and heavy rain can increase physiological stress for breeding adults and nestlings. Steenhof et al. (1993) suggested that nest substrate type may help mitigate some of the adverse effects of extreme weather. In particular, nests in transmission towers often provide partial shading and, in some cases, are more secure from wind damage than natural nests. Understanding the consequences of weather events and their effects on breeding success in different nesting substrates selected by Ferruginous Hawks is important for mitigating for projected changes to local weather events under changing climate regimes.

In this study, we used breeding season data from 8 years (2010–2017) of nest monitoring to examine the nest persistence and daily survival rates of nestlings (DSR) of Ferruginous Hawks in response to inclement weather. Our main objective was to identify if nest substrates selected by Ferruginous Hawks nest substrate can help mitigate severe weather events by analyzing (1) the persistence nests and substrates on the landscape; (2) how different measures of weather extremes (temperature, wind, and precipitation) affect fledgling production at different stages of the breeding season in different nest substrates; and (3) by comparing how DSR are impacted by weather at fine-scale (hourly) intervals between all nests and those that failed from assumed weather events between visits. Many nest platform designs consider structure longevity (e.g., depth of poles) and nestling survival (e.g., platform size); therefore, we predicted that nests on platforms would have the most prolonged persistence and higher productivity and survival rates than other substrates in response to extreme weather events.

## METHODS

### Ethics Statement

Our data collection methods were designed to limit harm or stress to individual adult and nestling hawks. This study complied with the Ethical Treatment of Animals Guidelines under the University of Alberta Animal Care #724, Permit AUP00000018. Before approaching nests on private land, access permissions were acquired from landowners. Nests were not approached or checked while it was raining or on cold (<10 ºC) or windy days (wind >30 km/h). During vulnerable stages early in the breeding season (nest building and incubation) for Ferruginous Hawks or other species, observers limited the time spent near nests to minimize the risk of nest abandonment.

## Study Area

This study was conducted across >97,000 km$^2$ in the foothills fescue, mixed, moist-mixed grasslands, and Cypress upland subregions of southern Alberta, Canada, across the present-day Ferruginous Hawk breeding range in the Grasslands Natural Region (Figure 1). The area is predominantly open-country grassland and rolling hills in the East to foothills in the West. Overall, the climate is semi-arid, with greater precipitation and lower average summer temperatures in the western foothills fescue subregion (14°C) that increase eastwards through the moist-mixed (15.5°C) and mixed (16°C) grasslands (Ecological Stratification Working Group 1996). Average annual precipitation in the Alberta prairies is 482 mm (Shepherd and McGinn 2003), ranging from 250 mm in the east to 450 mm in the west (Ecological Stratification Working Group 1996). Annual average surface wind speeds are highly variable in the prairies (14 to 22 km/h) with maximum gusts recorded up to 171 km/h in Alberta. Prevailing westerly winds blow from low-pressure systems in the Rocky Mountains with the highest average wind speeds occurring in the spring and fall (McGinn 2010).

In this study area, Ferruginous Hawks typically lay eggs inside stick nests supported by trees, cliff ledges, or various anthropogenic structures, such as artificial nesting platforms (ANPs) and power utility structures (Bechard and Schmutz 1995, Schmutz et al. 1984). Ferruginous Hawks are flexible in their selection of such nest substrates with an attraction for elevated substrates (natural or anthropogenic) likely because of the scarcity of natural elevated nesting structures within their range (Gilmer and Stewart 1983, Bechard and Schmutz 1995). Trees and shrubs are the most common nest substrate (49%; Olendorff 1993), with Balsam Poplar (*Populus balsamifera*) and Narrow-leaf Cottonwood (*Populus angustifolia*) being the dominant tree species, used in our study area (Natural Regions Committee 2006).

### Nest Searches

Block surveys were conducted from mid-April to early May before spring leaf out to ensure Ferruginous Hawks were on breeding territory at nest sites (Ng 2019). Nests were generally conspicuous before spring leaf-out, given their large size (often >1 m in height and diameter; Bechard and Schmutz 1995), and locations were determined using a global positioning system (GPS) to help relocate nests in subsequent years. Block selection considered different land cover types (i.e., grassland, cropland, and human footprint), presence and density of anthropogenic features such as roads and energy development, and associated infrastructure *a priori* using a geographic information system (ESRI 2017). The area was then stratified geographically to ensure an even distribution of blocks across Alberta. Within each stratum, blocks were randomly selected to ensure a balanced, randomized study design. Between 2010 and 2014, 9.6 km by 9.6 km sample blocks were surveyed within the entire study area. After 2014, search efforts were limited to 45 9.6 km by 9.6 km blocks in southwestern and southcentral Alberta as part of a focused study area (see Chapter 1). Active historical nests known to the project from previous years were also visited to check for occupancy and any incidental Ferruginous Hawk nests detected were also recorded and monitored.

Surveys were conducted during daylight hours after sunrise and before sunset and in fair to good weather conditions. We recorded the status (active or empty), date, and occupancy status (species, number of adults) of each nest. Nests were considered active when an adult Ferruginous

Hawk was present on, near, or actively defending (circling, calling or swooping at the observer) a nest, or when ≥1 live nestling or viable egg was observed (Steenhof and Newton 2007).

### Nest Monitoring

Most nests were located early in the breeding season, during the nest building, estimated clutch initiation, or incubation period, and visited weekly to determine nesting status, brood size, and age of young. This frequent visitation schedule helped avoid the biases encountered in studies using two or fewer surveys per year (Steenhof and Kochert 1982, Beardsell et al. 2017). We recorded adult presence and behavior, count and age of young, nest status, nest outcome, and reason for the outcome. Nests were considered destroyed if they fell, were unusable from damage, or when trees fell over. We assumed that destroyed nests resulted from extreme weather events unless there was any other evidence to the contrary. Young were aged using a Ferruginous Hawk photographic aging key (Moritsch 1985). Failed nests were classified by the cause of failure (i.e., damage or blow out from severe weather, predation, abandonment; Table 3.1). Pre-fledging visits were performed at each nest 40 days after the estimated date-of-first-hatch for that nest, and were revisited approximately every 7 days thereafter until young no longer remained in the nest.

### Response Variables

The maximum number of young ≥40 days observed at a nest was used to determine nest productivity. Nesting attempts were deemed successful if they produced ≥1 fledgling to 40 days after hatching (80% of maximum age when young first leave the nest). To account for interval-censored data, when nests failed between visits and the exact date of the nest fate outcome was unknown, we used the median date between the previous two visits (Beardsell et al. 2017). If there were an even number of days between nest visits, then the earlier date was used. Only nests with a known outcome were used in the final analysis.

### Nest and Weather Covariates

Each nest was characterized by the substrate type, dominant surrounding land use, and region. Land use was quantified by calculating the proportion of native grassland within a 2500 m radius of nests was calculated using ArcMap. The proportion of grassland in our study area is inversely correlated with the proportion of agriculture (Bayne et al. 2016); therefore, only grassland was used in our models. Weather data were obtained from Alberta Agriculture and Forestry weather stations. We used inverse distance-weighting to calculate weather parameters between nest visits (mean interval = 9.3 days) or for breeding season stages (see below for description) from all weather stations within a 50 km buffer of each nest ($\bar{x}$ = 32.7 km, range = 0.8–50 km, mean stations per nest = 8.46). For all analyses, we calculated the inverse distance-weighted number of days with 90th percentile wind, days with wind ≥30 km/h, average wind speed, maximum wind speed, average wind gust, and maximum wind gust. Wind speed data was collected at 2 m and 10 m from the ground but was often limited. Therefore, wind speed data was combined with priority assigned to 2 m because the approximate height of Ferruginous Hawk nests is closer to 2 m (Bechard and Schmutz 1995). We also calculated the inverse distance-weighted average, maximum and total precipitation, and the daily maximum, minimum, and average temperature between visits for each interval. To compute average weather parameters between nest visits we calculated daily averages first and then averaged these values to get the average for the exposure interval. Similarly, daily maximums and minimums were taken daily and then averaged over the entire exposure interval.

### Statistical Analysis

## Nest Survival by Substrate

We modelled the persistence of nest substrates during the breeding season using Kaplan-Meier estimates to account for right-censored data (i.e., the unknown time of destruction for nests that remained intact at the end of our study; Kaplan and Meier 1958) using the '*survival'* package in R studio (Therneau 2015). Survival probability of the nest substrate was calculated using the age of a nest substrate from the year it was first found to the year it was destroyed or when monitoring ended. Only nests that failed due to extreme wind events were of interest; therefore, nests that failed for other reasons were removed from the analysis. Here, we defined a nest failure as either a nest structure that was damaged beyond use or when the nest substrate was blown down (the term nest substrate is used hereafter to refer to nests and nest substrates that were damaged or destroyed for nest persistence models). When a nest fledged or failed between visits and an exact date was unknown, the median date between consecutive visits was used (Beardsell et al. 2017). We categorized substrates into three distinct groups: trees, elevated anthropogenic structures (towers), and artificial nest platforms. Substrates with limited sample size (n <10) were either dropped from the analysis (i.e., cliff nests [n = 5] and sheds [n = 1]) or grouped (i.e., radio towers [n = 1] and windmills [n = 2]) with elevated anthropogenic structures. Finally, ground nests (n = 2) were dropped from the analysis because they are not likely to fail from extreme wind events and the sample size was small. We used a log-rank test to determine if there is a significant difference in the probability of time-to-event (nest persistence) among nest substrates (Bland and Altman 2004). Post-hoc tests were used if significant differences were found in the log-rank test and a sequential Bonferroni correction (Holm 1979) was applied to control for Type I error rates.

We modelled the probability of nest substrate destruction from different wind events using mixed logistic regression. Our main objective was to test if wind was a significant cause of nest substrate destruction. Therefore, we used a moving window to calculate five different wind metrics during the breeding season and to test for the effects of 1) average daily wind speeds, 2) number of days when wind exceeded the 90th percentile (19.4 km/h) and 30 km/h, 3) number of days wind gusts exceeded the 90th percentile (59.1 km/h), and 4) average maximum daily wind gust. Analyzing multiple wind variables allowed us to compare differences among wind events, which are predicted to change differently under future climate scenarios. For instance, in our study area, average wind speeds are not expected to change significantly (Flannigan and Wang 2012); however, extreme wind events are predicted to increase by upwards of 40% in the Canadian prairies by 2100 (Cheng et al. 2014). Nest substrate was included in all models, to test for the importance of substrate type on nest persistence. A different wind parameter was included independently as a fixed effect in each model. No other parameters were considered for inclusion in persistence models and no interactions were included due to a limited sample size of failed nests.

### Productivity

We fit Generalized Linear Mixed Models (GLMM) to nest productivity data (number of young produced per year) with a zero-inflated Poisson error family. We first fit null models to compare Poisson, negative binomial, zero-inflated Poisson, and zero-inflated negative binomial error families and used log-likelihood and Akaike's Information Criterion for small sample sizes ($AIC_c$) to compare null model fit and advanced the model with the lowest $AIC_c$ score.

We applied a moving window to weather metrics according to conservatively estimated incubation (32 days; Bechard and Schmutz 1995) and nestling (50 days; Bechard and Schmutz

1995) periods based on estimated Julian clutch initiation dates (CID). CID were estimated using nestling age because egg laying was rarely observed. Some nests failed early in the breeding season and CID could not be confidently estimated. In those instances, the average CID in a given year was imputed (Ng 2019). Separate models were fit for each period of the breeding season to assess the influence of extreme weather at different periods in the breeding season. We tested 16 candidate models including several hypothesis-based interactions to compare productivity between incubation and nestling stages. For each model, we included one intrinsic nest variable (CID) and two habitat variables (prairie ecoregion and proportion of native grassland within 2.5 km of the nest) to account for potential nuisance variables not related to our hypotheses. Nest substrate was also included in all models to test for an effect on productivity. We then tested a null model, additive models, and 7 interactions (2 for incubation, 5 for nestling stage). For both stages, we examined interactions between Wind x Substrate, and Wind x Precipitation. We did not expect temperature to interact with other weather types and influence nest productivity during the incubation stage. Therefore, we included temperature in three nestling stage only models: Wind x Temperature, Temperature x Precipitation, and Temperature x Substrate.

### Daily Nestling Survival

We modelled DSR using generalized linear mixed models (GLMM) in RStudio. To account for nest visit intervals, DSR was calculated using logistic-exposure models, whereby a logistic-exposure link function (Shaffer 2004) was included in GLMMs. We predicted that extreme weather would negatively affect DSR. We used weather covariates from all provincial weather stations within 50 km of a given nest, and inverse-distance weighting was applied to stations closer to a nest with higher priority assigned to stations closer to a nest. We then calculated daily averages and weather extremes for wind, precipitation, and temperature for inclusion in our model. Few nests were monitored in 2010 where weather data was collected (n = 2), so we compared nest survival between 2010 and 2011, and found no significant difference between years (Student's t-test; *P* = 0.224), and pooled the years. Nest visit intervals >15 days were filtered from the dataset to ensure fine-scale weather parameters were measured and accounted for between each nest visit ($\overline{x}$ = 6.98 days). Similar to productivity models, we included intrinsic (CID and estimated nestling age from hatch) and habitat (prairie ecoregion and proportion of native grassland within 2.5 km of the nest) as nuisance variables. We considered 11 additive and 5 interaction models. We examined DSR in relation to weather events: Precipitation x Temperature (prey availability and hunting prowess [Dawson and Bortolotti 2000]), Precipitation x Wind (reduced temperatures in wet and rainy conditions [Anctil et al. 2014], and Wind x Temperature (cooling effect of wind [Steenhof et al. 1993]). We also tested interactions between Substrate x Wind (nest persistence in high winds [Steenhof et al. 1993]) and Substrate x Temperature (importance of shade provided by different substrates [Powers 1981, Steenhof et al. 1993]).

To further investigate the cause of nest failures, we conducted another DSR analysis with a separate dataset comparing all successful nests and all nests that failed from presumed wind events (i.e., nests or nest substrates damaged beyond use between nest visits). Nest survival analyses quantify a binary response variable to determine the probability of nesting success, but this analysis does not identify how nests failed. By including a second analysis, we could compare the original full dataset to identify the importance of wind events on DSR. The reduced dataset included a smaller sample size of failures, so the random effects structure was removed from all candidate models and further reduced the variables included in the modelling process

(Fisher et al. 2015). Intrinsic variables should not influence nest failure from wind events and ecoregion had no effect on models in the full dataset and were therefore not included in the reduced candidate model set. Given the nature of this subset (failed nesting attempts only), all interactions tested included wind: Substrate x Wind, Precipitation x Wind, and Wind x Temperature.

**Model development**

For the analyses described above, many nests were visited over multiple years (range = 1–8 years); therefore, we tested a random effect for Year (nest persistence and productivity models) and NestID (full DSR model) to account for repeated nest visits within or between years. Likelihood Ratio Tests (LRT) were used to test the significance of random effects in our final model. If random effects were overfitting the model (SD and variance near 0), then they were dropped (Pasch et al. 2013). A set of candidate models selected *a priori* to test for abiotic, landscape, and weather variables (Table B1). We included a quadratic effect for all temperature variables in the univariate testing stage of our model building because of the potential positive and negative effects of each weather type at either extreme. For instance, during the incubation period, cold temperatures can contribute to egg failures (Blair 1978, Sergio 2003), but nestlings may experience heat stress in extreme heat (Tomback and Murphy 1981). Additionally, we compared linear and quadratic models for all other continuous covariates (i.e., nest age, CID, proportion of grassland) and included the model with the lowest $AIC_c$ in candidate model sets.

Where different weather types (i.e., wind, precipitation, and temperature) were highly correlated ($r > 0.7$) separate models were fit for each metric. Analyses were performed in RStudio v1.0.143 (RStudio Team 2015) and results were considered statistically significant when 95% confidence intervals (CI) did not overlap with zero (Arnold 2010; 95% CIs are used to present parameter estimates throughout). Before hypothesis testing, we first compared univariate models of each weather metric and advanced the covariate with the lowest $AIC_c$. We calculated the $\beta$ : SE ratio for the top model ($\Delta AIC_c = 0$) of each candidate set to assess for uninformative parameters. The variable with the lowest ratio was removed and the model was refit. We continued this process while re-calculating $AIC_c$ at each step and, where the $AIC_c$ value was reduced, the most parsimonious model was retained (Pagano and Arnold 2009, Fisher et al. 2015). All weather models within $\Delta AIC_c \leq 2$ were considered separately for hypothesis testing. Further, any non-significant interactions were removed from top models, thereby allowing main effects to be the focus (Engqvist 2005). Continuous covariates were centered and scaled to account for differences in scale between variables and simplify interpretation of results. We assessed final model fit for zero-inflation, overdispersion, multicollinearity (VIF <3; Zuur et al. 2010), outliers, residual homogeneity, and normality of residuals. Lists of all models considered are provided in Appendix B.

## RESULTS

### Nest Persistence

We included 507 Ferruginous Hawk nest sites monitored between 2010 and 2017 across the Grassland Natural Region in Alberta, Canada. Overall, 9.27% (n = 47) of nests were destroyed by weather-related events. Tree (11.0%; 42/381) and tower (7.7%; 4/51) nests had the highest rates of destruction, and ANPs had the lowest rate of nest destruction (1.4%; 1/73). There was a significant difference in nest persistence for the three substrate types (log-rank test; $P$ = 0.008), driven primarily by the difference between nests in trees and ANPs ($P$ = 0.008). Overall nest survival was 0.57 after 7 years (Figure 2a). The average proportion of remaining nests was highest in towers (0.90) and platforms (0.75) and lowest in trees (0.45; Figure 2b). We monitored nests in platforms and towers for a maximum of 6 years (tree nests: maximum 7 years); therefore, year 6 was used to compare predicted survival rates between nest substrates.

A total of 973 nesting attempts from 507 unique nest sites between 2010 and 2017 were included in nest persistence weather models. Of the 973 nesting attempts, 47 resulted in nest or nest substrate destruction. Nesting attempts in trees were most susceptible to weather destruction (89.4% of failed tree nesting attempts resulted from weather events) whereas a relatively small proportion of nesting attempts in towers (8.5%) and ANPs (2.1%) were destroyed during the breeding season. The top model testing for the effects of wind on nest or nest substrate persistence included nest substrate and 90th percentile wind gusts. Nests in trees (reference category) had significantly lower persistence than nests in towers ($\beta = 1.093$ [0.228, 1.958]) and in nest platforms ($\beta = 1.441$ [0.514, 2.369). Nest persistence was significantly reduced by extreme wind gusts ($\beta = -0.252$ [-0.470, -0.034]; Figure 3).

**Productivity**

A total of 809 nesting attempts were monitored from 441 nest sites between 2010 and 2017 ($\overline{x} = 1.83$ attempts/ nest). Of the nesting attempts monitored, 564 were successful and 243 failed (30.0%). The main reasons for failure were damaged or fallen nests/trees (18.9%) and nest abandonment (15.9%; Table 1). A large proportion (37.4%) of nests were found empty, but the exact cause of failure could not be determined. It is possible that some of these failures were weather-related and young were not observed because scavengers removed carcasses. Failures were most common in trees with 33.9% of all tree nesting attempts failing ($n = 572$), whereas 23.9% ($n = 92$) and 18.6% ($n = 145$) of tower and platform nesting attempts failed, respectively.

The top productivity model included CID, ecoregion, substrate, and maximum precipitation during the nestling stage. CID later in the breeding season produced fewer young ($\beta$

= -0.103 [-0.153, -0.053]). Though nests in trees (reference category) produced fewer fledglings than in platforms ($\beta_{\text{Platform}}$= 0.149 [-0.006, 0.304]) or in tower nests ($\beta_{\text{Tower}}$ = 0.061 [-0.116, 0.239]), 95% confidence intervals overlapped with zero and this apparent difference was not significant. Nests in mixed grasslands (reference category) were significantly less productive those in moist-mixed grasslands ($\beta_{\text{MM}}$ = 0.163 [0.014, 0.313]), but not those in fescue grasslands ($\beta_{\text{Fescue}}$ = 0.137 [-0.064, 0.337]). Productivity was significantly lowered as maximum precipitation increased during the nestling season (β = -0.083 [-0.152, -0.015]; Figure 4). No top models ($\Delta\text{AIC}_c$ <2) included interaction effects.

**Daily Nestling Survival**

Our nestling survival analysis included 425 Ferruginous Hawk nesting attempts, 312 of which were unique nest sites between 2010 and 2017. On average, nests were visited every 7 days with an average of 5.2 visits per nesting attempt. Of the 425 nesting attempts monitored, 14.6% (62) attempts failed, 29.0% (18/62) of which failed due to weather-related events.

The top model for Ferruginous Hawk daily nesting survival (DSR; INTRINSIC + SUBSTRATE + GRASS + AVGTEMP + AVGWIND) had an $\text{AIC}_c$ weight of 0.70. Nests initiated earlier in the breeding season had significantly higher DSR, than later nests (β = -0.565 [-0.936, -0.193]). Survival rates decreased later into the season (β = -0.364 [-0.821, 0.093]), though not significantly so. Nest substrate was not a significant predictor of DSR ($\beta_{\text{Platform}}$ = 0.716 [-0.380 1.811]; $\beta_{\text{Tower}}$ = 0.851 [-0.588, 2.291], reference category = tree nests). DSR decreased as the proportion of native grassland within 2.5 km of a nest increased (β = -0.507 [-0.956, -0.058]). DSR also significantly decreased as average wind increased (β = -0.399 [-0.684, -0.113]) and appeared to decrease with increases in average temperature (β = -0.402 [-0.810, 0.007]), though not significantly.

A total of 18 nests failed from weather damage and were either blown out completely or destroyed beyond use; these were included in the analysis comparing nesting attempts that failed from wind events to all successful nesting attempts ($n = 363$). The top model (SUBSTRATE + GRASS + AVGTEMP + AVGWIND) had an $AIC_c$ weight of 0.32. The top three models were within $\Delta AIC_c = 0.37$ and all models included AVGWIND (Table 3). Similar to the top model comparing all successful and all failed nesting attempts, DSR significantly decreased as the proportion of native grassland around a nest increased ($\beta = -0.699$ [-1.388, -0.132]). Contrarily, DSR was significantly higher in platform nests ($\beta_{Platform} = 1.724$ [0.078, 4.634]) than in tree nests (reference category), but DSR for tower nesting did not significantly improve when compared to tree nesting ($\beta_{Tower} = 0.928$ [-0.684, 3.829]). Both AVGWIND ($\beta = -0.567$ [-0.843, -0.249]) and AVGTEMP ($\beta = -0.516$ [-1.012, -0.015]) were included in the top model and negatively influenced DSR; however, the effect of wind was heightened, and there was a lower effect of increasing average temperature, relative to the initial DSR analysis that included all nest failures (Figure 5, Figure 6). No top models ($\Delta AIC_c < 2$) for either analysis included interaction effects.

## DISCUSSION

Few studies have analyzed or discussed the longevity of Ferruginous Hawk nests or their persistence on the landscape. We found that the probability of a nest persisting declined as the number of years monitoring a nest increased and that after 7 years of monitoring, nest persistence was 0.57. After 7 years, nests in trees had the lowest persistence rate and drove overall nest persistence rates down, which supported our predictions. Tree nests were more susceptible to weather destruction than ANP nests (10.99% and 1.35%, respectively) and had significantly lower persistence rates (0.49 compared to 0.75 in ANPs). Previous studies have suggested that extreme wind events are likely a significant threat to Ferruginous Hawk nests (De Smet and Conrad 1992, Schmutz and Hungle 1989), and population recruitment may be significantly affected by weather-related events (Shank and Bayne 2015). However, to our knowledge the effect of wind on nest persistence had not been formally tested. We found that extreme wind gusts (defined as the number of days where wind gusts exceeded the 90th percentile) had a significant negative influence on nest destruction. Of 170 nesting attempts on ANPs, only a single nest failed from a weather-related event (0.58%) whereas 6.05% of nesting attempts in trees failed from wind events. Our nest persistence analysis provides additional support for the benefit of using nest platforms as a conservation tool.

During our study, 9.27% of nests or nesting substrates collapsed or were damaged beyond use from weather events, which was within the wide range of estimates from portions of this same study area (1.2% [Schmutz et al. 2008] to 23% [Bayne et al. 2016]). Studies show that trees are vulnerable to destruction over time, particularly under dry or drought conditions that increase their susceptibility to destruction in inclement weather (Hogg and Hurdle 1995). Trees in open grasslands also face pressures from clearing for agricultural conversion, rubbing from cattle (Houston and Bechard 1984), and reduced regeneration in drought conditions under future climate change scenarios (Hogg 2001). The availability of nest sites is increasingly important in prairie landscapes and maintaining or improving existing intact nests (and nest substrates) should be considered a priority for management, particularly in regions where nesting substrate availability is low. Various pressures exist that limit Ferruginous Hawk nest-site availability (Schmutz et al. 1988) including the removal of existing trees around homesteads or shelterbelts for agricultural conversion (Bellet 2013) and the senescence of lone trees (Fent and Richard

1999). Our findings further support the importance of identifying active and/ or suitable breeding sites that could benefit from additional substrates such as ANPs.

High daily rainfall events during the nestling period significantly reduced nesting productivity. We reported higher predicted fledgling rates in artificial nesting platforms than in trees, but the difference was not significant. The average number of fledglings per nesting attempt in our study was 1.72, with tree attempts producing the fewest average fledglings ($\overline{x}$ = 1.60), which was lower than for ANP nesting attempts ($\overline{x}$ = 2.04). We predicted that acute, high wind events would have the greatest negative effect on productivity, but did not find evidence to support this prediction. However, both extreme rainfall events and high seasonal total precipitation have contributed to decreased DSR in other raptor species (Kostrzewa and Kostrzewa 1990, Anctil et al. 2014, and Fisher et al. 2015). In heavy rain, adults will brood their young and remain at the nest for longer periods (Redpath et al. 2002), but nestling mortality can occur rapidly if brooding is not maintained (Anctil et al. 2014). Nestlings with downy feathers are particularly vulnerable to the rapid heat loss associated with the significant reduction of insulating capabilities of feathers when they are wet (Nye 1964). Young birds have the most down during the first half of the nestling stage and nestlings are most affected by heavy rain during this period (Zduniak 2009). The frequency of heavy precipitation events could increase by up to 40% before the end of the century in North America (Karl et al. 2009), which could have significant negative effects on fledgling rates.

We predicted that extreme wind would negatively affect DSR by blowing nests out of substrates and damaging them beyond use, or by blowing nestlings out of nests. Though DSR was not significantly influenced by extreme wind events, high daily average wind speeds were a strong negative predictor. Unlike predictions for severe weather events or extreme wind gusts, Flannigan and Wang (2012) did not predict changes would occur over the next century for mean wind speeds in the Canadian prairies and reported no trends in average wind speeds for Alberta's prairies between 1979 and 2010. Wallace et al. (2016) reported that June storms reduced nest productivity, but not DSR. Several other studies note that nests are prone to damage or blowing out when exposed to storm or extreme wind events (De Smet and Conrad 1992, Schmutz and Hungle 1989, Steenhof et al. 1993). Though our predictions were not supported, we expect that under future climate scenarios, more frequent and extreme wind events will result in lower DSR relative to average wind speeds.

Artificial nest platforms are commonly used in conservation programs for various species to improve habitat (Schmutz et al. 1984), encourage population growth (McClure et al. 2017), and mitigate potentially dangerous nesting situations (Kemper et al. 2020). Completing two separate analyses on DSR, where the first model included all nest failures and the second used a subset of only nests that failed from apparent weather damage, allowed us to assess the importance of nest substrate on DSR. Nest substrate became an important predictor for DSR only after modelling for nests that failed from blow outs or apparent weather destruction.

We reported 9 different substrate types used by Ferruginous Hawks, including 3 natural (cliff, ground, and tree) and 6 anthropogenic (platform, transmission tower, radio tower, shed, windmill, and distribution tower). Ferruginous Hawks nest primarily in trees (Olendorff 1993), but will use a diverse array of nesting substrates (Gilmer and Stewart 1983), with a preference for artificial sites when available (Schmutz et al. 1984). Relative to congenerics, Ferruginous Hawks appear to have greater success on anthropogenic structures, particularly in transmission towers (Steenhof et al. 1993). However, Steenhof et al. (1993) also noted that raptor and corvid nests in towers were more susceptible to failing from wind damage than nests on platforms. If constructed according to previous platform designs, large platforms should allow nestlings (up to four young) to lie flat when wind is high and avoid blowing out when the nest remains intact (Schmutz et al. 1984). In parts of our study area, a human-assembled stick-nest (in free-standing and transmission tower platforms) was wired onto each platform as a base to a) attract breeding pairs to a partially-constructed nest and b) limit nest damage in the event of high winds. Though not formally tested, anecdotal accounts suggest that at least some of these nests were used by hawks in the area. Implementing these subtle alterations to proven platform designs (see Schmutz et al. 1984 and Migaj et al. 2011) could mitigate the impacts of storms and high wind events; however, the suggested benefits of this technique should be tested in future studies.

## Management Implications and Conclusions

Average wind and rain in the Canadian Ferruginous Hawk breeding range are predicted to remain relatively similar to current averages. However, the frequency and intensity of wind and precipitation events are expected to increase, resulting from a warmer climate, an altered hydrological cycle (Stone et al. 2000), and changes to low-pressure systems (Cheng et al. 2014). Suggested management strategies for Ferruginous Hawks cite the importance of habitat amelioration by constructing artificial nest substrates (AFHRT 2009). Ferruginous Hawk nest success (apparent and daily survival rates of nestlings) in ANPs is significantly higher than nests on natural substrates (Schmutz et al. 1984, Steenhof et al. 1993, Wallace et al. 2016). Our study adds support to the existing literature by suggesting that nest attempts on ANPs have significantly higher productivity and daily survival when accounting for local weather patterns. Though ANP installation cannot directly reduce weather effects on nests, they are an effective measure to mitigate the loss of nesting structures (Olendorff 1983, Schmutz et al. 1984) and can reliably enhance nest persistence, productivity, and daily nestling survival. In addition to suggested considerations for ANP placement (Schmutz et al. 1984, Migaj et al. 2011), we recommend factoring regional climate trends and predicted changes into management plans. For instance, in southern Alberta, average wind speeds are not predicted to increase in future climate scenarios (Cheng et al. 2014). Prioritizing ANP installation in areas with present day and predicted future high winds could provide the support needed to increase the probability that hawks can maintain stable populations in wind-susceptible regions of their current range. However, negative effects of extreme winds exceeding the benefits provided by ANPs should also be considered. If hawks are attracted to platforms in areas where future wind speeds become so extreme that nest failures begin to increase across all substrate types, then the benefit of ANPs may be outweighed by relatively high nest failure rates. Further, care must also be taken to ensure that nest availability across the range is maintained and that the number of ANPs placed in a region does not create conditions where hawks are forced to compete for other limiting resources (i.e., food).

# TABLES AND FIGURES

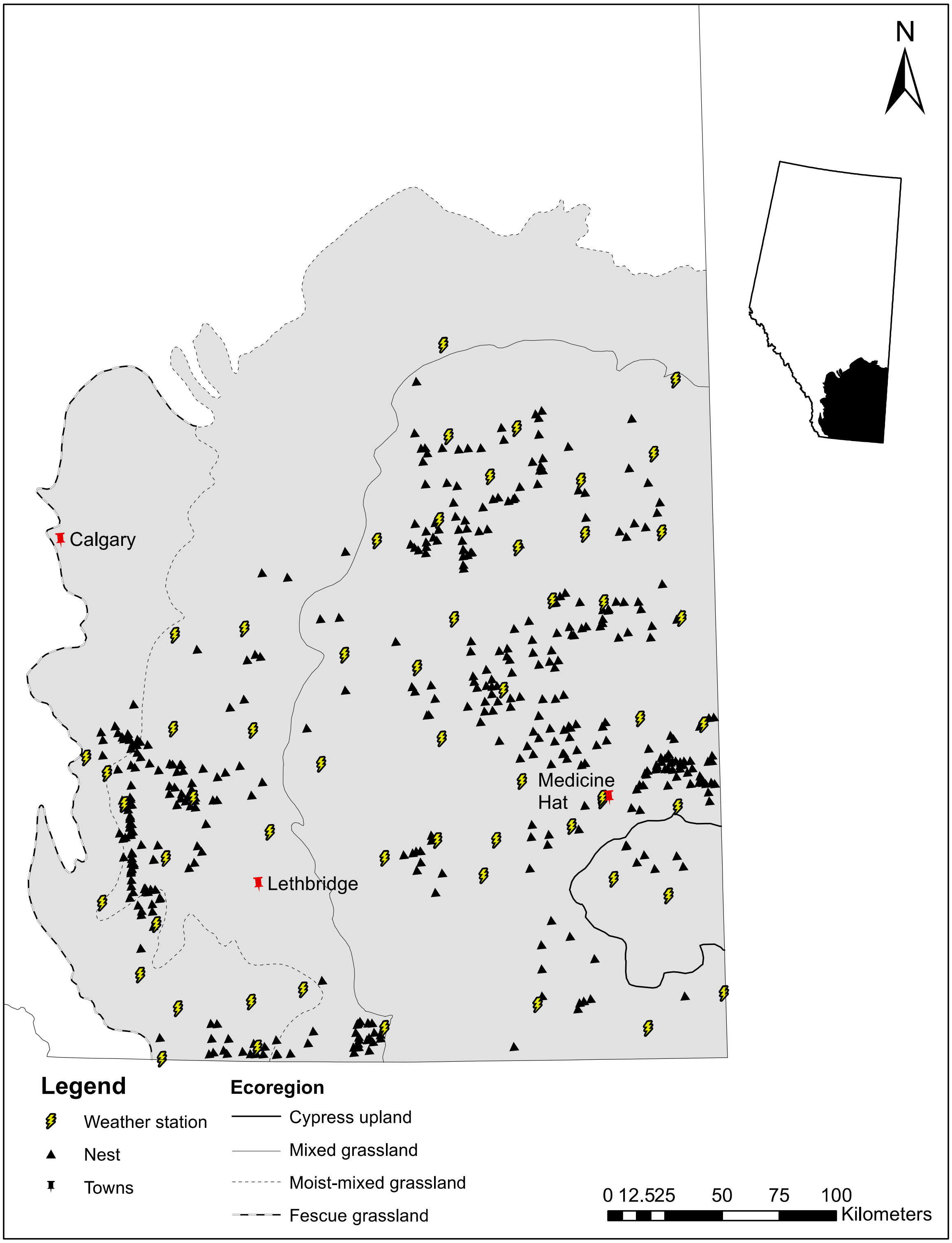

**Figure 3.1.** The project study area in southern Alberta with all weather stations within 50 km of a nest and all nests monitored between 2010 and 2017.

**Table 3.1.** Reasons for Ferruginous Hawk nesting failures from 809 nesting events monitored in southern Alberta, Canada. A total of 243 Ferruginous Hawk nesting attempts (30.0%) failed between 2010 and 2017.

| Fail Reason | Frequency | Percent (%) |
|---|---|---|
| Abandonment | 39 | 15.9 |
| Defunct/ damaged/ fallen | 46 | 18.9 |
| Eggs damaged/ gone | 12 | 4.9 |
| Exclusion by other species | 14 | 5.8 |
| Infertile Eggs | 3 | 1.2 |
| Nest Empty | 91 | 37.4 |
| Predation | 4 | 1.6 |
| Unknown | 24 | 9.9 |
| Young dead with wounds from predators | 4 | 1.6 |
| Young dead without wounds | 6 | 2.5 |

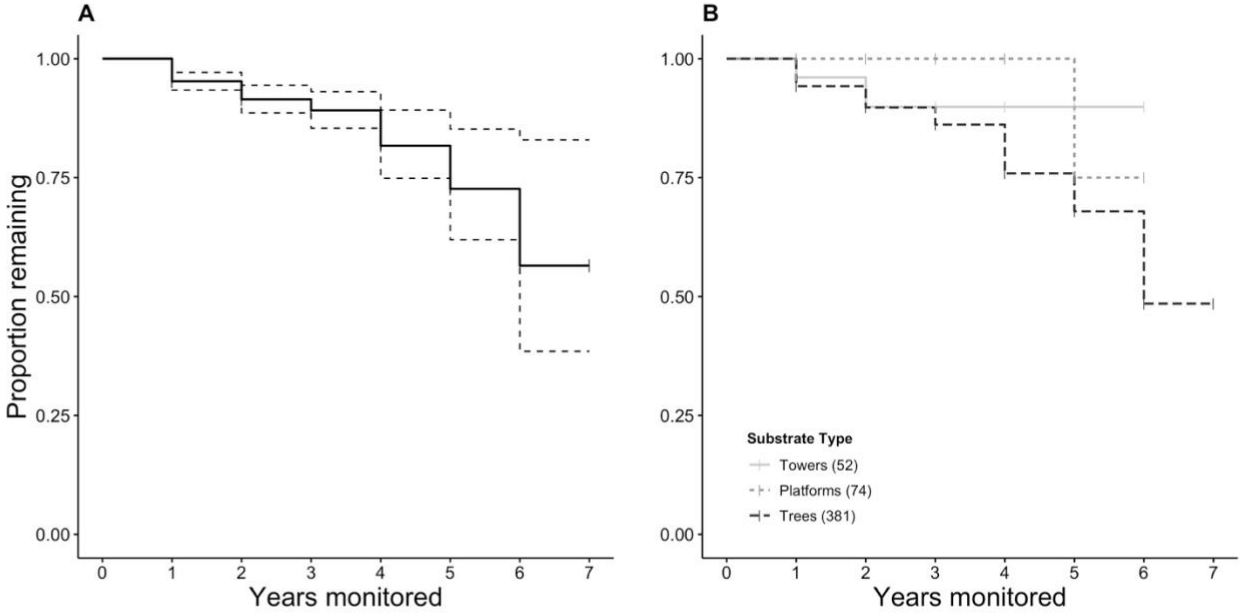

**Figure 3.2.** Survival curves (Kaplan-Meier) representing nest persistence for (A) all ($t_0 = 507$) Ferruginous Hawk nests monitored over a breeding season as a function of total years monitored, and (B) nest substrate type. Tick marks along curves represent censoring events when monitoring stopped at an intact nest. Dashed lines (*A*) represent 95% confidence intervals.

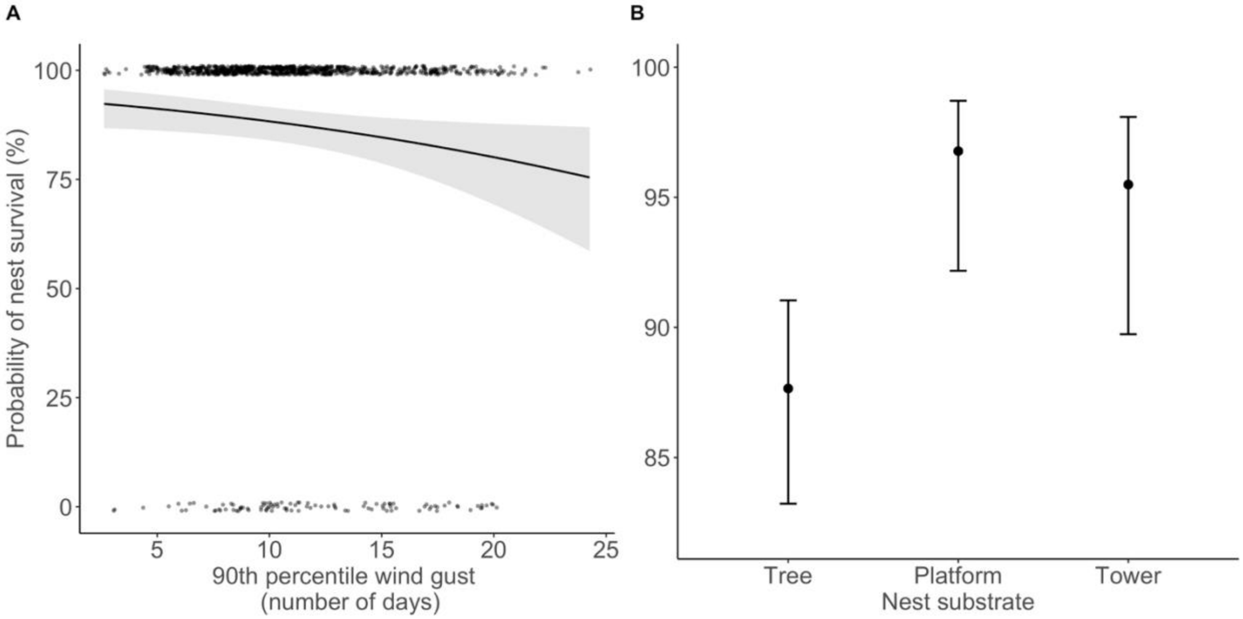

**Figure 3.3.** Predicted relationship between Ferruginous Hawk nest persistence and 90th percentile wind events during the breeding season between initial CID to fledging from the top mixed logistic regression model (ΔAICc = 0.00). Year was included as a random effect. Shaded grey lines represent 95% confidence interval and jittered dots represent data points.

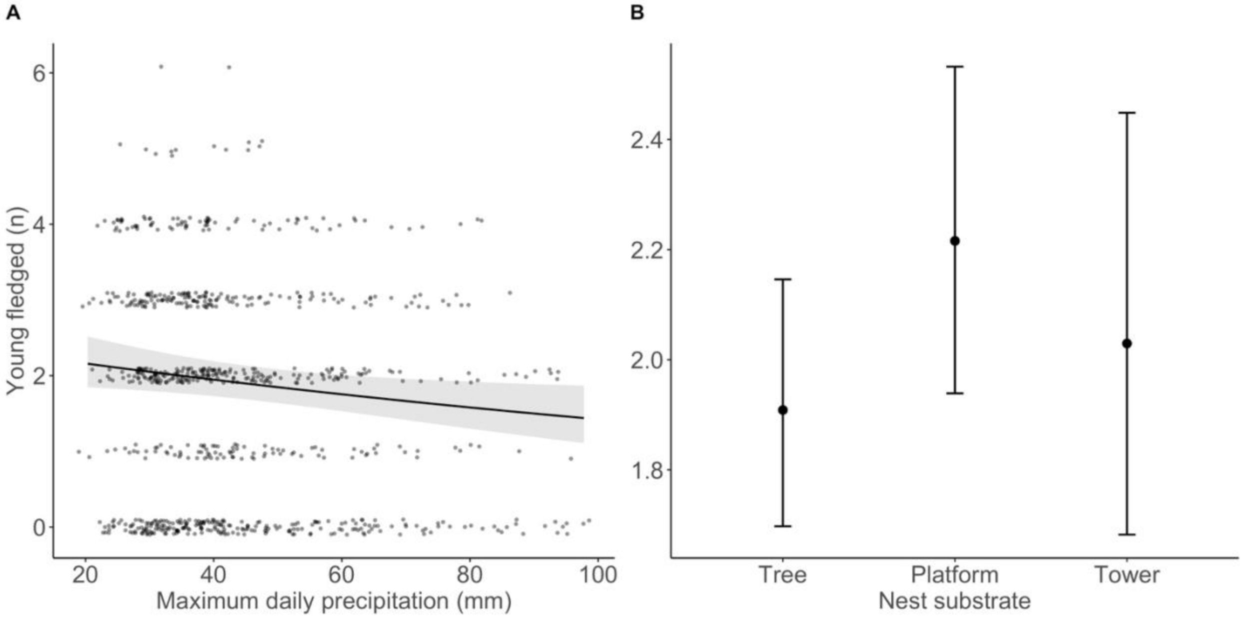

**Figure 3.4.** Predicted relationship between Ferruginous Hawk nest productivity and maximum precipitation events during the brooding period from the top selected (ΔAICc = 0.00) zero-inflated Poisson generalized linear mixed model. The top model also included CID, ecoregion, and nesting substrate as fixed effects. Year was included as a random effect. Shaded grey lines represent 95% confidence interval and jittered dots represent data points.

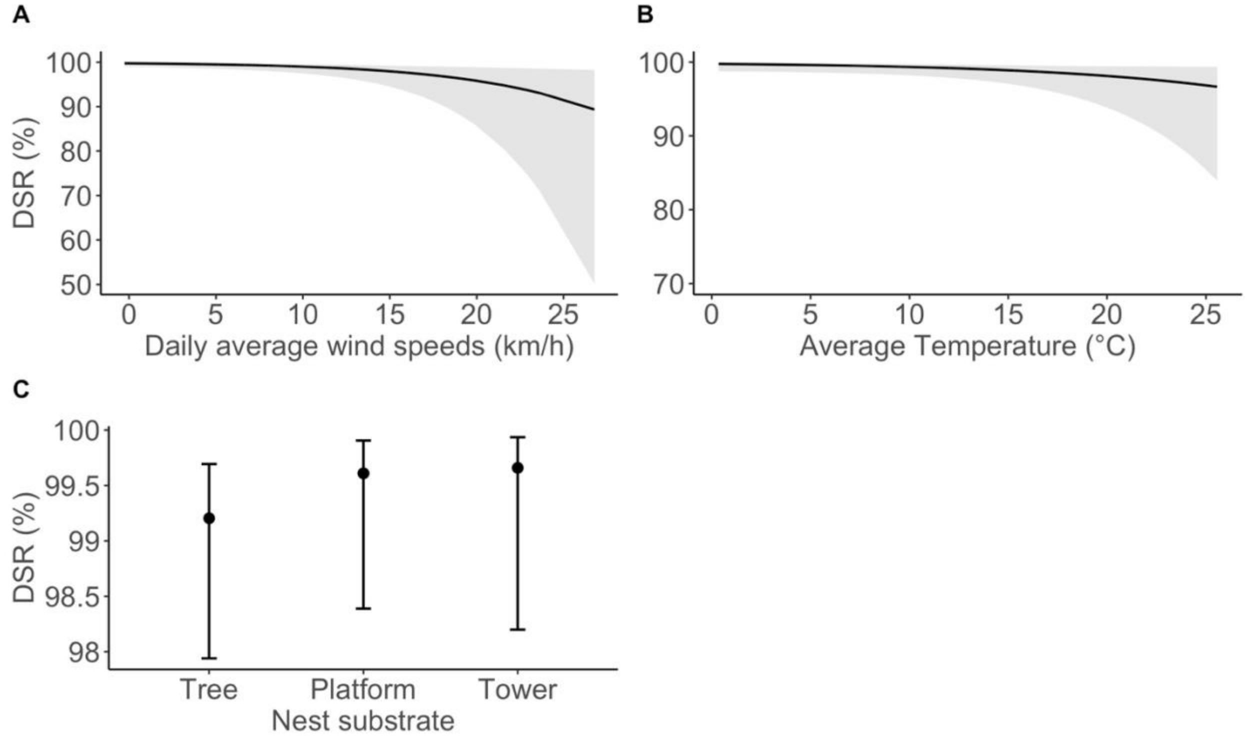

**Figure 3.5.** Predicted relationship between Ferruginous Hawk daily survival rates of all successful nests and all failures for (A) daily average wind speeds (km/h), (B) average temperature (°C), and (C) nest substrate from the top ($\Delta$AICc = 0.00) model fit with a logistic exposure link function. A random effect for NestID and fixed effects for intrinsic values, the proportion of grass within 2.5 km of the nest site, and substrate were also included in the model. Shaded grey lines represent 95% confidence intervals.

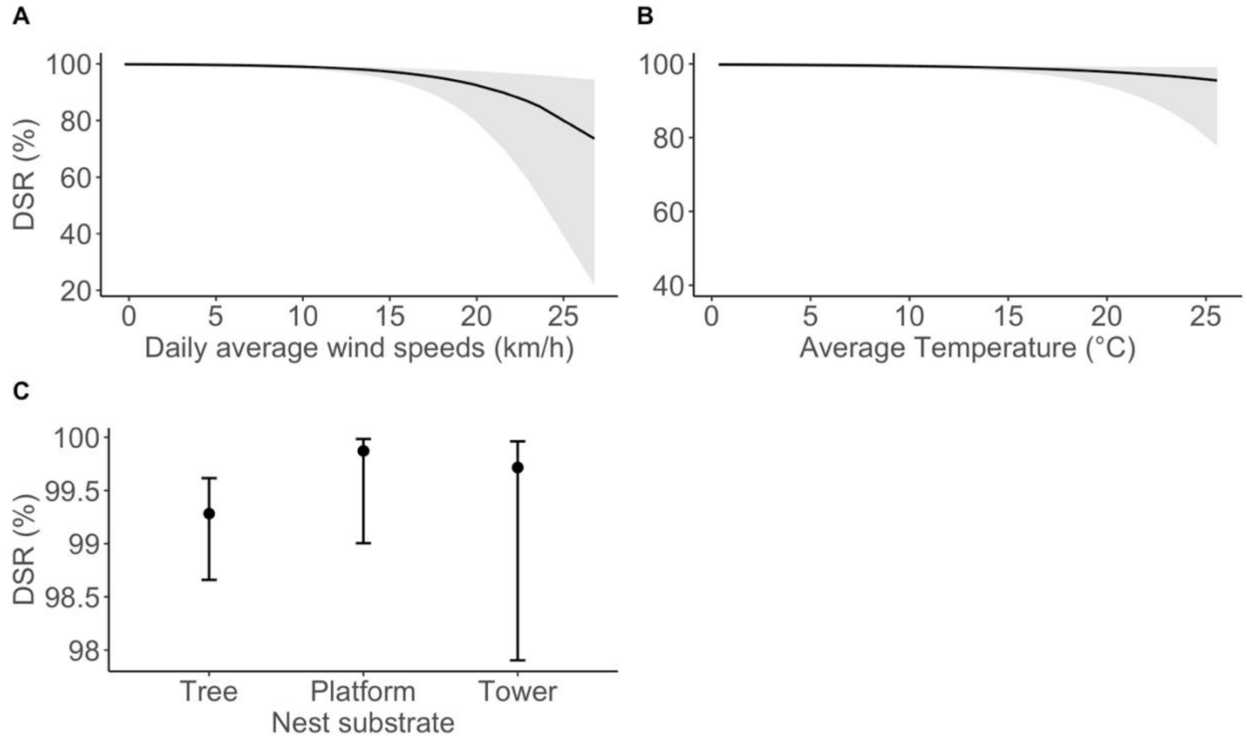

**Figure 3.6.** Predicted relationship between Ferruginous Hawk daily survival rates of all successful nests and those that failed from blowing out for (A) daily average wind speeds (km/h), (B) average temperature (°C), and (C) nest substrate from the top ($\Delta AIC_c = 0.00$) model fit with a logistic exposure link function. Shaded grey lines represent 95% confidence intervals.

# CHAPTER 4: Conclusion

## KEY FINDINGS

Raptors often prefer to nest on elevated anthropogenic substrates, when available, over natural substrates. My thesis focussed on (1) the importance of anthropogenic substrates used by Ferruginous Hawks for nesting in areas of temporary habitat alteration, and (2) on the significance of artificial nest platforms in mitigating the negative effects of extreme weather events on reproductive output. In Chapter 2, I applied a Before-During-After Control-Impact (BDACI) study design to test for the creation of an ecological trap, and for potential shifts to the raptor and raven community within 5 km of alterations to existing transmission lines. I did not find strong evidence for the presence of an ecological trap, nor did I find any negative effects on apparent nesting success, fledgling production, or nest-site reoccupancy. However, analyses revealed a significant trend in Ferruginous Hawk nest densities that were related positively with the number transmission towers present during the breeding season. The positive linear relationship between nest density and number of transmission-line towers raises several interesting questions with few tests in previous research (see *Management Applications and Future Research*). Raptor and raven abundance also appeared to shift during our study, but no species drove community change.

The implementation of robust BDACI or Before-After Control-Impact (BACI) study designs are important in understanding the effects of different construction projects associated with energy developments. To my knowledge, no previous work similar to Chapter 2 has been published and, with a nearly 30% increase in global energy demands forecast for upcoming decades (USEIA 2017), landscape modifications similar to those outlined in Chapter 2 with the potential to impact raptor breeding populations will likely increase in the near future. Previous research found that raptor densities increased significantly following new transmission line construction (Stahlecker 1978) and, in years following construction, the abundance of multiple species (including Ferruginous Hawks) increased substantially (Steenhof et al. 1993). The bulk of transmission line studies concentrate on the development of transmission lines in previously undeveloped areas with habitat that is attractive for large, stick-nesting birds, like raptors and ravens (Knight and Kawashima 1993, Restani et al. 2001). The attraction of these species to elevated anthropogenic structures has potential consequences on local fauna (e.g., Coates et al. 2008) and can accelerate range expansion by some species into previously unoccupied regions (e.g., Common Raven; Boarman and Berry 1995). Limited support for my predictions regarding the ecological trap hypothesis suggests that, at face value, the temporary alterations to nesting substrates pose a low threat to breeding Ferruginous Hawks. However, the significant, temporary increase in nest density followed by a reduction to pre-construction levels indicates that even apparently subtle changes to nest site availability with mitigation programs in place can affect local populations.

In Chapter 3, I demonstrated that Ferruginous Hawk nests persist longest in artificial nest platforms (ANP) and other anthropogenic structures (i.e., transmission and radio towers) and that tree nests are significantly more susceptible to weather-related destruction. There was strong evidence of extreme wind events (defined as the number of days in the breeding season with 90th percentile wind gusts) negatively impacting nest destruction by either damaging a nest beyond use or destroying the substrate supporting a nest. Nests in artificial platforms had significantly higher persistence rates than those in trees. The strongest weather effect size for fledgling productivity was high daily rainfall during the nestling period, which decreased nest productivity, though not significantly. There was also no significant influence of nest substrate in mitigating for the effects of heavy rainfall. Further, I found that nests in areas with high mean daily wind speeds had the lowest daily nesting survival rates (DSR), particularly when considering only those nests that failed from blow out. By comparing all nests in the study to the blow out-only subset, I was able to examine the influence of nest-substrate selection on DSR. While there was no difference between nest substrates when considering all nests, I found that nests in ANPs had greater nestling DSR than those in tree nests at breeding sites with high mean wind speed during the breeding season.

Results in Chapter 3 provide additional support for the importance of using ANPs as a management tool for raptors. The utility of ANPs is well documented for a variety of species and can (1) help improve habitat (Schmutz et al. 1984) and support population growth (McClure et al. 2017) in suitable regions lacking elevated natural nesting substrates, and (2) help manage nesting in dangerous or vulnerable locations (e.g., minimizing electrocution risk; Kemper et al. 2020). Few studies have assessed whether ANPs can reduce the risk of nesting failure from weather-related events. Though not specifically focusing on ANPs, Wallace et al. (2016) also found that nestling DSR was higher in ANPs than natural substrates and reported that June storms were an important predictor for Ferruginous Hawk nest productivity.

Unlike temperature and precipitation, future scenarios for mean wind trends are unclear (Cheng et al. 2014), but a warming climate is expected to cause increases in storm frequency and intensity and extreme wind events are projected to increase (Stone et al. 2000). Recent studies often omit wind from weather parameters while typically including temperature and precipitation. One study of severe windstorm effects on the nest density and reproductive parameters of three species of Mediterranean forest raptors found limited impacts of extreme wind, suggesting a possible adaptive response to storms (Martinez et al. 2013). Further, Ferruginous Hawks adults will pre-emptively increase their time spent on a nest, and on structural reinforcing their nest, ahead of approaching storms (Laux et al. 2015). Shank and Bayne (2015) reviewed and summarized known and predicted effects of climate change on Ferruginous Hawks in Alberta and recommended that (1) ANPs are strategically placed and construction designs provided by Migaj et al. (2011) are investigated, with modifications implemented if additional resistance to inclement weather can be provided (high priority action), and (2) determine if nest protection from extreme weather events improves nesting success and can reduce chances of nest collapse (medium priority action). My research in Chapter 3 provides support for the benefits of ANPs as a management tool for Ferruginous Hawks and offers new insights addressing the recommendations made by Shank and Bayne (2015).

## MANAGEMENT IMPLICATIONS AND FUTURE RESEARCH

In Alberta alone, developments are projected to add 4000 km of transmission lines in the next 21 years (Alberta Utilities Commission 2013), driven by an annual 2% increase in demand for electricity (Government of Alberta 2018). The provincial *Wildlife Directive for Alberta Transmission Lines and Substations* document, outlines wildlife issues and requirements for avoiding and reducing risks to wildlife during all stages of energy project construction. Research on the indirect effects of transmission line development on wildlife is currently limited to effects on nearby habitats and community changes to flora and fauna through anthropogenic influence (e.g., introduction of invasive plants, attraction of corvids and raptors to tall structures; Government of Alberta 2018). Current knowledge on the influence of transmission line construction on Species at Risk (SAR) is generally limited to predation by corvids and raptors on nearby SAR populations (e.g., Greater Sage-Grouse *Centrocercus urophasianus*, and various

SARA-listed reptiles and amphibians). Insight on these few species represents our limited knowledge of the indirect effects of transmission line development on species selecting habitats on or near transmission lines.

Though my thesis provides new insights on the indirect effects of transmission lines on breeding raptors, it also reveals knowledge gaps that were either not considered or that we were unable to monitor or quantify. The most obvious gap is understanding post-fledging dispersal and survival rates from nests in towers. Transmission towers may be up to 15 times taller than average tree nests. Initial fledgling dispersal distances and the ability for fledglings to return to the nest after fledging may be substantially impacted by nesting a unnatural heights. We were unable to address this question, in part from safety concerns (it was not feasible for us to access towers 30-45 m in height to attach transmitters to nestlings) and logistical constraints that would have required extensive monitoring of each nest to observe young fledging tower nests.

I reported that Ferruginous Hawk nest densities returned to near pre-construction levels following tower removal, but, with only two years of post-construction monitoring, was not able to conclusively report on any longer-term post-construction population effects. Where feasible, I recommend that projects engage in post-construction monitoring to assess any residual effects on breeding bird populations. This is particularly important where mitigation strategies are employed, such as the use of ANPs to promote the reoccupancy of breeding pairs near nests that were removed or destroyed for construction activities. The Government of Alberta (2018) requires an additional 2 years of post-construction monitoring (totaling 5 years). I reported nest densities dropping after the final phase of construction (when old transmission towers were removed), but steadily increasing in the three years post-tower removal. An additional 2 years of monitoring may reveal longer-term trends and evidence of the effectiveness of mitigations employed by the project developer. My research supports the requirement for the extra years of monitoring, which should be a *minimum* requirement for all energy development projects.

The installation of ANPs in raptor conservation is a commonly applied wildlife management technique for several species in a variety of situations. However, the effectiveness of ANPs in mitigating the negative influence of extreme weather events had not been previously explored, beyond anecdotal evidence. My results support the value of this simple conservation tool and provide additional evidence for the application of ANPs. Artificial platforms contributed to significantly higher nest persistence and nestling DSR than tree nests under both extreme wind events and high mean wind events. With extreme wind gusts expected to increase in Alberta (Cheng et al. 2014), I recommend that ANP installation is prioritized in areas presently experiencing high wind events (e.g., areas West of Lethbridge in Alberta) to help Ferruginous Hawks maintain their current breeding distribution where tree nests are most vulnerable to wind damage and destruction. Many suitable designs have been suggested for ANPs (see Schmutz et al. 1984, Migaj et al. 2011) and, within our study area, trivial alterations (i.e., nest securement to artificial nest platforms) were made to recommended construction blueprints to promote faster adoption of nest platforms by Ferruginous Hawks. By securing sticks, artificially arranged in the shape of a nest, to the base of a platform, nest resistance to destruction from extreme wind and severe storms could be further improved on. Currently, any evidence supporting the implementation of this change is anecdotal and requires further research.

Overall, my study provides new insights into the indirect effects of sudden and temporary alterations to long-term breeding substrates for Ferruginous Hawks. Nest platforms can alleviate the negative consequences of weather events on nest persistence and daily nesting survival rates of Ferruginous Hawks. I recommend that wildlife managers and industry consider the importance of weather events in management plans and mitigation strategies for future developments. The outcomes of my research also highlight the importance of working closely with industry partners to develop thorough study designs that allow for consistent monitoring of the species or system before, during, and after disturbances. BDACI and BACI designs are commonly applied to assess the potential effects of a disturbance, but fewer than 20% of energy development studies include a before and after component (Kuvlesky et al. 2007, Northrup and Wittemyer 2012) and, when included, pre-construction data are often limited to a single year (Richardson et al. 2017). I implore industry partners to initiate more research activities at proposed sites during the early planning stages to accurately report on ecosystem changes resulting from development.

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## APPENDIX A. Chapter 2: Response of Ferruginous Hawks to temporary habitat alterations for energy development in southwestern Alberta.

**Table A1.** Covariates considered in each model building step for nest density (ND), success (SU), productivity (PR), reoccupancy (RO), and community change (CC) models. All dates were converted to Julian Date and continuous covariates were standardized before analyses.

| Step | Covariate | Abbreviation | Model |
|---|---|---|---|
| Intrinsic | | | |
| | Survey start date | JulDate | ND, CC |
| | Non-Ferruginous Hawk stick nests | NonFEHA | ND |
| | All stick nests | Nest_Tot | CC |
| | Hatch date | Hatch_Adjust[†] | SU, PR, RO |
| | First day of nest monitoring | MonitoringStart | SU, PR, RO |
| | Date of nest outcome (failed or successful) | OutcomeDate | SU, PR, RO |
| | Nest substrate[‡] | Substrate_Bin<br>Substrate_Tri | SU, PR<br>RO |
| | Number of years nest monitored | YearsMonitored | RO |
| | First year of nest monitoring | YearOne | RO |
| | Previous year nest occupant | PrevYearOcc | RO |
| Landcover and Geography | | | |
| | Proportion of grass[§] | Grass100 | ND, SU, PR, RO, CC |
| | Prairie subregion of nest or block | Region | ND, SU, PR, RO, CC |
| Anthropogenic Development | | | |
| | Density of wells[§] | Wells_dens | ND, CC |
| | Count of wells | Wells | SU, PR, RO |
| | Density of distribution poles[§] | Poles_dens | ND |
| | Loose (unpaved) road[ǀ] | LooseRd | ND, SU, PR, RO |
| | Hard (paved) road[ǀ] | HardRd | SU, PR, RO |
| | Loose and hard road density (sum) | AnyRoad | CC |
| | Transmission lines[ǀ] | TX | ND, SU, PR, RO, CC |
| BDACI Impact | | | |
| | Phase | Phase | ND, SU, PR, RO, CC |
| | Site/ Treatment | Treatment | ND, SU, PR, RO, CC |

[†] Where hatch date could not be estimated, the average hatch date for that year was used.

[‡] Binned nest substrate groups were used based on the lowest $AIC_c$ for a respective response variable

[§] Proportion or density in a block survey (ND, CC) or within 2.5 km of a nest (SU, PR, RO)

[ǀ] Density (ND, CC) or length within a 2.5 km nest buffer (SU, PR, RO)

**Table A2.** Estimated coefficients (*β*), standard errors, *P*-values, and random effects for parameters included in the Ferruginous Hawk nest density model. Phase indicates time blocks between 2013–2019 and Site indicates impact and control blocks.

| **Predictors** | ***β*** | **SE** | ***P*** |
|---|---|---|---|
| **Fixed Effects** | | | |
| Grass100 | 0.758 | 0.289 | **0.009** |
| *Region* | | | |
| Foothills Fescue | Base | | |
| Mixed | 3.738 | 1.713 | **0.029** |
| Moist Mixed | 2.954 | 0.723 | **<0.001** |
| *Phase* | | | |
| Before | Base | | |
| During | -0.564 | 0.384 | 0.141 |
| After | -0.399 | 0.289 | 0.167 |
| *Site* | | | |
| Control | Base | | |
| Impact | -0.546 | 0.778 | 0.483 |
| Control x Before | Base | | |
| Impact x During | 0.967 | 0.443 | **0.029** |
| Impact x After | 0.703 | 0.348 | **0.044** |
| Intercept | -7.984 | 0.782 | **<0.001** |
| **Random Effects** | **Var** | **SD** | |
| BlockID | 3.726 | 1.930 | |

**Table A3.** Results of logistic regression generalized linear mixed effects model on the effects of intrinsic and land use factors and Phase x Treatment on Ferruginous hawk nest success in southern Alberta. "Base" indicated the reference values for categorical covariates. Treatment included three levels of distance determined by hawk home range size: IZ (≤ 2.5 km), CZ1 (2.5 km ≥ 10 km), CZ2 (≤ 10 km). Phase (construction timing) also consisted of three levels: Before (2013–14), During (2015–16), and After (2017–19). Continuous covariates were standardized before analysis.

| | **Success** | | |
|---|---|---|---|
| **Predictors** | ***β*** | **SE** | ***P*** |
| OutcomeDate$^2$ | -2.64 | 0.76 | **<0.001** |
| OutcomeDate | 7.67 | 1.09 | **<0.001** |
| HatchDate | -1.63 | 0.27 | **<0.001** |
| *Treatment* | | | |
| CZ2 | Base | | |
| IZ | 2.14 | 1.05 | **0.041** |
| CZ1 | 1.25 | 0.80 | 0.119 |
| *Phase* | | | |
| After | Base | | |
| Before | 0.03 | 0.68 | 0.962 |
| During | -0.62 | 0.59 | 0.295 |
| CZ2 x After | Base | | |
| IZ x Before | 0.67 | 1.49 | 0.652 |
| CZ1 x During | -0.14 | 1.31 | 0.912 |
| IZ x Before | -0.34 | 1.41 | 0.808 |
| CZ1 x During | -0.02 | 1.41 | 0.990 |
| Intercept | -0.14 | 0.39 | 0.712 |

**Table A4.** Results of linear regression generalized linear mixed effects model on the effects of intrinsic and landuse variables, and Phase x Treatment on Ferruginous hawk nest productivity in southern Alberta. "Base" indicated the reference values for categorical covariates. Treatment included three levels of distance determined by hawk home range size: IZ (≤ 2.5 km), CZ1 (2.5 km ≥ 10 km), CZ2 (≤ 10 km). Phase (construction timing) also consisted of three levels: Before (2013–14), During (2015–16), and After (2017–19). Covariates were standardized before analysis.

| | **Productivity** | | |
|---|---|---|---|
| **Predictors** | ***β*** | **SE** | ***P*** |
| $\text{OutcomeDate}^2$ | -0.65 | 0.08 | **<0.001** |
| OutcomeDate | 1.37 | 0.12 | **<0.001** |
| HatchDate | -0.31 | 0.03 | **<0.001** |
| *Treatment* | | | |
| CZ2 | Base | | |
| IZ | -0.05 | 0.09 | 0.608 |
| CZ1 | 0.01 | 0.09 | 0.939 |
| *Phase* | | | |
| After | Base | | |
| Before | -0.11 | 0.11 | **0.312** |
| During | -0.22 | 0.09 | **0.018** |
| CZ2 x After | Base | | |
| IZ x Before | 0.12 | 0.17 | 0.486 |
| CZ1 x Before | -0.01 | 0.18 | 0.936 |
| IZ x During | 0.29 | 0.13 | **0.032** |
| CZ1 x During | -0.08 | 0.16 | 0.633 |
| Intercept | 0.48 | 0.07 | **<0.001** |

**Table A5.** Results of logistic regression generalized linear mixed effects model on the effects of intrinsic and landuse variables, and Phase x Treatment on Ferruginous hawk nest reoccupancy in southern Alberta. "Base" indicated the reference values for categorical covariates. Treatment included three levels of distance determined by hawk home range size: IZ (≤ 2.5 km), CZ1 (2.5 km ≥ 10 km), CZ2 (≤ 10 km). Phase also consisted of three levels: Before (2013–14), During (2015–16), and After (2017–19). Covariates were standardized before analysis.

| | **Reoccupancy** | | |
|---|---|---|---|
| **Predictors** | ***β*** | **SE** | ***P*** |
| *PreviousYearOcc* | | | |
| FEHA | Base | | |
| Other | -1.29 | 0.47 | **0.006** |
| Unoccupied | -1.40 | 0.38 | **<0.001** |
| YearsMonitored | 0.53 | 0.11 | **<0.001** |
| LooseRd | -0.22 | 0.12 | 0.064 |
| *Treatment* | | | |
| CZ2 | Base | | |
| IZ | 0.07 | 0.38 | 0.844 |
| CZ1 | 0.04 | 0.41 | 0.927 |
| *Phase* | | | |
| After | Base | | |
| Before | -0.78 | 0.46 | 0.087 |
| During | -0.29 | 0.35 | 0.406 |
| CZ2 x After | Base | | |
| IZ x Before | -0.07 | 0.68 | 0.924 |
| CZ1 x Before | 0.03 | 0.78 | 0.969 |
| IZ x During | -0.10 | 0.52 | 0.852 |
| CZ1 x During | -0.01 | 0.57 | 0.988 |
| Intercept | 1.39 | 0.24 | **<0.001** |

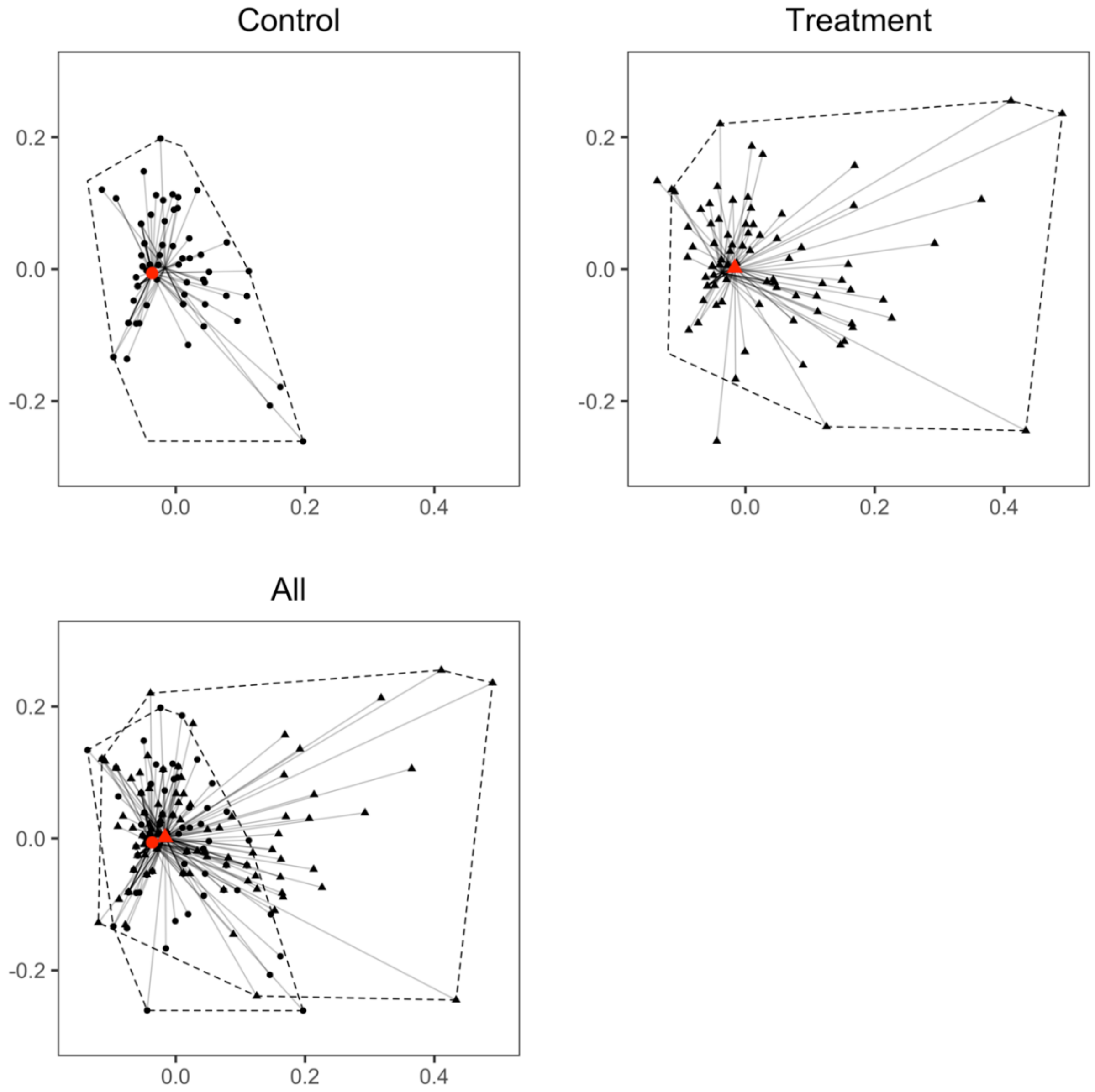
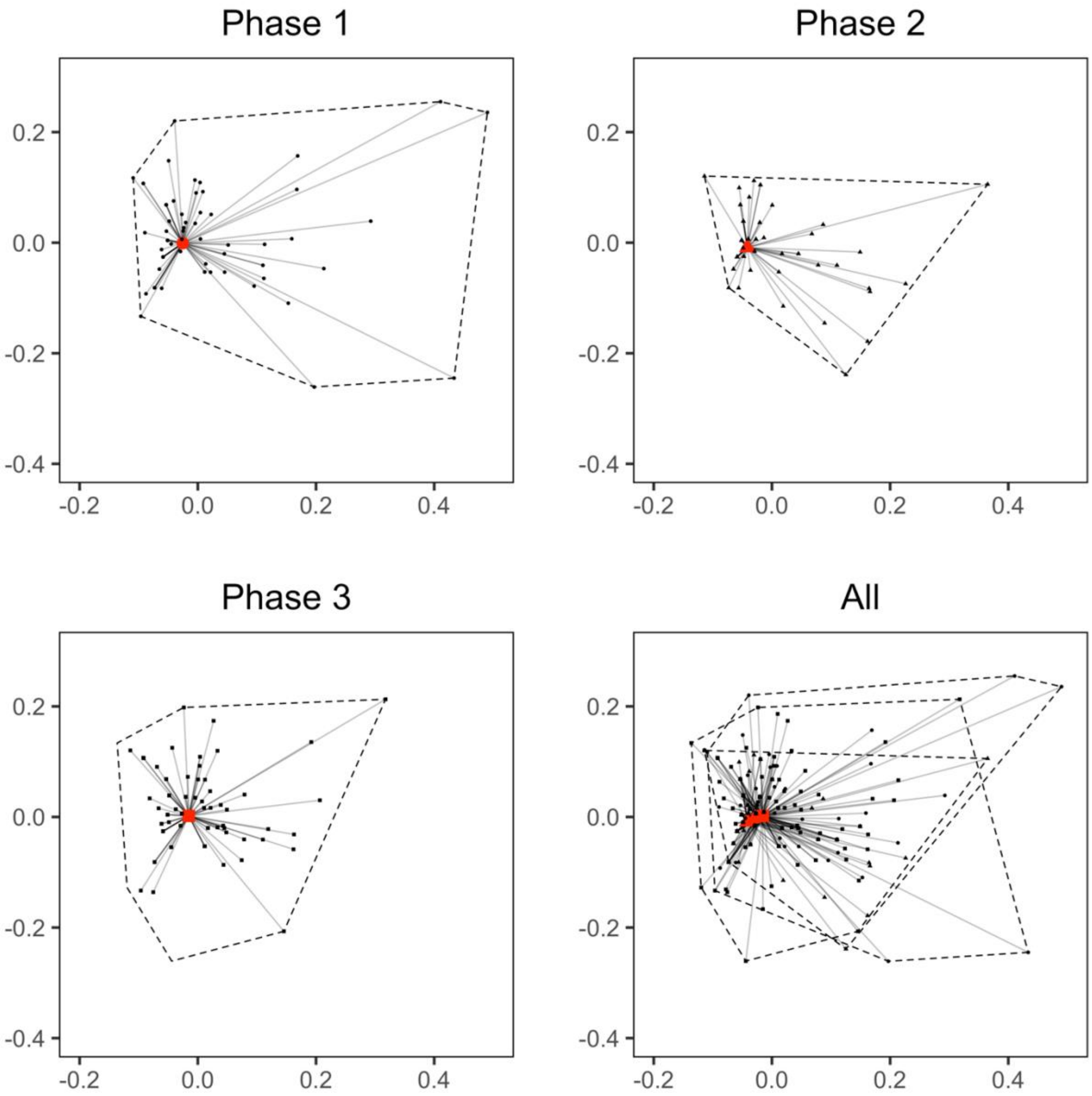


**Figure A1.** Visualization of the variation in Gower distances between species in control and impact sites. This process calculates the multivariate homogeneity of group variances from a distance matrix using the “vegdist” and “betadisper” functions in the R-package *vegan* (Oksanen et al. 2015).



Phase 1

Phase 2

Phase 3

All

**Figure A2.** Visualization of the variation in Gower distances between species during each construction phase. This process calculates the multivariate homogeneity of group variances from a distance matrix using the “vegdist” and “betadisper” functions in the R-package *vegan* (Oksanen et al. 2015).

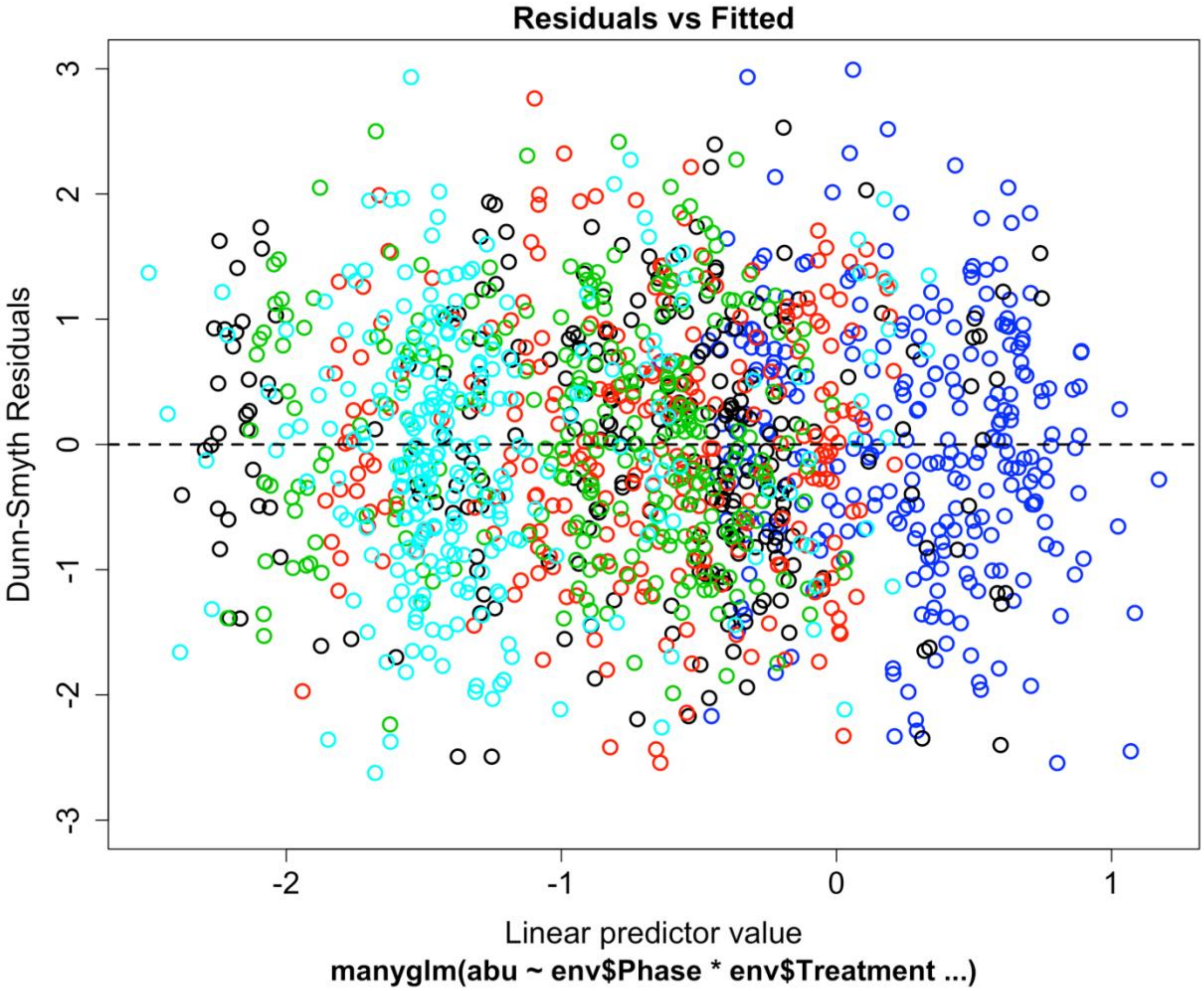


**Figure A3.** Dunn-Smyth residuals plotted against fitted values for the final ManyGLM model: manyglm(abu ~ Phase*Impact, offset = log(Area_Surveyed), family="negative_binomial).

## APPENDIX B. Chapter 3: The importance of nest substrate and effects of local weather events on Ferruginous Hawk nest persistence and breeding parameters.

**Table B1.** Covariates used to model fledgling productivity and DSR of Ferruginous Hawks in Alberta, Canada between 2010–2017. Weather metrics for fledgling productivity were calculated for each breeding season stage (incubation and nestling) whereas DSR metrics were calculated between each nest visit.

| Variables | Description | Data Source | Type |
|---|---|---|---|
| *Weather* | Inverse-distance weighted weather covariates from weather stations within 50 km of a nest site. All weather parameters based on the interval between nest visits | | |
| Temperature | Average, maximum, and minimum daily temperature (°C) | Alberta Agriculture and Forestry | Continuous |
| Precipitation | Total, average, maximum, and average days with 90th percentile precipitation (mm), days >1mm, days >7mm | Alberta Agriculture and Forestry | Continuous |
| Wind | Average, maximum, and days with 90th percentile and ≥30km/h wind | Alberta Agriculture and Forestry | Continuous |
| Wind gust | Average and maximum hourly wind gusts (km/h) | Alberta Agriculture and Forestry | Continuous |
| *Nest Characteristics* | | | |
| Substrate | Type of nest substrate (e.g., anthropogenic: platform, distribution pole, transmission tower, other miscellaneous structure; natural: tree, cliff, rocky outcrop) | Field Data | Categorical |
| Landcover | Proportion of dominant land cover (agriculture or grassland) surrounding nest at 2500 and 5000 m radii | Field Data | Continuous |
| *Period* | | | |
| Year | Year of study. Random effect | Field Data | Continuous |
| JulCID | Julian date of clutch initiation | Field Data | Continuous |
| *Geographic location* | | | |
| Region | Prairie subregion | Online spatial data | Categorical |

**Table B2.** Candidate models considered for assessing the persistence of Ferruginous Hawk nests and nesting substrates in response to different wind events during the breeding season. All models included a random effect for Year.

| Model | No. model parameters |
|---|---|
| NULL | 2 |
| SUB[†] | 4 |
| SUB + AVGWIND | 5 |
| SUB + WIND90TH | 5 |
| SUB + WIND30KMH | 5 |
| SUB + WINDGUST90TH | 5 |
| SUB + MAXGUST | 5 |

[†]Indicates nest substrate variable

**Table B3.** Candidate models considered for assessing Ferruginous Hawk nest productivity in response to weather variables during the incubation and nestling stages of the breeding season. Intrinsic parameters included CID and estimated nestling age from hatch. All models included a random effect for Year.

| Model | No. model parameters |
|---|---|
| **Incubation and nestling stage** | |
| NULL | 3 |
| INTRINSIC + SUB[†] | 6 |
| INTRINSIC + SUB + ECOREGION | 8 |
| INTRINSIC + SUB + LANDCOVER | 6 |
| INTRINSIC + SUB + ECOREGION + LANDCOVER | 9 |
| INTRINSIC + SUB + ECOREGION + LANDCOVER + WIND | 10 |
| INTRINSIC + SUB + ECOREGION + LANDCOVER + PRECIP | 10 |
| INTRINSIC + SUB + ECOREGION + LANDCOVER + TEMP | 10 |
| INTRINSIC + SUB + ECOREGION + LANDCOVER + WIND x SUB | 12 |
| INTRINSIC + SUB + ECOREGION + LANDCOVER + WIND x PRECIP | 12 |
| **Nestling stage only** | |
| INTRINSIC + SUB + ECOREGION + LANDCOVER + WIND x TEMP | 12 |
| INTRINSIC + SUB + ECOREGION + LANDCOVER + TEMP x PRECIP | 12 |
| INTRINSIC + SUB + ECOREGION + LANDCOVER + TEMP x SUB | 12 |

[†]Indicates nest substrate variable

**Table B4.** The final candidate model set considered for assessing the daily survival rate of Ferruginous Hawk nests in southern Alberta between 2010–2017. Intrinsic parameters included CID and estimated nestling age from hatch. Models with non-significant interaction terms were dropped from the final model set. All models included a random effect for NestID.

| **Model** | **No. model parameters** |
|---|---|
| NULL | 1 |
| INTRINSIC | 4 |
| INTRINSIC + SUB† | 6 |
| INTRINSIC + SUB + ECOREGION | 8 |
| INTRINSIC + SUB + LANDCOVER | 7 |
| INTRINSIC + SUB + ECOREGION + LANDCOVER | 9 |
| INTRINSIC + SUB + ECOREGION + LANDCOVER + AVGTEMP | 10 |
| INTRINSIC + SUB + ECOREGION + LANDCOVER + MAXPRECIP | 10 |
| INTRINSIC + SUB + ECOREGION + LANDCOVER + AVGWIND | 10 |
| INTRINSIC + SUB + ECOREGION + LANDCOVER + AVGTEMP + MAXPRECIP | 11 |
| INTRINSIC + SUB + LANDCOVER + AVGTEMP + AVGWIND | 9 |
| INTRINSIC + SUB + ECOREGION + LANDCOVER + MAXPRECIP + AVGWIND | 11 |
| INTRINSIC + SUB + ECOREGION + LANDCOVER + MAXPRECIP + AVGWIND + AVGTEMP | 12 |
| INTRINSIC + SUB + ECOREGION + LANDCOVER + AVGTEMP + MAXPRECIP + AVGTEMP x MAXPRECIP | 12 |

†Indicates nest substrate variable

**Table B5.** The final candidate model set considered for assessing the daily survival rate of all successful Ferruginous Hawk nests and those that failed from blowing out between 2010–2017. Models with non-significant interaction terms were dropped from the final model set. Models were simplified compared to models in Table A2 to account for small sample sizes of failed nests.

| **Model** | **No. model parameters** |
|---|---|
| NULL | 1 |
| SUB† + LANDCOVER | 4 |
| SUB + LANDCOVER + AVGTEMP | 5 |
| SUB + LANDCOVER + MAXPRECIP | 5 |
| SUB + LANDCOVER + AVGWIND | 5 |
| SUB + LANDCOVER + AVGTEMP + MAXPRECIP | 6 |
| SUB + LANDCOVER + AVGTEMP + AVGWIND | 6 |
| SUB + LANDCOVER + AVGWIND + MAXPRECIP | 6 |
| SUB + LANDCOVER + AVGWIND + MAXPRECIP + AVGTEMP | 7 |

†Indicates nest substrate variable

**Table B6.** (A) Models from the 95% confidence set of candidate models and null model for nest persistence as a response to wind events during the Ferruginous Hawk breeding season. For each model we present: the number of model parameters (*K*), AIC$_c$, ΔAIC$_c$, AIC$_c$ weights ($w_i$), and log-likelihood values (LL).

| **Model** | ***K*** | **AIC$_c$** | **ΔAIC$_c$** | **$w_i$** | **LL** |
|---|---|---|---|---|---|
| SUB[†] + WINDGUST90TH | 5 | 619.65 | 0.00 | 0.60 | -304.79 |
| SUB | 4 | 622.79 | 3.14 | 0.12 | -307.38 |
| SUB + WIND90TH | 5 | 623.39 | 3.74 | 0.09 | -306.66 |
| SUB + MAXGUST | 5 | 623.72 | 4.08 | 0.08 | -306.83 |
| SUB + WIND30KMH | 5 | 624.30 | 4.64 | 0.06 | -307.12 |
| NULL | 2 | 637.86 | 18.21 | <0.01 | -316.92 |

[†]Indicates nest substrate variable

**Table B7.** (A) Models from the 95% confidence set of candidate models and null model for nest productivity during the incubation and nestling stages of the Ferruginous Hawk breeding season. Intrinsic parameters included CID and estimated nestling age from hatch. For each model we present: the number of model parameters (*K*), AIC$_c$, ΔAIC$_c$, AIC$_c$ weights ($w_i$), and log-likelihood values (LL). Breeding period indicates timing of weather variables (I: Incubation; N: Nestling).

| **Model** | **Breeding Period** | ***K*** | **AIC$_c$** | **ΔAIC$_c$** | **$w_i$** | **LL** |
|---|---|---|---|---|---|---|
| INTRINSIC + SUB[†] + REGION + MAXPRECIP | N | 9 | 2562.08 | 0.00 | 0.65 | -1271.92 |
| INTRINSIC + SUB + HABITAT + WINDDAYSOVER30KM x MAXPRECIP | N | 12 | 2565.92 | 3.85 | 0.09 | -1270.76 |
| INTRINSIC + SUB + HABITAT + MAXTEMP | I | 10 | 2566.55 | 4.47 | 0.07 | -1273.13 |
| INTRINSIC + SUB + HABITAT + SUB x AVGTEMP | N | 12 | 2566.86 | 4.79 | 0.06 | -1271.23 |
| INTRINSIC + SUB + HABITAT | I | 9 | 2567.36 | 5.28 | 0.05 | -1274.56 |
| INTRINSIC + SUB + HABITAT + PRECIP7MMDAYS | I | 10 | 2569.16 | 7.08 | 0.02 | -1274.44 |
| NULL | - | 3 | 2607.02 | 44.95 | 0.00 | -1300.50 |

[†]Indicates nest substrate variable

**Table B8.** (A) Models from the 95% confidence set of candidate models and null model for daily survival rates during the Ferruginous Hawk breeding season. Intrinsic parameters included CID and estimated nestling age from hatch. For each model we present: the number of model parameters (*K*), $\text{AIC}_c$, $\Delta\text{AIC}_c$, $\text{AIC}_c$ weights ($w_i$), and log-likelihood values (LL).

| **Model** | ***K*** | **$\text{AIC}_c$** | **$\Delta\text{AIC}_c$** | **$w_i$** | **LL** |
|---|---|---|---|---|---|
| INTRINSIC + SUB[†] + GRASS + AVGTEMP + AVGWIND | 9 | 497.91 | 0.00 | 0.70 | -239.91 |
| INTRINSIC + SUB + HABITAT + AVGTEMP + AVGWIND + MAXPRECIP | 12 | 501.72 | 3.82 | 0.10 | -238.79 |
| INTRINSIC + SUB + HABITAT + AVGWIND + MAXPRECIP | 11 | 501.81 | 3.91 | 0.10 | -239.85 |
| INTRINSIC + SUB + HABITAT + AVGWIND | 10 | 503.35 | 5.45 | 0.03 | -241.63 |
| NULL | 2 | 522.38 | 24.47 | 0.00 | -259.19 |

[†] Indicates nest substrate variable

**Table B9.** (A) Models from the 95% confidence set of candidate models and null model for daily survival rates of all successful nests and those that failed from blowing out during the Ferruginous Hawk breeding season. For each model we present: the number of model parameters (*K*), $\text{AIC}_c$, $\Delta\text{AIC}_c$, $\text{AIC}_c$ weights ($w_i$), and log-likelihood values (LL).

| **Model** | ***K*** | **$\text{AIC}_c$** | **$\Delta\text{AIC}_c$** | **$w_i$** | **LL** |
|---|---|---|---|---|---|
| SUB[†] + GRASS + AVGTEMP + AVGWIND | 6 | 187.79 | 0.00 | 0.315 | -87.87 |
| SUB + GRASS + MAXPRECIP + AVGWIND | 6 | 187.94 | 0.147 | 0.293 | -87.95 |
| SUB + GRASS + AVGTEMP + AVGWIND + MAXPRECIP | 7 | 188.16 | 0.366 | 0.263 | -87.05 |
| NULL | 1 | 524.88 | 11/244 | 0.00 | -98.52 |

[†] Indicates nest substrate variable