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Research Paper

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 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 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 re-occupancy, and (5) changes to nesting raptor and raven community composition. We found no effect of phase and site on nest success, productivity, or re-occupancy. 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 higher 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 population, providing evidence that this population can be increased by adding nesting substrates (e.g., trees or nest platforms) to the landscape.

Réactions des buses rouilleuses aux altérations temporaires de l'habitat en raison du développement énergétique au sud-ouest de l'Alberta

RÉSUMÉ. Les prairies tempérées figurent parmi les biomes les plus altérés dans le monde entier, en grande partie en raison de la modification anthropogénique. La construction rapide de projets liés aux énergies renouvelables est nécessaire pour répondre à une demande croissante et la mise à jour des projets existants nécessite des modifications de l'infrastructure associée. Les effets directs de ces développements sur la faune sont relativement bien compris (par ex. le risque de mortalité). En revanche, on comprend mal les impacts indirects sur la reproduction des animaux à proximité des installations. Nous avons utilisé un modèle d'impact sur un site témoin avant-pendant-après (BDACI) pour déterminer l'influence des modifications des lignes électriques à haute tension sur une population menacée de buse rouilleuse (Buteo regalis) au sud de l'Alberta, au Canada. Sur la base de données recueillies entre 2013 et 2019, nous avons comparé la réaction des buses reproductrices aux trois phases du développement entre des sites de référence et des sites impactés afin de déterminer si le nombre de pylônes de transmission dans le paysage pouvait influencer cette population locale et si des modifications pourraient entraîner un puits de population ou un piège écologique. Des modèles mixtes linéaires généralisés ont été utilisés pour tester cinq réactions : (1) Densité des nids de buses rouilleuses, (2) succès des nids, (3) productivité, (4) réoccupation des sites de nidification et (5) changements de la composition de la communauté de rapaces nidificateurs et de corbeaux. Nous n'avons constaté aucun effet de la phase et du site sur le succès des nids, la productivité ou la réoccupation. Toutefois, la densité des nids a nettement augmenté de >37 % après l'ajout de pylônes, mais est revenue aux niveaux antérieurs à la construction après l'élimination des pylônes. En outre, la composition des communautés a beaucoup changé avec une variabilité supérieure à proximité des sites impactés. Notre étude est la première à tester les effets du développement énergétique sur les niveaux de population d'un rapace menacé en utilisant un modèle BDACI solide. Notre modèle expérimental démontre que la disponibilité de structures de nidification limite la taille de cette population et qu'il est possible d'augmenter cette population en ajoutant des substrats de nidification (par ex. des nids ou des plateformes de nidification) dans le paysage.

Key Words: *BACI; Buteo regalis; ecological trap; energy infrastructure; Ferruginous Hawk; human development; nest density*

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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) with a 28% increase in global energy demand 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 km² of new land is expected to be developed for energy-related projects by 2035 (McDonald et al. 2009). With these energy projects, associated infrastructure such as transmission lines often requires 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) that reduces avian breeding performance (D'Amico et al. 2018). 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 preferred 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). If 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 for particular species, is poorly understood (Richardson et al. 2017). Importantly, it is not always known if using such perching or nesting structures creates a bias in observer detection, or whether these structures are actually 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 *Buteos*, some studies suggest Ferruginous Hawks are the most likely 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). Despite the At Risk status of the Ferruginous Hawk, potential threats from the continued development and upgrading of energy projects and their associated infrastructure through grassland habitats remain largely unknown. Our study uses a unique opportunity to assess the response of a local population of Ferruginous Hawks to temporary alterations to nest-site availability via transmission line construction and decommissioning with 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 re-occupancy 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

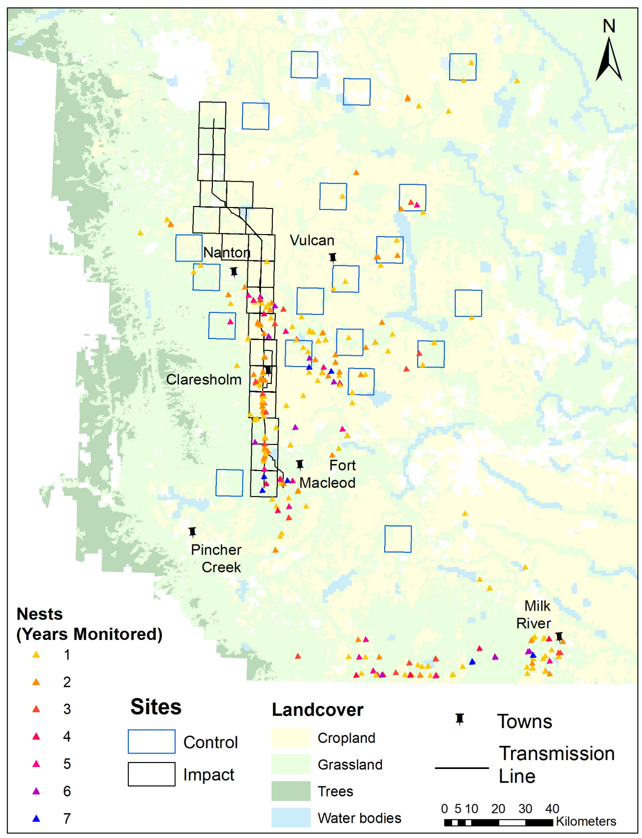
Ethics Statement

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 km² 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 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 between Fort MacLeod (49.72° N, -113.40° W) and Calgary (51.05° N, -114.07° W; Fig. 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 (Fig. 2). 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 horizontal 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. There was a median distance of 156 m between new and old transmission towers when both towers were present in 2015 and 2016. Towers with Ferruginous Hawk nests defined as active under provincial guidelines (i.e., occupied 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.

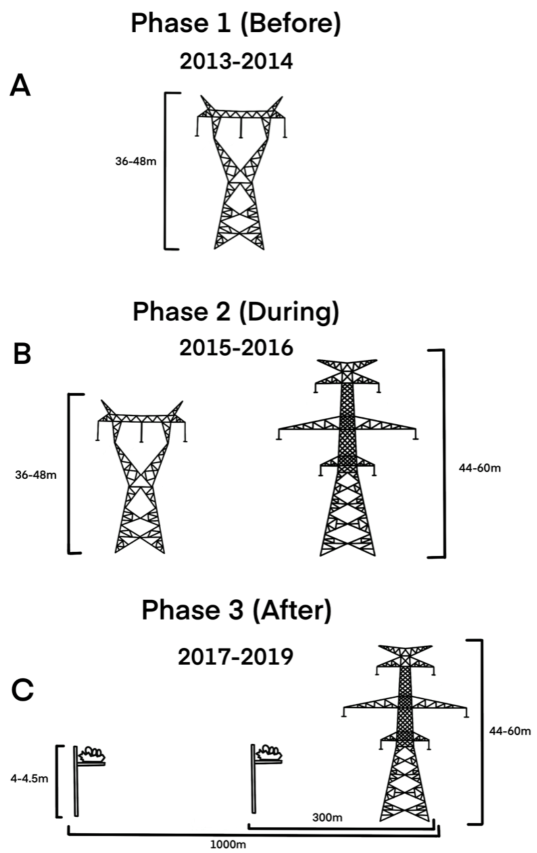
Fig. 1. Overview of the study area in southern Alberta, showing both the impact and control survey blocks surveyed from 2013-2019. Impact blocks (n=19) were placed to represent areas within 5km of transmission line development. Control blocks (n=19) were selected based on similar landscape characteristics of impact 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. Control blocks were selected based on similar landscape characteristics of corresponding impact sites (i.e., % grassland, cropland, and human footprint [e. g. roads and 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 (Fig. 1).

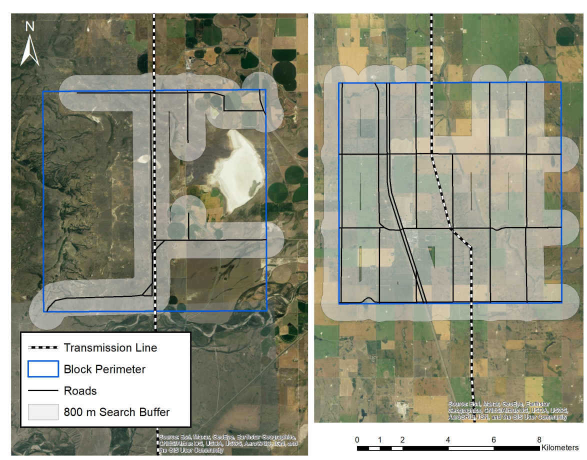
Fig. 2. Phases of construction, years of each phase, and tower heights and distances show the Before (A), During (B), and After (C) components of transmission line construction. The original single circuit 240-kV towers were replaced with larger double circuit 240-kV towers over three stages between 2014 and 2017. One or two nest platforms were installed between 300 and 1000 m away from transmission towers where active nests (i.e., occupied at least once in the previous three breeding seasons) were removed from old towers. Note: Transmission towers, platforms, and distances are not to scale.



Survey Protocol

Stick nest surveys were conducted between mid-April and early May to ensure nesting Ferruginous Hawks were present either on or near their nests to coincide with observable breeding behaviors. 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, iii) routes spanned each block from north to south and east to west, where possible, and iv) when a transmission line was present, the survey route was selected both parallel and perpendicular to the transmission 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 (Fig. 3). 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, μ = 9.4 m, median = 2.8 m).

Fig. 3. 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 (km2; 800m buffer around roads driven).



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 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 behavior. 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). 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 were (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.

Occasionally, we were unable to identify the occupant of a nest (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. Variable Definitions

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. All models were fit with a Phase (timing of construction) and Site (Impact and Control) interaction term to test for change using the BDACI design where a significant interaction indicates an effect of impacted sites on the response variable different than the control sites (Osenberg and Schmitt 1996, Morrison et al. 2008). Phase refers to the time of transmission line construction and included three levels: Before, During, and After. Two levels were included for Site: Impact and Control.

Nest success, productivity, and re-occupancy 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 km²; 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 large (CZ2; >10 km) distances from the transmission line. re-occupancy 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 nest success (e.g., historical nests that failed early could be used in re-occupancy models, but not in success or productivity analyses) and observer confidence in our ability to estimate productivity. Statistical Analysis

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 re-occupancy) Count data is often modeled with Poisson or, if overdispersed, a negative binomial distribution. 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. A random effect for BlockID (nest density model) or NestID (success, productivity, and re-occupancy models) was included to account for non-independence of repeated measures. 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 intrinsic variables not related to our primary questions. 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). Base models were developed in three steps and if the addition of a covariate improved the base model, then it was included in the next step. 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 by order of significance. If AIC_c was not lowered, then variables were not retained (Arnold 2010). All models within ΔAIC_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).

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. Analyses were performed in RStudio v1.0.143 (RStudio Team 2015) and results were considered significant at α <0.05. Community Analysis

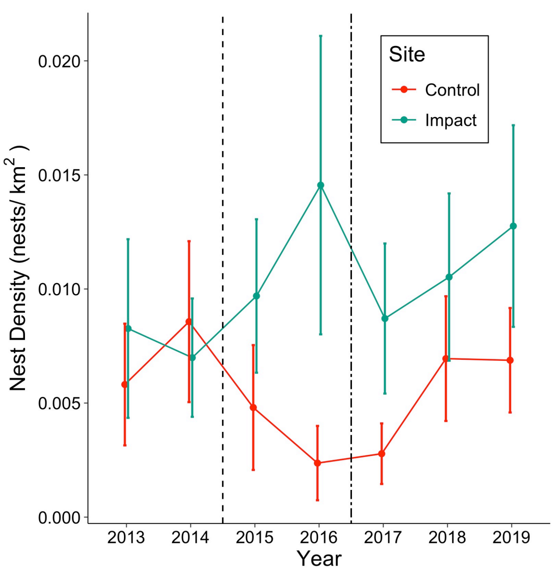
To detect patterns in our raptor and raven community dataset, we used multivariate analyses with the ManyGLM function of the mvabund package (version 4.0.1) in RStudio. This model-based approach to handling multivariate data tests the response of the community assemblage as a whole and then separately for each species with univariate tests (Wang et al. 2012). To account for non-independence in our repeated measures block design, we permuted the species abundance within each replicate (BlockID) and used PIT-trap (probability integral transformation residuals) bootstrap resampling, which returns dependable Type I error rates (Warton et al. 2017). Raw abundance data for each species was used as our response variable and an offset of the logarithm of area surveyed was included 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).

RESULTS

Nest Density

Between 2013-2019, 1,441.9 km²/ year were surveyed at impact blocks (n = 19) and 1,295.6 km²/ year at control blocks (n = 19) on average. Annually, we found an average of 0.56 Ferruginous Hawk nests/ block totaling 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/ km² in impact blocks and 0.005 nests/km² in control blocks. Across all years, impact block nest densities ranged from 0 to 0.092 nests/km² and 0 to 0.050 nests/km² in control blocks (Fig. 4, Table 1).

Fig. 4. 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.



The subregion (χ^2 = 16.94, P <0.001) and proportion of grassland (χ^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 (χ^2 = 5.98, P = 0.050; Table 2). Means in the impacted blocks for both During (β = 0.967, P = 0.029) and After (β = 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).

Table 1. Summary table of block surveys for impact (n = 19) and control blocks (n = 19) from 2013 to 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 (km²)	Nest Density (nests/km²) (*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

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; Fig. 5, Table 3), which had 6.83% higher success and produced 0.47 fledglings/ nest more than the next highest Treatment-Phase combination (CZ2, During).

OutcomeDateQuadratic and HatchDate were significant intrinsic variables included in the final nest success (χ^2 = 12.22, df = 1, P < 0.001 and χ^2 = 37.35, df = 1, P < 0.001, respectively) and productivity models (χ^2 = 59.99, df = 1, P < 0.001; χ^2 = 93.26, df = 1, P < 0.001, respectively). After controlling for these intrinsic variables we did not find a significant interaction between Phase and Treatment for either nest success (χ^2 = 0.51, df = 4, P = 0.973) or productivity (χ^2 = 5.37, df = 4, P = 0.252; Table 2) models. A significant effect of Impact Zones was observed (χ^2 = 9.05, df = 2, P = 0.011) with a large increase in successful IZ nests (β = 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.

Table 2. Summary statistics (Wald's χ^2 and P-values) of fixed effects from the Ferruginous Hawk response to habitat change models.

Model	Predictor	DF	χ^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*Phase	2	5.98	0.050
Success				
	OutcomeDa-teQuadratic	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*Phase	4	0.52	0.971
Productivity				
	OutcomeDa-tQuadratic	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*Phase	4	6.39	0.172
Reoccupancy				
	PrevYearOcc	2	18.91	<0.001
	YearsMonit-ored	1	23.55	<0.001
	LooseRd	1	3.43	0.064
	DZ	2	0.02	0.989
	Phase	2	7.25	0.023
	DZ*Phase	4	0.04	0.999

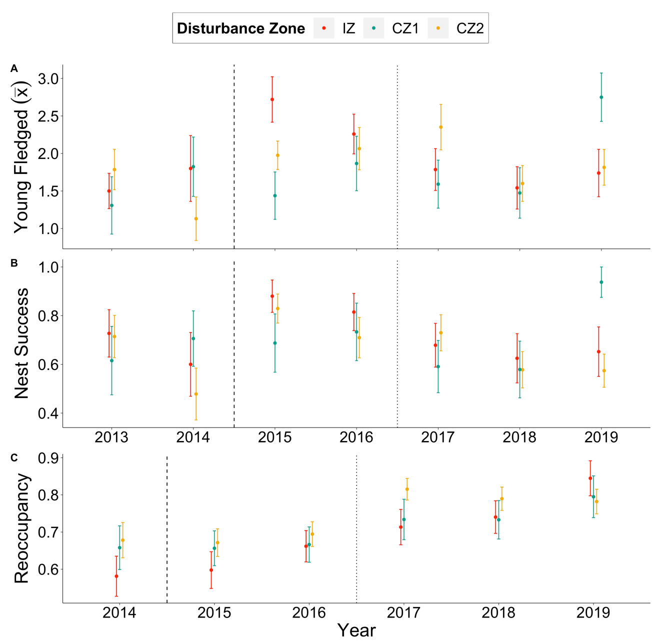
†Disturbance Zone

Table 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 911L Transmission Line (IZ < 2.5 km; CZ1 > 2.5 km < 10 km; CZ2 > 10 km)
‡Young defined as fledglings when ≥40 days old.
§Nest success defined by ≥1 fledgling observed in nest.

Fig. 5. 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.



Re-occupancy

We completed 437 re-occupancy 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 (χ^2 = 0.62, df = 4, P = 0.960; Fig. 5, Table 2). A significant effect of phase was observed (χ^2 = 9.95, df = 2, P = 0.007) with a low re-occupancy rates before construction (β = -1.35, P = 0.011). Random effects overfit the model (SD and variance <0.001) and were dropped from final models.

Table 4. Abundance and nest density values of nest-site competitors observed during block surveys from 2013 to 2019.

	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

Fig. 6. 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.

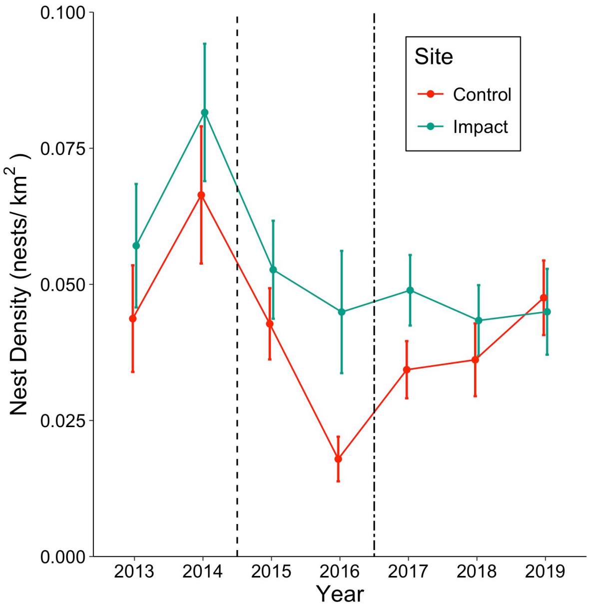
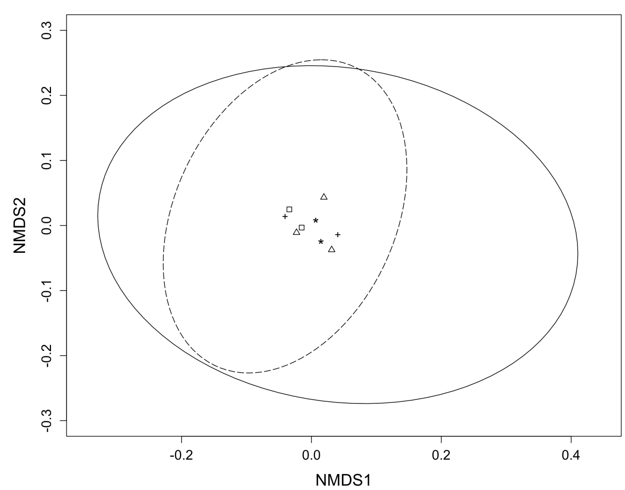


Fig. 7. Non-metric multidimensional scaling (NMDS) scores for the competitive nesting bird community structure at control and impact sites between 2013 and 2019. The "+" symbols indicate ellipse centroids. The solid ellipse represents the 0.7 standard deviation around the ellipse centroid of impact sites, 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". Distances between symbols indicate the level of similarity between sites where closer distances have similar community composition.



Community Analysis

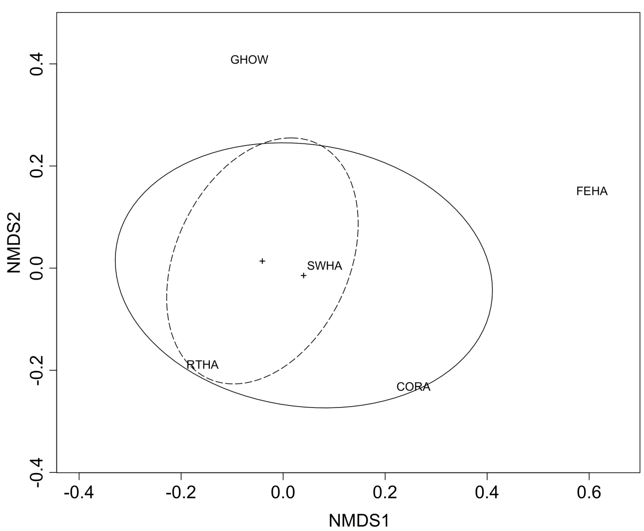
Four raptors and ravens were observed in each Phase and Site: Common Raven, Ferruginous Hawk, Great Horned Owl, Red-tailed Hawk, and Swainson's Hawk. Impact sites varied substantially relative to control sites with Ferruginous Hawks and Common Ravens most strongly associating with impact blocks (Fig. 7). Though species richness was unchanged, nest densities and species site affiliation varied largely (Table 4, Fig. 8).

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 (χ^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 success, productivity, and re-occupancy. 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 via transmission tower construction and subsequent removal. However, we found a significant change in nest densities where densities increased following the construction of new transmission towers and subsequently decreased following old tower removal.

Fig. 8. NMDS scores for the competitive nesting bird community structure at control and impact sites between 2013 and 2019. The "+" symbols indicate ellipse centroids. 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 (AOU) codes. Distances between AOU codes indicate the level of similarity between sites where closer distances have similar community composition.



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/ km²; Control: 0.0036 - 0.0072 nests/ km²), but both sites were similar to those observed in previous studies (0.003 - 0.063 nests/ km² [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/ km² [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 km² 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.

Table 5. Results of multivariate and univariate tests assessing species assemblage change following transmission line construction and decommission during our 7-year study. Only univariate tests with a significant Site*Phase interaction are included in the results.

	Res. Df	Df. Diff	χ^2	P
Multivariate				
Phase-only	255			
Site*Phase	252	3	6.34	0.030
Univariate				
No species significant			1.15<>3.58	0.095<>0.710

Table 6. Percent of species contribution to changes in community composition based on the individual contribution of each species to the Sum-of-LR.

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

Some evidence suggests that nest substrate availability can limit population densities of open-country raptors (Restani 1991, Janes 1994). Even at high initial densities, Ferruginous Hawk densities may increase after the addition of suitable artificial nest substrates to the surrounding landscape (Schmutz et al. 1984). Here, the significant, temporary increase in Ferruginous Hawk nest density followed by a return to pre-construction levels indicates that even relatively small changes to nest-site availability can affect local breeding populations. The steady increase in post-construction nest densities suggests that available nesting substrates are limited in the area and that Ferruginous Hawks will exploit newly abundant nesting substrates, when available. Further, the limited response of nest success and productivity following a significant increase in nest densities suggests that, if other factors important for breeding remain static or increased, the area can support a larger population of Ferruginous Hawks and that hawks were not limited by prey. However, nest-sites are not the only limiting factor for Ferruginous Hawks (i.e., prey abundance) so local nesting densities could vary in different areas after transmission line densities are increased. The introduction of new structures likely has the greatest impact on breeding raptors in areas of attractive habitat with limited nesting substrates (Smith and Murphy 1978, Knight and Kawashima 1993). Previous research recommends that Ferruginous Hawk conservation efforts should target areas with high prey density and install ANPs to enhance habitat (Wallace et al. 2016). Our results demonstrate the importance of considering nest-site availability as a limiting factor in breeding populations even in areas where the number of nest-sites was already inflated substantially (via existing transmission line towers).

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. Floaters have been reported in some Ferruginous Hawk populations (Ayers et al. 2009) but are absent from others (Schmutz et al. 2008). As part of a separate study, several hawks (n = 14; 13 males, 1 female) nesting on transmission line towers in our study area were monitored with GPS/ GSM transmitters. In 2017, a single male was confirmed to be occupying a territory overlapping with the transmission line but not using any nest-site (J. Watson, *personal communication*). 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 are 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). Though differences were not significant, Impact Zone nests fledged more young on average (1.95 fledglings) and had higher success rates (73.3%) than those in either Control Zone. Similarly, 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 have 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).

Early in the breeding season, Ferruginous Hawks are sensitive to anthropogenic disturbance near nest sites (White and Thurow 1985, Keeley and Bechard 2011). It is important to note 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 re-occupancy (>70%; Woffinden and Murphy 1989, Schmutz et al. 2008). Re-occupancy 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). High re-occupancy 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 re-occupancy rates between transmission tower construction and removal (64.6% and 59.5%, respectively), but there was no effect on re-occupancy from either disturbance. High re-occupancy rates have also been reported for birds returning to within two towers of a previous nest (82.4%). Slightly lower re-occupancy 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). In our study, re-occupancy 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). The re-occupancy rates in our study were possibly lower than those of other studies because of the relatively high number of nests in transmission towers where re-occupancy was low. Similarly, several studies have included wind damage and destruction as the greatest 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 as no single species was driving community change. After the removal of rare species, breeding raptor and raven diversity were 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 legally protected Ferruginous Hawk nests) were removed from transmission towers. Steenhof et al. (1993) suggested that raptors and ravens will not be deterred from nesting on towers after nest removal, however exact timelines of nest re-construction are not known. Though annual stick nest removal may not deter nesting on transmission towers, it could be limiting overall raptor and raven nest densities. We were unable to collect data for nest success, productivity, or re-occupancy 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 re-occupancy. 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 parameters and re-occupancy 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 nearly 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 that depend on associated infrastructure. 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.

Responses to this article can be read online at:
https://www.ace-eco.org/issues/responses.php/1958

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Appendix 1. Covariates considered for all models.

Table A1.1 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.

Model 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 Substrate_Tri	SU, PR 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)

Appendix 2. Results of all models.

Table A2.1. Estimated coefficients (β), standard errors, P-values, and random effects for parameters included in the Ferruginous Hawk nest density model. Phase indicates time blocks from 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 A2.2. 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 prior to analysis.

Predictors	β	SE	P
OutcomeDateQuadratic	-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 A2.3. Results of linear regression generalized linear mixed effects model on the effects of intrinsic and landuse factors, 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 prior to analysis.

Predictors	β	SE	P
OutcomeDateQuadratic	-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 A2.4. Results of logistic regression generalized linear mixed effects model on the effects of intrinsic and landuse factors, 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 prior to analysis.

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