IMPACTS OF WIND ENERGY DEVELOPMENT ON BREEDING *BUTEO* HAWKS IN THE COLUMBIA PLATEAU ECOREGION

by

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ABSTRACT

Post-construction raptor fatality and nest monitoring is typically conducted at wind energy projects nationwide. However, pre- and post-construction surveys may fail to locate all breeding pairs and most studies at individual wind projects lack the necessary sample size or survey design to assess the effects of turbines on nesting raptors after construction. To address these potential issues, I used an information-theoretic approach to examine the influence of multiple spatial and temporal variables on reproductive success, post-fledging survival, and the distribution of breeding pairs from three sympatric *Buteo* species in the Columbia Plateau Ecoregion (CPE). Although the probability of detecting breeding pairs was relatively high (71-90%, ± 0.09-0.05), and sampling units were likely to be re-occupied (76-100% ± 0.14-0.10), I was not able to locate all nests in the 2010 or 2011 breeding seasons despite multiple surveys for each species. The occurrence of breeding pairs was not associated with wind turbines or surrounding habitat types; instead ferruginous hawks (*Buteo regalis*) and red-tailed hawks (*Buteo jamaicensis*) selected areas in relation to the density of nesting substrates. Swainson's hawks (*Buteo swainsoni*) were more likely to nest in areas with other breeding *Buteo* pairs, but my results suggest that all three species may have minimized competition through staggered nesting and spatial segregation. According to nest survival models, the daily survival rate (DSR) of ferruginous hawk nests decreased as the number of wind turbines within the home range buffer (32 km^2) increased ($\hat{\beta}$ = -0.89, SE

= 0.39, 85% CI = -1.47 to -0.30). I found no effect of turbines on the DSR for red-tailed hawk nests or any additional variables affecting the DSR for Swainson's hawk nests. I radio-marked a combined total of 60 nestlings from all three species. After fledging, none of them died directly as a result of collisions with wind turbines. This was likely due, in part, to the limited size of the natal home range (2.38 km^2, SD = 1.48), and the relatively short duration of the post-fledging period ($\bar{x}$ range = 20.75 to 31.60 days ± 1.14 to 3.30). However, the DSR during the post-fledging period was best explained by species, distance to the nearest wind turbine ($\hat{\beta}$ = 1.14, SE = 0.67, 85% CI = 0.19 to 2.10), and a quadratic effect of age. Juveniles of all three species hatched from nests closer to turbines were more likely to die from predation or starvation just after fledging and prior to initiating natal dispersal compared to those from nests further away. Taken together, these results suggest a greater effect of wind turbines on ferruginous hawk reproduction compared to the other two congeneric species. The causes of this negative association between wind turbines and these reproductive measures are unknown, but could potentially include collision mortality or indirect impacts such as disturbance or displacement of adult hawks. I recommend that methods for raptor nest surveys on wind energy projects be standardized to better facilitate the meta-analysis of long-term data and account for imperfect detection of breeding pairs. Future research should focus on the risk of collision mortality to breeding adult raptors and indirect impacts to reproduction. These data will be vital to understanding the consequences of wind turbine impacts to regional populations.

PREFACE

This thesis consists of two chapters that are formatted following guidelines from the Journal of Wildlife Management to better facilitate publication as individual manuscripts. While each chapter examines the potential impacts of wind energy development on different aspects of the breeding chronology for *Buteo* hawks, there is some overlapping content in the introduction, study area, and field methods. Chapter One focuses on factors that influence the occurrence of breeding *Buteo* hawks and resource selection, while Chapter Two examines the effects of wind turbines and other specific variables on nest success and post-fledging survival.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE: OCCUPANCY PATTERNS AND RESOURCE SELECTION BY BREEDING *BUTEO* HAWKS IN RELATION TO WIND TURBINES

Abstract

Raptor nest monitoring is typically conducted at wind energy projects nationwide to determine the abundance of breeding pairs and ensure that turbine placement is outside of disturbance buffer zones. However, pre- and post-construction surveys may fail to locate all breeding pairs and most studies at individual wind projects lack the necessary sample size or survey design to assess the effects of turbines on nesting raptors after construction. To address these potential issues, I used multi-season occupancy models (MacKenzie et al. 2003) and an information-theoretic approach to examine the distribution of breeding pairs from three sympatric *Buteo* species in the Columbia Plateau Ecoregion (CPE) in relation to multiple spatial and temporal variables. Although the probability of detecting breeding pairs was relatively high (71-90%, ± 0.09-0.05), and sampling units were likely to be re-occupied (76-100% ± 0.14-0.10), I was not able to locate all nests in the 2010 or 2011 breeding seasons despite multiple surveys for each species. The occurrence of breeding pairs was not associated with wind turbines or surrounding habitat types; instead ferruginous hawks (*Buteo regalis*) and red-tailed hawks (*Buteo jamaicensis*) selected areas in relation to the density of nesting substrates. Swainson's hawks (*Buteo swainsoni*) were more likely to nest in areas with other breeding *Buteo* pairs, but my results suggest that all three species may have minimized competition through staggered nesting and spatial segregation. I recommend that methods for raptor nest surveys on wind energy projects be standardized to better facilitate the meta-analysis of long-term data and account for imperfect detection of breeding pairs. Wind energy developers should collect more than one year of pre-construction raptor nest data or examine locations of historical nests and potential nesting substrates to avoid higher-quality areas when siting turbines to minimize any possible impacts to breeding raptors.

Introduction

Wind energy development has greatly expanded in the U.S. and throughout the Columbia Plateau Ecoregion (CPE; Thorson et al. 2003) in recent years. As of 2012, Oregon had 3,153 MW of generating power, predominantly from projects in the CPE, ranking fourth in the U.S. for installed wind capacity. The state of Washington had 2,699 MW of generating capacity in 2012 and ranked sixth in the nation for total overall wind power installation (AWEA 2012). This rapid increase in wind energy development is expected to continue with an additional 14,306 MW in queue from future projects in Oregon and an additional 5,807 MW in Washington (AWEA 2012). Wind energy development has primarily occurred in rural areas that have not previously seen large-scale human disturbance, aside from farming and ranching activities. The response to this type of development from many species, such as the state-listed “Sensitive-critical” ferruginous hawk (*Buteo regalis*) in Oregon (Oregon Department of Fish and Wildlife 2006), is not yet known.

Impacts to wildlife resulting from anthropogenic activities, such as wind and other sources of energy development, can result from a wide variety of direct and indirect causes. Many of these impacts can reduce survival, breeding success, and other important wildlife population parameters. Direct impacts to birds primarily occur as collisions with turbines that result in injury or, more commonly, death (Erickson et al. 2001; Hunt 2002). Indirect impacts can also occur due to disturbance from increased human or mechanical noise/movement (Madders and Whitfield 2006), displacement from previously used areas (Drewitt and Langston 2006; Madders and Whitfield 2006), and habitat loss (Erickson et al. 2004; Drewitt and Langston 2006; Strickland et al. 2011). Although many of these impacts to wildlife have been shown to result from wind energy development, they appear to be highly dependent upon topography, habitat, species, and specifications of the development (Hoover and Morrison 2005; Smallwood et al. 2009).

In addition to lower survival of raptors through direct mortality, impacts of wind energy development may result in decreased reproductive success and changes to the abundance of local breeding populations. Reproduction can decline when adult raptors make behavioral changes in response to anthropogenic disturbance, such as increasing or adjusting home range sizes and making extra-home range movements (Andersen et al. 1990). Also, historical nesting areas are less likely to become re-occupied in the future when breeding raptors experience lower reproductive success or productivity (White and Thurow 1985; Neal 2007). Few studies have examined the potential effects of wind turbines on reproduction and occupancy of historical nesting areas, but negative impacts from other types of human activity and energy development have been found for some raptor species such as the ferruginous hawk (Olendorff 1993).

Of the three *Buteo* species breeding in the CPE, ferruginous hawks are especially sensitive to sources of human disturbance during the nesting season (White and Thurow

1985), but may be less likely to abandon breeding attempts in higher nesting substrates, such as transmission towers, compared with ground nests (Olendorff 1993; M.N. Kochert, U.S. Geological Survey, personal communication). Ferruginous hawks are known to nest further from buildings and roads, compared to red-tailed hawks (*Buteo jamaicensis*) and Swainson's hawks (*Buteo swainsoni*) (Bechard et al. 1990), indicating a potential avoidance of human activity compared to other sympatric species (Olendorff 1993). Ferruginous hawks may respond to repeated disturbance by flushing at greater distances (White and Thurow 1985; Keeley and Bechard 2011) and fledge fewer young (Olendorff 1973; White and Thurow 1985). Swainson's hawks respond differently to human disturbance (Dunkle 1977) depending on individual and regional variation (Fyfe and Olendorff 1976). In general, Swainson's hawks and red-tailed hawks seem tolerant of human activity (Preston and Beane 2009; Bechard et al. 2010).

The impacts of wind energy development on raptors during the breeding season are likely to vary because selection of resources during this period occurs at hierarchical spatial scales (Johnson 1980). Additionally, sympatric raptor species partition time, space, and resources to minimize interspecific competition (Newton 1979; Steenhof and Kochert 1985). This is especially true for breeding *Buteo* species that coexist throughout much of their range in the western U.S. and the CPE. Breeding pairs of raptors returning to the CPE will first select a large geographic area suitable for a territory and home range. Many raptor species exhibit strong territory and nest-site fidelity (Newton 1979), especially *Buteo* hawks (White and Thurow 1985; Lehman et al. 1998; Bechard et al. 2010). Breeding raptors, including *Buteo* hawks in the CPE, typically return to their historical territories or select an area based on landscape-scale variables such as anthropogenic activity and development (Bechard et al. 1990; Groskorth 1995; Keough and Conover 2012), surrounding habitat (Schmutz 1989; Bechard et al. 1990; Groskorth 1995), prey abundance (Schmutz 1989; Keough and Conover 2012), and nearby breeding raptors (Bechard et al. 1990; Restani 1991; Bosakowski et al. 1996; Keough and Conover 2012). After selecting a territory, breeding pairs then choose from available substrates in the area for nesting. *Buteo* hawks demonstrate a strong preference for specific types of nesting substrates (Schmutz et al. 1980; Bechard et al. 1990; Restani 1991) to further reduce competition for limited resources.

Raptor nest monitoring is conducted at wind energy projects nationwide to determine the abundance of breeding pairs and construct turbines outside of disturbance restriction buffers (Strickland et al. 2011). However, most studies at individual wind projects lack the necessary sample size for a robust analysis to fully examine impacts to the occurrence of breeding raptors. In addition, surveys for raptors may fail to locate all breeding pairs (Strickland et al. 2011), even in open habitats. Detection probability of nesting raptors may vary by species and depend upon a number of factors (Ayers and Anderson 1999; Martin et al. 2009). Study designs that fail to correct for imperfect detection could lead to biased estimates and incorrect inferences (MacKenzie et al. 2002), underestimating the abundance of the local breeding population and impacts resulting from turbine placement. Current site occupancy analyses (MacKenzie et al. 2002; 2003) provide a framework to examine the occurrence of animals over a given area in relation to a variety of variables while accounting for imperfect detection. This method of analysis is mathematically similar to a Resource Selection Function (RSF) at the population level (Design I; Manly et al. 2002) except that it minimizes the potential bias associated with imperfect detection of breeding pairs and associated nests through repeated surveys of a single sample of available resource units (MacKenzie 2006).

The goal of this study was to investigate factors that influence the occurrence of three sympatric breeding *Buteo* species (ferruginous hawk, red-tailed hawk, and Swainson's hawk) at different spatial scales of selection using methods to account for imperfect detection. In using the multi-season occupancy methods, I wanted to develop models that would permit me to relate vital rates of nesting areas (e.g., occupancy, local colonization, and local extinction of nesting areas) to various spatial characteristics. Ultimately, I hoped the inferences drawn from my analysis would inform the management actions of current and future wind energy projects. My specific objectives were to: 1) examine patterns in the occurrence of breeding hawks during two nesting seasons in relation to wind turbines and a limited number variables that have been shown to be important to these species; 2) determine the detection rate of breeding pairs under my study design; and 3) investigate patterns in resource selection that would indicate niche partitioning and potentially influence the distribution of breeding pairs.

Given the influence of spatial characteristics on resource selection for these three species, I hypothesized that the occurrence of hawks in my study would be related to wind turbines, competition from other breeding *Buteo* species, surrounding habitat, and nesting substrates. I predicted that wind turbines would negatively affect occupancy of nesting areas by breeding hawks. However, I also predicted the species-specific response to turbines would vary, given that red-tailed hawks and Swainsons's hawks are more tolerant of anthropogenic disturbance than ferruginous hawks. Additionally, increased intraspecific and interspecific competition has resulted in lower success (Schmutz et al.

1980; Cottrell 1981) and productivity (Zelenak and Rotella 1997) for these three congeneric species when nesting in close proximity. Swainson's hawks aggressively defend territories during the breeding season, sometimes removing other hawks from nests or excluding them from portions of breeding territories (Schmutz et al. 1980; Janes 1984). As a result, I predicted that increased intra- and inter-specific competition would negatively impact occupancy of nesting areas. These sympatric *Buteo* species also selected nests based on available substrates and habitat types elsewhere in the Pacific Northwest (Bechard et al. 1990). In general, ferruginous hawks nest in areas with low percentages of cultivated wheat (Schmutz 1989), where nest success rates are higher (Zelenak and Rotella 1997) compared to areas with greater proportions (>50%) or pure grassland habitats. Red-tailed hawks show more variation in selection of habitats, and Swainson's hawks readily nest in areas surrounded by wheat (Schmutz 1989; Bechard et al. 1990). Therefore, I predicted a similar relationship between the occurrence of breeding hawk pairs and dominant habitat types in my study area.

Methods

Study Area

The study area encompassed seven wind project areas in Gilliam and Morrow counties near Arlington, Oregon. Of these, five projects contained a total of 257 wind turbines that were constructed and became operational from 2006-2009: Leaning Juniper I (Pacificorp Energy), Pebble Springs (Iberdrola Renewables), Willow Creek Wind Farm (Invenergy), Rattlesnake Road Wind Farm (EDP Renewables, f.k.a. Horizon Wind Energy), and Wheat Field Wind Farm (EDP Renewables, f.k.a. Horizon Wind Energy).

One additional wind project (Leaning Juniper II, Iberdrola Renewables) was under construction in 2010 and became operational in early 2011 with 117 wind turbines. The study area also included one project in the permitting phase of wind energy development (Montague-Iberdrola Renewables), and areas that were not related to wind energy development (The Nature Conservancy's Boardman Conservation Area, Bureau of Land Management land, and privately-owned land). Most of the 374 turbines in the developed project areas were arranged in strings of two to 18 turbines, running north-south along ridges and plateaus, and spaced approximately 100 to 260 m apart within each string. The wind turbines were all newer-generation 2.1 megawatt Suzlon S88 turbines or 1.5 megawatt General Electric SLE turbines, both with tubular towers and of similar size.

Habitat types and land uses within the study area occurred as a mosaic that is consistent throughout the CPE (Oregon Department of Fish and Wildlife 2006). These habitat types included shrub-steppe, grasslands, dryland wheat, irrigated croplands, rolling hills, and steep basalt canyons. However, most of the non-agricultural vegetation consisted of introduced grasses with remnant patches of sagebrush (*Artemesia spp.*) and rabbitbrush (*Chrysothamnus spp.*) shrubs. Much of the land in the study area was privately owned and used for agriculture and livestock grazing. Additional land use activities included development for industrial transport and waste storage associated with the Columbia Ridge Landfill, small gravel quarry operations, and construction of future wind projects and associated infrastructure (access roads, transmission lines, operations and maintenance buildings, and electrical substations).

The study area included a wide variety of potential nesting substrates that would be suitable to breeding raptors in arid regions. Tree species were predominately native western juniper (*Juniperus occidentalis*) scattered throughout the area and few black cottonwood (*Populus trichocarpa*). Introduced tree species included black locust (*Robinia pseudoacacia*) and tree-of-heaven (*Ailanthus altissima*). Trees provided limited nesting opportunities for some raptor species such as ferruginous hawks, red-tailed hawks, Swainson's hawks, great horned owls (*Bubo virginianus*), and long-eared owls (*Asio otus*). Basalt cliff ledges provided additional nesting areas for red-tailed hawks, prairie falcons (*Falco mexicanus*), and great horned owls. Electrical transmission towers typically provide nesting opportunities for many raptor species, including ferruginous hawks, red-tailed hawks, and great horned owls (Steenhof et al. 1993). However, in the study area, only red-tailed hawks and common ravens (*Corvus corax*) have historically used transmission towers. A limited number of ground nests used by northern harriers (*Circus cyaneus*) were located in the study area and historical ferruginous hawk ground nests have been documented during previous surveys. Two artificial nest structures (one in 2010 and two in 2011), potentially suitable for ferruginous hawks, were also located in the study area. Nesting substrates were not evenly distributed throughout the study area, but instead consisted of isolated trees, small clusters and sparsely scattered patches of trees, regularly spaced lines of transmission towers, small cliff ledges, and long cliff faces along canyon walls.

Surveys and Study Design

In 2010 and 2011, I conducted ground surveys by vehicle and foot to search for medium and large breeding raptor species (i.e., larger than an American kestrel, *Falco sparverius*) and associated nests. I scanned with 10X binoculars and 20-45X spotting scopes at a minimum distance of 250 m from nests during brief observation periods to limit disturbance (Olendorff 1993), when possible. I systematically searched all historical and potentially suitable nesting substrates for each species of *Buteo* hawks (Bechard and Schmutz 1995; Preston and Beane 2009; Bechard et al. 2010) by covering large areas at once. All potential nesting substrates within the study area were visited a minimum of 1-3 times and successive surveys for each species were conducted within a relatively short time frame, usually 1-5 weeks. I used photographic guides to estimate the age of nestlings from each hawk species (Mortisch 1983; Mortisch 1985; Gossett and Makela 2005). I back-calculated from these ages to estimate the hatching date and subtracted an additional 33 days for the average length of incubation (Bechard and Schmutz 1995; Preston and Beane 2009; Bechard et al. 2010) to estimate the laying date for all successful and failed nests with young.

Northwest Wildlife Consultants, Inc. (NWC) provided additional nest survey data for portions of the study area following pre- and post-construction monitoring surveys of some wind energy projects, including during 2010 and 2011, with the approval of the participating companies. J. Watson also provided nest survey data for ferruginous hawks from early-season ground-based surveys by the Washington Department of Fish and Wildlife for a separate research project (J. Watson, unpublished data) and The Nature Conservancy provided nest survey data for the Boardman Conservation Area (BCA) in 2010. In some cases, these additional surveys were included to cover early surveys periods and areas with difficult or restricted access. Thus, they enabled me to obtain a complete coverage of the study area in both years and target breeding pairs with initial surveys during the early nesting stages (i.e., early-mid April for red-tailed hawks and ferruginous hawks, and early May for Swainson’s hawks).

To relate the occurrence of breeding *Buteo* hawks to variables of interest and determine the probability of detecting breeding pairs, I delineated resources into sampling units that contained suitable nesting substrates by superimposing a continuous randomly placed hexagonal grid over the study area (Wiens et al. 2011) in a standardized occupancy modeling approach (MacKenzie et al. 2002; MacKenzie et al. 2006). I created a separate grid overlay for each species to permit me to make inferences at a meaningful biological scale for each hawk species. By analyzing each species separately, I optimized estimation procedures, permitting each sampling unit to have a reasonable probability of occupancy (i.e., 0.2-0.8; MacKenzie et al. 2006). This also minimized the chance of multiple breeding pairs of the same species to simultaneously occupy a single sampling unit.

The grid size for each species was based on the average Nearest Neighbor Distance (NND) of conspecifics, measured as the distance between the centers of adjacent sampling units. According to previous *Buteo* hawks studies in the western U.S., the average NND was 3.1 km for ferruginous hawks (Bechard et al. 1990; Bechard and Schmutz 1995), 2.3 km for red-tailed hawks (Rothfels and Lein 1983; Janes 1984; Bechard et al. 1990; Bosakowski et al. 1996), and 2.0 km for Swainson's hawks (Fitzner 1980; Rothfels and Lein 1983; Bechard et al. 1990; Bosakowski et al. 1996). Therefore, I created 42 equal-sized grid cells with a 7.79 km^2 area for ferruginous hawks, 59 grid cells with a 4.99 km^2 area for red-tailed hawks, and 71 grid cells with a 3.46 km^2 area for Swainson's hawks. I removed individual sampling units from the analysis if they did not contain potential nesting substrates for a particular species (Schmutz 1989) and, therefore, could not be occupied by a breeding pair of hawks. Sampling units for ferruginous hawks contained trees, historical ground/cliff nests, or artificial platforms as potential nesting substrates. Sampling units for red-tailed hawks contained trees, cliff ledges, and transmission towers as potential nesting substrates. I only retained sampling units for Swainson's hawks if they contained trees because this substrate was used almost exclusively by this species in the study area, according to historical nest survey data.

I determined a sampling unit to be occupied if ≥ 1 pair of hawks was found to be breeding within the grid cell during surveys, as confirmed by the presence of a nest with evidence that eggs were laid (i.e., eggs or eggshells, young, and/or adults observed in incubation posture; Steenhof and Newton 2007). I excluded non-breeding hawks from the analysis because they could not be associated with a specific sampling unit under my design. Also, non-breeding pairs may have larger home ranges than breeding pairs (Marzluff et al. 1997) or leave their territory altogether, potentially allowing them to be double-counted if they move to another portion of the study area (Steenhof and Newton 2007).

Sources of Variation

I selected a limited number of covariates *a priori* based on previous studies to examine variation in the distribution of breeding pairs and selection of resources at multiple spatial scales (Table 1.1). However, I hypothesized that the number of breeding *Buteo* hawks may also fluctuate from 2010 to 2011 because reproduction (Steenhof and Kochert 1985) and nestling survival (Bechard 1983; Schmutz et al. 2006) vary annually in response to dominant prey types. Additionally, I suspected that my ability to locate breeding hawks in the study area would improve after the first field season. Therefore, I included covariates to represent annual changes in occupancy of a sampling units and the probability of detecting breeding hawks.

Covariates affecting the selection of landscape-scale resources, i.e. the number of wind turbines, number of *Buteo* nests, and percent of major habitat types, were measured at two spatial scales: within the sampling unit (sampling unit covariates) and within the average estimated home range of each species (home range covariates) (Table 1.1). I assumed that occupancy by breeding hawk pairs would indicate use of some or all of the resources within the sampling unit and in the larger home range buffer. Studies estimated the mean core area used by nesting ferruginous hawks and red-tailed hawks at 35 and 15 km^2, respectively (Andersen and Rongstad 1989; Leary et al. 1998), and the home range of Swainson's hawks in the Columbia Plateau at 8.86 km^2 and within the study area at 17.2 km^2 (Bechard 1982; Watson et al. 2010). Therefore, the number of wind turbines and percentages of habitat types within 3.2 km (32 km^2) of ferruginous hawk nests and 2.4 km (18 km^2) of red-tailed hawk and Swainson's hawk nests were included as home range-level covariates. I calculated all spatial variables using GIS techniques in ArcMap version 10.1 (ESRI, Redlands, California) and the Geospatial Modeling Environment (GME) plug-in tool (Beyer 2011). When a sampling unit was found to be occupied by breeding hawks, I measured the corresponding nest that contained evidence that eggs were laid. If no breeding pairs were detected in a sampling unit, I generated random coordinates and selected the nearest potential species-specific substrate (i.e., random nest) in the sampling unit each year that would be suitable for nesting. When more than one breeding pair was found to occupy a sampling unit, I randomly selected one nest for all measurements. Covariates specific to used and random nests included substrate measurements, distance to the nearest wind turbine, and distance to conspecific and other *Buteo* nests (Table 1.1).

I included two landscape-scale measurements of wind turbines to account for their uneven spatial distribution and wide range of potential impacts to nearby nests: distance from the nest to the nearest wind turbine, and number of wind turbines within the sampling unit and the home range buffer for each species. I also created two covariates representing annual changes in occupancy by the difference in the number of wind turbines within the sampling unit and home range buffer from 2010 to 2011, to account for construction of the additional wind energy project area. I included three variables, distance to the nearest *Buteo* and conspecific nest, and number of *Buteo* nests in the sampling unit, to represent competition from nearby breeding hawks. Also, I wanted to determine how specific nesting substrates influenced occupancy in my study and ensure that random nests selected in sampling units where breeding pairs were not detected were sufficient for nesting by that species. Therefore, I included the type and height of the substrate, and the number of potential and historical substrates in the sampling unit as covariates. Finally, I created covariates with the percent of dominant habitat types within the sampling unit and home range buffer to examine the impact of surrounding vegetation on occupancy by breeding hawks.

To determine the percent of habitat surrounding each nest, I imported the 1:100,000 Ecological Systems map of Oregon (Oregon Natural Heritage Information Center 2010). I compared this map to observations in the field, and then edited the GIS dataset to reflect recent changes and combined land use and habitat types from the Oregon Land Cover Standard (Oregon Geospatial Enterprise Office 2006) into four broad categories: native vegetation, exotic grassland, agriculture, and non-agricultural vegetation. Areas with intensive agriculture management resulting in tall crops such as dryland wheat (cultivated crops code), or little to no vegetation due to plowing (fallow fields, early stage CRP), were combined in "Agriculture." Habitat types consisting of native vegetation (playa, shrubland, perennial grasslands codes) were combined into "Native." Areas with non-native, or invasive, vegetation typically found in grazed areas (annual grasslands code) were designated as "Grass." A final category combined the areas designated as "Native" and "Grass" into "Non-agricultural" habitat. The area of habitats that would not be suitable for use by raptors (open water), or found in low percentages and variation across the study area (residential, developed land use codes, and irrigated alfalfa) were not included in the analysis. I did not include alfalfa with dryland wheat because the vegetation canopy might influence prey availability (Bechard 1982), and intensive agricultural practices, such as plowing, exclude some prey species (Houston and Bechard 1984). Irrigated crops that are regularly harvested, such as alfalfa, increase foraging opportunities for raptors while those harvested once, such as dryland wheat, only facilitate foraging after harvesting is complete (Leary et al. 1998).

Data Analysis and Model Selection

I assessed the validity of the timing of species-specific surveys and tested for evidence that these sympatric hawks partitioned the nesting season in time by staggering nest initiation with a one-way analysis of variance (ANOVA) test in JMP version 10 (SAS Institute Inc. 2012). I checked the assumptions of a normal distribution for each species by examining outliers in boxplots and normal quantile plots prior to analysis, and checked for homogeneity of variance using a residual plot after the ANOVA. Following a significant result, I performed a means comparisons using Tukey's Honestly Significant Difference (HSD) test to further examine the differences between the three species. This test is typically robust, but considered conservative with unequal sample sizes between groups.

I used an information-theoretic approach to evaluate occupancy of sampling units by breeding pairs of each subject species separately with multi-season occupancy analyses (MacKenzie et al. 2003) using Program MARK 6.2 (White and Burnham 1999). This method of analysis enabled me to determine the probability of locating ≥ 1 breeding pair in designated sampling units and relate the presence of breeding hawks with covariates (MacKenzie et al. 2006) for each species. This analysis also utilizes changes in occupancy of individual sampling units from one year to the next to estimate local colonization (γ) and extinction (ε) probabilities. For my analysis, I used the alternative parameterizations of the recursive equation from MacKenzie et al. (2003) to directly estimate annual occupancy (ψ_{2010}, ψ_{2011}) and per-survey detection probability (p), and then estimate either colonization (γ) or extinction (ε) directly and derive the remaining parameter using the following equation:

$$\psi_{t+1} = \psi_t (1-\varepsilon_t) + (1-\psi_t)\, \gamma_t$$

These parameterizations of the equation estimate changes in occupancy as a Markov process to account for temporal autocorrelation resulting from surveying the same sampling units over multiple years (MacKenzie et al. 2003). I estimated extinction (ε) directly and derived colonization (γ) for ferruginous hawks because I found a decrease in the naïve occupancy from 2010 to 2011. I estimated colonization (γ) directly and derived extinction (ε) for red-tailed hawks and Swainson's hawks due to an increase in naïve occupancy in the second year. Using the alternative parameterizations, I was able to specify different values for certain variables in the same sampling unit to account for annual changes in the number of wind turbines, nearby hawk nests, and measurements of nesting substrates. The multi-season occupancy analysis assumes 1) there is no unmodeled heterogeneity in rate parameters; 2) sampling units are closed to changes within the season or during survey periods; 3) detection of species at each sampling unit are independent; and 4) all occupied sampling units are classified correctly.

I created a detection history for each sampling unit with nesting substrates based on surveys for breeding pairs. Visits to each sampling unit were recorded as occupied (1) if at least one breeding pair of hawks was located and confirmed by nesting activity, or as unoccupied (0) if no nesting activity was found. Visits to sampling units conducted after confirming occupancy were recorded as missing observations (-) because they added no additional information to the detection probability, i.e. using the so-called removal design (Azuma et al. 1990; Mackenzie and Royle 2005; Martin et al. 2009). Additionally, if sampling units were not surveyed at all or not extensively during follow-up surveys, they were also recorded as missing observations.

Determining if sampling units are closed to changes in status, i.e. assuring population closure, can be especially difficult to assess. The true population size may be underestimated because breeding pairs do not initiate nesting synchronously and nest failure may occur before surveys take place (Ayers and Anderson 1999), making some pairs more difficult to locate (Steenhof and Kochert 1982). In order to meet the assumptions of population closure, I determined if breeding pairs were “available” for detection during surveys by comparing the survey dates with the estimated laying date.

Nesting attempts that failed during incubation or before nestlings could be aged were assumed to start at the average initiation date because I found no evidence of a seasonal trend in failure based on nest survival analyses (see Chapter Two). If hawk pairs did not initiate nesting before a survey, I recorded the visit to the sampling unit as a missing observation. Additionally, all potential substrates within the sampling units were checked and those with signs of nesting activity by *Buteo* hawk species were recorded as occupied even if adults were not present during surveys or nest failure occurred before the first check. These measures should have minimized the chance of missing breeding pairs due to early nest failure.

I used a multi-step hierarchical modeling process to reduce the number of parameters in the final model set. First, I selected the best-approximating base temporal model to determine if occupancy or detection probability remained constant $\{\psi(.)\ p(.)\}$ or varied annually $\{\psi(\mathrm{yr})\ p(\mathrm{yr})\}$. I used the “dot” model notation of Program MARK (White and Burnham 1999) to specify parameters and models that remain constant, similar to a null model of no effect. Next, I created models for each hypothesis category by adding standardized individual covariates to the base temporal design for each species $\{\psi(\mathrm{covariate},\ ./\mathrm{yr}\ )\ p(./\mathrm{yr})\}$. I ranked models in each category and selected the top model from each to compete across categories in the final model set. Finally, I built all possible additive model combinations containing the best-approximating temporal design and the top covariates from each hypothesis category (Appendix A.1). Additive models were considered uninformative and removed from the analysis if they contained ≥ 1 additional covariate not found in higher-ranking models (Arnold 2010), resulting in the final model set.

I ranked models at each stage by Akaike's Information Criterion corrected for small sample sizes (AIC$_c$), and evaluated the strength of support for models at each stage using model weights (w_i) and the difference in AIC$_c$ value (ΔAIC$_c$; Burnham and Anderson 2002). I used the logistic model to estimate parameters and incorporated covariates by specifying a logit link (MacKenzie et al. 2002). To account for uncertainty in model selection, I used model averaging for those models ≤ 2.0 ΔAICc units. I used a model averaging spreadsheet (Mitchell 2008) to calculate model averaged parameter estimates and slope coefficients. I also calculated the unconditional standard error (Burnham and Anderson 2002) using the delta method (Seber 1982). Finally, I back-transformed the parameter estimates using the logistic equation and rescaled the standardized coefficients. I estimated the effect of each covariate using the slope coefficient ($\hat{\beta}$) and evaluated the strength of the effect by the degree to which it overlapped 85% confidence intervals, allowing my results to be fully AIC compatible (Arnold 2010). With the model-averaged estimate of per-survey detection probability (p) I calculated the cumulative probability of detecting ≥ 1 breeding pair of hawks at a sampling unit (p^*) over the total number of surveys (k) for each species as $1 - (1 - p)^{k}$ (MacKenzie and Royle 2005).

Results

I found a significant difference in the timing of nest initiation for all three hawk species ($F_{(0.05)\ 2,\ 87} = 169.35$, $P < 0.001$) (Table 1.2; Figure 1.1). Red-tailed hawks initiated nesting first in early-mid April ($\bar{x}$ Julian date = 91.27, SE = 2.89 days, $P = 0.001$), with ferruginous hawks approximately ten days later ($\bar{x}$ Julian date = 101.75, SE = 2.73 days, $P < 0.001$), and Swainson's hawks almost a month afterwards in early May

($\bar{x}$ Julian date = 126.48, SE = 1.97 days, $P < 0.001$). During survey periods, I located ≥ 1 breeding ferruginous hawk pair in nine of 42 sampling units in 2010 (21%) and eight of 42 sampling units in 2011 (19%) with two annual surveys. I found 19 of 59 red-tailed hawk sampling units occupied by ≥ 1 breeding pair in 2010 (32%) and 22 of 59 sampling units in 2011 (37%) with two annual surveys. I detected ≥ 1 breeding pair of Swainson's hawks in 32 of 71 sampling units in 2010 (45%) and 44 of 71 sampling units in 2011 (62%) with three annual surveys.

Two ferruginous hawk sampling units were occupied by an additional conspecific pair in 2010 and one sampling unit was occupied by two breeding pairs in 2011. I found one sampling unit occupied by two breeding red-tailed hawk pairs in 2011. For Swainson's hawks, I found three sampling units with two pairs each in 2010 and seven sampling units with two pairs each in 2011. Across all nests with documented evidence of nesting activity, the NND in this study was similar to that used to create the size of survey units. The combined yearly average NND in my study was was 3.1 km for ferruginous hawks (SD = 1.96, $N = 21$), 2.6 km for red-tailed hawks (SD = 1.32, $N = 45$), and 1.7 km for Swainson's hawks (SD = 0.97, $N = 89$).

Ferruginous hawks nested exclusively in western juniper trees, predominantly outside of the northwestern corner of the study area, although one non-breeding individual was seen adding nesting material to historical ground nests situated on top of a small cliff in this area in 2011. Most red-tailed hawks nested in the western portion of the study area that was dominated by basalt cliffs, and large cottonwood or western juniper trees in canyon bottoms. Red-tailed hawks were the most versatile in use of nesting substrate types during this study with 48% cliff-faces, 36% western juniper, 10%

black locust, and 7% black cottonwood, but none in artificial structures. Ferruginous hawks and Swainson's hawks showed the greatest overlap in the types of nesting substrates used. Swainson's hawk nests were placed in 95% western juniper, 4% tree-of-heaven, and 1% black locust, but showed no obvious patterns of spatial segregation from the other two species.

Factors contributing to occupancy of sampling units varied for each species (Table 1.3). A global model that treated annual occupancy and detection probability as constant had greater support for ferruginous hawks and red-tailed hawks, but these parameters were best modeled separately by year for Swainson's hawks. The best approximating models for ferruginous hawks included the number of historical nesting substrates and the distance from nests to the nearest conspecific breeding pair; together, these models contained 80% of the total weight (w_i = 58% and 22%, respectively). The model averaged parameter estimates of occupancy by breeding ferruginous hawks overlapped slightly with 0 for the number of historical nests in a sampling unit ($\widehat{\beta}$ = 0.54, SE = 0.42, 85% CI = -0.06 to 1.14) indicating a weak positive relationship. Occupancy by ferruginous hawks also tended to be greater for sampling units closer to conspecific nests ($\hat{\beta}$ = -0.21, SE = 0.40, 85% CI = -0.79 to 0.37), but this was an unreliable effect (Figure 1.2). For red-tailed hawks, an additive model of conspecific distance and the relative density of potential nesting substrates (w_i = 58%), and a univariate model for the density of nesting substrates (w_i = 27%), contained 84% of the total model weight. Parameter estimates showed that occupancy by red-tailed hawks was only slightly higher for nests further from conspecifics ($\hat{\beta}$ = 0.42, SE = 0.40, 85% CI = -0.15 to 0.98), but this was also not a reliable predictor. However, occupancy by ≥ 1 breeding pair of red-tailed hawks was greater for sampling units with moderate ($\hat{\beta}$ = 0.82, SE = 0.31, 85% CI = 0.37 to 1.27) and high ($\hat{\beta}$ = 0.46, SE = 0.35, 85% CI = -0.05 to 0.97) relative densities of substrates. Occupancy by red-tailed hawks was significantly greater in areas with moderate densities of substrates compared to those with low densities (Figure 1.3). For Swainson's hawks, a univariate model of the number of breeding pairs within the sampling unit contained 98% of the model weight. Occupancy by Swainson's hawks varied by year, but was significantly greater at sampling units with other breeding hawk pairs in both years ($\hat{\beta}$ = 0.96, SE = 0.36, 85% CI = 0.44 to 1.47) (Figure 1.4).

Detection probability, occupancy, extinction, and colonization of sampling units varied by species under my design, but showed some similar trends (Table 1.4). The probability of detecting ≥ 1 breeding pair of hawks over multiple surveys was relatively high for all three *Buteo*s. The cumulative probability of detecting ≥ 1 breeding pair of ferruginous hawks and red-tailed hawks at least once in delineated sampling units over two surveys was 95% (85% CI = 0.65 to 1.00) and 92% (85% CI = 0.75 to 0.98) for each species, respectively. Cumulative detection probability varied by year for Swainson's hawks, but was estimated at 98% in 2010 and 100% in 2011 (85% CI = 0.88 to 1.00) over three surveys. Estimates of occupancy based on the model averaged or best-approximating model for each species were fairly close to naïve estimates for each species. The model averaged estimate of occupancy across two seasons was underestimated for ferruginous hawks (19%) compared to the annual naïve estimates (21% and 19%), but was still within the 85% confidence interval. This may reflect the fact that the alternative parameterizations can be numerically unstable because colonization and extinction must be constrained to 0-1 values (MacKenzie et al. 2006), likely resulting in slight adjustments to the derived parameters. However, occupancy for red-tailed hawks and Swainson's hawks correctly determined that naïve occupancy underestimated the true portion of breeding pairs when detection probability was not 100%. The actual portion of sampling units occupied by breeding ferruginous hawks was probably higher than the naïve estimate, as is the case with red-tailed and Swainsons's hawk, because of the relatively high cumulative detection probability.

Local extinction and colonization of sampling units were more similar for ferruginous hawks and red-tailed hawks than for Swainson's hawks. Ferruginous hawk sampling units with breeding pairs in 2010 had a 76% chance of remaining occupied while those that were empty had a 95% of remaining unoccupied. Red-tailed hawk sampling units with breeding pairs had an 81% chance of remaining occupied, and those that were empty had an 89% chance of remaining unoccupied. With the increase in breeding pairs of Swainson's hawks in 2011, sampling units occupied in 2010 had an estimated 100% chance of remaining occupied, and unoccupied sampling units were only 59% likely to stay empty.

Discussion

I found the detection probability under my design was relatively high, but I was not able to locate all breeding pairs in occupied sampling units in either year despite multiple surveys for each species. The occurrence of breeding pairs was not associated with wind turbines or surrounding habitat types; instead ferruginous hawks and red-tailed hawks selected areas in relation to the density of nesting substrates. Swainson's hawks were more likely to nest in areas with other breeding *Buteo* pairs, but my results suggest that all three species may have minimized competition through staggered nesting and spatial segregation. The high re-occupancy of sampling units and association between breeding pairs and landscape-scale resources suggests that some areas may be considered higher-quality for nesting by these three species.

Survey Design and Model Assumptions

Incorporating a resource selection approach into the multi-season analysis framework proved to be very effective. I was able to examine the influence of different variables on the spatial selection of landscape and nest-specific resources by breeding *Buteo* hawks. The occupancy modeling framework also enabled me to account for imperfect detection of breeding pairs and limit potential bias in estimates of rate parameters. Historical data collected from raptor nest monitoring during pre- and post-construction of wind energy projects was invaluable to the design of this study. However, due to inconsistent survey efforts during pre- and post-construction raptor nest monitoring among different wind projects in previous years, I was unable to analyze these data in a Before-After/Control Impact Design (BACI) (Anderson et al. 1999).

Results from the estimated nest initiation dates in my study provide some evidence that the species-specific surveys were properly timed to begin during the incubation and early nestling stages, likely maximizing the number of breeding pairs that could be detected. Swainson’s hawks and red-tailed hawks may sometimes lay a second clutch following nest failure (Preston and Beane 2009; Bechard et al. 2010) potentially leading to biased estimates of the mean nest initiation dates, but I found no evidence of re-nesting by any species. I did not explicitly model sources of variation in detection probability aside from annual differences. However, there may be some variation between the use of helicopter flights and ground-based surveys that should be examined in future studies. Although all surveyors and survey methods missed a small portion of breeding pairs and associated nests, detection probability was still high for all three species based on a single survey (71-90%). Observers detected 41% of ferruginous hawk nests from fixed-wing aerial survey transects in south-central Wyoming, after excluding ground nests, and detection probability primarily depended upon the distance from the transect route, observer experience, and type of nesting substrates (Ayers and Anderson 1999). My study area did include some differences in the types of nesting substrates, but contained few ground nests or large areas with dense juniper groves that have a lower detection probability (Ayers and Anderson 1999). Also, all observers in my study were well trained and experienced in identifying raptors species and locating nests. Ground and helicopter surveys were not conducted as transects, but instead observers systematically searched all potential nesting substrates. Thus, I assumed that all surveyors had approximately the same probability of locating nests and determining occupancy by breeding pairs in any given area. In a study of golden eagle (*Aquila chrysaetos*) occupancy, historical territories were systematically surveyed initially from a helicopter and searched on foot during later surveys (Martin et al. 2009). These authors also found relatively high annual detection probabilities of breeding eagle pairs (90-100%) with properly-timed surveys.

Effects of Covariates and Niche Partitioning

My study revealed differences in factors influencing occupancy, density of breeding pairs, and timing of nest initiation across the study area. Sampling units with breeding pairs in 2010 had a high probability of occupancy again in 2011 for all species (76-100%), while sampling units without breeding pairs were likely to remain empty (59-

96%). Previous studies on ferruginous hawks (White and Thurow 1985; Lehman et al. 1998; Watson and Pierce 2003; Schmutz et al. 2008) and Swainson's hawks (Schmutz et al. 2006) that have also found nest and territory fidelity or re-occupancy rates from these species to be relatively high (71- 100%).

I found little support that wind turbine covariates predicted annual occupancy or changes in short-term occupancy of sampling units for any species in the study area. Results from previous studies on the occupancy of nests and territories in relation to different types of energy development have been mixed and demonstrate the need for longer-term studies. Raptors, including ferruginous hawks, red-tailed hawks, and Swainson's hawks, did not nest within 3.2 km of wind turbines in Minnesota despite similarities in habitat and nesting substrates in the project area (Usgaard et al. 1997). However, raptors continued to nest near wind turbines at the same level after development for one large project area in eastern Washington (Erickson et al. 2004). White and Thurow (1985) found that eight of nine (89%) breeding ferruginous pairs exposed to various types of simulated disturbance did not return the following year, although re-occupancy of other territories was high (93%). Keough and Conover (2012) found that nest-site selection by ferruginous hawks was actually higher near oil and gas wells in Utah, possibly due to a time lag effect, an indirect benefit through increased habitat for prey or increased survival of juvenile hawks, or an unknown relationship between habitat quality and areas with wells. The occurrence of breeding raptors is strongly correlated with prey abundance and availability (Schmutz 1989; Keough and Conover 2012) and may have influenced *Buteo* hawks in my study as well. However, quantifying prey parameters was beyond the scope of this study.

Additional types of human activity in and around the study area, such as construction of new wind energy projects and associated infrastructure (i.e., access roads, power lines, substations, etc.), could also have affected breeding hawks and masked the effects of wind turbines on occupancy. One wind energy project began construction during the 2010 breeding season and increased the number of turbines by 31% in the study area by the time it was operational in early 2011. Another wind project not associated with this study began construction in the summer of 2011 within the potential range of influence to some breeding pairs in my study area. While I included covariates for the increase in turbines during 2011 that might impact local extinction or colonization of sampling units, I was unable to account for disturbance from construction activity or lag-time effects on occupancy from older wind projects (i.e., constructed from 2006 to 2009). Also, I assumed that the impacts of wind turbines were similar across the study area, but collision fatality rates may vary by project area or region (Strickland et al. 2011). Even for wind energy projects in my study, the mean estimated collision fatality rates for raptors varied greatly with some of the lowest reported in the CPE (0.04 raptors/ megawatt (MW)/year; Gritski and Kronner 2010) to one of the highest (0.38 raptors/MW/year; NWC 2011), although all turbines were similar models and sizes.

I found no evidence of habitat preference by any species in the study area. I assumed that the probability of occupancy would follow a linear relationship with the percent of habitat types within the sampling units and surrounding home range buffers. However, this relationship may be curvilinear instead (Zelenak and Rotella 1997; Schmutz 1989) and increased edge habitats may be associated with greater prey densities (Schmutz 1989; Zelenak and Rotella 1997; Keough and Conover 2012). I observed a broad matrix of habitat types in my study area and a high amount of fragmentation due to agricultural conversion, cattle grazing, and invasive vegetation, but did not account for habitat fragmentation in my covariates.

Breeding *Buteo* hawks and associated nests did not appear to be distributed randomly across the study area, but instead were associated with specific areas in relation to nearby raptors and surrounding substrates. Red-tailed hawks were more likely to nest in sampling units containing relatively higher densities of potential substrates suitable for nesting by this species, such as cliffs, trees, and transmission towers, compared to areas with fewer of these features. Territory occupancy and productivity of red-tailed hawks are highly correlated to the density and dispersion of perches because prey is more accessible to hunt without the energetic expenditure of sustained flight (Janes 1984; Preston and Beane 2009). Potential nesting substrates in my study could also have been used as hunting perches by red-tailed hawks and explain the relationship I observed between probability of occupancy and relative density of nesting substrates. Breeding ferruginous hawks also nested in relation to substrate density and were more likely to be found in sampling units with higher numbers of historical nests. While this relationship was weak, this result is not surprising because ferruginous hawks typically nest in lone trees or on the periphery of areas with clusters of trees (Bechard and Schmutz 1995). They are also known to refurbish historical nests rather than build new ones (White and Thurow 1985; Bechard and Schmutz 1995), which may facilitate annual nest rotation within the territory (Bechard and Schmutz 1995).

Contrary to my prediction that all three species would minimize spatial overlap with competitors, Swainson’s hawks were more likely to be found nesting in sampling units with other breeding hawk pairs. A similar association has also been found for this species in other areas throughout its range. Thurow and White (1983) suspected that Swainson's hawks nesting within close proximity to ferruginous hawks may have provided cooperative territorial defense from predators in Idaho. Schmutz (1989) found that the distribution of breeding hawk pairs in Alberta did not change following a more than 50% increase in the population size. Schmutz hypothesized that new breeding pairs did not nest into suboptimal habitats, but instead settled into higher quality areas that were already saturated, likely because the abundance of resources reduced competition and territory sizes. I suspect that the uneven distribution of breeding pairs in my study, selection of specific types of resources, and high re-occupancy rates of sampling units observed for all species may also be reliable indicators of the overall quality in certain portions of the study area based on the abundance of resources.

My results suggest that sympatric *Buteo* hawks in the CPE exhibit signs of niche partitioning in time, and for space and certain resources, but they appear to vary by species. Red-tailed hawks and ferruginous hawks had the greatest similarity in timing of nest initiation, but showed spatial segregation across the study area and selected different types of nesting substrates. However, the distribution of breeding Swainson's hawks showed no obvious spatial pattern compared to other *Buteo* species and they initiated nesting 3-4 weeks later than red-tailed hawks and ferruginous hawks on average. Schmutz et al. (1980) and McConnell et al. (2008) noted that these same three hawk species segregated on the basis of habitat in Alberta and Oklahoma with red-tailed hawks using woodland areas, ferruginous hawks occupying open arid landscapes, and Swainson's hawk nesting in most habitat types in proportion to availability. Restani

(1991) observed a similar relationship in Montana, but with greater species-specific differences. He found that red-tailed hawks and ferruginous hawks shared the greatest overlap in nesting chronology and prey use, but used the least similar nesting substrates. Meanwhile, Swainson's hawks and ferruginous hawks shared similar substrates, but had the lowest dietary overlap.

Despite the abundance of Swainson's hawks near sympatric breeding pairs, other types of partitioning could minimize overlap in the use of nearby resources. Some studies have suggested that temporal isolation through staggered nesting is relatively ineffective in reducing competition (Bechard et al. 1990; Restani 1991). Prey selection has been shown to vary by species for these *Buteo* hawks in some areas (Fitzner 1980; Restani 1991; Giovanni et al. 2007) although overlap is frequently high (80-90%; Schmutz et al. 1980; Cottrell 1981). Most researchers conclude that these sympatric breeding hawks likely coexist by maximizing spatial isolation through habitat use and selection of specific nesting substrates (Schmutz et al. 1980; Cottrell 1981; Bechard et al. 1990; Restani 1991). There may be some differences in habitat use between these hawks in the CPE, but the goal of this portion of the study was to examine the occurrence of breeding pairs in relation to resources available to each species across the study area. Further comparison of the nesting substrates and surrounding habitat used by these species may help confirm differences in selection for specific resources.

Management Implications and Recommendations

I found no evidence that breeding hawks avoided nesting in areas with wind turbines during this study, but I did identify other important management implications to raptor nest monitoring on wind energy projects. Of particular interest, all three species exhibited high fidelity to sampling units and selection of these areas was associated with specific types of resources. These characteristics may be important indicators of the quality of nesting areas to breeding *Buteo* hawks in the CPE. These areas appear to continue attracting breeding pairs in the short term regardless of wind energy development, possibly leading to increased collision mortality or other types of impacts in the future. While regional raptor populations may sustain increased mortality due to wind turbines (Hunt 2002; Johnson and Erickson 2010), other demographic parameters such as reproductive success and juvenile survival are critical to population sustainability and may be affected as well.

Impacts to the distribution and abundance of breeding pairs resulting from wind energy development in the CPE may not be seen immediately due to the high fidelity or re-occupancy of specific areas by *Buteo* species. Long-term monitoring of breeding raptors will be critical in identifying any impacts related to wind energy development over time. Proper study designs, such as a BACI with robust sample sizes and matched reference areas, or a gradient-response design along the entire range of impacts, are necessary to evaluate the long-term impact of turbines (Anderson et al. 1999) and should be considered for monitoring procedures at all wind energy projects. Under these designs, survey methods should be standardized to allow for a meta-analysis using multiple project areas that will each likely have small sample sizes. The extent of the survey area should reflect the range of potential impacts to those species expected or observed, especially those possessing special status by federal or state regulations. Given the results of this study, I recommend that at least two surveys be conducted and timed to maximize detection of breeding pairs for each species after the majority have initiated incubation, but before too many nest failures have occurred. Current guidelines recommend that post-construction monitoring be conducted at historical nesting territories and those identified from an initial pre-construction survey (Strickland et al. 2011). However, I further recommend that pre- and post-construction surveys of wind energy projects search all potential nesting substrates suitable for each species within the survey area for signs of nesting activity as well, even if an area was not historically occupied. Not all nesting territories are likely to be used every year (Steenhof and Newton 2007) and not all breeding pairs will be located during surveys. Furthermore, breeding hawks may move to other nesting substrates or establish new territories in response to nearby raptors and natural changes to nesting substrates, or potentially from wind energy development. Given the substantial increase in breeding Swainson's hawks in this study, surveys may also need to be conducted for more than one or two seasons prior to construction of new wind energy projects. If more than one year of pre-construction surveys is not possible, I suggest developers examine locations of historical nests and all potential nesting substrates when micro-siting wind turbines to avoid impacts to breeding pairs that may occupy these areas in the future.

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Table 1.1. Description of candidate models used to assess sampling unit occupancy by breeding pairs of ferruginous hawks, red-tailed hawks, and Swainson's hawks in the Columbia Plateau Ecoregion of north-central Oregon, 2010 – 2011.

Hypothesis Category	Model Name	Model Description
Wind turbines	turb_su/hr	Number of wind turbines in each sampling unit (su) or home range (hr) buffer
	turb_dist	Distance from used or random nest to nearest wind turbine
Habitat	ag/native/grass/ nonag_su/hr	Percent of each habitat in sampling unit (su) or home range (hr) buffer
Competition	buteo_su	Number of *Buteo* nests in sampling unit (su)
	buteo_dist	Distance from used or random nest to nearest *Buteo* nest
	consp_dist	Distance from used or random nest to nearest conspecific nest
Substrates	sub_type	Primary type of nesting substrate (tree, ground, cliff, artificial)
	sub_height	Height of substrate (m)
	DBH	Diameter at breast-height to the nearest for tree nests (m)
	num_sub	Relative number of potential nesting substrates (high, medium, low)
	hist_sub	Number of historical nesting substrates suitable for each species

Table 1.2. One-way Analysis of Variance (ANOVA) results used to evaluate the difference in nest initiation dates between ferruginous hawks, red-tailed hawks, and Swainson's hawks in the Columbia Plateau Ecoregion of north-central Oregon, 2010 – 2011.

Source	Degrees of Freedom	Sums of Squares	MS	F-Ratio	Prob > F
Species	2	24192.13	12096.10	169.35	< 0.0001
Error	87	6214.10	71.40		
C. Total	89	30406.22			

Table 1.3. Ranking of multi-season models used to assess variation in sampling unit occupancy (ψ), extinction (ε), colonization (γ), and detection probability (p) for ferruginous hawks, red-tailed hawks, and Swainson's hawks in the Columbia Plateau Ecoregion of north-central Oregon, 2010 – 2011. Model set reduced after removing those with uninformative parameters.

Ferruginous Hawk Models	AIC$_c$	ΔAIC$_c$	w_i	-2Log(L)	K
ψ(hist_sub,.) ε(.) p(.)	88.63	0.00	0.58	1.00	4
ψ(consp_dist,.) ε(.) p(.)	90.55	1.92	0.22	0.38	4
ψ(.,.) ε(.) p(.)	92.45	3.82	0.09	0.15	3
ψ(grass_hr,.) ε(.) p(.)	93.66	5.03	0.05	0.08	4
ψ(.,.) ε(turb_hr) p(.)	93.82	5.19	0.04	0.07	4
ψ(grass_hr,.) ε(turb_hr) p(.)	95.14	6.51	0.02	0.04	5

Red-tailed Hawk Models	AIC$_c$	ΔAIC$_c$	w_i	-2Log(L)	K
ψ(consp_dist + num_sub,.) γ(.) p(.)	168.04	0.00	0.58	1.00	6
ψ(num_sub,.) γ(.) p(.)	169.59	1.56	0.27	0.46	5
ψ(consp_dist,.) γ(.) p(.)	172.08	4.05	0.08	0.13	4
ψ(turb_dist,.) γ(.) p(.)	173.53	5.50	0.04	0.06	4
ψ(.,.) γ(.) p(.)	174.13	6.09	0.03	0.05	3
ψ(ag_su,.) γ(.) p(.)	175.16	7.12	0.02	0.03	4

Swainson's Hawk Models	AIC$_c$	ΔAIC$_c$	w_i	-2Log(L)	K
ψ(buteo_su) γ(.) p(yr)	251.58	0.00	0.98	1.00	6
ψ(.) γ(.) p(yr)	261.72	10.15	0.01	0.01	5
ψ(num_sub) γ(.) p(yr)	261.93	10.36	0.01	0.01	7
ψ(nonag_su) γ(.) p(yr)	262.82	11.24	0.00	0.00	6
ψ(turb_hr) γ(.) p(yr)	263.23	11.65	0.00	0.00	6

Notes: AIC$_c$ is Akaike Information Criterion adjusted for small sample sizes. ΔAIC$_c$ for the *i*th model is computed as AIC$_c$ – min (AIC$_c$). w_i is the AIC$_c$ weight. L in -2Log(L) is the model likelihood. K is the number of model parameters. In the ψ parameter, the first covariate represents occupancy in 2010 and the second represents occupancy in 2011. Dot models indicate no variation in the model parameter.

Table 1.4. Estimates (± SE and 85% confidence intervals) for occupancy (ψ), extinction (ε), colonization (γ), and detection probability (p) of breeding hawk pairs in sample units in the Columbia Plateau Ecoregion of Oregon during 2010 and 2011, based on the model averaged or best approximating model for each *Buteo* species.

Parameter	Ferruginous Hawk	Red-tailed Hawk	Swaison's Hawk
ψ_{2010}	0.19 ± 0.06, 0.12-0.30	0.38 ± 0.08, 0.28-0.50	0.48 ± 0.08, 0.32-0.63
ψ_{2011}	0.19 ± 0.06, 0.12-0.30	0.38 ± 0.08, 0.28-0.50	0.69 ± 0.06, 0.59-0.77
ε	0.24 ± 0.14, 0.07-0.59	0.19 ± 0.11, 0.10-0.28	0.00 ± 0.10, 0.00-0.12
γ	0.05 ± 0.03, 0.01-0.25	0.11 ± 0.08, 0.04-0.28	0.41 ± 0.08, 0.26-0.58
p_{2010}	0.78 ± 0.14, 0.41-0.95	0.72 ± 0.13, 0.50-0.87	0.71 ± 0.09, 0.50-0.86
p_{2011}	0.78 ± 0.14, 0.41-0.95	0.72 ± 0.13, 0.50-0.87	0.90 ± 0.05, 0.77-0.96

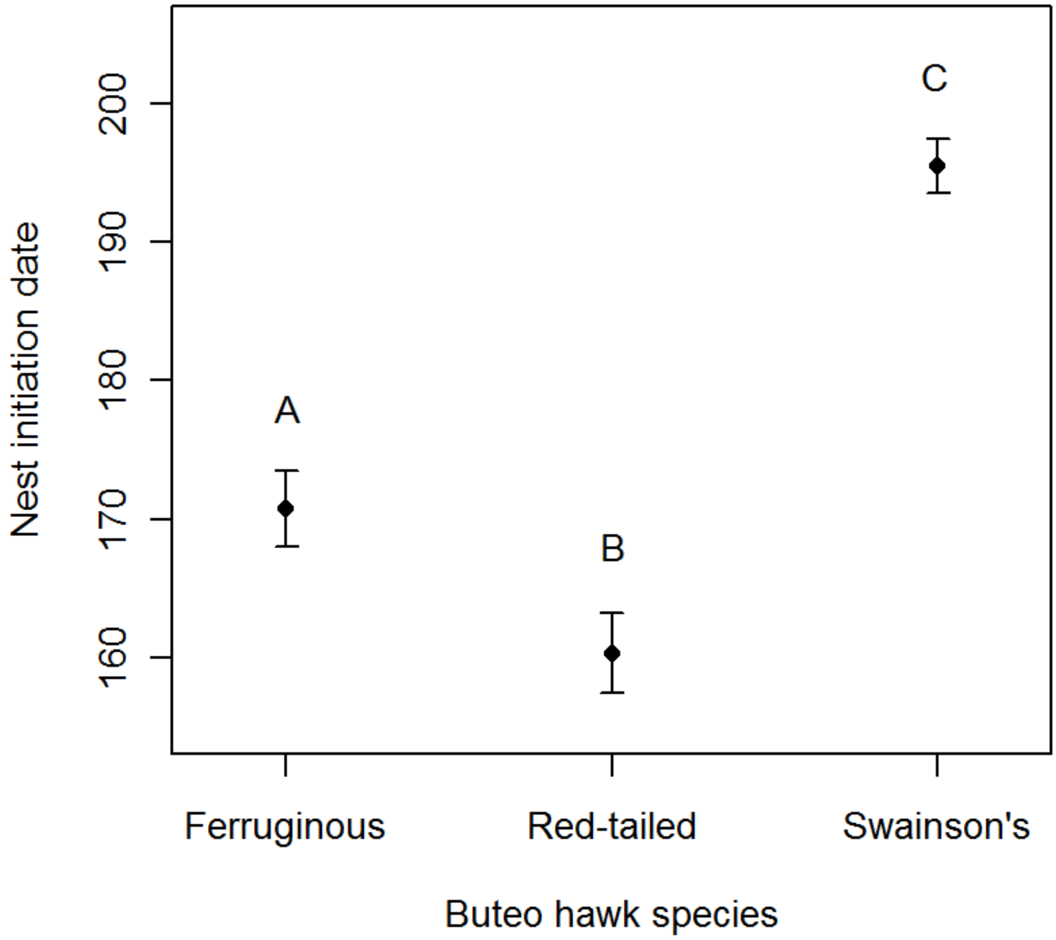

Figure 1.1. Mean Julian nest initiation date (day 1 = 1 January) and standard error for three sympatric species of *Buteo* Hawks in the Columbia Plateau Ecoregion of Oregon during 2010 and 2011, based on estimated nestling ages. Letters indicate a significant difference in the initiation date based on a means comparison using Tukey's Honestly Significant Difference (HSD) test.

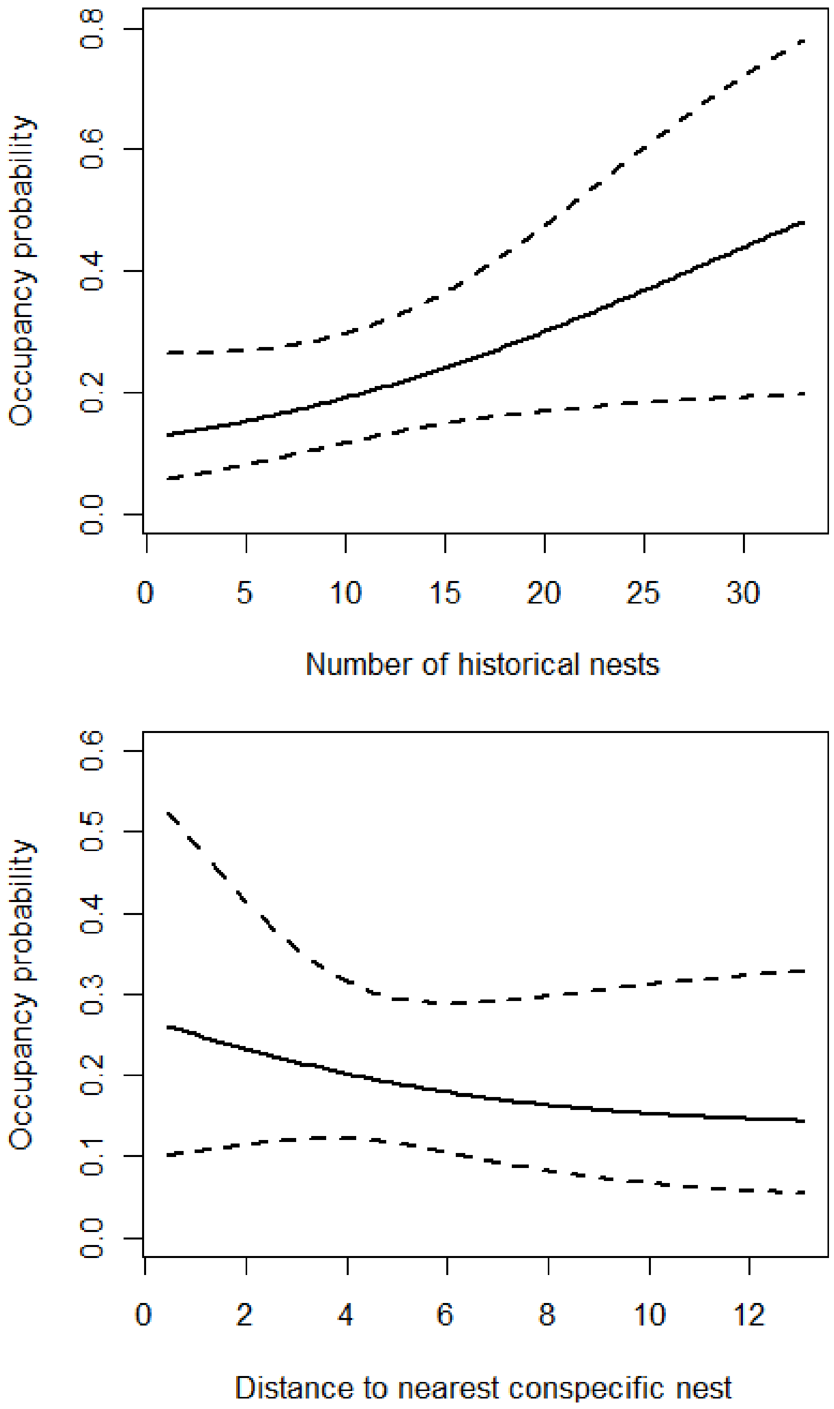

Figure 1.2. Predicted influence of the best-approximating models on occupancy of sampling units by breeding ferruginous hawks in the Columbia Plateau Ecoregion of Oregon during 2010 and 2011with 85% confidence intervals, holding all other variables constant.

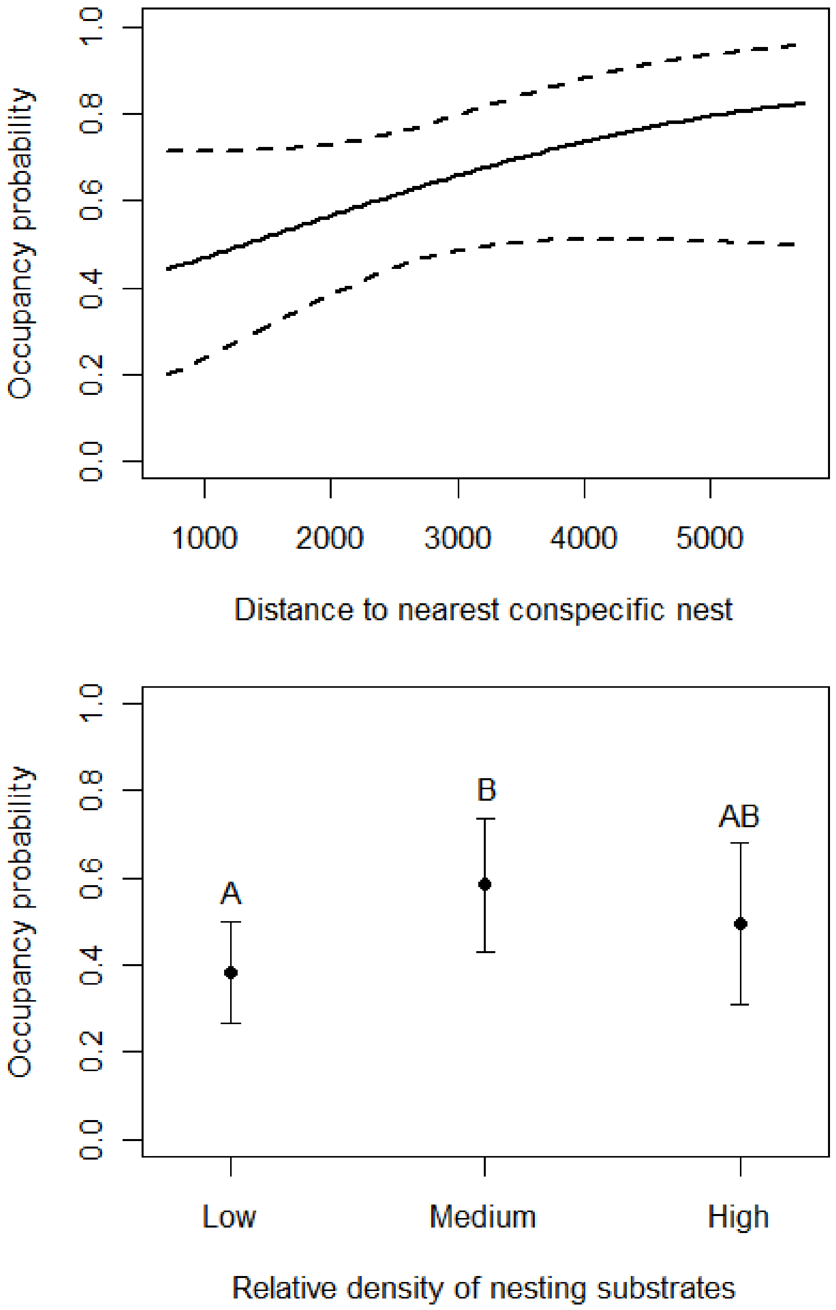

Figure 1.3. Predicted influence of the best-approximating models on occupancy of sampling units by breeding red-tailed hawks in the Columbia Plateau Ecoregion of Oregon during 2010 and 2011 with 85% confidence intervals. The top figure displays conspecific distance for sampling units with a moderate density of substrates and the bottom figure displays the relative density of nesting substrates per sampling unit, holding conspecific distance constant.

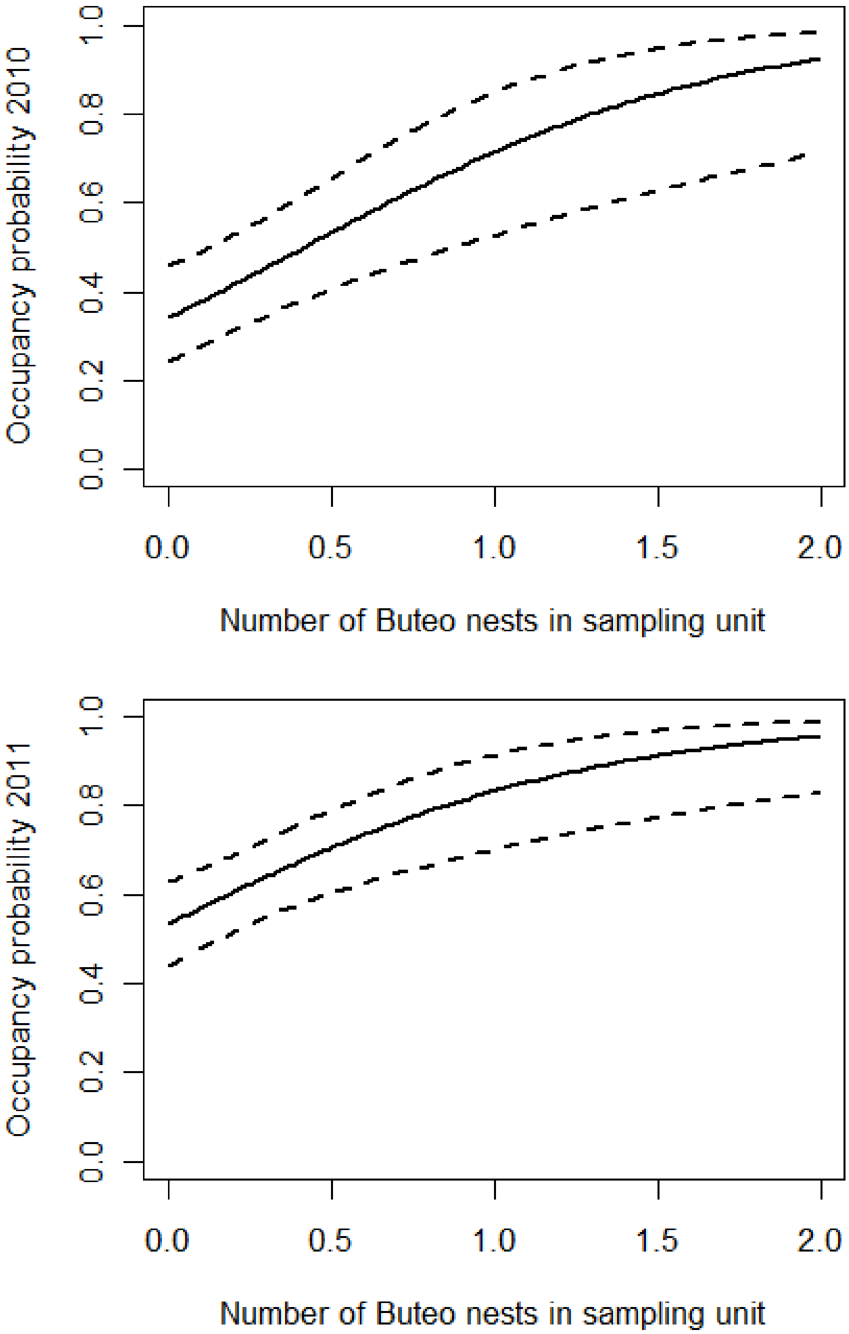

Figure 1.4. Predicted influence of the number of *Buteo* nests on annual occupancy of sampling units by breeding Swainson's hawk in the Columbia Plateau Ecoregion of Oregon during 2010 and 2011 with 85% confidence intervals.

Appendix A.1

Full ranking of multi-season models used to assess variation in sampling unit occupancy (ψ), extinction (ε), colonization (γ), and detection probability (*p*) for ferruginous hawks, red-tailed hawks, and Swainson's hawks in the Columbia Plateau Ecoregion of north-central Oregon, 2010 – 2011.

Table A.1. Full ranking of multi-season models used to assess variation in sampling unit occupancy (ψ), extinction (ε), colonization (γ), and detection probability (*p*) for ferruginous hawks, red-tailed hawks, and Swainson's hawks in the Columbia Plateau Ecoregion of north-central Oregon, 2010 – 2011.

Ferruginous Hawk Models	AIC$_c$	ΔAIC$_c$	w_i	-2Log(*L*)	*K*
ψ(hist_sub,.) ε(.) *p*(.)	88.63	0.00	0.43	1.00	4
ψ(consp_dist,.) ε(.) *p*(.)	90.55	1.92	0.17	0.38	4
ψ(consp_dist + grass_hr,.) ε(.) *p*(.)	91.16	2.53	0.12	0.28	5
ψ(consp_dist,.) ε(turb_hr) *p*(.)	92.07	3.44	0.08	0.18	5
ψ(.,.) ε(.) *p*(.)	92.45	3.82	0.06	0.15	3
ψ(consp_dist + grass_hr,.) ε(turb_hr) *p*(.)	92.65	4.02	0.06	0.13	6
ψ(grass_hr,.) ε(.) *p*(.)	93.66	5.03	0.03	0.08	4
ψ(.,.) ε(turb_3.2k) *p*(.)	93.82	5.19	0.03	0.07	4
ψ(grass_hr,.) ε(turb_hr) *p*(.)	95.14	6.51	0.02	0.04	5

Red-tailed Hawk Models	AIC$_c$	ΔAIC$_c$	w_i	-2Log(*L*)	*K*
ψ(consp_dist + num_sub,.) γ(.) *p*(.)	168.04	0.00	0.39	1.00	6
ψ(num_sub,.) γ(.) *p*(.)	169.59	1.56	0.18	0.46	5
ψ(num_sub + turb_dist,.) γ(.) *p*(.)	171.24	3.20	0.08	0.20	6
ψ(num_sub + ag_su,.) γ(.) *p*(.)	171.39	3.36	0.07	0.19	6
ψ(consp_dist + turb_dist,.) γ(.) *p*(.)	171.51	3.47	0.07	0.18	5
ψ(consp_dist,.) γ(.) *p*(.)	172.08	4.05	0.05	0.13	4
ψ(turb_dist + numb_sub + ag_su,.) γ(.) *p*(.)	172.98	4.94	0.03	0.08	7
ψ(consp_dist + turb_dist + ag_su,.) γ(.) *p*(.)	173.23	5.20	0.03	0.07	6
ψ(turb_dist,.) γ(.) *p*(.)	173.53	5.50	0.03	0.06	4
ψ(consp_dist + ag_su,.) γ(.) *p*(.)	173.80	5.76	0.02	0.06	5
ψ(.,.) γ(.) *p*(.)	174.13	6.09	0.02	0.05	3
ψ(turb_dist + ag_su,.) γ(.) *p*(.)	174.60	6.57	0.01	0.04	5
ψ(ag_su,.) γ(.) *p*(.)	175.16	7.12	0.01	0.03	4

Swainson's Hawk Models	AIC$_c$	ΔAIC$_c$	w_i	-2Log(*L*)	*K*
ψ(buteo_su,yr) γ(.) *p*(yr)	251.58	0.00	0.98	1.00	6
ψ(.,yr) γ(.) *p*(yr)	261.72	10.15	0.01	0.01	5
ψ(num_sub,yr) γ(.) *p*(yr)	261.93	10.36	0.01	0.01	7
ψ(nonag_su,yr) γ(.) *p*(yr)	262.82	11.24	0.00	0.00	6
ψ(turb_hr,yr) γ(.) *p*(yr)	263.22	11.65	0.00	0.00	6
ψ(nonag_su + num_sub,yr) γ(.) *p*(yr)	263.45	11.87	0.00	0.00	8
ψ(turb_hr + num_sub,yr) γ(.) *p*(yr)	263.88	12.31	0.00	0.00	8
ψ(nonag_su + turb_hr,yr) γ(.) *p*(yr)	264.84	13.26	0.00	0.00	7
ψ(num_sub + turb_hr + nonag_su,yr) γ(.)	265.67	14.10	0.00	0.00	9

p(yr)

Notes: AIC$_c$ is Akaike Information Criterion adjusted for small sample sizes. ΔAIC$_c$ for the ith model is computed as AIC$_c$ – min (AIC$_c$). w_i is the AIC$_c$ weight. L in -2Log(L) is the model likelihood. K is the number of model parameters. In the ψ parameter, the first covariate represents occupancy in 2010 and the second represents occupancy in 2011. Dot models indicate no variation in the model parameter.

CHAPTER TWO: FACTORS INFLUENCING NEST SUCCESS AND POST-FLEDGING SURVIVAL OF *BUTEO* HAWKS ON WIND ENERGY PROJECTS

Abstract

Post-construction raptor fatality and nest monitoring is conducted at wind energy projects to determine the species-specific risk of collisions, compare mortality rates for individual projects with larger geographic areas, and assist with turbine placement to minimize impacts. However, wind turbines may also affect reproduction of breeding raptors if adults are indirectly impacted by development activity or if fledglings face an increased risk of collisions. I used nest survival analyses with an information-theoretic approach to examine the influence of multiple spatial and temporal variables on nest success and post-fledging survival for three sympatric breeding *Buteo* species in the Columbia Plateau Ecoregion (CPE). The daily survival rate (DSR) of ferruginous hawk (*Buteo regalis*) nests decreased as the number of wind turbines within the home range buffer (32 km^2) increased ($\hat{\beta}$ = -0.89, SE = 0.39, 85% CI = -1.47 to -0.30). I found no effect of turbines on the DSR for red-tailed hawk (*Buteo jamaicensis*) nests or any additional variables affecting the DSR for Swainson's hawk (*Buteo swainsoni*) nests. I radio-marked a combined total of 60 nestlings from all three species. After fledging, none of them died directly as a result of collisions with wind turbines. This was likely due, in part, to the limited size of the natal home range (2.38 km^2, SD = 1.48), and the relatively short duration of the post-fledging period ($\bar{x}$ range = 20.75 to 31.60 days ± 1.14

to 3.30). However, the juvenile DSR during the post-fledging period was best explained by species, distance to the nearest wind turbine ($\hat{\beta}$ = 1.14, SE = 0.67, 85% CI = 0.19 to 2.10), and a quadratic effect of age. Juveniles of all three species hatched from nests closer to turbines were more likely to die from predation or starvation just after fledging and prior to initiating natal dispersal compared to those from nests further away. Taken together, these results suggest that wind turbines impacted reproductive efforts by all three species to some degree, but these effects were greater for ferruginous hawks compared to the other two congeneric species. The causes of this negative association between wind turbines and these reproductive measures are unknown, but could potentially include collision mortality or indirect impacts such as disturbance or displacement of adult hawks. Future research should focus on the risk of collision mortality to breeding adult raptors and the indirect impacts to reproduction. These data will be vital to understanding the consequences of wind turbine impacts to regional populations.

Introduction

Production of energy through wind power has been commercially available in North America since the early 1980s (AWEA 1995; Erickson et al. 2001) and is one of the fastest-growing forms of renewable energy in the United States (Arnett et al. 2007). Many states are developing mandates for energy from renewable sources, especially from wind energy. As of 2012, Oregon had 3,153 MW of generating power with an additional 14,306 MW in queue from future projects. The state of Washington had 2,699 MW of generating capacity in 2012 with an additional 5,807 MW in queue (AWEA 2012). Given the current desire for cleaner sources of alternative energy, wind energy development is projected to continue to increase in the coming years. However, in some cases, the response of endangered or sensitive species to wind energy development, such as in the Columbia Plateau Ecoregion (CPE; Thorson et al. 2003), is unknown. Ferruginous hawks (*Buteo regalis*) are listed as “Sensitive-critical” in Oregon and “Threatened” (Washington Department of Fish and Wildlife 1996), but the Oregon Conservation Strategy lists “impacts from wind turbines in the Columbia Plateau” as a data gap for this species (Oregon Department of Fish and Wildlife 2006). As a result, there is currently a need for a greater understanding of impacts from wind energy development on wildlife and the resulting effects to broader population demographics.

Although wind energy can be produced without many of the negative environmental effects of other energy sources, such as polluting emissions and carbon dioxide, wind energy development has the potential to impact wildlife, especially birds, in a number of ways. Impacts to wildlife resulting from anthropogenic activities, among them wind and other sources of energy development, can be direct or indirect. Both types of impacts can cause a reduction in survival, breeding success, and other important wildlife population parameters. Direct impacts can include collision fatalities (Erickson et al. 2001; Hunt 2002), electrocution by power lines (Erickson et al. 2001), and habitat fragmentation. Indirect impacts can include disturbance from increased human or mechanical noise/movement (Madders and Whitfield 2006), displacement from previously used areas (Drewitt and Langston 2006; Madders and Whitfield 2006), and physiological responses (Fernández and Azkona 1993) such as increased production of stress hormones. Although many of these impacts to wildlife have been shown to result from wind energy development, they also appear to be highly dependent upon topography, habitat, species, and specifications of the development, such as wind turbine type and arrangement (Hoover and Morrison 2005; Smallwood et al. 2009).

Standardized post-construction raptor fatality and nest monitoring is typically conducted at wind energy projects to determine the species-specific risk of collisions, compare mortality rates for individual projects with larger geographic areas, and assist with the placement of turbines outside of restriction buffers (Strickland et al. 2011). Collision mortality is the most commonly studied impact of wind energy development (Erickson et al. 2001), especially for adult breeding birds (Sterner et al. 2007). The risk of collisions, however, may depend upon age or breeding status (Orloff and Flannery 1992; Hunt 2002; Sterner et al. 2007), although without clearly distinguishing between these factors, it is difficult to determine what parts of the raptors life cycle may be at greater risk. Turbine collisions may be of particular concern for fledglings compared to other age classes (Orloff and Flannery 1992). Juveniles at this stage of development gradually increase foraging flight behaviors (Hunt 2002) that have been attributed to an increased risk of collisions (Hoover and Morrison 2005), such as kiting in strong wind, but may have limited flight ability to avoid turbines (Orloff and Flannery 1992). However, without identifying individuals using marking techniques (color bands, radio-transmitters, etc.), it can be difficult to determine if a wind turbine collision fatality for a juvenile raptor occurred during the post-fledging period within the natal range, or after reaching independence from adults.

Impacts to raptors over the breeding season may also vary because nesting occurs in a sequential process during which failure may occur at any stage (Newton 1979; Steenhof and Newton 2007). Mated pairs of raptors must first locate a suitable nesting area in which to defend against intra- and inter-specific competition, select a suitable substrate and build a nest, lay and incubate eggs, and finally protect and feed growing young until they reach independence and initiate dispersal. Because of the hierarchical nature of nesting stages, studies examining impacts of wind turbines may find that results are confounded by other effects of human activity or development (Drewitt and Langston 2006; Madders and Whitfield 2006). For example, indirect impact of habitat loss or displacement may result in fewer breeding pairs occupying historical nests, thereby potentially leading to lower collision mortality rates. Birds not displaced by indirect impacts of wind turbines may face an increased risk of collision mortality (Erickson et al. 2001; Madders and Whitfield 2006) by habituating to turbines or flying near the rotor swept area (Orloff and Flannery 1992). Breeding pairs that do not abandon nesting attempts in response to anthropogenic activity may also make behavioral changes that could affect reproduction and survival, such as increasing or adjusting home range sizes and making extra-home range movements (Andersen et al. 1990). Impacts to any stage of nesting can influence demographic parameters that determine population growth and stability, such as survival of adults, productivity, and recruitment of young.

Few studies have examined the potential effects of wind turbines on reproduction for raptors. Negative effects of other types of human activity and energy development on breeding raptors provide reason to better understand the impacts from wind energy development and consequences to local populations. Of the three *Buteo* species breeding in the CPE, ferruginous hawks are especially sensitive to sources of human disturbance during the nesting season (White and Thurow 1985), but may be less likely to abandon breeding attempts in higher nesting substrates, such as transmission towers, compared with ground nests (Olendorff 1993; M.N. Kochert, U.S. Geological Survey, pers. commun.). Ferruginous hawks nest further from buildings and roads, compared to red-tailed hawks (*Buteo jamaicensis*) and Swainson's hawk (*Buteo swainsoni*) (Bechard et al. 1990), indicating a potential avoidance of human activity compared to other sympatric species (Olendorff 1993). Ferruginous hawks may respond to repeated disturbance by flushing at greater distances (White and Thurow 1985; Keeley and Bechard 2011) and fledging fewer young (White and Thurow 1985). Ferruginous hawks exposed to simulated energy development activity have lower success rates and are more likely to abandon historical nests (White and Thurow 1985). Gas and oil production has resulted in decreased reproductive success for ferruginous hawks in some areas (Keough 2006), but not others (Zelenak and Rotella 1997). Swainson's hawks respond differently to human disturbance (Dunkle 1977) depending on individual and regional variation (Fyfe and Olendorff 1976). In general, Swainson's hawks and red-tailed hawks are seemingly tolerant of human activity (Preston and Beane 2009; Bechard et al. 2010).

Given the potential for varying responses of these sympatric *Buteo* hawks to human activity, I sought to determine if wind energy development impacted the reproduction of breeding pairs for each species during the nesting season. The goals of this study were to examine nest success and post-fledging survival in relation to influential factors, including wind turbines. My specific objectives were: 1) determine what landscape-scale and nest variables best explain variation in nest success; 2) examine sources of mortality for fledglings and determine the influence of variables on post-fledging survival; and 3) examine species-specific differences in life-history characteristics that might influence the risk of collisions during the post-fledging period.

Methods

Study Area

The study area encompassed seven wind projects in Gilliam and Morrow counties near Arlington, Oregon. Of these, five projects contained a total of 257 wind turbines that were constructed and became operational from 2006-2009: Leaning Juniper I (Pacificorp Energy), Pebble Springs (Iberdrola Renewables), Willow Creek Wind Farm (Invenergy), Rattlesnake Road Wind Farm (EDP Renewables, f.k.a. Horizon Wind Energy), and Wheat Field Wind Farm (EDP Renewables, f.k.a. Horizon Wind Energy). One additional wind project (Leaning Juniper II, Iberdrola Renewables) was under construction in 2010 and became operational with 117 wind turbines in early 2011. The study area also included one project in the permitting phase of wind energy development (Montague-Iberdrola Renewables) and areas that were not related to wind energy development (The Nature Conservancy's Boardman Conservation Area, Bureau of Land Management land, and privately-owned land). Most of the 374 turbines in the developed project areas were arranged in strings of two to18 turbines, running north-south along ridges and plateaus, and spaced approximately 100 to 260 m apart within each string. The wind turbines were all newer-generation 2.1 megawatt Suzlon S88 turbines or 1.5 megawatt General Electric SLE turbines, both with tubular towers and of similar size.

Habitat types and land uses within the study area occurred as a mosaic that is consistent throughout the CPE (Oregon Department of Fish and Wildlife 2006). These habitat types included shrub-steppe, grasslands, dryland wheat, irrigated croplands, rolling hills, and steep basalt canyons. However, most of the non-agricultural vegetation consisted of introduced grasses with remnant patches of sagebrush (*Artemesia spp.*) and rabbitbrush (*Chrysothamnus spp.*) shrubs. Much of the land in the study area was privately owned and used for agriculture and livestock grazing. Additional land use activities included development for industrial transport and waste storage associated with the Columbia Ridge Landfill, small gravel quarry operations, and construction of future wind projects and associated infrastructure (access roads, transmission lines, operations and maintenance buildings, and electrical substations).

The study area included a wide variety of potential nesting substrates that would be suitable for breeding raptors in arid regions. Tree species were predominately native western juniper (*Juniperus occidentalis*) scattered throughout the area and few black cottonwood (*Populus trichocarpa*). Introduced tree species included black locust (*Robinia pseudoacacia*) and tree-of-heaven (*Ailanthus altissima*). Trees provided limited nesting opportunities for some raptor species such as ferruginous hawks, red-tailed hawks, Swainson's hawks, great horned owls (*Bubo virginianus*), and long-eared owls (*Asio otus*). Basalt cliff ledges provided additional nesting areas for red-tailed hawks, prairie falcons (*Falco mexicanus*), and great horned owls. Electrical transmission towers typically provide nesting opportunities for many raptor species, including ferruginous hawks, red-tailed hawks, and great horned owls (Steenhof et al. 1993). However, only red-tailed hawks and common ravens (*Corvus corax*) nests have been located on transmission towers in the study area during pre- and post-construction surveys. A limited number of ground nests used by northern harriers (*Circus cyaneus*) were located in the study area, and historical ferruginous hawk ground nests have been documented during previous surveys. Nesting substrates were not evenly distributed throughout the study area, but instead consisted of isolated trees, small clusters, and sparsely scattered patches of trees, regularly spaced lines of transmission towers, small cliff ledges, and long cliff faces along canyon walls.

Study Design and Radio-Marking

In 2010 and 2011, I conducted ground surveys by vehicle and on foot to search for medium and large breeding raptor species (i.e., larger than an American kestrel, *Falco sparverius*) and associated nests during the early nesting stages. I systematically searched all historical and potentially suitable nesting substrates for each species of *Buteo* hawks (Bechard and Schmutz 1995; Preston and Beane 2009; Bechard et al. 2010) by scanning with 10X binoculars and 20-45X spotting scopes at a minimum distance of 250 m from nests during brief observation periods to limit disturbance (Olendorff 1993), when possible. Northwest Wildlife Consultants, Inc. (NWC) provided additional nest survey data for portions of the study area following pre- and post-construction monitoring surveys of some wind energy projects, including during 2010 and 2011, with the approval of the participating companies. J. Watson also provided nest survey data for ferruginous hawks from early-season ground-based surveys by the Washington Department of Fish and Wildlife for a separate research project (J. Watson, unpublished data) and The Nature Conservancy provided nest survey data for the Boardman Conservation Area (BCA) in 2010.

I used modified definitions from Steenhof and Newton (2007) to define measures of reproduction for *Buteo* hawks (Appendix A.2). I used the term “nest area” instead of “nesting territory” to avoid confusion with the ethological definition of a territory, which is based on an observed defensive behavior. I considered nest areas occupied if two breeding-aged hawks were determined to be paired, or if at least one adult was observed in territorial defense or reproductive-related activity (i.e., nest building, brooding young, or presence of a new or recently repaired nest). Further, I considered pairs occupying nest areas as breeding if evidence of egg laying was documented (e.g., presence of eggs or eggshells, young, and/or adults observed in incubation posture). I did not monitor non-breeding territorial pairs or consider them in measures of reproduction because they may have larger home ranges than breeding pairs (Marzluff et al. 1997) or leave their territory altogether, potentially allowing them to be missed or double-counted if they move to another portion of the study area (Steenhof and Newton 2007). The number of non-breeding pairs could not be determined under my survey design, but could also have been impacted by wind turbines.

Nesting attempts were monitored every 7-10 days until confirmation of nest success or failure. A nesting attempt was considered successful when at least one nestling reached 33 days old, i.e., at least 80% of the average fledging age for all three species (Steenhof 1987; Preston and Beane 2009; Bechard et al. 2010) based on estimated ages from photographic guides (Mortisch 1983; Mortisch 1985; Gossett and Makela 2005). Productivity of all nests was measured as the number of young that reached 80% of fledging age. I back-calculated from the ages of juveniles to estimate the hatching date and subtracted an additional 33 days for the average length of incubation (Bechard and Schmutz 1995; Preston and Beane 2009; Bechard et al. 2010) to estimate the laying date. I defined the post-fledging period as the time after fledging when juveniles voluntarily left the nest for the first time, but still depended on adults for food and protection. I assumed juveniles reached independence and initiated natal dispersal, the movement from the site of birth to the location of the first breeding attempt (Greenwood 1980), when they could no longer be located within the adult nesting area.

Nests with young that were at least 33 days old were selected for radio-marking based on distance to the nearest wind turbine, and logistical constraints such as area access and estimated fledging date. I used a gradient-response design to select nests because the spatial distribution of wind turbines within the study area encompassed a wide range of potential impacts to breeding adult hawks and juvenile fledglings. Under this design, I selected nests for radio-marking across the gradient with approximately half exposed to wind turbines within an 800 m radius buffer (2.01 km^2). I used this buffer because Pope (1999) found that 95.4% of locations for fledgling ferruginous hawks fell within this distance in the average natal range size (0.34 km^2) and Fitzner (1980) found the average home range size of fledgling Swainson’s hawks to be 1.85 km^2. This sampling design was used to examine the risk of direct collision mortality of radio-marked fledglings and any indirect impacts to survival that might be related to breeding adults.

Once nests were selected, one or more nestlings were chosen for radio-marking. I suspected that rank within a brood may affect juvenile survival (Bechard 1983). However, survival of ferruginous hawks (Zelenak et al. 1997; Schmutz et al. 2008) and Swainson’s hawks (Schmutz et al. 2006) was not expected to vary by sex during the post-fledging period. Therefore, I alternately selected between the smallest and largest young in nests without regard to sex or age to ensure that both males and females were sampled for all ranks within each brood (Zelenak et al. 1997). Those selected were equipped with a 20g backpack VHF radio-transmitter and metal lock-on USGS band. An additional 16 nestlings (six red-tailed hawks and 10 Swainson's hawks) not chosen for radio-marking were banded with a metal lock-on USGS band to obtain incidental information on mortality and locations. I used methods per Guetterman et al. (1991) to attach backpack transmitters using teflon ribbon straps secured with a single copper crimp or sewn with cotton thread. All handling, banding, and radio-marking techniques were conducted in compliance with Boise State University protocols for the Institutional Animal Care and Use Committee (IACUC number 006-AC10-006).

I checked transmitter signals of radio-marked fledglings at least three to five times per week to detect mortalities until juveniles reached independence and initiated natal dispersal. Each transmitter was equipped with a mortality sensor to indicate a lack of movement after six to eight hours, allowing me to locate dead birds quickly and identify cause of death before carcasses were scavenged or became too decomposed. Additionally, I obtained visual locations of radio-marked juveniles two to five times per week to estimate the natal home range size, alternately selecting between three time periods during daylight hours (early: 6:00 am-10:00 am, mid-day: 10:00 am-3:00 pm, and late: 3:00 pm-7:00 pm). These locations were determined by first following the signal of the radio-marked juvenile, then confirming individual identification by observing the transmitter unit or identifying juveniles based on plumage and vocalizations at a distance. To avoid influencing the location and behavior of radio-marked juveniles, non-visual map-based estimates were sometimes used to determine locations when obtaining a visual location would have caused flushing. This approach was employed when the observer could obtain a strong telemetry signal, usually within approximately 15 m of a juvenile perched on the ground, in a tree or on a cliff-face, and walk a half to full circle around the individual to estimate the location without a visual observation.

Radio-marked juveniles were monitored throughout each summer during the post-fledging period. When a signal for a radio-marked fledgling could not be detected, I first attempted to locate the individual within the natal range and adult nesting area, and then searched for the signal throughout the study area and from all prominent landscape features. In the few instances when transmitter failure occurred, juveniles could easily be located by observing the transmitter unit or band during visits to the natal area. Some telemetry signals could have been blocked by topographic features, so I continued to scan for all radio-marked juveniles within the study area for the remainder of the season and conducted a final sweep at the end to locate any returning juveniles or remaining mortalities that were not previously located. I assumed all fledglings that could not be located after extensive searching of the adult nesting areas had reached independence and initiated natal dispersal. I determined sources of juvenile mortality and nest failure, when possible, by observing clues near nests and conducting field necropsies of carcasses.

Sources of Variation to Nest Success and Post-fledging Survival

I selected some covariates *a priori* that I thought would influence nest success and post-fledging survival, based on previous raptor studies. I grouped these variables into hypothesis categories to represent variation in survival over time (temporal covariates) and in relation to different spatial characteristics: wind turbines, habitat, and competition from nearby breeding *Buteo* hawks (Table 2.1). I assumed that landscape-scale variables would be relevant to breeding adults at varying degrees within the average home range around the nest and would impact survival of fledglings indirectly. I also created one nest-level category that represented the influence of competition from nest-mates (brood size and rank within brood) on post-fledging survival. However, due to low productivity across all species, I combined the second and third oldest ranking radio-marked juveniles into one category to compare against survival of the oldest nestling. I calculated all spatial variables using GIS techniques in ArcMap version 10.1 (ESRI, Redlands, California) and the Geospatial Modeling Environment (GME) plug-in tool (Beyer 2011).

Temporal Covariates. Previous studies have shown nesting chronology (Steenhof et al. 1997), reproduction (Steenhof and Kochert 1985), and nestling survival (Bechard 1983; Schmutz et al. 2006) of *Buteo* hawks to vary annually and seasonally in response to fluctuations of dominant prey types. Survival is also likely to vary during the post-fledging period because juvenile raptors rely on adults for provisioning and are relatively sedentary after leaving the nest (Bechard and Schmutz 1995; Preston and Beane 2009; Bechard et al. 2010). Furthermore, survival of juvenile northern goshawks (*Accipiter gentilis*) (Wiens et al. 2006) and ferruginous hawks (Watson and Pierce 2003) decreased in the first few weeks of dispersal upon reaching independence from adults. Given these factors, I included year and hatch date as two time-invariant variables where values remained constant throughout the breeding season. I predicted that pairs arriving to the study area earlier would select the optimal nesting areas and initiate incubation earlier. I also included other temporal variables, Julian date (day 1 = 1 January) and the age of nests (day 1 = estimated initiation date) or radio-marked juveniles (day 1 = fledging date), as time-varying covariates where values are different on each calendar day. I used the mean species-specific Julian initiation date for nests that failed during incubation. Finally, I created two quadratic parameterizations of date and age because I predicted that survival would be highest during the middle of the post-fledging period (Wiens et al. 2006) when fledglings are able to move to higher perches to avoid ground predation and are provisioned by adults.

Wind Turbine Covariates. I predicted that increased wind energy development would have a negative effect on nest success and post-fledging survival. However, the uneven spatial distribution of wind turbines represented a wide range of potential impacts to nearby nests. I included two landscape-scale measurements of wind turbines to account for this uncontrolled variation: distance from the nest to the nearest wind turbine, and number of wind turbines within varying intervals (1.6 km, 2.4 km, and 3.2 km) within the average home range size for each species. I selected these intervals because I did not have more precise estimates of home range sizes for breeding adults and to account for uncertainty in the range of estimates from previous studies. These studies estimated the mean core area used by nesting ferruginous hawks and red-tailed hawks at 35 and15 km^2, respectively (Andersen and Rongstad 1989; Leary et al. 1998), and the home range of Swainson's hawks in the Columbia Plateau at 8.86 km^2 and within the study area at 17.2 km^2 (Bechard 1982; Watson et al. 2010). Therefore, I considered wind turbines within 3.2 km (32 km^2) of ferruginous hawk nests and 2.4 km (18 km^2) of red-tailed hawk and Swainson's hawk nests to be within the potential range of influence to breeding adults along an impact gradient.

Competition Covariates. Increased intraspecific and interspecific competition has resulted in lower success (Schmutz et al. 1980; Cottrell 1981) and productivity (Zelenak and Rotella 1997) for these three congeneric species when nesting in close proximity. Swainson's hawks aggressively defend territories during the breeding season, sometimes removing other hawks from nests or excluding them from portions of breeding territories (Schmutz et al. 1980; Janes 1984). I predicted that increased intra- and inter-specific competition would negatively impact nest success and fledgling survival, and measured the distance from each nest to the nearest breeding *Buteo* and conspecific pairs. I also created a separate buffer around each nest to represent the effect of competition from nearby breeding *Buteo* hawks. Because I did not conduct behavioral observations to determine territorial boundaries for breeding pairs, the size of this buffer was equal to half the average Nearest Neighbor Distance (NND) of conspecific breeding pairs for each species. The average NND was 3.1 km for ferruginous hawks (Bechard et al. 1990; Bechard and Schmutz 1995), 2.3 km for red-tailed hawks (Rothfels and Lein 1983; Janes 1984; Bechard et al. 1990; Bosakowski et al. 1996), and 2.0 km for Swainson's hawks (Fitzner 1980; Rothfels and Lein 1983; Bechard et al. 1990; Bosakowski et al. 1996). Therefore, this buffer included the number of *Buteo* nests within 1.5 km for ferruginous hawks, 1.2 km for red-tailed hawks, and 1.0 km for Swainson's hawks.

Habitat Covariates. In general, ferruginous hawks nest in areas with low percentages of cultivated wheat (Schmutz 1989), where nest success rates are higher (Zelenak and Rotella 1997) compared to areas with greater proportions (>50%) or pure grassland habitats. Red-tailed hawks show increased variation in selection of habitats, and Swainson's hawks readily nest in sites surrounded by wheat (Schmutz 1989; Bechard et al. 1990). I created covariates with the percent of dominant habitat types within 2.0 km and 3.0 km buffers around each nest to examine the impact of surrounding vegetation on nest success and juvenile survival. These two spatial intervals of habitat correspond to the approximate home range estimates for each species and allowed me to compare my results to the habitat buffers from previous studies (Bechard et al. 1990; McConnell et al. 2008).

To determine the percent of habitat surrounding each nest, I imported the 1:100,000 Ecological Systems map of Oregon (Oregon Natural Heritage Information Center 2010). I compared this map to observations in the field, and then edited the GIS dataset to reflect recent changes and combined land use and habitat types from the Oregon Land Cover Standard (Oregon Geospatial Enterprise Office 2006) into four broad categories: native vegetation, exotic grassland, agriculture, and non-agricultural vegetation. Areas with intensive agriculture management resulting in tall crops such as dryland wheat (cultivated crops code), or little to no vegetation due to plowing (fallow fields, early stage CRP), were combined in “Agriculture.” Habitat types consisting of native vegetation (playa, shrubland, perennial grasslands codes) were combined into “Native.” Areas with non-native, or invasive, vegetation typically found in grazed areas (annual grasslands code) were designated as “Grass.” A final category combined the areas designated as “Native” and “Grass” into “Non-agricultural” habitat. The area of habitats that would not be suitable for use by raptors (open water), or found in low percentages and variation across the study area (residential, developed land use codes, and irrigated alfalfa) were not included in the analysis. I did not include alfalfa with dryland wheat because vegetation canopy might influence prey availability (Bechard 1982), and intensive agricultural practices, such as plowing, exclude some prey species (Houston and Bechard 1984). Irrigated crops that are regularly harvested, such as alfalfa, increase foraging opportunities for raptors while those harvested once, such as dryland wheat, only facilitate foraging after harvesting is complete (Leary et al. 1998).

Data Analysis

I determined the effect of covariates on reproduction using a nest survival analysis. Basic survival models consist of a logistic regression where the outcome for each subject is binomial, either alive or dead. Solely using the final outcome of a nest in this context (i.e., apparent nest success or ANS; Appendix A.2) can be positively biased because successful nests are more likely to be detected than those that fail early in the breeding cycle and the exact day of failure is not typically known (Steenhof and Newton 2007). Mayfield (1975) developed an alternative approach to account for uncertainty in the day of nest initiation and failure (i.e., censored observation intervals). The Mayfield method calculates nest success as a function of survival over the days under observation assuming a constant daily survival rate (DSR).

Recent survival analyses have been further extended to produce estimates based on maximum likelihood estimation (Bart and Robson 1982) with generalized linear models (McCullagh and Nelder 1989) to examine time-varying covariates using a binomial likelihood. Current methods permit the analysis of DSR in relation to multiple categorical and continuous variables using a specified link function, allow for variable observation intervals with censored data, and relax the assumption of a constant DSR over the season of interest (Dinsmore et al. 2002; Rotella et al. 2004). Nest survival models have also been recommended for “ragged” telemetry data when monitoring intervals are uneven among samples and over time because the exact date of mortality is not known (Rotella et al. 2004). Nest survival models were ideal for estimating post-fledging survival with my data because some dead birds were not located immediately and the fate of those with failed transmitters was not known definitively. I performed one analysis for the survival of all radio-marked fledglings combined and included an additive effect of species. However, I conducted a separate nest survival analysis for each hawk species to estimate nest success because I predicted that breeding adults would respond to covariates differently. I was not able to account for these differences in model selection or using interactions of variables with all three species combined.

I used the methods outlined by Rotella et al. (2004) and Stephens et al. (2005) to model the effect of variables on survival of *Buteo* hawks in PROC NLMIXED (SAS Institute Inc. 2003). These methods use programming statements to iteratively perform a logistic regression for each day a subject is under observation and calculate the probability that the nest or individual survives the interval. I used the logit link, the natural link function for data with a binomial distribution (McCullagh and Nelder 1989), to characterize the relationship between DSR and covariates from my hypothesis categories. The DSR of a nest or radio-marked fledgling with fixed effects of time-varying and time-invariant covariates, and a random effect, was calculated as follows:

$$DSR_{ijs} = \frac{\exp[\beta_0 + u_s + \beta_1(T + i) + \beta_k X_k]}{\{1 + \exp[\beta_0 + u_s + \beta_1(T + i) + \beta_k X_k]\}}$$

In this equation, DSR_{ijs} is the daily survival rate on the *i*th day ($i = 0, 1, \ldots, t - 1$) on the *j*th interval for nest or juvenile *s* (Dinsmore et al. 2002). B_o is the intercept term; u_s is the random effect of nest area on the intercept of the model (normally distributed with a mean = 0); B_1 is the slope co-efficient for time-varying covariates; *T* is the age or Julian date (time-varying covariates) of the nest at the beginning of the interval and is then incremented by a day for each day in the interval ($i = 0, 1, \ldots, t - 1$); B_k is the slope coefficient for the *k*th time-invariant covariate; and X_k is the value of the *k*th time-invariant covariate. Thus, I modeled the relationship between the logit of S_i, i.e., $\ln(S_i/(1 -$

S_i)), and the covariates as linear, whereas the relationship between S_i and the covariates was logistic or *S*-shaped. Finally, I estimated nest success as (DSR) ^{t}, where t is the number of days during incubation (33) and length of the nestling period to 80% of the average fledging age (33 days old).

Nest survival analyses assume that fates of subjects are known and independent, can be correctly aged when they are first found, and that DSRs are homogenous as modeled (Dinsmore et al. 2002). In my data, the survival of individual nest areas monitored in both years may not represent independent samples if breeding adults or nests or were subjected to the same level of spatial covariates. Also, the survival of radio-marked brood-mates may be correlated because they are dependent upon the same adults. In both of these analyses, overdispersion could occur if the observed variance in survival exceeds the theoretical variance specified by the model, such as when the sample units are not independent (Rotella et al. 2007). I tested for evidence of overdispersion in the most highly parameterized and top-ranked models in all post-fledging survival analyses using the goodness-of-fit test outlined by Sturdivant et al. (2007). In this test, the fate of radio-marked juveniles was considered independent at the 0.05 α-level. A rejection of the null hypothesis indicated some dependence in survival among radio-marked brood-mates. I incorporated nest area as a random effect in all models used to estimate nest success to account for this likely source of correlation (Rotella et al. 2004; 2007).

I used an information-theoretic approach to evaluate the effects of variables on the DSR of nests and radio-marked juveniles during the post-fledging period. I used a multi-step hierarchical modeling process to reduce the number of parameters in the final model set. First, I selected the best-approximating base model from the temporal hypothesis category to determine if survival remained constant or varied across the breeding season. Next, I created models within each hypothesis category that included the standardized individual covariates with an additive effect of the top-ranking base temporal model. I ranked models within each category and selected the top model from each to compete across categories in the final model set. If the top-ranking model within the hypothesis categories improved the fit of the base temporal model, I created further additive models to represent combinations of different hypotheses (Appendix B.2; C.2). Finally, I removed additive models that contained uninformative parameters, i.e., if they contained ≥1 additional covariate not found in higher-ranking models (Arnold 2010), resulting in the final model set.

I ranked models at each stage by Akaike's Information Criterion corrected for small sample sizes (AIC_c), and evaluated the strength of support for models at each stage using model weights (w_i) and the difference in AIC_c value ($\Delta\mathrm{AIC}_c$; Burnham and Anderson 2002). To account for uncertainty in model selection, I used model averaging for those models with a $\Delta\mathrm{AICc} \leq 2.0$. I used a model averaging spreadsheet (Mitchell 2008) to calculate the model averaged parameter estimates and slope coefficients. I also calculated the unconditional standard error (Burnham and Anderson 2002) using the delta method (Seber 1982). Finally, I back-transformed the parameter estimates using the logistic equation and rescaled the standardized coefficients. I estimated the effect of each covariate using the slope coefficient ($\hat{\beta}$). I also evaluated the strength of the effect by the degree to which it overlapped 85% confidence intervals, allowing my results to be fully AIC compatible (Arnold 2010).

I assessed life-history characteristics that I thought would influence the risk of collision fatality and the survival rate of juvenile *Buteo* hawks over the breeding season. I hypothesized that the risk of collision mortality would vary depending upon the extent and duration of exposure to wind turbines. Specifically, I predicted that collision fatalities of juvenile fledglings would increase with the size of the natal home range and the length of the post-fledging period. For juveniles that did not die or incur transmitter failure, I estimated the length of the post-fledging period from the first day of fledging to the last day the juvenile was located in the natal area. I also estimated the natal range size for individuals with ≥ 15 locations during the post-fledging period. Although larger sample sizes (> 30 per individual) are typically recommended for home range analyses, animals with relatively small home ranges or specialized patterns of movements that vary less by day or season require fewer locations for accurate estimation of range use (Millspaugh and Marzluff 2001). This may be especially true for fledglings associated with a central point of use (i.e., the nest), where they are dependent upon adults and exhibit little activity in the first weeks following fledging (Bechard and Schmutz 1995; Preston and Beane 2009; Bechard et al. 2010).

I calculated the 95% Minimum Convex Polygon (MCP) to compare my results with previous studies and fixed kernel estimate of the natal home range size during the post-fledging period with the “adehabitat” package (Calenge 2006) using R statistical software (R Version 2.13 www.r-project.org, accessed 08 July 2011). The fixed kernel estimate is considered to be less biased compared to the MCP because it is based on the probability of use as calculated from independent locations (Kernohan et al. 2001) from the Utilization Distribution (Van Winkle 1975). Previous studies have shown that the fixed kernel can be highly sensitive to the choice of bandwidth used for smoothing the data (Seaman et al. 1999; Kernohan et al. 2001; Gitzen et al. 2006). I used the scaled-reference bandwidth, computed with the *ad hoc* smoothing parameter and a bivariate-normal kernel, because it results in lower bias compared to other methods when movement patterns consist of a single patch of highly concentrated use, such as near a nest (Gitzen et al. 2006).

I examined species-specific differences in the size of the natal home range and length of the post-fledging period with separate one-way analysis of variance (ANOVA) tests in JMP version 10 (SAS Institute Inc. 2012). I examined outliers using boxplots, normal quantile plots, and the Shapiro-Wilk Test to determine if the data were normally distributed. I found that transformations of the data were not sufficient in meeting the assumptions of normality. Therefore, I used the non-parametric Kruskal-Wallis Rank Sums Test and assessed all group means with the Steel-Dwass Test following significant results.

Results

I located 71 breeding hawk pairs in 2010 and 84 breeding hawk pairs in 2011 (21 ferruginous hawks, 45 red-tailed hawks, and 89 Swainson’s hawks). I found no evidence of re-nesting, although Swainson’s hawks and red-tailed hawks may lay a second clutch following nest failure (Preston and Beane 2009; Bechard et al. 2010). I monitored a subset of these nests and found that nest success estimated from the DSR, ANS, and productivity differed among the three species of *Buteo* hawks in the study area (Table 2.2). I documented nest failures for 6 of 17 ferruginous hawk (ANS = 65%), 4 of 35 red-tailed hawk (ANS = 89%), and 23 of 67 Swainson’s hawk (ANS = 66%) breeding attempts. Nest failures appeared to result from a wide variety of sources. Predation of the nest or adults formed the largest percentage of identified causes of nest failure (18%), but most nests (58%) were abandoned for unknown reasons. One Swainsons's hawk nest was destroyed from human activity (3%), resulting from juniper removal by the landowner. One ferruginous hawk nest and four Swainson's hawk nests were blown from juniper trees during strong winds (15%). Two adult Swainson's hawks found as turbine collision fatalities in the study areas could be attributed to nearby nest failures (6%), but collision fatality surveys did not encompass all wind energy projects during my study. An additional adult Swainson's hawk was found dead from a wind turbine collision < 250 m away from its presumed nest and lone nestling. This juvenile was radio-marked prior to fledging and successfully reached independence with provisioning from the remaining adult.

Productivity for ferruginous hawks (0.81 fledglings/breeding pair, $N = 16$) was within the range reported by other studies (0.60 to 3.60 fledglings/breeding pair), but far below the mean reported for this species in Washington and Oregon ($\bar{x}$ = 1.76 fledglings/breeding pair) and in the western US ($\bar{x}$ = 1.94 fledglings/breeding pair) as reported by Olendorff (1993). Swainson's hawk productivity in my study (1.06 fledglings/breeding pair) was also within the range reported by other studies (1.05 to 1.85 fledglings/breeding pair), but below the average ($\bar{x}$ = 1.28 fledglings/breeding pair) reported for this species in the western US (Cottrell 1981; Fitzner 1980; Restani 1991; Andersen 1995; Bechard et al. 2010). Of the studies with similar low reproductive rates, most attributed lower productivity to decreased prey (Bechard 1983; Steenhof and Kochert 1985; Woffinden and Murphy 1989), or increased foraging distances because of urbanization (England et al. 1995). Productivity for red-tailed hawks in my study (1.83 fledglings/breeding pair) was above the average ($\bar{x}$ = 1.45 fledglings/breeding pair) for this species in the western U.S. (Johnson 1975; Cottrell 1981; Janes 1984; Restani 1991; Hansen and Flake 1995; Steenhof and Kochert 1985).

Nest Survival

The dataset for each species included 772 observation days for 17 attempts at 12 nest areas for ferruginous hawks, 870 observation days for 35 attempts at 25 nest areas for red-tailed hawks, and 3,029 observation days for 67 attempts at 49 nest areas for Swainson's hawks. Because I monitored many of the same nest areas in both 2010 and 2011, I incorporated this potential source of variation as a random effect in the analysis for each species. Due to the low number of ferruginous hawk nests and sparse number of failed nesting attempts by red-tailed hawks, I limited my model selection to avoid over-parameterization (Burnham and Anderson 2002). Therefore, I only included wind turbine covariates with a random effect of nest area for these two species. I analyzed the full suite of models from hypothesis categories for the Swainson's hawk nest survival analysis.

The top-ranking model for ferruginous hawks included the number of wind turbines within 3.2 km (32 km^2 area) and was well supported compared to the null model (i.e., ≤ 2.0 ΔAICc units) (Table 2.3). Further, this model predicted that DSR of ferruginous hawk nests would decrease as the number of wind turbines within this home range buffer increased ($\hat{\beta}$ = -0.89, SE = 0.39, 85% CI = -1.47 to -0.30) (Figure 2.1). Based on this model, I calculated that 54% of ferruginous hawk nests in my study area were successful. Further, ferruginous hawk nest success was predicted to be 13% lower

(SE = 0.01), on average, for every 10 turbines within 3.2 km of a nest (Figure 2.1). Conversely, I found little evidence that any wind turbine variables influenced DSR for red-tailed hawks, and none of the other covariates analyzed for Swainson's hawks demonstrated stronger support compared to the null model (Table 2.3). Thus, based on a constant DSR, I estimated that 74% of red-tailed hawk nests and 63% of Swainson's hawk nests in my study were successful.

Juvenile Survival

I selected 25 nests each year and radio-marked a total of 10 ferruginous hawks, 27 red-tailed hawks, and 23 Swainson's hawks to examine the potential for direct mortality from turbine collisions and survival during the post-fledging period in relation to covariates. Two ferruginous hawk nests and six red-tailed hawk nests had two nestlings radio-marked, and one red-tailed hawk nest had three nestlings radio-marked. Conversely, only one nestling was radio-marked in each selected Swainson's hawk nest. Of 60 radio-marked juveniles, I documented 13 mortalities (three ferruginous hawks, five red-tailed hawks, and five Swainson's hawks) (Table 2.4). The mean number of days between the last observation of juveniles alive to the first day they were found dead was 3 days, but the range was wide (1-11 days). I also documented two transmitter failures for red-tailed hawk fledglings early after deployment in 2011 and was unable to determine the fate of these individuals. However, I was able to locate them visually within the natal range until the average age of independence and used these data in estimating the DSR.

Three of the observed mortalities for radio-marked juveniles technically did not occur during the post-fledging period, but two were included in the mortality estimates. One Swainson's hawk was found dead 16 km away from the nest, most likely killed by a great-horned owl that was seen near the carcass. I assumed this individual had reached independence and initiated natal dispersal because of the distance at which it was found and because it was an extreme outlier in the survival analysis based on age at death. For these reasons, this individual was only included in the analysis during the post-fledging period over the interval in which it survived. Two radio-marked juvenile ferruginous hawks from the same nest also did not technically die during the post-fledging period, but were included in the survival analysis because of their relative age at death. They appeared to have been abandoned by the breeding adults and had not yet reached independence. The younger of the two was killed by siblicide prior to leaving the nest although it was within the average fledging age. The brood-mate of this juvenile successfully fledged, but seemed to disperse prematurely five days later. This individual was located approximately 8 km away from the nest 11 days later and appeared to have died of starvation.

The apparent mortality rate during the post-fledging period was 30% for ferruginous hawks (3/10), 20% for red-tailed hawks (5/25), excluding the unknown fates of two fledglings with failed transmitters, and 17% for Swainson’s hawks (4/23), excluding one found after reaching independence. Sources of mortality for juvenile radio-marked hawks varied (Table 2.4), but did not include collisions with wind turbines. I found evidence that post-fledging survival was species-specific, varied by age, and was influenced by surrounding landscape-scale variables (Table 2.5). I found no evidence of overdispersion with the goodness-of-fit test of the global and top-ranking models from AIC_c model selection ($P \geq 0.10$ in both cases). Therefore, I assumed that the fates of radio-marked juveniles were independent and did not include a random effect in post-fledging survival models. Consistent with my predictions, I found a strong quadratic effect of age on DSR for all three species; survival was lowest for younger juveniles during the first few days after fledging and also for older juveniles just prior to dispersal (Figure 2.2). The top three models in the final set contained 72% of the total model weight and included quadratic age and distance to the nearest wind turbine distance. The model averaged effect of wind turbine distance was positive for all three species ($\hat{\beta}$ = 1.14, SE = 0.67, 85% CI = 0.19 to 2.10), but effect of this variable was strongest for ferruginous hawks (Figure 2.3). The percentage of exotic grassland habitat in a 2.0 km buffer ($\widehat{\beta}$ = -0.23, SE = 0.40, 85% CI = -0.80 to 0.33) and the distance to the nearest *Buteo* nest ($\hat{\beta}$ = 0.16, SE = 0.33, 85% CI = -0.31 to 0.63) were also included in the best-approximating models and contained 24% of the model weight each, but model averaged estimates of these variables were unreliable predictors for all *Buteo* species.

Post-fledging Period

Because most raptors, such as *Buteo* hawks, demonstrate high individual variation in the length of the post-fledging period and move progressively further away from the nest (Pope 1999), it may be difficult to determine when juveniles reach independence (Newton 1979). However, telemetry data in my study indicated that once fledglings initiated dispersal, they left the area very quickly and were far away or often could not be located again despite my best efforts. I continued to receive signals outside of the study area for many juveniles after this period, however they were frequently far enough away that I could only obtain a general idea of direction. Locating individuals after dispersal was logistically difficult, except for the mortalities mentioned previously, primarily due to access issues on private land, navigating around major topographical features, and very large movements of juveniles during this period. Signals were located in all directions from the study area, including across the John Day River Canyon to the west and into the state of Washington across the Columbia River to the north. As a result, I felt confident in determining when juveniles initiated natal dispersal in my study area.

For those radio-marked juvenile *Buteo* hawks that survived to independence, I found differences among species in the length of the post-fledging period (Kruskal-Wallis $\chi^2 = 12.06$, df = 2, $P = 0.002$) (Figure 2.4). Ferruginous hawks had the shortest mean length of the post-fledging period ($N = 8$, $\bar{x} = 20.75 \pm 3.30$ days) and was significantly different from red-tailed hawks ($Z = 2.99$, $P = 0.008$), but not from Swainson’s hawks ($Z = 3.23$, $P = 0.36$). The post-fledging period was significantly longer ($Z = -2.54$, $P = 0.03$) for red-tailed hawks ($N = 20$, $\bar{x} = 31.60 \pm 2.09$ days) compared to Swainson’s hawks ($N = 18$, $\bar{x} = 26.56 \pm 1.14$ days). I retained the juvenile ferruginous hawk previously mentioned as having been found dead after premature dispersal because exclusion of this data point did not influence the results of this analysis.

Of the radio-marked fledglings, four ferruginous hawks, 17 red-tailed hawks and 18 Swainson’s hawks had ≥ 15 locations ($\bar{x} = 20.64 \pm 0.72$). The pooled natal home range for all three species was 0.48 km^2 (SD = 0.37) based on the MCP, and was similar to the 0.34 km^2 (SD = 0.29) reported by Pope 1999. However, the 95% fixed kernel estimate was much larger (2.38 km^2, SD = 1.48; Figure 2.5), even after I excluded one red-tailed hawk with a 19.95 km^2 natal home range as an outlier from this analysis. The exclusion of these data did not influence the results, but did provide a more conservative estimate of the natal range. The MCP method typically overestimates the home range size (Kernohan et al. 2001), but my fixed kernel estimates may have been larger because

I documented very little movement outside of the core natal area. I found no difference between the three hawk species in the 95% fixed kernel natal home range size during the post-fledging period (Kruskal-Wallis $\chi^2 = 2.24$, df = 2, $P = 0.33$). However, I may have lacked the statistical power to find a difference with my sample size, especially for ferruginous hawks.

Discussion

My results provide some evidence of landscape-scale effects on reproduction of *Buteo* hawks, although identified impacts pertained to specific stages of the breeding cycle and the response to wind turbines varied by species. Nest success was lower for ferruginous hawks in areas with greater numbers of turbines within 3.2 km of nests, but I did not find an effect of any wind turbine variables on red-tailed hawk or Swainson's hawks. No radio-marked fledglings died directly as a result of collisions with wind turbines or other types of wind energy development activity. Instead, my data suggest that fledglings may not face a significant risk of collision mortality, likely due, in part, to low overall activity, limited size of the natal home range, and the relatively short duration of exposure to wind turbines during the post-fledging period. I found that the DSR during the post-fledging period was best explained by species, distance to the nearest wind turbine, and a quadratic effect of age. Taken together, these results suggest a greater impact of wind turbines on ferruginous hawks compared to the other two congeneric species.

Effects of Covariates

In my study, four of nine breeding attempts at ferruginous hawk nests < 1.9 km away from a wind turbine were successful, fledging one young each. However, only one juvenile ferruginous hawk from these nests survived the entire post-fledging period and dispersed. In contrast, seven of eight breeding attempts at ferruginous hawk nests > 1.9 km away from turbines were successful and all six radio-marked young from five of these nests dispersed. Including red-tailed hawks and Swainson's hawks, all radio-marked juveniles found dead in my study were hatched from nests located < 1.9 km from the nearest wind turbine, within the average home range size of all three hawk species. While no fledglings were killed from collisions, and one Swainson's hawk drowned in a stock tank, juveniles from nests near wind turbines were more likely to die by predation or natural causes such as starvation just after fledging and prior to reaching independence.

Contrary to my predictions, predominant habitat types, competition from nearby breeding *Buteo* hawks, and nest-level covariates had little influence on nest success and post-fledging survival. Although the percentage of grassland habitat within 2.0 km and distance to the nearest *Buteo* nest were included in the best approximating models of the post-fledging analysis, neither variable had a large effect on survival according to model averaged parameter estimates. I was not able to include additional variables in nest survival models for ferruginous hawks and red-tailed hawks because of the limited number of nests that I was able to monitor for these two species. Habitat and competition could also explain variation in nest success if my sample size permitted the inclusion of additional variables. However, the effect of wind turbines on both ferruginous hawk nest success and post-fledging survival supports findings from some previous studies on other types of energy development (White and Thurow 1985; Keough 2006). Zelenak and Rotella (1997) failed to find impacts of oil and gas development on ferruginous hawk nest success in Montana; however, drilling was not taking place and, as a result, human activity was low. They concluded that higher ground squirrel densities near secondary access roads and increased edge habitat may have increased reproduction near wells and associated infrastructure. I was not able to estimate prey abundance or availability in my study, but these measures play an important role in *Buteo* hawk reproduction (Steenhof and Kochert 1985; Keough 2006).

Habitat types surrounding the nest did not influence nest success for Swainson's hawks or post-fledging survival by any species. However, I observed a broad matrix of habitat types in my study area and a high amount of fragmentation due to agricultural conversion, cattle grazing, and invasive vegetation. I did not account for habitat fragmentation in my covariates, but increased edge habitat has been associated with higher prey densities in other *Buteo* studies (Schmutz 1989; Zelenak and Rotella 1997; Keough 2006). Ultimately, I suspect that habitat variables were not better supported by the data because they were not measured precisely enough to reflect prey abundance or availability.

I found little support that competition variables influenced reproductive measures for any species and suspect the competitive interactions between these three species may be more complex than I predicted. For example, Swainson's hawks nesting within close proximity to sympatric *Buteo* species may not have a negative effect on reproduction (Thurow and White 1983; Janes 1984) until some threshold distance (≤ 0.2-0.3 km) is reached (Schmutz et al. 1980). In some cases, Swainson's hawks nesting within close proximity to ferruginous hawks may even provide cooperative territorial defense from predators (Thurow and White 1983). These sympatric breeding hawks may instead minimize competition through spatial isolation of habitat use and selection of specific nesting substrates (Schmutz et al. 1980; Cottrell 1981; Bechard et al. 1990; Restani 1991). However, other raptor species may have also competed with breeding hawks for limited resources. Great horned owls appeared to be the most likely cause of juvenile mortality and nest failure resulting from avian predators. I was unable to effectively locate all the great horned owl nests because of the timing of surveys and did not include them in competition covariates.

Post-fledging Survival

Despite the concern about increased collision mortality for juvenile raptors at older-generation wind energy projects (Orloff and Flannery 1992), I found no wind turbine-related mortality of radio-marked juveniles during the post-fledging period in my study. Additionally, collision mortalities located during post-construction monitoring in and near my study area during the breeding season (Leaning Juniper I, Gritski et al. 2008; Pebble Springs, Gritski and Kronner 2010; Klondike III P1, Gritski et al. 2010a; Klondike III P2, Gritski et al. 2010b; Rattlesnake Road Wind Farm, Gritski et al. 2011; Wheat Field Wind Farm, Gritski and Downes 2011; Willow Creek Wind Project, NWC 2011), and other non-telemetry incidental mortalities found during this study, show that most of these *Buteo* mortalities have been adults and sub-adults. According to the reported age and date of locations for these collision mortalities, no juveniles were found and only a few unknown age classes of hawk species that occurred from June-September (approximately 25%) could even potentially be fledglings. This indicates that juvenile hawks are probably less vulnerable to collision fatality during the relatively short post-fledging period compared to other ages and life-history stages. Juvenile hawks may also be susceptible to collisions with turbines after initiating dispersal, but I was unable to monitor radio-marked individuals effectively outside of the study area.

Apparent mortality rates of juveniles in my study were slightly higher than previously reported estimates. The mean mortality rate of ferruginous hawk fledglings across studies was 18% (range = 0-34%, Zelenak et al. 1997; Pope 1999; Watson and Pierce 2003; Keough 2006; Ward and Conover 2013). Post-fledging mortality was also low for juvenile red-tailed hawks (0%, *N* = 0/9, Johnson 1973; 0%, *N* = 0/7, Andersen 1994) and Swainson's hawks (13%, *N* = 2/15, Fitzner 1980). Similar to my results, predation (68%) and starvation (18%) formed a large percentage of mortality in these studies. Keough (2006) and Ward and Conover (2013) also found that post-fledging survival of ferruginous hawks was lower than most estimates, which they primarily attributed to predation by golden eagles (*Aquila chrysaetos*) during years of low prey abundance. However, Keough also found that greater numbers of nestlings, fledglings, and dispersed young per nest were associated with larger distances from gas and oil wells, indicating some indirect impacts of this type of development to reproduction, similar to the results from my study.

I found that brood rank was a poor predictor of survival and my sampling design explained little of the difference between my data and mortality rates from other studies. Rank could still potentially be an important predictor of survival, but the low productivity observed in my study did not allow me to sample ranks after the second oldest nestling sufficiently. I also found no evidence of overdispersion to suggest that survival of brood mates was correlated, and thus assumed the fates of individuals were independent. This assumption is further supported by studies with multiple juvenile radio-marked ferruginous hawks (Zelenak et al. 1997) and northern goshawks (*Accipiter gentilis*) (Wiens et al. 2006) that also found survival estimates of brood mates to be independent.

The cumulative effects of decreased post-fledging survival on breeding populations are uncertain because mortality is expected to increase sharply for juvenile *Buteos* during the first year of life after reaching independence. Ferruginous hawk mortality rose to 46-66% (Schmutz and Fyfe 1987; Woffinden and Murphy 1989; Harmata et al. 2001; Schmutz et al. 2008) based on band recoveries only, or to 86% including radio-marked juveniles (Harmata et al. 2001) during the first year. Annual survival of juveniles *Buteo* hawks may remain relatively constant (Schmutz et al. 2008), but annual fluctuations could have population-level consequences (Schmutz et al. 2006). Future studies examining raptors should not assume that increased nest failure or post-fledging mortality is inconsequential, but instead consider the species-specific response by local breeding populations.

Implications/Recommendations

I recommend that raptor nest monitoring and post-construction fatality surveys be conducted simultaneously during the breeding season. This information will permit a greater understanding of the breeding status of birds killed by collisions and help determine if they could be associated with nearby nests. I further recommend that survey methodology be standardized across project areas to allow estimation of success based on nest survival analyses (i.e., Dinsmore et al. 2002; Rotella et al. 2004) or other methods to reduce bias in reproductive estimates (Steenhof and Kochert 1982; Brown et al. 2013).

Monitoring of individual wind energy projects is unlikely to be designed entirely under an optimum Before-After/Control Impact Design (BACI) (Anderson et al. 1999) due to the difficulties in locating matched reference areas. Instead, raptor nest surveys and monitoring could be conducted across the entire gradient of potential impacts to those species suspected to occur in the area, such as in this study. Also, pre-construction nest surveys should include reproductive monitoring to determine success and productivity. These data will better facilitate any future meta-analyses across multiple project areas that will likely each have small sample sizes and provide a basis for comparison after wind energy projects are operational.

Based on the sources of mortality for radio-marked juveniles in this study, fledgling *Buteo* hawks may not be at a high risk for collision mortality from newer-generation wind turbines, like those operating in my study area and throughout the CPE. Mortality estimates derived from post-construction monitoring provide further evidence that juveniles in general are less likely to be found as collision fatalities compared to other age classes. The age, date of fatality location, and additional information on the condition of remains found during post-construction fatality monitoring is valuable information in determining relative risk of collisions to specific groups. This information is frequently not collected or not presented in post-construction reports even though it could help determine what age and life-history stages are most impacted.

Future research should focus on the risk of collision mortality to other ages and life history stages of *Buteo* hawks in the CPE that are more commonly found as collision fatalities, such as sub-adults and adults. Given my results, breeding adult hawks may also be indirectly impacted from wind turbines. Therefore, understanding factors that increase the risk of collisions for adult breeding hawks and indirect impacts on reproduction may be more vital in determining the consequences to population demographics.

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Table 2.1. Description of candidate models used to assess variation in nest success and post-fledging survival for ferruginous hawks, red-tailed hawks, and Swainson's hawks in the Columbia Plateau Ecoregion of north-central Oregon, 2010 – 2011.

Hypothesis Category	Model Name	Model Description
Base Model		
	Intercept	Null model indicating that DSR is constant (i.e. no effect)
	Spp	Survival varies by species
	Age/Age^2	Time-varying survival based on the standardized age or quadratic age at fledging
	Date/Date^2	Time-varying survival based on the Julian date or quadratic date at fledging
	Hatch	Estimated Julian hatch date based on oldest nestling
	Year	Annual changes in survival
	Spp+Age/Age^2	Time-varying age or quadratic age by species
	Spp+Date/Date^2	Time-varying date or quadratic date by species
	Spp+Hatch	Julian hatch date by species
	Spp+Year	Annual survival by species
Landscape Models		
Wind Turbines		
	Turb_Dist	Continuous distance from occupied nest to nearest wind turbine
	Turb_1.6 km/2.4 km/ 3.2 km	Density of turbines within interval surrounding nest
Habitat		
	Ag_2.0 km/3.0 km	Percent of intensively managed agriculture within 2.0 and 3.0 km of nest
	Native_2.0 km/3.0 km	Percent of native grassland and shrubland in within 2.0 and 3.0 km of nest
	Grass_2.0 km/3.0 km	Percent of invasive grasses within 2.0 and 3.0 km of nest
	NonAg_2.0 km/3.0 km	Percent of non- agricultural habitat (native and exotic) within 2.0 and 3.0 km of nest
Competition		
	Buteo_D	Distance from occupied or random nest to nearest Buteo nest
	Conp_D	Distance from occupied or random nest to nearest Conspecific nest
	Buteo_NND	Number of occupied Buteo nests within the

		average NND distance for each species
Nest and Juvenile Models		
	Brood	Number of young in each brood that survive to fledging age
	Rank	Rank in brood (oldest vs. all others) from young that survive to fledging age
Random Effects Models		
	Nest	Random effect of nest area (mean = 0)

Table 2.2. Estimates of nest success and productivity for *Buteo* species in the Columbia Plateau Ecoregion of north-central Oregon from 2010 to 2011.

Species	Nest Success [a] (ANS) [b]	Productivity per Breeding Pair	Productivity per Successful Nest	Sample Size
Ferruginous Hawk	54 (65)	0.81 [c]	1.3 [c]	17
Red-tailed Hawk	74 (89)	1.83	2.06	35
Swainson's Hawk	63 (66)	1.06	1.61	67

[a] Nest success estimated from the best-approximating nest survival model for breeding pairs with at least one nestling 33 days old.

[b] Apparent Nest Success (ANS) calculated as the proportion of total breeding pairs with at least one nestling 33 days old.

[c] Productivity per 16 breeding pairs due to incomplete information for one nest.

Table 2.3. Ranking of nest survival models for each *Buteo* species in the Columbia Plateau Ecoregion of north-central Oregon, 2010 – 2011. Model set reduced after removing those with uninformative parameters.

Ferruginous Hawk Models	AIC_c	ΔAIC_c	w_i	$-2\text{Log}(L)$	K
Turb_3.2 km+Nest	47.07	0.00	0.79	41.04	3
Intercept+Nest	49.68	2.61	0.21	45.66	2

Red-tailed Hawk Models	AIC_c	ΔAIC_c	w_i	$-2\text{Log}(L)$	K
Turb_1.6 km+Nest	35.052	0.00	0.64	29.02	3
Intercept+Nest	36.166	1.11	0.36	32.15	2

Swainson's Hawk Models	AIC_c	ΔAIC_c	w_i	$-2\text{Log}(L)$	K
Date+Turb_1.6 km+Nest	178.67	0.00	0.22	170.66	4
Turb_1.6 km+Nest	178.80	0.13	0.21	172.79	3
Intercept+Nest	179.16	0.48	0.17	175.15	2
Date+Nest	179.32	0.65	0.16	173.32	3
Buteos_NND+Nest	179.69	1.02	0.13	173.68	3
Native_3.0 kmk+Nest	180.23	1.56	0.10	174.22	3

Notes: AIC_c is Akaike Information Criterion adjusted for small sample sizes. ΔAIC_c for the *i*th model is computed as AIC_c – min (AIC_c). w_i is the AIC_c weight. L in $-2\text{Log}(L)$ is the model likelihood. K is the number of model parameters.

Table 2.4. Causes of death for radio-marked juvenile *Buteo* hawks in the Columbia Plateau Ecoregion of north-central Oregon during 2010 and 2011.

Final status	Ferruginous hawk	Red-tailed hawk	Swainson's hawk	Percent mortality
Dispersed	7	20	19	--
Transmitter failure	0	2	0	--
Mortality-predation	1	3	2	54
Mortality-unknown natural cause [a]	1	0	1	15
Mortality-starvation or disease	1	2	1	31
Mortality-turbine collision	0	0	0	0
Totals (n=60)	10	27	23	

[a] Included one ferruginous hawk that died from siblicide and one Swainson’s hawk that died from drowning.

Table 2.5. Ranking of models to examine factors influencing post-fledging survival of radio-marked *Buteo* species in the Columbia Plateau Ecoregion of north-central Oregon, 2010 – 2011. Model set reduced after removing those with uninformative parameters.

Model	AIC$_c$	ΔAIC$_c$	w_i	-2Log(L)	K
Age+Age^2+Spp+Turb_Dist+Grass_2.0 km	73.93	0.00	0.24	59.85	7
Age+Age^2+Spp+Turb_Dist+Buteo_D	73.94	0.01	0.24	59.86	7
Age+Age^2+Spp+Turb_Dist	73.97	0.04	0.24	61.91	6
Age+Age^2+Spp+Grass_2.0 km	76.03	2.10	0.08	63.97	6
Age+Age^2+Spp+Buteo_D+Grass_2.0 km	76.41	2.48	0.07	62.33	7
Age+Age^2+Spp+Buteo_D	76.95	3.02	0.05	64.89	6
Age+Age^2+Spp	77.36	3.44	0.04	67.32	5
Age+Age^2	77.54	3.61	0.04	71.52	3
Intercept	137.02	63.10	0.00	135.02	1
Spp	139.37	65.44	0.00	133.35	3

Notes: AIC$_c$ is Akaike Information Criterion adjusted for small sample sizes. ΔAIC$_c$ for the *i*th model is computed as AIC$_c$ – min (AIC$_c$). w_i is the AIC$_c$ weight. L in -2Log(L) is the model likelihood. K is the number of model parameters.

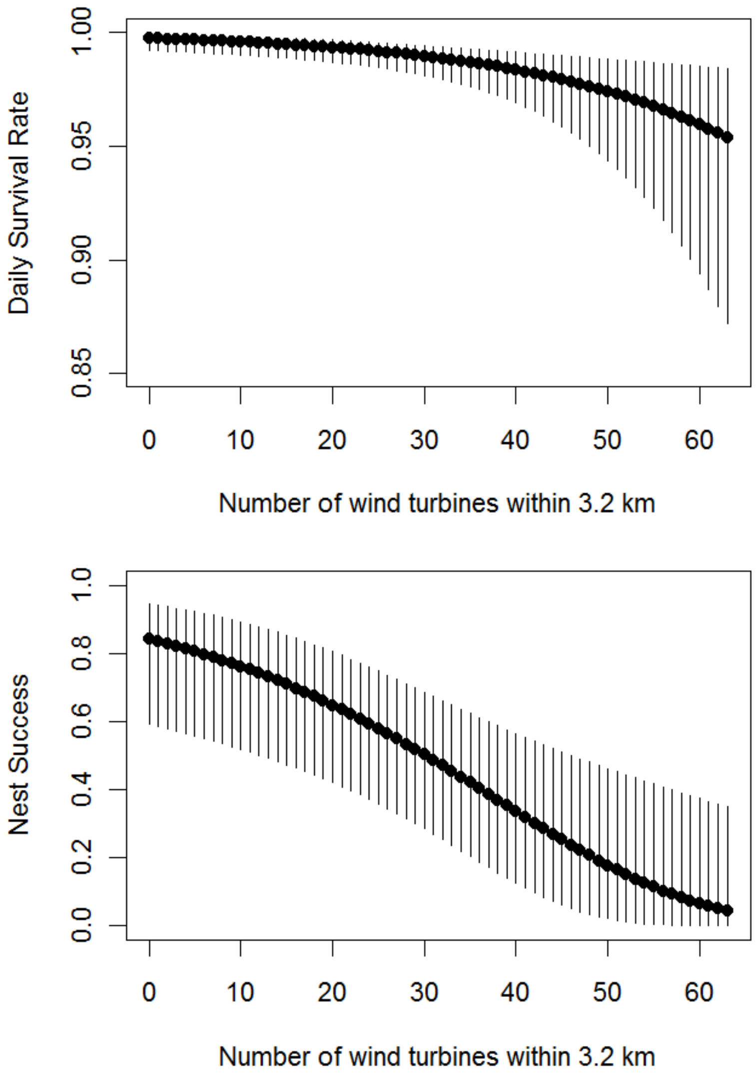

Figure 2.1. Influence of the number of wind turbines within 3.2 km of ferruginous hawk nests in the Columbia Plateau Ecoregion of Oregon during 2010 and 2011 on the daily survival rate (DSR) and estimated success over the nesting period (66 days). Solid dots represent the mean survival rate and lines represent 85% confidence intervals.

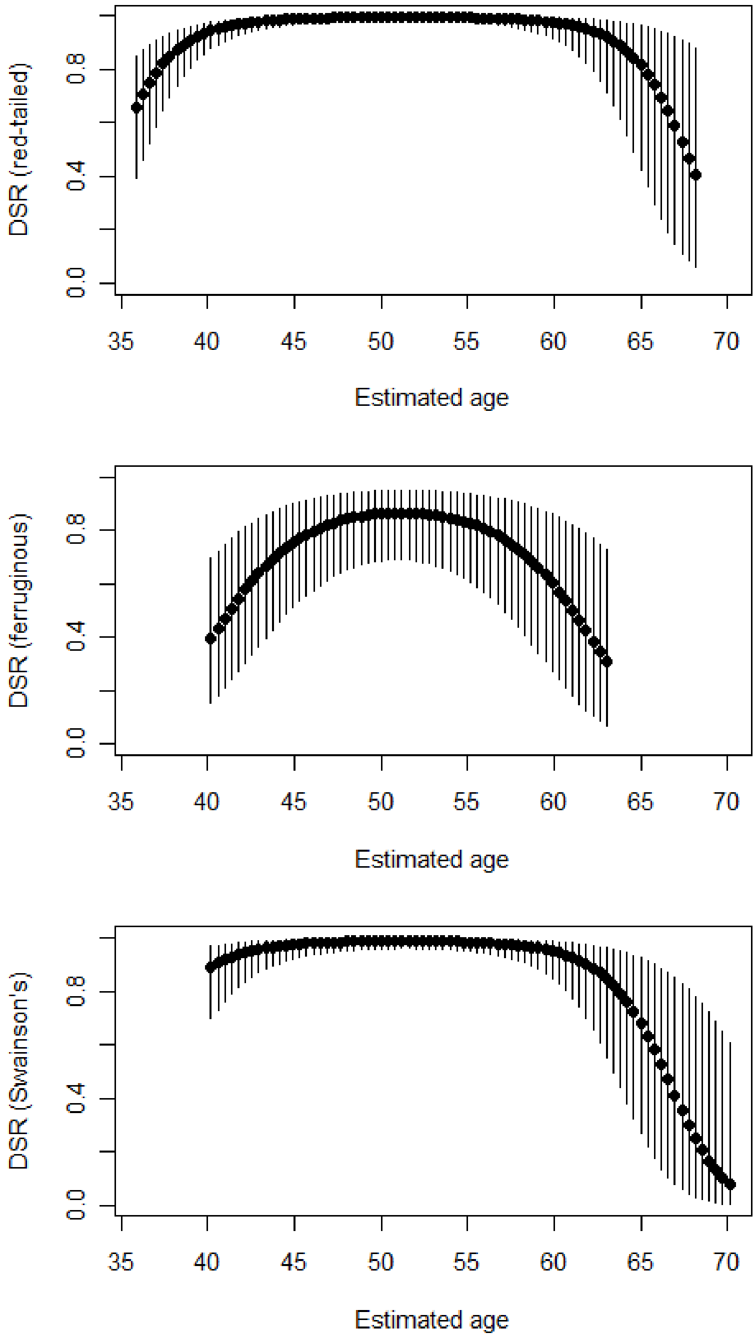

Figure 2.2. Influence of age (days) of radio-marked *Buteo* hawks in the Columbia Plateau Ecoregion of Oregon during the post-fledging period of 2010 and 2011on the daily survival rate (DSR), holding all other variables constant. Solid dots represent the mean DSR and lines represent 85% confidence intervals.

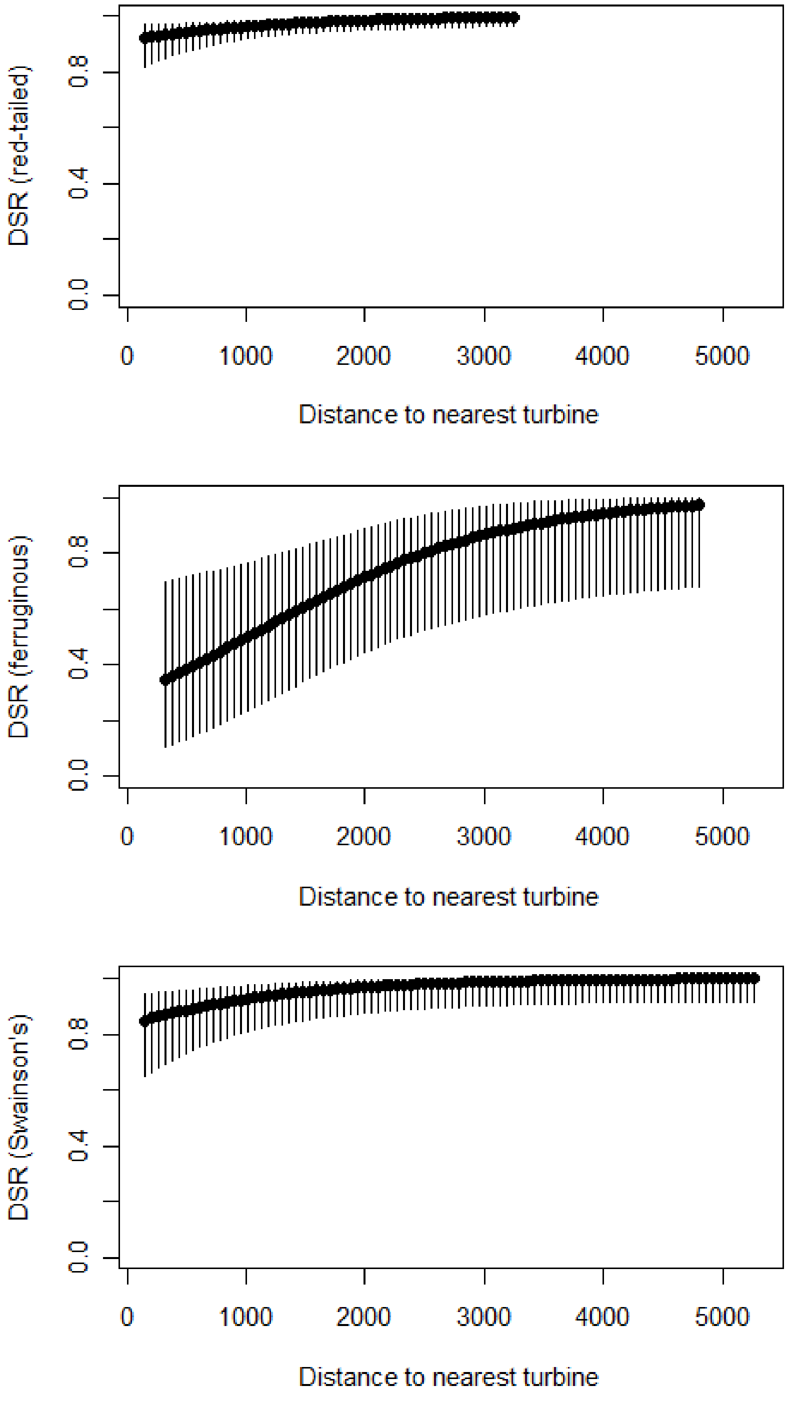

Figure 2.3. Influence of wind turbine distance from the nest of radio-marked *Buteo* hawks in the Columbia Plateau Ecoregion of Oregon during the post-fledging period of 2010 and 2011 on predicted daily survival rate (DSR), holding all other variables constant. Solid dots represent the mean DSR and lines represent 85% confidence intervals.

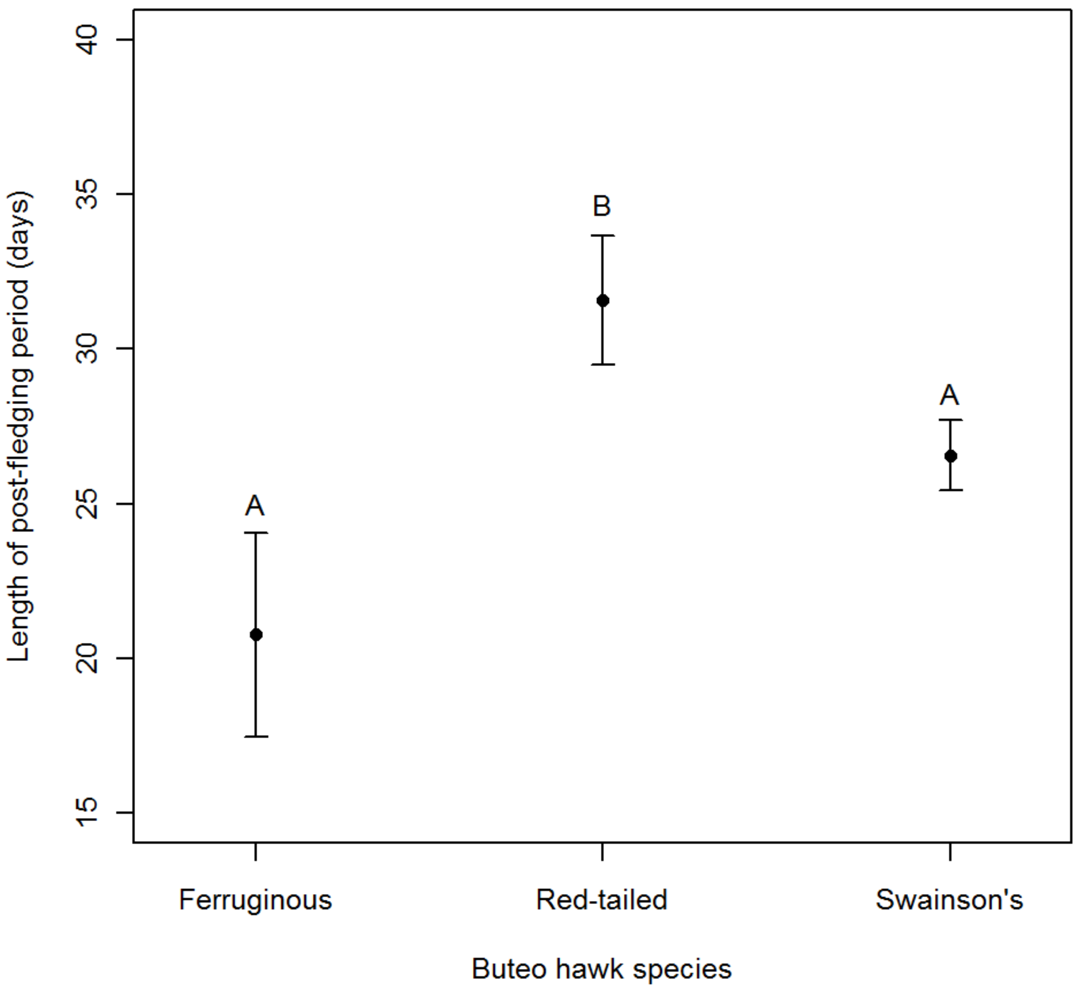

Figure 2.4. Mean length (dots) and standard error (bars) of the post-fledging period for juvenile radio-marked *Buteo* hawks in the Columbia Plateau Ecoregion of Oregon in 2010 and 2011. Group means were compared using the non-parametric Wilcoxon Rank Sums test and letters indicate a significant difference based on the Steel-Dwass test.

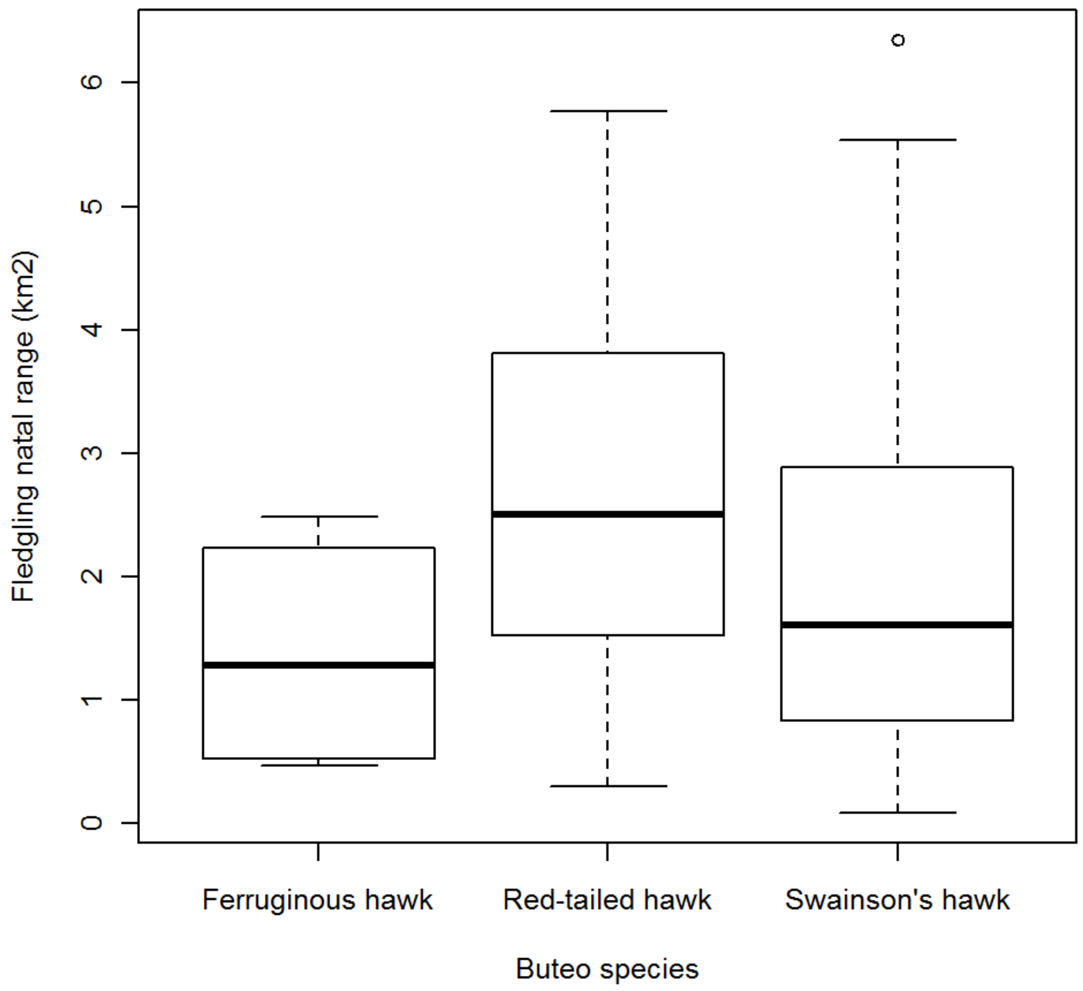

Figure 2.5. Estimated 95% fixed kernel post-fledging range (km^2) of juvenile radio-marked *Buteo* hawks in the Columbia Plateau Ecoregion during 2010 and 2011. Solid lines indicate the median and surrounding boxes display the 25th and 75th percentiles. Whiskers extent to 1.5 times the interquartile range of observations and dots indicate extreme values.

Appendix A.2

Glossary of terms adapted from Steenhof and Newton (2007) used to define reproductive measures for *Buteo* species.

Table A.2. Glossary of terms adapted from Steenhof and Newton (2007) used to define reproductive measures for *Buteo* species.

Apparent Nest Success. Calculated as the percent of used nests where at least one nestling reaches 80% of average fledgling age.

Breeding Pair. A term commonly used to replace the ambiguous term “active” to describe a breeding attempt (i.e. if eggs were laid by a breeding pair of raptors). Evidence of an occupancy breeding attempt can be determined by locating well-worn nests with signs that eggs were laid, such as eggs or eggshells, young, and/or adults observed in incubation posture.

Fledging stage. The period in which young voluntarily leave the nest for the first time.

Natal Dispersal. Period between leaving the place of birth (or natal area) and the first breeding attempt. In this study, initiation of natal dispersal was identified for radio-marked fledglings when they could no longer be located within the natal range and were assumed to have reached independence.

Nest Area/Historical Territory. An area within the home range of a mated pair that contains, or historically contained, one or more nests where no more than one pair is known to have bred at one time.

Nest Area/Territory Occupancy. A determination made if two or more breeding aged birds are located in a nest area during the breeding season. Nest areas were considered occupied if two breeding aged hawks were determined to be paired or if at least one adult was observed in territorial defense or reproductive-related activity was documented (i.e., nest building, brooding young, or presence of a new or recently repaired nest).

Nest Survival. The probability that a nesting attempt survives from initiation to completion with at least one young that reaches the minimum acceptable age to determine nest success.

Post-fledging Period. The time when young are still dependent on the adults to provide a majority of food between fledging and initiation of natal dispersal from the nesting area.

Productivity. Number of young that reach the minimum acceptable age for assessing success (see above) in a given season.

Successful (nest or breeding pair). One in which at least one young reaches the minimum acceptable age for assessing success (80% of the average fledging age for *Buteo* hawks)

Appendix B.2

Full ranking of nest survival models for each Buteo species in the Columbia Plateau Ecoregion of north-central Oregon, 2010 – 2011.

Table B.2. Full ranking of nest survival models for each *Buteo* species in the Columbia Plateau Ecoregion of north-central Oregon, 2010 – 2011.

Ferruginous Hawk Models	AIC$_c$	ΔAIC$_c$	w_i	-2Log(L)	K
Turb_3.2 km+Nest	47.07	0.00	0.35	41.04	3
Turb_2.4 km+Nest	47.59	0.52	0.27	41.56	3
Turb_Dist+Nest	48.44	1.37	0.18	42.41	3
Turb_1.6 km+Nest	49.61	2.54	0.10	43.58	3
Intercept+Nest	49.68	2.61	0.10	45.66	2

Red-tailed Hawk Models	AIC$_c$	ΔAIC$_c$	w_i	-2Log(L)	K
Turb_1.6 km+Nest	35.05	0.00	0.31	29.02	3
Turb_Dist+Nest	35.49	0.44	0.25	29.46	3
Intercept+Nest	36.17	1.12	0.18	32.15	2
Turb_2.4 km+Nest	36.43	1.38	0.15	30.40	3
Turb_3.2 km+Nest	36.98	1.94	0.12	30.96	3

Swainson's Hawk Models	AIC$_c$	ΔAIC$_c$	w_i	-2Log(L)	K
Date+Turb_1.6 km+Nest	178.67	0.00	0.19	170.66	4
Turb_1.6 km+Nest	178.80	0.13	0.17	172.79	3
Intercept+Nest	179.16	0.48	0.15	175.15	2
Date+Nest	179.32	0.65	0.13	173.32	3
Buteos_NND+Nest	179.69	1.02	0.11	173.68	3
Date+Buteos_NND+Nest	179.97	1.30	0.10	171.96	4
Native_3.0 km+Nest	180.23	1.56	0.09	174.22	3
Date+Native_3.0 km+Nest	180.67	2.00	0.07	172.66	4

Notes: AIC$_c$ is Akaike Information Criterion adjusted for small sample sizes. ΔAIC$_c$ for the *i*th model is computed as AIC$_c$ – min (AIC$_c$). w_i is the AIC$_c$ weight. L in -2Log(L) is the model likelihood. K is the number of model parameters.

Appendix C.2

Full ranking of models to examine factors influencing post-fledging survival of radio-marked Buteo species in the Columbia Plateau Ecoregion of north-central Oregon, 2010 – 2011.

Table C.2. Full ranking of models to examine factors influencing post-fledging survival of radio-marked *Buteo* species in the Columbia Plateau Ecoregion of north-central Oregon, 2010 – 2011.

Model	AIC$_c$	ΔAIC$_c$	w_i	-2Log(L)	K
Age+Age^2+Spp+Turb_Dist+Grass_2.0 km	73.93	0.00	0.16	59.85	7
Age+ Age^2+Spp+Turb_Dist+Buteo_D	73.94	0.01	0.16	59.86	7
Age+ Age^2+Spp+Turb_Dist	73.97	0.04	0.15	61.91	6
Age+Age^2+Spp+Turb_Dist+Buteo_D+Grass _2.0 km+Rank	74.45	0.52	0.12	56.33	9
Age+Age^2+Spp+Turb_Dist+Buteo_D+Grass _2.0 km	74.57	0.64	0.11	58.47	8
Age+Age^2+Spp+Grass_2.0 km	76.03	2.10	0.05	63.97	6
Age+Age^2+Spp+Buteo_D+Grass_2.0 km	76.41	2.48	0.05	62.33	7
Age+Age^2+Spp+Buteo_D	76.95	3.02	0.03	64.89	6
Age+Age^2+Spp	77.36	3.44	0.03	67.32	5
Age+Age^2	77.54	3.61	0.03	71.52	3
Age+Age^2+Spp+Rank	78.01	4.08	0.02	65.95	6
Age+Age^2+Grass_2.0 km	78.07	4.14	0.02	70.04	4
Age+Age^2+Turb_Dist	78.24	4.31	0.02	70.21	4
Age+Age^2+Buteo_D	78.83	4.91	0.01	70.81	4
Age+Age^2+Turb_Dist+Grass_2.0 km	79.08	5.15	0.01	69.04	5
Age+Age^2+Rank	79.14	5.21	0.01	71.11	4
Age+Age^2+Turb_Dist+Buteo_D	79.72	5.80	0.01	69.68	5
Age+Age^2+Buteo_D+Grass_2.0 km	79.78	5.85	0.01	69.74	5
Age+Age^2+Turb_Dist+Buteo_D+Grass_2.0 km	80.87	6.94	0.01	68.81	6
Intercept	137.02	63.10	0.00	135.02	1
Spp	139.37	65.44	0.00	133.35	3

Notes: AIC$_c$ is Akaike Information Criterion adjusted for small sample sizes. ΔAIC$_c$ for the *i*th model is computed as AIC$_c$ – min (AIC$_c$). w_i is the AIC$_c$ weight. L in -2Log(L) is the model likelihood. K is the number of model parameters.