Home-range habitat selection by Ferruginous Hawks in western Canada: implications for wind-energy conflicts

Janet W. Ng¹, Troy I. Wellicome¹, Lionel F. V. Leston¹ and Erin M. Bayne¹

¹Department of Biological Sciences, University of Alberta, Edmonton, Alberta, Canada; ²Canadian Wildlife Service, Environment and Climate Change Canada, Edmonton, Alberta, Canada

ABSTRACT. Global wind-energy development has increased exponentially in recent decades and is expected to double in capacity in Canada by 2040. Wind-farm development has significant implications for wildlife, particularly for raptors, where injury or death from turbine strikes and other cumulative effects are well documented. Minimizing conflict is important for species at risk, such as the Ferruginous Hawk (Buteo regalis), because negative impacts from wind farms may hinder conservation and recovery actions. Understanding Ferruginous Hawk habitat selection is needed to assess the potential spatial overlap with wind-farm development and make spatially explicit predictions of conflict risk. Our objectives were (1) to develop a predictive map of habitat selection by Ferruginous Hawks at the home-range scale; and (2) to identify areas of high and low potential conflict with current and future wind-energy developments, by overlaying predictive habitat maps with wind potential within the Canadian Ferruginous Hawk range. We showed that landscape composition and configuration, current industrial development, soil characteristics, and seasonal climate influenced Ferruginous Hawk home-range habitat selection. Our risk analyses identified areas at medium to very high risk of conflict with wind energy, but also large areas with low wind-energy development potential and high conservation value that would be valuable for species conservation and management. Importantly, how wind potential is measured has a strong influence on the level of risk. Our habitat model and risk assessment do not replace ground assessments, but can be used during the pre-development phase to proactively site new wind farms away from potential risk for Ferruginous Hawks.

INTRODUCTION
Worldwide, electricity consumption is expected to grow 1% through 2050 (U.S. Energy Information Administration 2021). In an attempt to reduce carbon emissions, there is a growing move toward the use of renewable energy to create electricity. Wind energy has grown exponentially in response to this demand. The Canadian Renewable Energy Association estimates that national wind-energy capacity grew by 5% across Canada in 2021 (https://renewablesassociation.ca/by-the-numbers/) and that the rate of growth is expected to increase significantly over time (Canadian Renewable Energy Association 2022). This degree of wind-energy development will have implications for wildlife (Fargione et al. 2012, Tack and Fedy 2015).

Sélection de l’habitat du domaine vital par la Buse rouilleuse dans l’Ouest du Canada : répercussions pour les conflits potentiels avec les parcs éoliens

RÉSUMÉ. Le développement mondial de l’énergie éolienne a augmenté de façon exponentielle au cours des dernières décennies et on s’attend à ce que la capacité de production double au Canada d’ici 2040. L’installation de parcs éoliens a des répercussions importantes sur la faune, en particulier sur les rapaces, pour lesquels les blessures ou les mortalités causées par collisions avec les éoliennes et d’autres effets cumulatifs sont bien documentés. Il est important de minimiser les conflits pour les espèces en péril, comme la Buse rouilleuse (Buteo regalis), car les effets négatifs des parcs éoliens peuvent faire obstacle aux mesures de conservation et de rétablissement. Nous devons comprendre la sélection de l’habitat de la Buse rouilleuse pour évaluer le chevauchement spatial potentiel avec les futurs parcs éoliens et faire des prédictions spatialement explicites du risque de conflit. Nos objectifs étaient (1) d’élaborer une carte prédictive de la sélection de l’habitat par la Buse rouilleuse à l’échelle du domaine vital; et (2) d’identifier les zones de conflit potentiel élevé et faible avec les parcs éoliens actuels et futurs, en superposant les cartes prédictives de l’habitat avec le potentiel éolien dans l’aire de répartition de la Buse rouilleuse au Canada. Nous avons trouvé que la composition et la configuration du paysage, le développement industriel actuel, les caractéristiques du sol et le climat saisonnier influençaient sur la sélection de l’habitat du domaine vital de la Buse rouilleuse. Nos analyses du risque ont permis d’identifier des zones présentant un risque de conflit moyen à très élevé avec les parcs éoliens, mais aussi de vastes zones à faible potentiel pour le développement éolien et à grande valeur de conservation qui seraient importantes pour la conservation et la gestion de l’espèce. Nous avons remarqué que la façon dont le potentiel éolien est mesuré a une forte influence sur le niveau de risque. Notre modèle d’habitat et notre évaluation du risque ne remplacent pas les évaluations faites au sol, mais peuvent être utilisés pendant la phase de pré-développement afin d’installer de manière proactive les nouveaux parcs éoliens loin des risques potentiels pour les Buses rouilleuses.

Key Words: Buteo regalis, conservation offset, distribution model, on-shore wind energy, renewable energy, resource selection function

Copyright © 2022 by the author(s). Published here under license by the Resilience Alliance.

Corresponding author: Erin M Bayne, bayne@ualberta.ca
Impacts of wind energy on wildlife include both direct and indirect impacts (Allison et al. 2019). Increased mortality from turbine strikes (Pagel et al. 2013), barotrauma (Baerwald et al. 2008), behavioural avoidance (Hoover and Morrison 2005, Drewitt and Langston 2006, Dohm et al. 2019, Fielding et al. 2021), and acoustic masking are known issues associated with wind turbines (Northrup and Wittemyer 2012). Cumulative effects of associated infrastructure also occur at wind farms (Zimmerling et al. 2013, Smith and Dwyer 2016) through increased roads, which further decrease available habitat and fragment the landscape (Northrup and Wittemyer 2012). Higher vehicle volume on roads has increased mortality through collisions (Litvaitis and Tash 2008). Collision or electrocution risk can also increase with higher densities and closer proximity to power lines (Sergio et al. 2004, Shaw et al. 2018) built to support wind farms. Finally, the construction phase of wind-farm development can have a negative impact on wildlife, with potentially greater impact than the subsequent operation of the wind farm (Pearce-Higgins et al. 2012). These large-scale cumulative effects can be additive and can negatively affect habitat use and selection, survival, and reproduction of wildlife (Carrete et al. 2009). Therefore, pre-construction assessments for new wind farms should consider more than just the risk of the wind turbines themselves, but also the broader spatial and temporal scales of cumulative effects on wildlife (Marques et al. 2014, Watson et al. 2018a).

Prudent siting (i.e., macro-siting) of wind farms is one way to reduce potential negative impacts before construction begins (Baisner et al. 2010, Zimmerling et al. 2013, Balotari-Chiebao et al. 2016, Smith and Dwyer 2016, Zwart et al. 2016). Micro-siting of turbines (i.e., siting individual turbines) can potentially reduce risk even more by evaluating where animals are most likely to be within or passing through a specific wind farm (Smallwood et al. 2009, Johnston et al. 2014, Vignali et al. 2022). Once constructed, wind farms rely on a variety of mitigation techniques, often related to timing of windfarm activities (Allison et al. 2017, McClure et al. 2021a), sometimes with limited success (Smallwood and Bell 2020). Thus, understanding how habitat selection varies at different temporal and spatial scales is important to reducing conflict with species at risk from anthropogenic development.

Ferruginous Hawks (Buteo regalis) are a threatened species in prairie Canada (COSEWIC 2008), where their breeding range extends from southeastern Alberta through southern Saskatchewan to southwestern Manitoba (Ng et al. 2020). Across their North American range, they have been observed using habitat < 50 m from wind turbines at relatively high rates compared to other birds (Smallwood et al. 2009) and Ferruginous Hawk injury and death from turbine strikes have been documented (Watson et al. 2018b). Furthermore, Kolar (2013) found that Ferruginous Hawk daily nest success was lower in areas with more wind turbines per home range, suggesting additive cumulative effects are occurring. Post-fledging daily survival rate increased farther away from turbines (Kolar 2013, Kolar and Bechard 2016). Reoccupancy rates of Ferruginous Hawk home ranges also decreased 50% in < 5 years following wind-farm construction in Washington (J. Watson, Washington Department of Fish and Wildlife, personal communication). Diffendorfer et al. (2021) found that Ferruginous Hawks had relatively higher potential of population-level impacts from wind-turbine collisions relative to most other raptors. Thus, siting wind-energy development away from habitat with high suitability for nesting Ferruginous Hawks is one way to reduce risk to this species (Watson et al. 2018a).

To achieve more effective wind-farm siting requires quantification and mapping areas of Ferruginous Hawk habitat suitability at different spatial scales. We collated Ferruginous Hawk locations to develop and validate habitat-selection models across the entirety of the range of the Ferruginous Hawk in Canada. We then used this spatially explicit model to identify areas of conflict between Ferruginous Hawks and wind-farm development in order to provide wind-farm developers and regulators the ability to identify areas of lower conflict. Specifically, we (1) developed a predictive map of nesting-habitat selection by Ferruginous Hawks at the home-range scale over the extent of their breeding range in Canada; (2) identified areas of high and low potential conflict with current and future wind-energy developments, by overlaying predictive habitat maps with wind potential within the Canadian Ferruginous Hawk range; and (3) tested if different wind-potential scenarios related to optimal wind speeds at different turbine heights changed the geographical distribution of risk.

**METHODS**

**Study area**

Our study area included the fescue, moist-mixed, and mixed-grass ecoregions of southern Alberta and Saskatchewan, ranging from the US-Canada border to 52°50′N latitude, between longitudes of 114°0′W and 103°0′W (Fig. 1). The climate was semi-arid, where temperatures averaged 14.8°C (April to September) and annual precipitation was on average 322.6 mm (Environment and Climate Change Canada, Historical Climate Data for Medicine Hat, Alberta, Canada, https://climate.weather.gc.ca/index_e.html). Dominant land covers reflect major land uses, which was farming and ranching. Farmland was predominately cropland and dominant crops including wheat, canola, peas, and lentils. Irrigation was common in parts of the study area, but the majority of cropland was not irrigated. Native grassland was generally used for grazing cattle and was dominated by blue grama (Bouteloua gracilis), needle-and-thread grass (Stipa comata), wheatgrass species (Agropyron spp.), and rough fescue. Petroleum development, both natural-gas and oil extraction, was found throughout the study area. Development was generally clustered on or near gas or oil fields, with well density ranging from 0 to > 20 wells per section (256 ha). The study area is the northern portion of the Ferruginous Hawk range, but historically has nest densities in some areas far lower than the core of the range while areas near the Alberta-Saskatchewan border have some of the highest Ferruginous Hawk nest densities in the world (Schmutz et al. 2008). Ferruginous Hawks arrived in mid-March and remained until fall migration in September/October (Ng et al. 2020).

**Species data**

Nest-location data was provided by researchers and biologists who submitted nests records to provincial (Alberta Fish and Wildlife Information Management System and Saskatchewan...
Avian Conservation and Ecology 17(2): 33
http://www.ace-eco.org/vol17/iss2/art33/

Fig. 1. Map of study area in Alberta and Saskatchewan, Canada. Ferruginous Hawk (*Buteo regalis*) nests reported between 2005–2010 are represented by dots. Grass cover is represented by light gray.

Conservation Data Centre) and federal (Environment Canada Wildspace) databases. Data were also collected by naturalists, such as hobby banders, who are required to meet a standard skill level for bird identification before being granted a banding permit. We used data from multiple sources to increase our sample size and cover as much of the Canadian range as possible. Only nests that were confirmed by observations of territorial adults, eggs, nestlings, or incubating females were included. We constrained nest data to be from nests observed between 2005 and 2010.

The majority of nests were recorded with a hand-held Global Positioning System (GPS; accuracy to ± 10 m), but a minority of nests were reported with < 400 m accuracy because the observer lacked landowner permission to approach the nest. A subset of nests were difficult to distinguish as unique or duplicate nests because they were reported in multiple instances, either by different agencies, at varying spatial precisions, or over several years because nests are often used for multiple years. We resolved the varying spatial precision and eliminated possible duplicates by generalizing nest locations to the quarter-section (64 ha) in which they were observed. Each used quarter-section was reduced to a centroid, which represented the potential centre of the home range. This was a conservative approach to eliminating duplicate nests through the years. We expected little to no impact on our analysis because the landscape and climate variables we assessed were highly correlated between the quarter-section (~400 m radius) and unit of analysis we used to approximate home ranges. In addition, random quarter-sections were selected across the study area to provide a set of points to describe the available landscape. We collapsed historical nest data, from 2005 to 2010, to 2147 used quarter-sections, and characterized available units by randomly selecting 11,841 quarter-sections from the study area.

**Predictor variables**

We categorized 57 predictor variables into five model sets: geography, land cover, human development, soil, and climate (Appendix 1). Grouping variables into model sets allowed us to select the best-fitting variables from those that were correlated with each other. This helped us reduce a large number of predictor variables in order to determine how the variables within each of the five model sets influenced Ferruginous Hawk home-range selection. Furthermore, variables within some of the model sets, such as land cover and human development, can be manipulated by land managers, regulatory agencies, and industry advisors, and therefore may be important for developing management strategies for conservation and recovery. Geography, soil, and climate cannot be manipulated, but, in other studies on species of concern at broad spatial extents, are good predictors of habitat selection and thereby are likely to be useful for helping in macro-siting during pre-development planning (Cumming et al. 2013).

We used ArcGIS Release 10.1 (ESRI 2012) to measure predictor variables around used and random available points. Each variable was quantified at a 30-m resolution. Variables were summarized around a centroid, which represented the potential centre of the home range. We expected little to no impact on our analysis because the landscape and climate variables we assessed were highly correlated between the quarter-section (~400 m radius) and unit of analysis we used to approximate home ranges. In addition, random quarter-sections were selected across the study area to provide a set of points to describe the available landscape. We collapsed historical nest data, from 2005 to 2010, to 2147 used quarter-sections, and characterized available units by randomly selecting 11,841 quarter-sections from the study area.

**Predictor variables**

We categorized 57 predictor variables into five model sets: geography, land cover, human development, soil, and climate (Appendix 1). Grouping variables into model sets allowed us to select the best-fitting variables from those that were correlated with each other. This helped us reduce a large number of predictor variables in order to determine how the variables within each of the five model sets influenced Ferruginous Hawk home-range selection. Furthermore, variables within some of the model sets, such as land cover and human development, can be manipulated by land managers, regulatory agencies, and industry advisors, and therefore may be important for developing management strategies for conservation and recovery. Geography, soil, and climate cannot be manipulated, but, in other studies on species of concern at broad spatial extents, are good predictors of habitat selection and thereby are likely to be useful for helping in macro-siting during pre-development planning (Cumming et al. 2013).

We used ArcGIS Release 10.1 (ESRI 2012) to measure predictor variables around used and random available points. Each variable was quantified at a 30-m resolution. Variables were summarized around a centroid, which represented the potential centre of the home range. We used a 2500-m radius buffer to approximate the 50% core area of a Ferruginous Hawk home range (Watson 2020). We characterized available landscapes by generating a random point within each randomly selected quarter-section to represent available habitat and quantifying landscapes with a 2500-m radius buffer.
Geographic variables include elevation, standard deviation of elevation (to characterize heterogeneous terrain), latitude, and longitude. Latitude and longitude are included as a surrogate for unmeasured spatial gradients in environmental conditions as well as to ensure range boundaries for the species were properly accounted for. Particularly because we studied birds nesting in the northern portion of the species range, it was important to control for potential influences related to range boundaries (i.e., northern periphery of the species range).

Land-cover variables included proportion of grassland (hereafter, grass), distance to nearest grass, and total edge (AAFC 2009). Total edge was calculated as the sum length along interfaces between grass and cropland. Variables related to composition of cropland (hereafter, crop) within the 2500-m radius buffer were not included because crop is inversely correlated with grass in southern Alberta. Landcover composition and edge density were used as predictors of hawk-habitat selection because certain habitat configurations influence foraging patterns of hawks (Wakeley 1978).

Human-development variables described oil-and-gas infrastructure and linear features (IHS Global Canada Ltd. 2013). We quantified infrastructure that existed in 2010 and assumed that, although development is ongoing, density of human development features are spatially auto-correlated within 2500-m radius buffers. Oil-and-gas infrastructures were grouped into surface wells (i.e., both oil-and-gas wells) and facilities, but were also considered separately as oil wells, gas wells, and noise-producing facilities. Linear features included roads, pipelines, and transmission lines. Distance to nearest feature was measured for all infrastructure types. Point features such as oil-and-gas wells were counted within each buffer distance and total line length within each buffer was summed for linear features. There is widespread concern that human land use and industrial development reduce habitat suitability for Ferruginous Hawks (Keough and Conover 2012). Determining if already impacted areas would be better places for additional development versus allowing wind farms in areas with relatively little disturbance is a question asked by regulators (Hegmann et al. 1999).

Soil Landscapes of Canada Version 3.2 (digital map and database at 1:1 million scale) was used to characterize soil around each nest location (Soil Landscapes of Canada Working Group 2010). Soil was characterized by regional texture, and proportions of parent materials and soil orders. Soil characteristics are associated with habitat composition and configuration, where specific landscapes may provide suitable habitat for hawks. In addition, Richardson’s ground squirrels, an important prey species for Ferruginous Hawks, are a fossorial species that are correlated with specific soil characteristics.

Climate variables included both spring (March through May) and summer (June through August) seasons. Climate normals were based on data from 1960 to 2000, and average precipitation and minimum, maximum, and average temperatures were extracted for each used and available point (Climate WNA Version 5.41; Wang et al. 2011). Climate normals were used because our objective was to evaluate regional climate patterns associated with home-range habitat selection, rather than short-term weather-related patterns related to, for example, annual reproductive performance. Climate is an important determinant of natural land cover and of the distribution of many prey species, and also influences land-use patterns, so could potentially be an important predictor of Ferruginous Hawk habitat selection. Predictor variables were standardized prior to analysis by subtracting the mean and dividing by the standard deviation for each variable.

Model development

We used STATA 11.0 (Statacorp 2009) for all statistical analyses. We followed a standard data-exploration protocol to evaluate data for outliers, collinearity, and heterogeneity of variance (Zuur et al. 2010). Within each model set, Akaike information criterion (AIC) values (Burnham and Anderson 2002) were calculated for models with different predictor variables that were highly correlated. We removed the variable with the least explanatory power based on AIC values from correlated variables that described similar phenomena within a model set. We also used AIC values to evaluate whether linear or quadratic forms for each variable performed best, and then included the form with the lowest AIC value. The variable with the lowest AIC value, hence higher explanatory power, was included in each modelling step.

We used logistic regression to create a second order used versus available resource selection function (RSF) to develop a Ferruginous Hawk home-range habitat-selection model for each of the five model sets (Boyce et al. 2002, Manly et al. 2002, Johnson et al. 2006). A hierarchical information-theoretic approach was used to develop the best model from the simplified number of variables in each model set. We used a backwards stepwise elimination process to create the most parsimonious set of variables within a model set (P > 0.10; Arnold 2010) if the resulting model AIC also decreased. Retained variables within model sets included only those terms that were significant at P < 0.1. The combined variables forming the all-inclusive model were created by using all retained terms within the five model sets.

We used this stepwise approach with each group of variables to reduce the number of variables that described a general ecological phenomena that is known to influence hawk-habitat selection while ensuring that major ecological concepts known to influence habitat selection by hawks were considered. We chose this approach over other methods like multi-model comparison via AIC or machine learning for five reasons. First, soil and climate are known to be predictive of Ferruginous Hawk distribution in other parts of their range (Carr and Melcher 2017) but there are few a priori predictions in the literature that generalize what those relationships might look like in our study area. Second, the variables in the different model sets were not intended to be mutually competing hypotheses about what drove habitat selection of hawks. Instead, variables in each model are known from the literature to have an influence on hawk selection and we expected all the variables would be predictive, but we did not know a priori which variables within a model set would be most predictive. Third, our goal was primarily to get a model that was predictive and done in a way that was repeatable. Fourth, managers requested models that had predictive coefficients that could be described as an equation rather than importance scores that come from machine-learning approaches. Fifth, similar approaches have been used to model other species at risk at this spatial scale successfully in the past (Stevens et al. 2011, Ball et al. 2016). We compared model fit from our approach to a boosted regression tree and found the Spearman correlation coefficient
was high at 0.86. Model performance was evaluated using area under the curve (AUC) based on receiver operating curves (ROC; Hosmer et al. 2013).

**Model validation**

We collected an independent sample of Ferruginous Hawk nest locations to evaluate the predictive capability of the habitat-selection model. An independent set of data for model validation was particularly important because the core dataset was collected opportunistically. A validation using systematically collected and independent data is thus a particularly robust evaluation. Our validation data set was based on stratified random sampling, whereby surveys were geographically spread throughout the study area and distributed along a low to high grassland-cropland gradient and industrial-development gradient. Nest surveys were conducted in 2012 and 2013 and we found 119 active hawk nests across Alberta and Saskatchewan.

We evaluated the area-adjusted probability of use relative to predicted selection by ranking RSF values into five equal-interval bins and then comparing the frequency of test data relative to the expected frequency. We used linear-regression statistics (Johnson et al. 2006) to evaluate the fit of the model, where a high R², a slope not different from 1.0, and an intercept not different from zero was deemed a good model. We also evaluated the correlation between the proportion of expected and observed nests in each bin rank using Spearman’s rank correlation.

**Identifying potential conflict zones**

A predictive map was generated for the study area using the resulting RSF equation. Given the documented fatalities of Ferruginous Hawks from turbine strikes (Watson et al. 2018b) and the results of other studies (Kolar 2013, Kolar and Bechard 2016, Diffendorfer et al. 2021), we assume that the overlap of wind-farm development and Ferruginous Hawk home ranges would increase the likelihood of negative impacts to hawks.

We then identified areas of potentially higher conflict between Ferruginous Hawks and wind farms by assessing the potential for future wind-farm development across the study area. Spatial data for wind potential were obtained from the Canadian Wind Energy Atlas (http://www.windatlas.ca/index-en.php). Estimated mean wind power was generated from a model using over 43 years of averaged spatial wind data. The spatial resolution for the modeled data is 4.8 km by 4.8 km pixels. We used a moving-window analysis to average wind into 2.5 km pixels to correspond to the scale of our habitat-selection analysis. We then classified mean wind power in each pixel into wind-power classes (WPC). This is the industry standard used to classify mean wind speed into seven categories, where wind speed averages 0 to > 31.7 km/h (Elliott et al. 1987). Our estimates for wind potential are modeled for turbines 50 m and 80 m above the ground. Many current turbines are 50 m in height but there is a growing tendency for commercial turbines to be taller (80 to 140 m). The most common turbine height is ~80 m (Wiser and Bolinger 2017). The recommended guideline for commercially viable developments is wind speeds over 6.5 m/s, which applies to both 50 m and 80 m turbine heights (Elliott et al. 1987).

Several wind farms in Alberta and Saskatchewan are located in areas classified as WPC 2, which is lower than the recommended guideline of WPC 3 for commercial development. However, wind potential is only one factor considered when siting a wind farm, and proximity to existing transmission lines is another high priority factor. We accounted for the increase of commercial development potential near transmission lines by weighting WPC in areas that were within 25 km of a transmission line. Our additive model is termed wind-development potential (WDP) where WPC + 1 = WDP, where development potential is binned similarly to wind speed, except with an added component to weight areas in close proximity to transmission lines and, therefore, more easily connected to the power grid.

We included in the low WDP category areas those with low potential for wind-energy development for other reasons, such as being in military bases, forested land, areas within 5 km of cities, or protected areas such as parks and National Wildlife Areas. In addition, we categorized areas designated as wind-avoidance areas (Saskatchewan Ministry of Environment 2016) as having low wind-development potential. This allowed these protected landscapes to be included in our analyses by forcing them to have low wind potential while at the same time assessing their suitability for Ferruginous Hawk habitat, allowing us to evaluate if the landscapes can be considered high conservation value for hawks. We classified RSF values into five equal-interval bins, and overlaid the RSF map onto the 50-m and 80-m WDP maps to spatially identify areas with high wind and high hawk potential (high conflict risk), high wind and low hawk suitability (low environmental liability risk), and low wind and high hawk suitability (high conservation potential; Tables 1 and 2)

**RESULTS**

**Habitat Selection**

The fits of each model set, as well as the all-inclusive model, are summarized in Table 3. The top model evaluated for the geography model set included the quadratic forms of latitude and longitude, predicting the approximate centre of the study area to have the highest probability of selection by hawks. Hawks selected landscapes with moderate amounts of grassland (Fig. 2) and with lower densities of grassland-cropland edge (Fig. 3). Home ranges were also more likely to be selected near water, based on a natural log functional form (Fig. 4). Hawks selected areas that were consistently warmer in the spring and summer. Hawks are more likely to select home ranges in areas where soil orders are composed of decreased proportions of vertisolic, chernozemic, regosolic, and luvisolic soil. Deposition modes were likely to be morainal till, undifferentiated mineral, undifferentiated bedrock, and residual material, and eolian, glaciolacustrine, glaciofluvial, and fluvoeolian soils. Selected home ranges were also characterized by soils composed of less silt and sand. Home ranges were more likely to be in landscapes with higher densities of resource roads and closer to active oil wells (Fig. 5).

The all-inclusive model developed from the top models for each variable class was reduced further after variables with p-value > 0.10 were removed, resulting in a model weight of 0.99 (Table 3). We used the logistic form to develop a resource selection map (Fig. 6) using standardized beta coefficients from each variable (Table 4) in the global all-inclusive model.

The all-inclusive model area under the curve based (AUC) on ROC score was 0.81, suggesting the model was good at predicting
Table 1. Potential conflict risk between Ferruginous Hawks (*Buteo regalis*) and wind-farm development, as ranked by relative probability of home-range selection by hawks spatially overlaid onto wind development potential for 50-m tall turbines. Conflict risk is predicted to increase as resources selection function (RSF) values increase in areas with medium to high wind development potential (WDP). This risk model is based on the all-inclusive model in Table 4 and we classified RSF values into five equal-interval bins. Ferruginous Hawk habitat selection bin (1 = low, 5 = high).

| WDP† | 1     | 2     | 3     | 4     | 5     |
|------|-------|-------|-------|-------|-------|
| 1    | Low   | Low   | Low   | Low   | Low   |
| 2    | Low   | Low   | Low   | Low   | Low   |
| 3    | Low   | Medium | Medium | Medium | Medium |
| 4    | Low   | Medium | High   | High   | High   |
| 5    | Low   | Medium | High   | Very high | Very high |
| 6    | Low   | Medium | High   | Very high | Very high |
| 7    | Low   | Medium | High   | Very high | Very high |

*No landscapes within the Ferruginous Hawk range in Alberta and Saskatchewan fall into WDP 8.

‡Lands with high potential for conservation value to Ferruginous Hawks.

Table 2. Potential conflict risk between Ferruginous Hawks (*Buteo regalis*) and wind-energy development, as ranked by relative probability of home range selection by hawks spatially overlaid onto wind development potential for 80-m tall turbines. Conflict risk is predicted to increase as resources selection function (RSF) values increase in areas with medium to high wind development potential (WDP). This risk model is based on the all-inclusive model in Table 4 and we classified RSF values into five equal-interval bins. Ferruginous Hawk habitat selection bin (1 = low, 5 = high).

| WDP† | 1     | 2     | 3     | 4     | 5     |
|------|-------|-------|-------|-------|-------|
| 1    | Low   | Low   | Low   | Low   | Low   |
| 2    | Low   | Low   | Low   | Low   | Low   |
| 3    | Low   | Low   | Low   | Low   | Low   |
| 4    | Low   | Medium | Medium | Medium | Medium |
| 5    | Low   | Medium | High   | High   | High   |
| 6    | Low   | Medium | High   | Very high | Very high |
| 7    | Low   | Medium | High   | Very high | Very high |

*No landscapes within the Ferruginous Hawk range in Alberta and Saskatchewan fall into WDP 8.

‡Lands with high potential for conservation value to Ferruginous Hawks.

the relative probability of habitat selection by hawks. AUC for each model set (Table 3) demonstrated the relative contribution of each model set to the overall model performance of the all-inclusive model. Model validation performed adequately; because the adjusted R2 (0.64) was moderately high, the slope was not significantly different from 1.0 (slope was 0.70, p-value = 0.53), and the intercept (2.2) was near zero, suggesting the model was a good predictor of the independent sample of nest locations. The Spearman's rank correlation was rho = 0.76 (p-value = 0.01). The top two of five RSF variable bins accounted for 99.5% of the 2147 locations used to build the RSF model and 90% of the 119 nest locations used to test the home-range habitat-selection model.

**Risk of hawk-wind conflict**

Commercial development of wind power is currently high enough to be viable within much of the Ferruginous Hawk range in Alberta and Saskatchewan, leading to potential risk of direct collisions or indirect effects (Tables 1 and 2, Fig. 7). Land with risk, i.e., medium, high, and very high risk, covers 61% and 67% of the range for 50-m and 80-m turbine hub height, respectively. The amount of very high conflict risk covers 2% of the Ferruginous Hawk range if wind farms were restricted to 50-m
Table 3. Results from the top-ranked models, composed of top variable classes, comparing model fit for home range habitat selection of Ferruginous Hawks (*Buteo regalis*; n = 2147 used quarter-sections) from Alberta and Saskatchewan, Canada, 2005–2010. A model’s ΔAIC improves as variable sets are added and the addition of soil characteristics resulted in the biggest difference in ΔAIC. See Table 4 for the retained variables in each variable class. k is the number of variables in the model, LL is the log-likelihood and a measure of model fit, AIC is the calculated Akaike’s Information Criterion, delta AIC (ΔAIC) is the relative difference between a model and the model with the lowest AIC, w is the Akaike weight, and AUC (Area Under Curve) is calculated from a ROC curve.

| Geography | Land cover | Soil | Climate | Industry | k | LL       | AIC       | ΔAIC | wi  | AUC |
|-----------|------------|------|---------|----------|---|----------|-----------|------|-----|-----|
| x         | x          | x    | x       | x        | 27| -4,829.20| 9,714.41  | 0.00 | 0.99| 0.807|
| x         | x          | x    | x       | x        | 34| -4,827.42| 9,724.84  | 10.43| 0.01| 0.807|
| x         | x          | x    | x       | x        | 31| -4,849.72| 9,763.43  | 49.02| 0.00| 0.804|
| x         | x          | x    | x       | x        | 31| -4,863.98| 9,791.96  | 77.55| 0.00| 0.802|
| x         | x          | x    | x       | x        | 23| -4,889.94| 9,837.88  | 123.47| 0.00| 0.799|
| x         | x          | x    | x       | x        | 26| -4,972.37| 9,998.73  | 284.32| 0.00| 0.788|
| x         | x          | x    | x       | x        | 26| -5,018.76| 10,091.52| 377.11| 0.00| 0.782|
| x         | x          | x    | x       | x        | 23| -5,027.98| 10,103.97| 389.56| 0.00| 0.781|
| x         | x          | x    | x       | x        | 11| -5,203.23| 10,430.47| 716.06| 0.00| 0.756|
| x         | x          | x    | x       | x        | 9 | -5,264.57| 10,549.14| 834.73| 0.00| 0.753|
| x         | x          | x    | x       | x        | 17| -5,453.27| 10,942.54| 1,228.13| 0.00| 0.726|
| x         | x          | x    | x       | x        | 3 | -5,467.58| 10,943.15| 1,228.74| 0.00| 0.714|
| x         | x          | x    | x       | x        | 3 | -5,559.46| 11,126.92| 1,412.51| 0.00| 0.686|
| x         | x          | x    | x       | x        | 5 | -5,585.35| 11,182.70| 1,468.29| 0.00| 0.693|

† Final all-inclusive model with variables p-value > 0.10 removed.

**DISCUSSION**

**Patterns of selection**

We developed a predictive home-range habitat-selection model for Ferruginous Hawks in Canada. Ferruginous Hawks were more likely to select home ranges in heterogeneous landscapes characterized by approximately half cropland and half grassland cover, similar to patterns in previous studies at smaller scales and in other parts of their range (Wakeley 1978, Schmutz 1989, McConnell et al. 2008, Wiggins et al. 2014). Hawks selected for home ranges with low to medium edge density, where relative probability of selection decreased if edge density surpassed 80 km in the surrounding 2500-m radius. Selection for mosaic landscapes with some edge may be related to foraging, as hawks do hunt in grazed grassland (Wakeley 1978), fragmented turbine hub height and 8% with 80-m turbine hub height. Land with high conservation value, where wind-development potential is low and relative probability of selection by hawks is high, covers 36% and 29% of the range, for the respective turbine hub heights of 50 m and 80 m.

**Fig. 4.** Relative predicted probability of home-range habitat selection by Ferruginous Hawks (*Buteo regalis*) in Alberta and Saskatchewan, Canada, 2005–2010, relative to the distance to nearest water when all other model variables are held at their mean values. Error bars are 95% confidence intervals estimated at specific values of the continuous predictor.

**Fig. 5.** Relative predicted probability of home-range habitat selection by Ferruginous Hawks (*Buteo regalis*) in Alberta and Saskatchewan, Canada, 2005–2010, relative to distance to nearest active oil well when all other model variables are held at their mean values. Error bars are 95% confidence intervals estimated at specific values of the continuous predictor.
Ferruginous Hawks were slightly more likely to select home ranges near active oil wells and in areas with high resource road density. Keough and Conover (2012) found a similar relationship where Ferruginous Hawks in Utah were also more likely to nest nearer to active oil wells. Other Ferruginous Hawk studies have found positive (Zelenak and Rotella 1997) or negative associations with roads, depending on road type, year, and spatial scale of analyses (Smith et al. 2010, Wallace et al. 2016). Oil wells and roads are often associated with other infrastructure, such as fencing, power poles, and auxiliary buildings, which are used as perches by hawks (Plumpton and Andersen 1998, Ng et al. 2020). Prey availability also may be increased near wells as small-mammal abundance, including ground squirrels, can be higher in areas with natural gas extraction (Hethcoat and Chalfoun 2015). Ferruginous Hawks may also select home ranges near wells and roads because it is common practice to mow vegetation along resource roads and around wells, which may increase the availability of prey to foraging Ferruginous Hawks, which select for shorter vegetation where ground squirrels are more accessible (Bechard 1982, Marsh et al. 2014). Most prior studies have been conducted in sage- or juniper-dominated landscapes; therefore, understanding the potential effects of nesting near oil development associated with higher amounts of human disturbance in moist-mixed and mixed grassland is important for fully understanding Ferruginous Hawk habitat use and selection.

Soil and climate variables were also reasonable predictors of Ferruginous Hawk home-range habitat selection (Table 4). A similar study that examined home-range selection for Burrowing Owls (Athene cunicularia) found that soil and climate were the best predictors among a suite of analogous variable classes (Stevens et al. 2011). We found soils within the home-range buffers were more likely to be coarse and were likely formed by glacial deposits, river or floodplain flow, and wind. Soils associated with
Implications for wind development

We developed a risk-assessment tool to identify potential conflict risk between wind-energy development and Ferruginous Hawks nesting in Canada. Our predictive habitat model with wind-development potential found that 2–8% of the Ferruginous Hawk range in Alberta and Saskatchewan is potentially at very high risk of conflicting with wind-power development. Conversely, we predict 33–39% of the Ferruginous Hawk range in Alberta and Saskatchewan has potentially low conflict risk. Our spatially explicit models allow managers to assess and mitigate conflict with hawks at current wind farms in risk zones or proactively reduce the risk of conflict by siting future wind farms away from potentially high risk zones. Our study showed that the relative probability of Ferruginous Hawk habitat selection varied across their range, meaning that there are low, medium, and high risk locations for new wind farms. We recommend avoiding siting wind farms in landscapes that have heterogeneous landcover, such as patch-mosaic landscapes with both grassland and cropland, and areas with moderate edge density, where the relative probability of home-range selection is high. Siting wind farms on landscapes that are dominated by cropland will result in the least amount of risk for nesting Ferruginous Hawks.

Potential cumulative effects associated with wind power must also be considered when siting developments. For example, to-date, wind developments in Alberta and Saskatchewan have been located in zones below the highest wind potential, but near existing transmission lines to connect to the power grid. From a short-term perspective, there is a concern because Ferruginous Hawks will nest on transmission towers (Steenhof et al. 1993) in suitable landscapes (Paryako et al. 2021). If wind turbines are placed in the home ranges of hawks nesting in transmission towers, then the risk of turbine strikes will increase. Long-term planning can proactively reduce this risk by siting future transmission lines away from suitable hawk habitat, thereby also directing wind-farm development away from hawk habitat.
Fig. 7. Predicted potential conflict risk between Ferruginous Hawks (*Buteo regalis*) and wind-energy development in southern Alberta and Saskatchewan, Canada, 2005–2010. Turbine hub height scenarios are mapped by (Top) 50 m and (Bottom) 80 m. Black shading indicates areas with high environmental liability where wind development potential is high and relative probability of selection by Ferruginous Hawks is also high. Stippled areas identify areas with high conservation value because the wind development potential is likely low, but probability of selection by hawks is high.

The amount of area with risk was greater for the 80-m than the 50-m turbine hub height scenario. Therefore, we expect that with increased turbine height in the near future, areas with risk potential will likely expand because more landscapes will meet commercially viable wind potential. However, our study identified over 100,000 km² as low environmental liability under our current scenarios, suggesting that there will still be large low risk areas available for potential development. Smaller turbine capacity is typically associated with lower wildlife collision rates, but there is also less risk of collision associated with fewer larger turbines per unit energy output (Thaxter et al. 2017). However, mortality rates may be constant per unit of energy produced across turbine sizing and spacing (Huso et al. 2021) and larger turbine capacity are associated with increased collision rates (Thaxter et al. 2017). Decisions about turbine capacity, overall rotor swept area, rated capacity, and number of turbines per farm could be prescriptive,
where design and construction decisions are made relative to risk (McClure et al. 2021a, 2021b). Similarly, a prescriptive approach that considers risk relative to local landscape characteristics is important for siting individual turbines (Murtatroyd et al. 2021, Sandhu et al. 2022, Vignali et al. 2022). As well, mapping can be updated as new wind-development potential maps are generated under new technology scenarios. However, our maps do not preclude the need for ground assessments, such as pre-construction hawk surveys, or necessity for mitigation options at each wind farm (May et al. 2020). Rather, our models can be used as coarse-filter tools for landscape-scale planning in the early stages of wind-farm development because they identify potential high conflict, low environmental liability, and high conservation value zones. Such maps are core elements of the designation of critical habitat for species at risk in Canada.

As land use and climate continue to change, patterns of temperature, precipitation, and circulation are expected change at regional to global scales. Changes in land cover and climate in our study area may change where our model predicts home-range habitat selection. In addition, changes to wind patterns may change the wind potential map. Given expected changes to land cover and wind patterns, it would be prudent to replicate our models in the future with updated land-cover and wind-potential maps as they become available.

Our study found that the total area of potential high risk to Ferruginous Hawks was relatively low, especially when compared to large portions of the remaining study area that were categorized as having relatively low environmental liability (i.e., high wind-development potential and low probability of hawk-habitat selection). Last, in cases where wind farms are located in high risk zones, we have identified areas with high Ferruginous Hawk conservation value (i.e., probability of hawk-habitat selection is high and wind-development potential is low) that could be considered for Ferruginous Hawk conservation offsets (Fargione et al. 2012, Dwyer et al. 2018). Although our mapping products are specific to Ferruginous Hawks, we propose that next conservation steps include hotspot mapping for multiple species, in which a similar process of identifying spatial risk is conducted with species prone to negative effects from wind-farm construction and operation (Bennett et al. 2014, Mahoney and Chalfoun 2016). Future risk-assessment studies should also incorporate Ferruginous Hawk migration ecology, such as avoiding migration routes, topographic features frequently used during migration, or using shut-downs during peak migration seasons (Liechti et al. 2013).

Responses to this article can be read online at: https://www.ace-eco.org/issues/responses.php/2255

Acknowledgments:

We would like to thank the numerous field and research assistants who helped make this project a success, as well as the following funding partners for their support: Canadian Wildlife Service.

LITERATURE CITED

Agriculture and Agri-Food Canada (AAFC). 2009. Land cover for agricultural regions of Canada, circa 2000. Agriculture and Agri-Food Canada, Ottawa, Ontario, Canada. https://open.canada.ca/data/en/dataset/16d2f828-96bb-468d-9b7d-1307c81e17b8

Allison, T. D., J. F. Cochrane, E. Lonsdorf, and C. Sanders-Reed. 2017. A review of options for mitigating take of Golden Eagles at wind energy facilities. Journal of Raptor Research 51:319-333. https://doi.org/10.3356/JRR-16-76.1

Allison, T. D., J. E. Diffendorfer, E. F. Baerwald, J. A. Beston, D. Drake, A. M. Hale, C. D. Hein, M. M. Huso, S. R. Loss, and J. E. Lovich. 2019. Impacts to wildlife of wind energy siting and operation in the United States. Issues in Ecology 21:1-24.

Arnold, T. W. 2010. Uninformative parameters and model selection using Akaike’s information criterion. Journal of Wildlife Management 74:1175-1178. https://doi.org/10.1111/j.1367-2005.2010.tb01236.x

Baerwald, E. F., G. H. D’Amours, B. J. Klug, and R. M. Barclay. 2008. Barotrauma is a significant cause of bat fatalities at wind turbines. Current Biology 18:R695-R696. https://doi.org/10.1016/j.cub.2008.06.029

Baisner, A. J., J. L. Andersen, A. Findsen, S. W. Yde Granath, K. Ø. Madsen, and M. Desholm. 2010. Minimizing collision risk between migrating raptors and marine wind farms: development of a spatial planning tool. Environmental Management 46:801-808. https://doi.org/10.1007/s00267-010-9541-z

Ball, J. R., P. Sólymos, F. K. A. Schmiegelow, S. Haché, J. Schieck, and E. M. Bayne. 2016. Regional habitat needs of a nationally listed species, Canada Warbler (Cardellina canadensis), in Alberta, Canada. Avian Conservation and Ecology 11(2):10.

Balogtari-Chiebao, F., J. E. Brommer, T. Niinimäki, and T. Laaksonen. 2016. Proximity to wind-power plants reduces the breeding success of the white-tailed eagle. Animal Conservation 19:265-272. https://doi.org/10.1111/acv.12238

Bechard, M. J. 1982. Effect of vegetative cover on foraging site selection by Swainson’s Hawk (Buteo swainsonii). Condor 84:153-159. https://doi.org/10.2307/1367658

Bennett, V. J., A. M. Hale, K. B. Karsten, C. E. Gordon, and B. J. Suson. 2014. Effect of wind turbine proximity on nesting success in shrub-nesting birds. American Midland Naturalist 172:317-328. https://doi.org/10.1674/0003-0031-172.2.317
IHS Global Canada Ltd. 2013. IHS energy data (geospatial database). IHS Global Canada Ltd., Calgary, Alberta, Canada.

Johnson, C. J., S. E. Nielsen, E. H. Merril, T. L. McDonald, and M. S. Boyce. 2006. Resource selection functions based on use-availability data: theoretical motivation and evaluation methods. Journal of Wildlife Management 70:347-357. https://doi.org/10.2193/0022-541X(2006)70[347:RSFBOU]2.0.CO;2

Johnston, N. N., J. E. Bradley, and K. A. Otter. 2014. Increased flight altitudes among migrating Golden Eagles suggest turbine avoidance at a rocky mountain wind installation. PLoS ONE 9: e93030. https://doi.org/10.1371/journal.pone.0093030

Keough, H., and M. R. Conover. 2012. Breeding-site selection by Ferruginous Hawks within Utah’s Uintah Basin. Journal of Raptor Research 46:378-388. https://doi.org/10.3356/JRR-12-07.1

Kieseccker, J. M., J. S. Evans, J. Fargione, K. Doherty, K. R. Foresman, T. H. Kunz, D. Naugle, N. P. Nibbelink, and N. D. Niemuth. 2011. Win-win for wind and wildlife: a vision to facilitate sustainable development. PLoS ONE 6:e17566. https://doi.org/10.1371/journal.pone.0017566

Kolar, P. S. 2013. Impacts of wind energy development on breeding Buteo Hawks in the Columbia Plateau ecoregion. Thesis. Boise State University, Boise, Idaho, USA.

Kolar, P. S., and M. J. Bechard. 2016. Wind energy, nest success, and post-fledging survival of Buteo Hawks. Journal of Wildlife Management 80:1242-1255. https://doi.org/10.1002/jwmg.21125

Leary, A. W., R. Mazaika, and M. J. Bechard. 1998. Factors affecting the size of Ferruginous Hawk home ranges. Wilson Bulletin 110:198-205.

Liechti, F., J. Guélat, and S. Komenda-Zehnder. 2013. Modelling the spatial concentrations of bird migration to assess conflicts with wind turbines. Biological Conservation 162:24-32. https://doi.org/10.1016/j.biocon.2013.03.018

Litvaitis, J. A., and J. P. Tash. 2008. An approach toward understanding wildlife-vehicle collisions. Environmental Management 42:688-697. https://doi.org/10.1007/s00267-008-9108-4

Mahoney, A., and A. D. Chalfoun. 2016. Reproductive success of Horned Lark and McCown’s Longspur in relation to wind energy infrastructure. Condor 118:360-375. https://doi.org/10.1650/CONDOR-15-25.1

Manly, B. F. J., L. L. McDonald, and D. L. Thomas. 2002. Resource selection by animals: statistical design and analysis for field studies. Kluwer Academic Publishers, Secaucus, New Jersey, USA.

Marques, A. T., H. Batalha, S. Rodrigues, H. Costa, M. J. R. Pereira, C. Fonseca, M. Mascarenhas, and J. Bernardino. 2014. Understanding bird collisions at wind farms: an updated review on the causes and possible mitigation strategies. Biological Conservation 179:40-52. https://doi.org/10.1016/j.biocon.2014.08.017

Marsh, A., T. I. Wellicome, and E. Bayne. 2014. Influence of vegetation on the nocturnal foraging behaviors and vertebrate prey capture by endangered Burrowing Owls. Avian Conservation and Ecology 9(1):2. https://doi.org/10.5751/ACE-00640-090102

May, R., T. Nygård, U. Falkdal, J. Åström, Ø. Hamre, and B. G. Stokke. 2020. Paint it black: efficacy of increased wind-turbine rotor blade visibility to reduce avian fatalities. Ecology and Evolution 10:8927-8935. https://doi.org/10.1002/ece3.6592

McClure, C. J. W., B. W. Rolek, M. A. Braham, T. A. Miller, A. E. Duerr, J.D. McCabe, L. Dunn, and T. E. Katzner. 2021a. Eagles enter rotor-swept zones of wind turbines at rates that vary per turbine. Ecology and Evolution 11:11267-11274. https://doi.org/10.1002/ece3.7911

McClure, C. J. W., B. W. Rolek, L. Dunn, J. D. McCabe, L. Martinson, and T. Katzner. 2021b. Eagle fatalities are reduced by automated curtailment of wind turbines. Journal of Applied Ecology 58:446-452. https://doi.org/10.1111/1365-2664.13831

McConnell, S., T. J. O’Connell, and D. M. Leslie. 2008. Land cover associations of nesting territories of three sympatric Buteos in shortgrass prairie. Wilson Journal of Ornithology 120:708-716. https://doi.org/10.1676/07-048.1

Murgatroyd, M., W. Bouten, and A. Amar. 2021. A predictive model for improving placement of wind turbines to minimise collision risk potential for a large soaring raptor. Journal of Applied Ecology 58:857-868. https://doi.org/10.1111/1365-2664.13799

Ng, J. W. 2019. Habitat quality and conservation for Ferruginous Hawks using a cumulative effects approach. Dissertation. University of Alberta, Edmonton, Alberta, Canada.

Ng, J. W., M. D. Giovanni, M. J. Bechard, J. K. Schmutz, and P. Pyle. 2020. Ferruginous Hawk (Buteo regalis), version 1.0. In P. G. Rodewald, editor. Birds of the world. Cornell Lab of Ornithology, Ithaca, New York, USA. https://doi.org/10.2173/bow.ferhaw.01

Northrup, J. M., and G. Wittemyer. 2012. Characterizing the impacts of emerging energy development on wildlife, with an eye towards mitigation. Ecology Letters 16:112-125. https://doi.org/10.1111/j.1461-0248.2012.01804.x

Pagel, J. E., K. J. Kritz, B. A. Millsap, R. K. Murphy, E. L. Kershner, and S. Covington. 2013. Bald eagle and golden eagle mortalities at wind energy facilities in the contiguous United States. Journal of Raptor Research 47:311-315. https://doi.org/10.3356/JRR-12-00019.1

Parayko, N., J. Ng, J. Marley, R. Wolach, T. Wellicome, and E. Bayne. 2021. Response of Ferruginous Hawks to temporary habitat alterations for energy development in southwestern Alberta. Avian Conservation and Ecology 16(2):17. https://doi.org/10.5751/ACE-01958-160217

Pearce-Higgins, J. W., L. Stephen, A. Douse, and R. H. W. Langston. 2012. Greater impacts of wind farms on bird populations during construction than subsequent operation: results of a multi-site and multi-species analysis. Journal of Applied Ecology 49:386-394. https://doi.org/10.1111/j.1365-2664.2012.02110.x

Plumptton, D. L., and D. E. Andersen. 1998. Anthrophogenic effects on winter behavior of Ferruginous Hawks. Journal of Wildlife Management 62:340-346. https://doi.org/10.2307/3802297
Proulx, G., K. MacKenzie, and N. MacKenzie. 2012. Distribution and relative abundance of Richardson's ground squirrels, *Urocitellus richardsonii*, according to soil zones and vegetation height in Saskatchewan during a drought period. Canadian Field-Naturalist 126:103-110. https://doi.org/10.22621/cfn.v126i2.1324

Sandhu, R., C. Tripp, E. Quon, R. Thed, M. Lawson, D. Brandes, C. J. Farmer, T. A. Miller, C. Draxl, P. Doubrawa, et al. 2022. Stochastic agent-based model for predicting turbine-scale raptor movements during updraft-subsidized directional flights. Ecological Modelling 466(C). https://doi.org/10.1016/j.ecolmodel.2022.109876

Saskatchewan Ministry of Environment. 2016. Wildlife Siting Guidelines for Saskatchewan Wind Energy Projects. Report No. 2016-FWB 01, Saskatchewan Ministry of Environment, Regina, Saskatchewan, Canada.

Schmutz, J. K. 1989. Hawk occupancy of disturbed grasslands in relation to models of habitat selection. Condor 91:362-371. https://doi.org/10.2307/1368315

Schmutz, J. K., D. T. T. Flockhart, C. S. Houston, and P. D. McLoughlin. 2008. Demography of Ferruginous Hawks breeding in western Canada. Journal of Wildlife Management 72:1352-1360. https://doi.org/10.2193/2007-231

Sergio, F., L. Marchesi, P. Pedrini, M. Ferrer, and V. Penteriani. 2004. Electrocution alters the distribution and density of a top predator, the eagle owl *Bubo bubo*. Journal of Applied Ecology 41:836-845. https://doi.org/10.1111/j.0021-8901.2004.00946.x

Shaw, J. M., T. A. Reid, M. Schugens, A. R. Jenkins, and P. G. Ryan. 2018. High power line collision mortality of threatened bustards at a regional scale in the Karoo, South Africa. Ibis 160:431-446. https://doi.org/10.1111/ibi.12553

Smallwood, K. S., and D. A. Bell. 2020. Effects of wind turbine curtailment on bird and bat fatalities. Journal of Wildlife Management 84:685-696. https://doi.org/10.1002/jwmg.21844

Smallwood, K. S., L. Neher, and D. A. Bell. 2009. Map-based repowering and reorganization of a wind resource area to minimize Burrowing Owl and other bird fatalities. Energies 2:915-943. https://doi.org/10.3390/en20400915

Smallwood, K. S., L. Rugge, and M. L. Morrison. 2009. Influence of behavior on bird mortality in wind energy developments. Journal of Wildlife Management 73:1082-1098. https://doi.org/10.2193/2008-555

Smith, J. A., and J. F. Dwyer. 2016. Avian interactions with renewable energy infrastructure: an update. Condor 118:411-423. https://doi.org/10.1650/CONDOR-15-61.1

Smith, J. P., S. J. Slater, and M. C. Neal. 2010. An assessment of the effects of oil and gas field activities on nesting raptors in the Rawlins, Wyoming, and Price, Utah, field offices of the Bureau of Land Management. U.S. Department of the Interior, Bureau of Land Management, Grand Junction, Colorado, USA.

Soil Landscapes of Canada Working Group. 2010. Soil landscapes of Canada version 3.2 (digital map and database). Agriculture and Agri-Food Canada, Ottawa, Ontario, Canada.

StataCorp. 2009. Stata Statistical Software, Release 11. StataCorp LP, College Station, Texas, USA.

Stevens, A. F. J., E. M. Bayne, and T. I. Wellicome. 2011. Soil and climate are better than biotic land cover for predicting home-range habitat selection by endangered burrowing owls across the Canadian Prairies. Biological Conservation 144:1526-1536. https://doi.org/10.1016/j.biocon.2010.10.032

Tack, J. D., and B. C. Fedy. 2015. Landscapes for energy and wildlife: conservation prioritization for golden eagles across large spatial scales. PLoS ONE 10:e0134781. https://doi.org/10.1371/journal.pone.0134781

Thaxter, C. B., G. M. Buchanan, J. Carr, S. H. M. Butchart, T. Newbold, R. E. Green, J. A. Tobias, W. B. Foden, S. Brien, and J. W. Pearce-Higgins. 2017. Bird and bat species’ global vulnerability to collision mortality at wind farms revealed through a trait-based assessment. Proceedings of the Royal Society B: Biological Sciences 284:20170829. https://doi.org/10.1098/rspb.2017.0829

U.S. Energy Information Administration. 2021. Annual Energy Outlook with projects to 2050. U.S. Energy Information Administration, Washington, D.C., USA.

Vignali, S., F. Lörcher, D. Hegglin, R. Arlettaz, and V. Braunisch. 2022. A predictive flight-altitude model for avoiding future conflicts between an emblematic raptor and wind energy development in the Swiss Alps. Royal Society Open Science 9:211041. https://doi.org/10.1098/rsos.211041

Wakeley, J. S. 1978. Factors affecting the use of hunting sites by Ferruginous Hawks. Condor 80:316-326. https://doi.org/10.1002/jwmg.21532

Wallace, Z. P., P. L. Kennedy, J. R. Squires, L. E. Olson, and R. J. Oakleaf. 2016. Human-made structures, vegetation, and weather influence Ferruginous Hawk breeding performance. Journal of Wildlife Management 80:78-90. https://doi.org/10.1002/jwmg.1000

Watson, T., A. Hamann, D. L. Spittlehouse, and T. Q. Murdock. 2011. ClimateWNA-high-resolution spatial climate data for western North America. Journal of Applied Meteorology and Climatology 51:16-29. https://doi.org/10.1175/JAMC-D-11-043.1

Watson, J. L. 2020. Ferruginous Hawk (*Buteo regalis*) home range and resource use on northern grasslands in Canada. Thesis. University of Alberta, Edmonton, Alberta, Canada.

Watson, J. W., I. N. Keren, and R. W. Davies. 2018b. Behavioral accommodation of nesting hawks to wind turbines. Journal of Wildlife Management 82:1784-1793. https://doi.org/10.1002/jwmg.1000

Watson, J. W., I. N. Keren, and R. W. Davies. 2018a. Behavioral accommodation of nesting hawks to wind turbines. Journal of Wildlife Management 82:1784-1793. https://doi.org/10.1002/jwmg.21532

Watson, J. W., I. N. Keren, and R. W. Davies. 2018b. Behavioral accommodation of nesting hawks to wind turbines. Journal of Wildlife Management 82:1784-1793. https://doi.org/10.1002/jwmg.21532

Watson, J. W., I. N. Keren, and R. W. Davies. 2018b. Behavioral accommodation of nesting hawks to wind turbines. Journal of Wildlife Management 82:1784-1793. https://doi.org/10.1002/jwmg.21532

Watson, J. W., I. N. Keren, and R. W. Davies. 2018b. Behavioral accommodation of nesting hawks to wind turbines. Journal of Wildlife Management 82:1784-1793. https://doi.org/10.1002/jwmg.21532

Watson, J. W., I. N. Keren, and R. W. Davies. 2018b. Behavioral accommodation of nesting hawks to wind turbines. Journal of Wildlife Management 82:1784-1793. https://doi.org/10.1002/jwmg.21532

Watson, J. W., I. N. Keren, and R. W. Davies. 2018b. Behavioral accommodation of nesting hawks to wind turbines. Journal of Wildlife Management 82:1784-1793. https://doi.org/10.1002/jwmg.21532
Swainson's Hawks on an agricultural landscape in the Great Plains. Southwestern Naturalist 59:356-363. https://doi.org/10.1894/MCG-01.1

Wiser, R. H., and M. Bolinger. 2017. 2016 wind technologies market report. U.S. Department of Energy, Office of Scientific and Technical Information, Oak Ridge, Tennessee, USA. https://doi.org/10.2172/1375677

Zelenak, J. R., and J. J. Rotella. 1997. Nest success and productivity of Ferruginous Hawks in northern Montana. Canadian Journal of Zoology 75:1035-1041. https://doi.org/10.1139/z97-124

Zimmerling, J. R., A. C. Pomeroy, M. V. d'Entremont, and C. M. Francis. 2013. Canadian estimate of bird mortality due to collisions and direct habitat loss associated with wind turbine developments estimation. Avian Conservation and Ecology 8 (2):10. https://doi.org/10.5751/ACE-00609-080210

Zuur, A. F., E. N. Ieno, and C. S. Elphick. 2010. A protocol for data exploration to avoid common statistical problems. Methods in Ecology and Evolution 1:3-14. https://doi.org/10.1111/j.2041-210X.2009.00001.x

Zwart, M. C., A. J. McKenzie, J. Minderman, and M. J. Whittingham. 2016. Conflicts between birds and on-shore wind farms. Pages 489-504 in M. F. Angelici, editor. Problematic wildlife: a cross-disciplinary approach. Springer, Cham, Switzerland. https://doi.org/10.1007/978-3-319-22246-2_23
**APPENDIX 1.** All environmental and anthropogenic variables included in the global habitat model for Ferruginous Hawks in Alberta and Saskatchewan, Canada, 2005 – 2010.

| Variable and units                              | Data Source                               |
|------------------------------------------------|-------------------------------------------|
| **Geography**                                   |                                           |
| Elevation (m)                                   | Climate WNA v5.41                         |
| Standard deviation of elevation (m)             |                                           |
| Longitude                                       |                                           |
| Latitude                                        |                                           |
| **Land cover**                                  |                                           |
| Distance to nearest grassland (km)              | Agriculture and Agri-Food Canada 2000     |
| Proportion of grassland within 2500m of the nest|                                           |
| Edge density (total length of edge where grass and crop interface) (km) |                                           |
| Distance to nearest water (log transformed; km) |                                           |
| **Human Development**                           |                                           |
| Distance to nearest power transmission line (km)| IHS Energy 2013                           |
| Transmission line density (total length of transmission line) (km) |                                           |
| Distance to nearest road (km)                   |                                           |
| Road density (total length of road) (km)        |                                           |
| Distance to nearest pipeline (km)               |                                           |
| Pipeline density (total length of pipeline) (km) |                                           |
| Distance to nearest oil or gas facility (km)    |                                           |
| Total number of oil or gas facilities           |                                           |
| Distance to nearest sound-producing oil or gas facility (km) |                                           |
| Total number of sound-producing oil or gas facilities |                                           |
| Distance to nearest surface oil or gas well (km) |                                           |
| Total number of surface oil or gas well         |                                           |
| Distance to nearest oil well (km)               |                                           |
| Total number of oil wells                       |                                           |
| Distance to nearest gas well (km)               |                                           |
| Total number of gas wells                       |                                           |
| **Soil**                                        |                                           |
| Proportion of eolian parent material            | Soil Landscapes of Canad v3.2              |
| Proportion of lacustrine parent material        | Agriculture and Agri-Food Canada.         |
| Proportion of fluvial parent material           |                                           |
| Proportion of till parent material              |                                           |
| Proportion of colluvial parent material         |                                           |
| Proportion of fluvoeolian parent material       |                                           |
| Proportion of fluvialacustrine parent material  |                                           |
| Proportion of lacusto-till parent material      |                                           |
| Proportion of residual parent material          |                                           |
| Proportion of glaciofluvial parent material     |                                           |
| Proportion of glaciolacustrine parent material  |                                           |
| Proportion of undifferentiated bedrock parent material |                                           |
| Proportion of undifferentiated organic parent material |                                           |
| Proportion of brunisolic order soils            |                                           |
| Proportion of luvisolic order soils             |                                           |
| Proportion of vertisolic order soils            |                                           |
| Proportion of chernozemic order soils           |                                           |
| Proportion of gleysolic order soils             |                                           |
| Proportion of regosolic order soils             |                                           |
Proportion of solonetzic order soils
Categorical soil texture, from 1 (fine) to 7 (coarse)
Proportion of clay
Proportion of silt
Proportion of sand
Proportion of carbon
Proportion of very fine sand

| Climate                  |                           | Climate WNA v5.41                   |
|--------------------------|---------------------------|-------------------------------------|
| Minimum spring temperature (°C) |                           | (years = 1960-2000)                |
| Minimum summer temperature (°C) |                           |                                    |
| Maximum spring temperature (°C) |                           |                                    |
| Maximum summer temperature (°C) |                           |                                    |
| Average spring temperature (°C) |                           |                                    |
| Average summer temperature (°C) |                           |                                    |
| Average spring precipitation (mm) |                         |                                    |
| Average summer precipitation (mm) |                         |                                    |