THE ASSOCIATIONS BETWEEN WEATHER AND TOPOGRAPHY ON GOLDEN EAGLE FLIGHT BEHAVIOUR AT A WIND FARM IN THE CANADIAN ROCKIES

by

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ABSTRACT

I documented flight tracks of migratory golden eagles in proximity to a pre-operational wind farm in northeast British Columbia, Canada. This is the first Canadian research along a golden eagle migration corridor that indentifies weather and topographic factors associated with flight altitudes in relation to a proposed ridge-top wind farm development. In both spring and fall migration seasons (2008–2010) I documented golden eagle flight behaviour in two parts: (1), to determine what temporal, spatial and/or weather variables were associated with eagle flights near the proposed ridge-top turbine string (called the risk-zone); and (2), to determine if weather, topography and/or flight behaviour were associated with eagle altitudes as they entered the risk-zone. I found entries into the risk-zone were positively correlated with hourly passage rates across all years and between seasons. For eagles that entered the risk-zone, flight altitudes increased with increasing wind speed, were lower under head-winds compared to cross- and tail-winds, and were lower over sloped compared to flat ridge-top topography. Post-construction observations are needed to quantify avoidance behaviours in addition to wind data collected near turbine height. I highlight the need for a Cumulative Impact Assessment for the region to oversee the potential accumulation of small impacts on golden eagles at the population level.

CO-AUTHORSHIP

For all chapters in this thesis, I was the primary investigator and led the design of studies, collection of data and conducted all analyses. I wrote the initial drafts of all manuscripts and was responsible for incorporating comments and feedback on previous drafts into the final versions seen in the thesis. However, despite the use of first person singular in the writing within the thesis, I would like to acknowledge that this work was not conducted in isolation. The submitted manuscripts (chapters 2 and 3) include data that was jointly collected with James Bradley and Andrea Pomeroy, and both of these persons provided editorial comments in submitted manuscripts, and are included as co-authors. Further, my supervisor, Ken Otter, contributed to experimental design, data analysis and writing on all components of the thesis and is included in all papers submitted from this data set.

<u>The following are the authorships associated with each chapter</u>:

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CHAPTER ONE – GENERAL INTRODUCTION

1.1 Avian Migration

Avian migration is a global phenomena influenced by the seasonal differences in resources at different latitudes. A directed movement between breeding and wintering grounds, migration is cued in response to differential availability of daylight, food and within- and between-species competition (Bildstein 2006a, Able 1973). An estimated 19% of the world's bird species are migratory (1,855), and of these, approximately 11% are listed as threatened (see: http://www.birdlife.org/ flyways/index.html).

Although differences exist between migration strategies, the key features for successful migration are common for all birds. These include the minimization of time, energy and risk (Alerstam and Lindstrom 1990). Successful migration depends on three components: (1) finding appropriate breeding and wintering grounds, and being able to return to them in subsequent years; (2) timing movements so that they coincide with favourable climate and time of year; (3) and being in good physical condition with sufficient fat reserves to undertake the journey (Bildstein 2006a). During migration, birds will temporarily halt at stopover sites to refuel, and may adjust their movement and longevity within these stopover areas to minimize the risks associated with predation (Lank et al. 2003).

1.1.1 Diurnal Migration

Migratory birds are divided into two categories based on whether they migrate during the day (diurnal) or at night (nocturnal). Most raptors, including other species such as cranes, are diurnal soaring migrants that take advantage of lift created by rising air. Nocturnal migrants on the other hand seek a stable atmosphere removed from diurnal turbulence (Kerlinger and Moore 1989, Alerstam 1990). In addition to atmospheric structure, the ability to forage for food during the day, while also avoiding predators, are also believed to play a role in shaping migration patterns (Kerlinger and Moore 1989).

Raptors can soar and gain lift in a variety of conditions, such as in isolated thermals where warm rising air provides lift, thermal streets (linear arrays of thermals), deflection updrafts created by mountain slopes, lee waves over land (high altitude updrafts created by deflection), and sea thermals over tropical and subtropical oceans (Bildstein 2006a). Horizontal winds can either help (increase lift in side-winds or reduce drag in tail-winds), or hinder (increase drag in headwinds) migrating raptors (Alerstam 1990). As a result of the reliance on terrain-induced lift, diurnal migrants generally migrate at lower altitudes than nocturnal migrants because they are more closely tied to landscape features (Kerlinger and Gauthreaux 1985, Alerstam 2009).

The benefits of diurnal migration includes the inexpensive cost of soaring flight, the ability to fly and forage while covering large distances, and the ability to visually inspect stop-over areas (Alerstam and Lindstrom 1990). Research into the low cost of soaring flight found that white storks (*Ciconia ciconia*) used 12 times more energy during flapping flight compared to soaring (Pennycuick 1972), and that the metabolic rates of soaring turkey vultures (*Cathartes aura*) did not differ significantly from a resting state (Mandel et al. 2008). The low energy costs of soaring flight used by migratory raptors thereby allows for migration to occur under most weather conditions, provided that some updrafts are present and visibility is not completely obscured (Thorup et al. 2006a).

Not only does the low cost of soaring flight enable raptors to migrate under a variety of conditions, but the costs of resting is comparatively high, thereby favouring continued migration when refuelling is not possible (Thorup et al. 2006a). Supporting evidence for the opportunistic abilities of raptors to migrate under non-ideal weather conditions was outlined in a study on satellite-tagged ospreys (*Pandion haliaetus*) (Thorup et al. 2006a). They found that once migration was initiated, tagged ospreys moved regardless of whether wind conditions were favourable (the most efficient conditions were tail-winds, but they moved in a variety of different conditions). Despite this, the birds were likely expending little additional energy by moving in other wind conditions, as they relied primarily on soaring flight. Increased flight speeds, however, occurred when assisted by tail-winds (Thorup et al. 2003). Because soaring flight is energy-efficient, soaring migrants have the flexibility to travel under varied conditions, which allows for continual movement under various weather conditions until they reach a desired location for refuelling (Alerstam 1979, Yates et al. 2001). Nevertheless, weather conditions associated with poor visibility can disrupt the regional timing and ultimate success of raptor movements (Bildstein 2006a).

1.1.2 Migration Routes Used by Soaring Migrants

Along with breeding and moulting, migration is one of the major energy stresses in a bird’s life. Not only do migratory birds have to be in good physical condition to breed, but birds require sufficient energy reserves to survive potentially hazardous weather conditions en route (Alerstam 1990). Due to the variety of landscapes covered by migrants, from distant breeding and wintering grounds to migration stopover areas in between, migrants have to be able to successfully perceive and navigate around potential hazards in the landscape.

The degree to which hazards in the landscape pose a threat to avian migrants can depend on their migration strategy. Birds that migrate in large groups (narrow-front migration) may experience greater impacts should flight trajectories bring large numbers of birds into high-risk areas (i.e. towers and guy-wires or wind farm turbines). For most species of raptor, however, migration is considered a broad-front phenomenon in which birds travel individually and are not under strong social influence to travel in groups (Bildstein 2006a). Nevertheless, broad-front migrants can be funnelled by landmasses and large bodies of water, which can shape migration pathways and channel birds into narrow corridors, or leading lines, and which act to concentrate birds (Mueller and Berger 1967b). For example, the channelling of raptors occurs along inland lakes and the coast because most raptors will not traverse a body of water greater than 25 km, but rather will fly around them when encountered. Therefore, bottlenecks occur within and between continents when birds encounter either narrow land bridges between large bodies of water, or points of land that extend into water towards another landmass (Mueller and Berger 1967b, Bildstein 2006b). Examples include areas in the Great Lakes of Eastern North America, the narrow land area of Panama in Central America, and the Strait of Gibraltar in Spain. Concerns arise when modifications of the airspace, particularly by the introduction of wind turbines, occurs in regions where migratory raptors are channelled by such landscape features.

Migration corridors along mountain chains can also concentrate birds into leading lines, especially for large-bodied raptors such as golden eagles (*Aquila chrysaetos*) that rely on strong winds for lift during migration (Mueller and Berger 1967b, Fuller et al. 1998, Alerstam 2001, Alerstam et al. 2006, Goodrich and Smith 2008). Mountain topography can create ideal conditions for soaring migrants due to lift created by upward-deflected winds along mountain slopes (Bildstein 2006a). Since soaring migrants employ flight strategies that place them at lower altitudes within the landscape they are more prone to collisions with anthropogenic obstacles within the airspace, particularly at landscape bottlenecks and regions where birds are channelled into leading lines (Hedenstrom 1993, Thorup et al. 2006b). Additionally, strong head-winds, which increase in strength with increasing altitude, could further increase collision hazards along leading lines of migration as birds have been found to fly at lower altitudes under these conditions as a means to reduce drag (Hedenstrom 2002, Drewitt and Langston 2008).

1.2 Anthropogenic Impacts and Sources of Mortality on Birds

With the rapid increase in resource developments, including modifications of the airspace by wind energy developments, the pressures imposed by collision fatalities on populations is both spatially and temporally complex. On a global perspective, the leading contributors of mortality for migratory birds include habitat degradation and the effects of deforestation resulting from resource extraction (Kirby et al. 2008). Habitat degradation at locations used by migratory birds (breeding, wintering or stop-over grounds) can result in the loss of critical resources the birds require to fuel reproduction or migration (Drewitt and Langston 2008).

For raptors, the additional threats of pollution, poisoning, and direct prosecution has put, and continues to put, a toll on populations worldwide (Ferrer et al. 1991, Lehman 2001). Other sources of mortality include hunting, collisions with man-made structures (including masts, windows and vehicles), electrocution from power lines, and disturbance. In addition, it is believed that many of these threats are likely to be exacerbated by global warming (Kirby et al. 2008). The recent growth of the wind energy industry has also added turbine-collisions as another source of mortality. This is of particular concern when developments are located in important bird areas, including breeding and wintering areas of threatened species or along raptor migration corridors (Drewitt and Langston 2008).

1.2.1 Impacts of Wind Energy Developments on Birds

Potential negative effects of wind energy developments on birds include habitat loss in the vicinity of the wind farm, displacement of birds from their migratory pathways (based on avoiding areas of high disturbance), barrier effects and mortality due to turbine collisions (Drewitt and Langston 2006). Depending on the size of the farm, the effects of habitat loss in terrestrial environments appears to be minimal due to the small amount of land occupied by the turbine base (Drewitt and Langston 2008). An exception to this may be in marine environments, where changes to the sea-floor could have wider impacts on the foraging ecology of seabirds (Drewitt and Langston 2006, Fox et al. 2006, Drewitt and Langston 2008). Where habitat loss at the turbine base is low, however, the loss of aerial habitat may be higher.

Disturbance created during the construction of wind farms results in the removal of otherwise suitable habitat for birds, and if this is sufficiently large, can lead to displacement of birds from the area (Drewitt and Langston 2006). Disturbance can occur during both the construction phase and once the wind farm is operational, the latter due to the visual or auditory effects of turbines. Although a few studies have shown a change in habitat used by birds post-development (Pedersen and Poulsen 1991), few studies exist with the proper before- after-control impact design needed to determine an effect (Erickson et al. 2001, Drewitt and Langston 2006).

The avoidance of birds from flying near the wind farm developments is considered as displacement. Concerns arise when the farm location requires birds to expend more energy to fly around developments, especially when located between nesting and feeding areas (Drewitt and Langston 2008). A study at the offshore development Nysted in Denmark found a small proportion of seabirds flew between turbines when spaced at 480 m apart. Although the birds were not being completely displaced by the structures, the majority of birds avoided the turbine rows altogether (Kahlert et al. 2004a). This highlights the need for more research, particularly at the species-level, with regards to avoidance behaviours and how flight patterns change once a wind farm is constructed. Such research would determine the impacts of new developments on habitat use and energy expenditure by birds.

Considered a form of displacement, a barrier effect occurs when birds completely avoid approaching the farm, which has been found to occur with common eiders (*Someteria mollissima*) during their migratory flights (Larsen and Guillemette 2007). During the day, the eiders remained up to 3 km away from a development, but came closer (within 1 km), at night (Larsen and Guillemette 2007). Although this precludes areas around the farm for foraging, the result is favourable as it may also result in decreased chances of collision. To date barrier effects on populations are believed to be non-significant for most bird species and as such considerably less attention has been given for documenting displacement and avoidance behaviours. Nonetheless, as wind farm developments expand in size and area, the potential exists for cumulative impacts should several farms interact to disrupt either breeding/feeding areas or migratory routes (Drewitt and Langston 2006).

Collisions with wind turbines are likely to impose the greatest impacts on migratory birds, and studies suggest that raptors face disproportionately greater fatalities than other bird species (Desholm 2009, Masden et al. 2010). The following covers the current consensus on this topic.

1.2.2 Raptor Turbine Collision risk

Based on a risk-index that accounted for both abundance and species-specific vulnerability to collision mortality with wind turbines, birds of prey and waterbirds were identified as groups of highest priority for collision reduction efforts and continuing research (Desholm 2009, Masden et al. 2010). Only passerines were assessed as being at a low risk from collision impacts because even large numbers of fatalities typically represent only a tiny proportion of the overall population (Desholm 2009, Masden et al. 2009). By comparison, smaller populations of large predatory raptors, such as eagles, experience slow population growth, which means the loss of a few birds through collisions can have a more significant impact on the overall population (Ferguson-Lees and Christie 2001).

Where raptor collisions have occurred with wind turbines, common findings suggest that mortality events were aggregated by season, spatially (some turbines killed more birds than others), and by taxonomic group (some species affected more than others) (Hunt 1995, Barrios and Rodriguez 2004, de Lucas et al. 2004, Smallwood et al. 2009). In addition, raptor collision risk with turbines is not related to species abundance, but rather reflects species-specific flight behaviour within proximity to a wind energy development (Thelander and Rugge 2001, de Lucas et al. 2008). To date, fewer turbine fatalities have been documented for migratory raptors than for resident or breeding/wintering populations, however few studies exist in dense raptor-migration areas (Whitfield 2009, Masden et al. 2010), and fatality assessments have been criticized as being flawed (Drewitt and Langston 2008, Whitfield 2009, Masden et al. 2010). Despite this, numerous new wind installations are being approved for development that are located in known migratory corridors, yet post-construction monitoring of the response of birds to initial farms in these corridors are lacking or are yet to be conducted. Our understanding of post-construction behaviour, particularly whether birds are displaced or are able to avoid turbines, comes from only a few studies with restricted locations (Barrios and Rodriguez 2007, de Lucas et al. 2007, Smallwood 2007).

A study in Navarra, Spain, found that although raptor fatality events were significantly greater than expected – based on passage rates within 250 m from turbine locations – the majority of mortalities belonged to a single species, the griffon vulture (*Gyps fulvus*) (Lekuona and Ursua 2007). Griffon vultures are a large-bodied species that gain height slowly in thermals, and require fairly large amounts of space as they ascend via circle-soaring (Spaar and Bruderer 1996). This species has been found to be at greater risk of collision with turbines when they gain height by thermalling in relatively weak winds over gentle slopes (Barrios and Rodriguez 2004).

Golden eagles exhibit similar flight behaviour to griffin vultures due to their large size and low wing-loading (weight/wing surface area) and are a species susceptible to collision mortality with turbines in California, USA (Thelander and Rugge 2001). Although most of the golden eagle fatality events involved overwintering birds that were hunting within a wind farm development, research is lacking for wind farm developments along migration routes. One exception is a study in Wyoming, USA, where post-construction fatality events proved to be lower than that estimated by a pre-construction collision-risk model (Whitfield 2009). This suggests that for wind farm developments oriented parallel to the main lines of migration, micro-siting turbines away from the main slopes used during migration can reduce conflicts between eagles and turbines. Nevertheless, much has yet to be learned regarding the cumulative impacts that multiple developments will have on migratory golden eagle populations, and the large number of golden eagle fatalities by developments in California, USA supports concerns regarding new developments within golden eagle habitat, whether migratory, breeding or wintering. Additionally, because golden eagles are vulnerable at the population level to additive mortality – due to being long-lived and slow to reproduce – they warrant special attention with regards to the encroachment of wind energy developments into their range (McIntyre and Collopy 2006, Katzner et al. 2007).

1.3 Methods Used to Assess Raptor Turbine Collision Risk

The rapid expansion of wind energy developments into areas where raptor migration densities are high (particularly in mountainous and the Great-Lakes regions of North America) has raised concern that there is insufficient research on the impacts of such installations on migratory populations (Sherrington 2003, Katzner et al. 2006, Katzner et al. 2007, Whitfield 2009). Currently in western North America, only one collision risk study exists along a major golden eagle migration route (Wyoming, USA), and these findings are not available through publication in a peer-reviewed journal (Whitfield 2009). Accordingly, the Hawk Migration Association of North America (based in eastern North America) makes a strong public stance on their website that "any pre-construction wind-farm assessment located in an area of relatively dense raptor migration, breeding, or wintering populations should abandon construction unless proven that the farm poses little impact" (see: http://www.hmana.org/ read_article.php?id=9). This caution is born from a lack of knowledge regarding the degree to which birds will change flight behaviour post-construction, as well as species- and regional-specific variation in collision impacts along migration routes. However, despite the fact that significant raptor mortality events have occurred at only a small handful of wind farms around the world (Altamont Pass Wind Resource Area in CA, USA; Navarra and Tarrifa, Spain) and for the most part involve resident or overwintering birds (Thelander and Rugge 2001, Barrios and Rodriguez 2004, de Lucas et al. 2004, Smallwood et al. 2007), concerns regarding cumulative impacts remain. Hence, even if collisions and barrier effects are low at individual wind installations, there are legitimate concerns over cumulative impacts at the population level for some species, particularly for golden eagles.

In addition to a lack of research in collision-risk assessments for migratory raptors, comparisons between studies have been difficult due to wide variations in methods (Drewitt and Langston 2006). Most post-construction assessments of risk in North America involve carcass searches, many of which do not include adjustments for searcher bias and scavenger removal, and ultimately provide little valuable information (see Winkleman 1992, Painter et al. 1999, Erickson et al. 2001, Osborn et al. 2009). However, a few studies adopted thorough methods that attempted to account for the associated errors of carcass searches, which is currently becoming incorporated into new studies (Smallwood et al. 2010). In Europe, a few studies further incorporated methods that estimated time of mortality to associate weather conditions with fatality events (de Lucas et al. 2007, Lekuona and Ursua 2007, Smallwood et al. 2010). However, since most post-construction fatality assessments only involve carcass searching, few studies exist that can compare pre-construction risk predictions or identify factors associated with fatality events (i.e. weather-related factors) (Drewitt and Langston 2006). Of those that do exist, many are not published in peer-reviewed journals and exist primarily in the grey-literature as reports where they are have limited impact (see Hunt 1995, Thelander and Rugge 2001, Whitfield 2009).

Results reported from some studies indicate low turbine-collision fatality events for migratory raptors (Erickson et al. 2001, Barrios and Rodriguez 2004), although many of these studies were not positioned in an area of dense raptor migration and vary in species composition and abundance. One of the major setbacks in assessing the impacts of wind energy developments on migratory raptors is that many of the findings do not make it clear to the reader whether low fatality events were due to low raptor abundance in the area or to actual low collision rates (and high displacement or turbine avoidance) (Drewitt and Langston 2008). This is likely due to the fact that post-construction risk assessment, mainly carcass searching, does not provide information on species abundance. Therefore, since raptor abundance and species composition often varies between wind farm locations, particularly if they are in different ecosystem types, low fatality events (i.e. few carcasses found) at one development therefore does not necessarily reflect high rates of avoidance by a raptor species at all locations (Drewitt and Langston 2006). Thus, while low fatalities are being reported from some studies, the results are not always informative and applicable to regions differing in topography type and/or species composition since mortality events are believed to be species- and area-specific and may be associated with the type of flight behaviour exhibited in a region (Barrios and Rodriguez 2007, de Lucas et al. 2008). It is to be concluded that currently, more research is needed to ascertain species-specific responses to wind energy developments in a framework that takes into account topography-type (i.e. mountains versus prairies), particularly for developments in areas heavily used by raptors.

1.3.1 Carcass Searches

One of the main reasons why many operational wind farm assessments fail to provide information regarding the causes of collision mortalities is because they involve carcass searches as the sole method of assessing fatality events (Drewitt and Langston 2008). This results in the scarce existence of species-specific flight behaviour data post-construction, which does not allow for the documentation of behaviours associated with carcass-identified mortality events (Drewitt and Langston 2006). Because carcass searching methodologies are not designed to take into account visual observations of local abundance and flight behaviour (and mortalities found on the ground may or may not correlate with raptor use of the area), much has yet to be learned regarding how raptor behaviour changes, if at all, once the turbines are operational (i.e. avoidance behaviours and displacement). In addition, carcass searches alone likely fail to provide accurate data on soaring raptor injuries because a bird with a distal injury to the wing can soar away to die in an area removed from carcass searches (known as crippling bias) (Drewitt and Langston 2008). From a research perspective, carcass searches for raptors may highlight problem turbines, but on their own fail to explain why mortality events take place at the species level.

Some studies have supplemented carcass searches with visual observations to create a risk-index based on raptor use of the wind farm area. An example is a study by Barrios and Rodriguez (2004) in southern Spain who were able to account for the proportion of high-risk turbine area approaches (within 50 m) to general passage within 250 m, while documenting flight behaviour. Here, raptor fatalities were higher for circle-soaring birds and were comprised almost entirely of resident birds (17%), with migrants representing only 0.07% of mortality events, although the study area was described as not being within the main line of migration (Barrios and Rodriguez 2007). Another exception is a study by Lekuona and Ursua (2007) in northern Spain that incorporated behavioural observations along with carcass searches into their methodology. They found that although raptors consisted of only 20% of bird detections, they represented 72% of fatality events compared to non-raptor species. Hence, despite the improved methodologies being designed to incorporate searcher efficiency and scavenger removal (Smallwood et al. 2010), carcass searches alone are usually not able to answer questions behind fatality events, nor identify weather-related behaviour pattern s specific to a development.

1.3.2 Collision Risk Models

A method becoming more popularly used for estimating collision risk at proposed wind energy developments is the collision risk model. Collision risk models require visual documentation of flight behaviour within a three-dimensional risk area around a proposed turbine location. Numerous types of these models exist, however, most are based on two parameters: (1), the probability of a bird to pass within the area occupied by the turbine blades (rotor-swept area), and (2), the probability of a bird to be hit a turbine blade (Band et al. 2007).

Currently, the most commonly used collision risk model is the `Band’ model (Band et al. 2007). Most often used as a predictor of risk pre-construction, carcass searches are then used post-construction to validate predictions. One of the limitations of the Band model, however, is the built-in assumption that birds do not avoid turbines (Band et al. 2007). Because the model aims to assess risk before turbines are constructed, the use of the Band model requires the inclusion of an avoidance estimate for the species in question. Challenges exist when using behavioural avoidance estimates from other study locations because of variation in behaviour, topography and weather conditions between study locations (Whitfield 2009).

Where avoidance rates have been assessed, the rates have been found to be quite high (95-99.9%), although relatively speaking they are lower for soaring migrants (~95-99%) compared to other bird species (99%), and variation between studies exists (Chamberlain et al. 2006, de Lucas et al. 2007, Whitfield 2009). A recommendation by Band et al. (2007) is the documentation of species-specific avoidance behaviours at a development post-construction to increase the accuracy of the model. This, however, requires the implementation of observations post-construction, which is rarely done (Drewitt and Langston 2008). Another limitation of the Band model is the increased likelihood of overestimating avoidance in developments where bird abundance is low (Whitfield 2009). Ultimately, the application of the Band model requires a reasonable sample size in order to inform researchers about species-specific avoidance behaviours, which can be expensive in both time and effort.

Results from the applications of the Band model suggest that soaring birds detect and avoid functioning turbines (de Lucas et al. 2007). For Griffon vultures in Tarifa, Spain, birds were found to avoid functioning turbines more often than expected compared to turbines that were idle (de Lucas et al. 2007). Of the birds they followed, 71% changed direction when they detected spinning turbines (de Lucas et al. 2007). Other species have also demonstrated avoidance; using radar technology in Denmark, most sea ducks have been found to divert their flight paths around turbine clusters at a distance of 3 km during the day and up to 1 km at night (Kahlert et al. 2004a, Kahlert et al. 2004b, Desholm and Kahlert 2005). The potential use of the Band model, accompanied with information on species-specific avoidance rates at wind farm locations, could provide more accurate predictions along migration corridors and allow for standardized comparisons between developments in an area (Band et al. 2007, Whitfield 2009). However, challenges exist with this method which makes it unsuitable at some locations with limited personnel, especially if densities of birds are low (Whitfield 2009). Ultimately, the desired post-construction methods (i.e. band model, risk-index) would implement methods used in pre-construction risk assessments, in addition to carcass searches, to determine the efficacy of a given method in predicting risk.

Another area of needed research is tower design. Almost all of the raptor mortality events at Altamont Pass in California occurred with older turbine models that are considerably smaller than today's models (Hunt 1999, Thelander and Rugge 2001, Hoover and Morrison 2005, Smallwood and Thelander 2008). The newer towers are taller and have longer blades (80m to the hub with 47m blades, versus the original 30m to the hub with 9m blades used in the early 1990's), and thereby occupy a larger proportion of the airspace. Although the longer blades equates to faster blade tip speeds, it also means that birds have more time to pass through the rotor swept area, particularly at the outer edge of the blades, and are likely to be less dangerous (Whitfield 2009). However, the effects of the greater area swept by the blades is not known, as much of the existing research on migratory raptors in North America is based on the smaller and shorter wind turbines. Therefore, risk-assessment research with regards to taller and newer turbines is needed, especially for migrant raptors. In addition, fatality events based on rated capacity (i.e. # fatalities/MW turbine versus # fatalities/turbine) – instead of on a general per turbine basis – should be used to better inform wind energy development managers regarding mortality events associated with turbine size (Whitfield 2009, Smallwood et al. 2010).

Lastly, as information is gathered regarding site-specific impacts on birds, the need for cumulative-impacts at the population level is critical when attempting to contextualize collision mortality events (Masden et al. 2010). Because many raptors are long-distance migrants that often become concentrated in regions along their route, a regional assessment that accounts for the synergistic impacts of each sequential development along a migration route would help inform the potential threshold capacity for wind development in a region.

1.4 Overview of Thesis

1.4.1 General Methods

Stand-watch observations for migratory golden eagles were conducted over two fall (2008 and 2009) and spring (2009 and 2010) seasons. I conducted fall observations between 1 – 10 October in 2008, and between 13 September and 24 October in 2009. Spring counts were conducted between 28 March and 17 April 2009, and between 17–28 March 2010. Sampling protocol was based on methods developed jointly by Stantec (formerly Jacques-Whitford AXYS) and UNBC as part of the Environmental Assessment in 2007 (Thomas 2008, Pomeroy et al. 2009). I modified the data collection process slightly in the fall of 2009 and spring of 2010 to address my research questions, and consequently, some of the thesis focuses only on this latter dataset.

My effort to capture the majority of golden eagle migration in the fall of 2009 is based on information obtained from data collected in 2007–2008, which identified the fall as the most abundant migration period, in addition to information made available by the Rocky Mountain Eagle Research Foundation located in southern Alberta, Canada (www.eaglewatch.ca). Spring monitoring in 2009 documented low passage rates (≤ 1 golden eagle/hr), and was therefore omitted from analyses. Hence, the questions addressed in this thesis utilize the data collected in the fall of 2009 and spring of 2010, and where suitable, include data from the fall of 2008. Although other migratory raptors species were observed, the golden eagle represented over 75% of all fall detections, and is thus the focal species of this thesis.

Observations were conducted from three separate vantage points that permitted a view of the ridge top in addition to the surrounding area, including the valley bottom. I conducted these observations between the hours of 900 and 1530 Pacific Daylight Time, for a total of six hours per day. Two three-hour surveys were conducted per day (am/pm), and observation locations were rotated to create a balanced survey design.

For each golden eagle observed, three-dimensional points were created along each individual's flight track. Points were created upon first sight of the bird, in addition to any changes in direction, height or behaviour. The creation of a spatial point entailed a compass bearing, a clinometer angle (%) for height relative to the observer, and a ground distance estimation (m). Ground distances were estimated with the help of known landmark features (idle turbines, power poles and cut-blocks from forestry activities) in addition to the use of satellite image maps with known distance rings. Priority in the number of data points for an individual eagle was given for birds that approached within 2 km the study ridge, although all birds detected within 4 km were given a minimum of 2 points. Spatial points were imported into GIS for a `track analysis' of golden eagle movements in a three-dimensional format that enabled both path analyses and information on height (above ground level) for birds as they approached the ridge-top of interest.

1.4.2 Research Questions

Chapter 2 of this thesis describes the spatial use of the study site, defined by two main migration routes located to the east or west of the study ridge, in relation to temporal and local weather conditions for both the fall and spring migration seasons. More specifically, I aim to identify if route used equated to behaviours that increased collision risk in a season, mainly by assessing the frequency with which eagles entered a predefined area called the risk-zone, also the proposed ridge-top string of turbines. Additionally, risk events were contrasted between seasons to determine if an eagle that travelled in an aggregation (i.e. clumped with other eagles) entered the risk-zone area more often than individuals that travelled alone. Large scale movement patterns, in addition to other flight behaviours that could potentially increase golden eagle collision risk in the post-construction phase, are an important first step in understanding potential risk events, in addition to how behaviours may change post-construction.

The third chapter looks solely at tracks that entered the proposed ridge-top string of turbines (the risk-zone) to determine if any weather variables, flight behaviours, and/or topographical features were associated with the heights at which golden eagles entered the risk-zone. I then further examined the data to determine the proportion of individuals that entered at turbine height (≤ 150 m) and above cut-in speed (14 km/hr or 4 m/s). Here I rely on the extensive 2009 fall data set, and contrast it to observations in the spring of 2010, to identify the factors that were associated with low flight altitudes. The information presented here is predominantly based only on one season and relies on weather collected at ground level; further research is needed post-construction, and at other developments in the Hart

Range, to confirm associations identified, quantify collision risk and identify avoidance behaviours.

1.5 Study Site

The Dokie Wind Energy Project is located in the Peace River Regional District of northeast British Columbia, Canada (Figure 1.1). The North Dokie site (55^{o} 46’ 28.00”N, 122^{o}16’48.75”W) is the first stage of the proposed 300 MW project. North Dokie is comprised of two ridges (Johnson Col [elevation 1200 m] and Johnson Ridge [elevation 1400 m]) which will support a total of 48 3-MW Vestas turbines, for a total output of 144 MW (15 on Johnson Col – also the study ridge, and 33 on Johnson Ridge; Figure 1.2). Turbines stand 80 m tall to the hub with 47 m blades, for a total height of 127 m.

Construction began at North Dokie in 2008, which consisted mainly of tree-clearing and road construction. During the sampling period in 2008 one standing idle turbine was present at the north end of Johnson Col (JC15; also the study ridge). However, by December of 2008, five widely-spaced turbines were erected (three on the study ridge and two on Johnson Ridge) before the company filed for bankruptcy and thereby stalled construction for a year until the development was sold in early 2010. As such, three widely-spaced idle turbines, approximately 1.5 km apart, located at the south end (JC01), near the north end (JC15), and in the middle (JC09) of the study ridge, were standing during stand-watches conducted in the fall of 2009 and spring of 2010 (Figure 1.2).

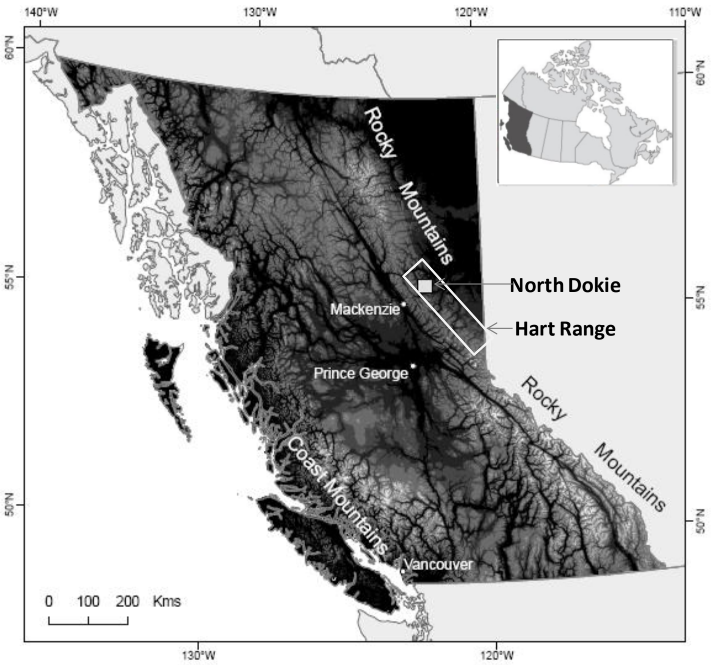

Figure 1.1 Location of the Dokie Wind Energy Project in the Peace River Regional District of northeast British Columbia, Canada. The Hart Range represents the extension of the Front Ranges to the south.

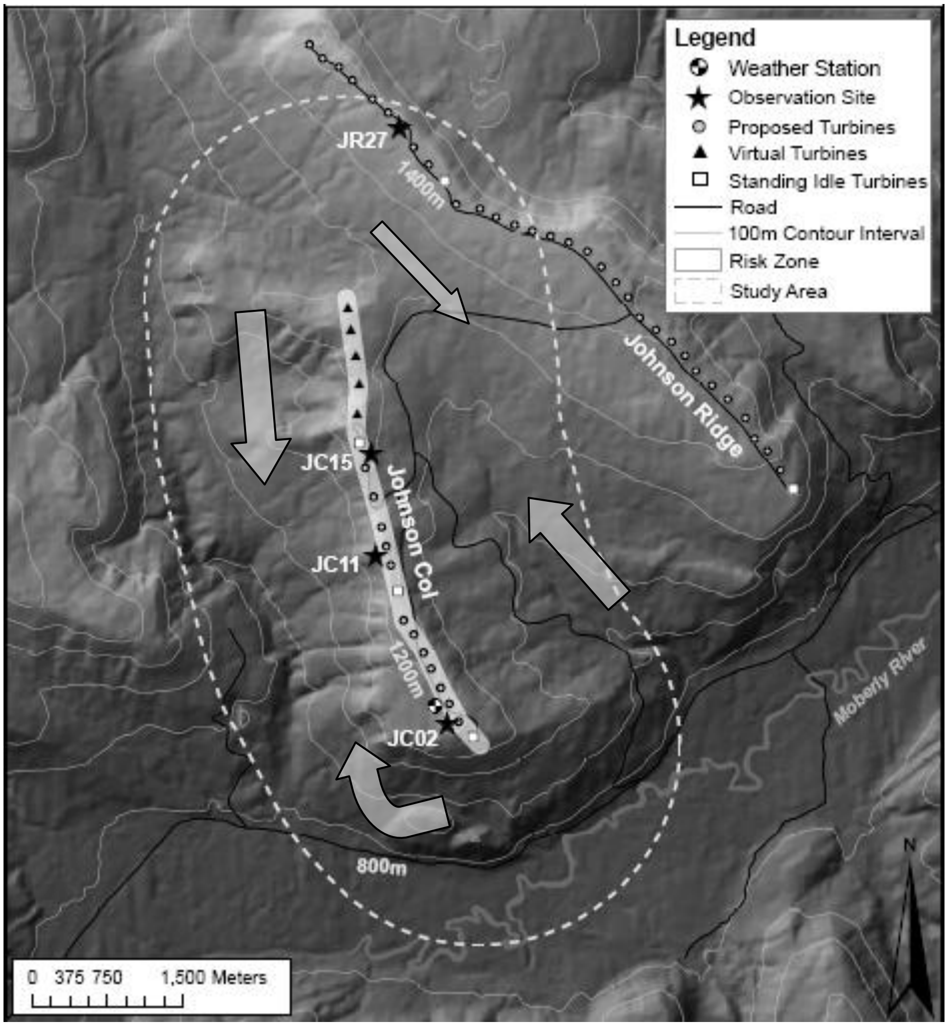

Figure 1.2 The Dokie Wind Energy Project – northern section – in the Peace River Regional District of northeast British Columbia, Canada. Both the study area and risk-zone represents a 2 km and 100 m buffer around the turbine string. Large arrows represent general migration patterns for the fall (southward) and spring (northward).

Stand-watches took place from a total of three observation sites per season (JC02, JC11 and JR27 in the fall; JC02, JC15 and JR27 in the spring), except for the fall of 2008 where only two locations were used (JC02 and JR27) (Figure 1.2).

CHAPTER TWO – FACTORS ASSOCIATED WITH MIGRATORY GOLDEN EAGLE FLIGHT BEHAVIOUR AT A PRE-OPERATIONAL WIND FARM IN THE CANADIAN ROCKY MOUNTAINS.

2.0 Abstract

I documented passage rates and routes of migratory golden eagles at a ridge-top wind farm under construction in the Rocky Mountain foothills of northeast British Columbia, Canada in both fall and spring seasons. The Dokie Wind Energy Project is the first development in BC along a major golden eagle (*Aquila chrysaetos*) migration route, known as the Hart Range. Passage routes were incorporated into a geographic Information system to identify possible associations between the frequency with which eagles entered into a predefined risk-zone on the study ridge with local weather variables and migration route used through the site (east versus west). In both spring and fall, I found that approaches into the risk-zone were only explained by hourly passage rates, indicating that higher passage rates best explained flight into the risk-zone. Eagles were also more likely to enter the risk-zone when using the eastern route (compared to the western route) to traverse the site, which was favoured under head-wind conditions in the fall and low wind conditions in the spring. Additional years of sampling, in addition to research on the factors associated with golden eagle flight altitudes, is needed.

2.1 Introduction

Post-construction research on raptor collisions at wind farm developments suggests that fatality events are not always related to species abundance (de Lucas et al. 2008). Rather, fatality events vary depending on species-specific flight behaviour, which is affected by weather and topography (Barrios and Rodriguez 2004, de Lucas et al. 2004, Hoover and Morrison 2005, Katzner et al. 2007). In other words, collision fatalities can be higher than expected for species that are less commonly observed due to species-specific differences in flight behaviour (Hoover and Morrison 2005, de Lucas et al. 2008).

Research suggests that soaring raptors are at greater risk of collision mortality with wind turbines than other bird species, in part because of their reliance on topography for lift (Barrios and Rodriguez 2004, Drewitt and Langston 2008). The complex intermountain terrain is favourable for large-bodied soaring species such as golden eagles (*Aquila chrysaetos*) because of the increased opportunities for winds and lift (i.e. slope winds, deflected winds and thermals) compared to other areas with less topographic relief (Kerlinger and Moore 1989, Hedenstrom 1993, Spaar and Bruderer 1996, Yates et al. 2001). For this reason, golden eagle migration in North America is often concentrated in locations where conditions are favourable for providing these updrafts, such as mountain ranges lying perpendicular to the main axes of prevailing winds (Alerstam 2001, Bildstein 2006: 125).

To date, little is known regarding the flight behaviour of migratory golden eagles with regards to ridge-top wind energy developments in the Rocky Mountains of North America. With the large potential for wind energy development in the Rocky Mountain foothills northeast British Columbia, Canada – also situated along leading lines of golden eagle migration – the documentation of species- and site-specific flight behaviour associated with weather conditions could assist researchers and wind farm managers to identify potential collision threats.

The various sources of lift in the intermountain terrain originating from differing combinations of local weather conditions may result in differing localized movement patterns within a site (Yates et al. 2001). For wind energy developments in mountainous regions, this opportunistic use of available lift may result in varying collision risk with turbines. This temporal and spatial variation in potential collision hazard may increase conflicts with eagles and wind energy developments should they overlap with constricted migration corridors (Steinen et al. 2007).

In addition to potentially influencing local routes through an area, local weather conditions can further aggregate birds (Omland and Hoffman 1996, Bildstein 2006b). The slow height-gaining process of circle-soaring flight for heavy-bodied raptors can aggregate birds into loose groups by slowing down migration speed (Spaar and Bruderer 1997, Klaassen et al. 2008). If conditions aggregate raptors within the area of elevated collision-risk, such as at turbine height and close to turbine locations, risk of collisions may be elevated. A better understanding of the weather variables that are associated with aggregated passage and route followed prior to construction could be used to identify weather conditions associated with elevated collision risk.

Raptors are known to initiate migration within a narrow date range each year. Likely triggered by the change in day-length, the consistency of annual migration events are believed to be genetically driven (Alerstam 1990). Findings in migration research indicate that daily passage rates exhibit more within-year variation, likely due to weather and count efforts, than total numbers counted between-years (Leshem and Yom-Tov 1996, Bildstein 2006a). For example, the arrival of migrant raptor species at a watch-station in Israel over a four-year period was highly predictable by date, with only ± 1-5.5 days variation observed between years (Leshem and Yom-Tov 1996). Hence, the passage of migrant raptors in both space and time can be predicted fairly accurately.

In North America, golden eagle migration is channelled along the major mountain chains, with 4-6 thousand migratory golden eagles counted each fall at an established hawkwatch location in southwest Alberta, with up to a half or a third of that number counted each spring (Sherrington 2003). Lower spring counts are likely in part due to the lack of mixed-age classes observed in the fall and possibly to the use of a more eastern route (Yates et al. 2001, Sherrington 2003). The Dokie Wind Energy Project (North Phase; hereafter referred to as North Dokie) in the Peace River District of northeast BC, located approximately 800 km north of the count location, is positioned along the same eastern Rocky Mountain corridor used by golden eagles to the south (Yates et al. 2001, McIntyre and Collopy 2006, Sherrington 2003) and is a region identified by the Provincial Government of British Columbia as having a large potential for wind development (Larson 2010). Although not a species of concern in western Canada, count data are currently being analysed for a potential downward trend (Hoffman and Smith 2003, Sherrington 2003, McIntyre and Collopy 2006). Long-lived and slow to reproduce, golden eagle populations are susceptible to population declines due to additive mortality with the removal of individuals, and therefore deserve special attention.

The North Dokie site is representative of the general topography of the eastern Rocky Mountains, with ridges aligned NW – SE; the result of extensive thrust faulting in the region (Yates et al. 2001, Sherrington 2003). Furthermore, the conditions characterized at the site during migration are representative of the general weather patterns for the Hart Range, with prevailing winds in the fall originating from the southwest (Yates et al. 2001, Sherrington 2003).The consistency in these two variables through the Hart Range makes information collected at North Dokie directly applicable to other proposed wind farms in the region.

We conducted stand-watch observations at ridge-top wind farm development that was stalled at the construction phase to record flight paths of migratory golden eagles. We used a Geographic Information System (GIS; ArcGIS version 9.3) to determine the associations between the frequencies at which eagles approached the ridge-top area with weather variables and local migration routes through the site. The study aims are twofold: first, to identify temporal and weather conditions that were associated with the frequency and distribution of passage (clumped versus uniform passage and route in relation to the study ridge [east versus west]); and second, to identify how these parameters affected the frequency of eagle entries to the string of turbines. I aim to provide information at the site level to minimize impacts, which will also be applicable at the regional level as a management tool for identifying similar patterns at new energy facilities in this and other regions along the Rocky Mountain migratory corridor.

2.2 Methods

2.2.1 Study Area

The Dokie Wind Energy Project (55^{o} 46’ 28.00”N, 122^{o}16’48.75”W) is located approximately 40 kilometres west of the town of Chetwynd in northeast British Columbia, Canada (Figure 1.1). North Dokie consists of two ridges; a 4.5 km ‘Johnson Col’, oriented approximately in a north-south direction and parallel to migration pathways, and a 6 km 'Johnson Ridge' to the east of Johnson Col (Figure 1.2). Southwest of Johnson Col is a large and deep valley that separates the ridge from the high peaks of the Rockies (2000-2200 m). The smaller Johnson Col is of slightly lower elevation (1200 m) compared to Johnson Ridge (1400 m), and is slated to hold 15 of the 48 proposed 3-MW Vestas turbines. Previous work has shown Johnson Col to have higher eagle passage during fall migration (Thomas 2008, Pomeroy et al. 2009), and is the study ridge for the purpose of this research.

Turbines are 80 metres in height to the hub, with 47 m blades, for a total of 127 m in height. During both the fall 2009 and spring 2010 migration seasons, only three widely-spaced idle turbines, approximately 1.5 km apart, were standing on Johnson Col; one at each end of the proposed turbine string, and one in the middle of the ridge (Figure 1.2). The 2008 fall season had only one idle turbine standing at the north end of Johnson Col. I considered the construction phase as essentially underdeveloped for the purposes of this study, as there was no turbine construction in 2009 and 2010, and research indicates that soaring raptors do not exhibit avoidance to idle standing structures (de Lucas et al. 2007).

Although golden eagles were not the only species observed, they made up the majority of birds observed (Table 2.1). Sharp-shinned hawks migrate through the study area in early- to mid-September, but preliminary observations suggest that their overall numbers are unlikely to be comparable to the golden eagles sightings (N. Johnston and J. Bradley, UNBC, unpublished data).

Table 2.1: Raptor species composition observed within 2 km from the ridge-line at North Dokie between September 13 and October 24, 2009.

Species	Latin Name	Count
Osprey	*Pandion haliaetus*	6
Bald Eagle	*Haliaeetus leucocephalus*	6
Northern Harrier	*Circus cyaneus*	21
Sharp-Shinned Hawk	*Accipiter striatus*	62
Cooper’s Hawk	*Accipiter cooperii*	3
Northern Goshawk	*Accipiter gentilis*	3
Red-Tailed Hawk	*Buteo jamaicensis*	6
Rough-Legged Hawk	*Buteo lagopus*	10
Golden Eagle	*Aquila chrysaetos*	417
American Kestrel	*Falco sparverius*	8
Merlin	*Falco columbarius*	7
Gyrfalcon	*Falco rusticolus*	2
Falcon Species	*Falco* species	1
Unknown Species	N/A	3

2.2.2 Sampling Methods

I conducted golden eagle stand-watches over two fall migration periods; between 1-10 October (36 observation hours) in 2008 and between 13 September–-24 October in 2009 (181 hours). Spring migration surveys were conducted in one season between 17–28 March in 2010 (72 observation hours). All observations were made between the hours of 900 and 1530 Pacific Daylight Time, for a total of 6 hours per day. Although I collected data between 28 March–21 April in the spring of 2009, the peak of raptor movement likely occurred prior to these dates as few observations were reported (≤ 1 golden eagle/hr). Therefore, the spring 2009 data has been omitted from analysis. Poor weather, namely low visibility due to snow or fog, limited the number of days and hours within a day that sampling could occur. The resulting total effort is 39 days (217 hours) in the fall and 12 days (72 hours) in the spring.

I followed the sampling effort and methods developed by UNBC and Stantec Inc. (formerly Jacques-Whitford AXYS) from observations conducted in previous years (2007–2009). However, I prioritized tracking of birds approaching within 2 km of the study ridge, taking a number of additional sampling points so as to more closely approximate the true flight path of birds entering areas of the proposed turbine string (see below).

Stand-watch observations were conducted by a pair of observers from three observation sites per season; two on the study ridge (Johnson Col; JC02 and JC11 [JC15 in the spring]; except for 2008 which was sampled from JC02 only) and one on Johnson Ridge (JR27), which provided a clear view of the north end of Johnson Col while also allowing for a 360 degree view of the surrounding area and view into the valley bottom (Figure 1.2).

Although Johnson Col was the study ridge, all observation sites also provided good views of Johnson Ridge; despite low passage rates (≤ 1 bird/hr) these are included when observed within 2 km of Johnson Col.

Two three-hour stand-watches were conducted per day. Observation sites were rotated to include a balanced design between time of day and area covered. Estimated golden eagle location data were collected using a compass bearing to the bird, a clinometer angle of bird height relative to the observer, and an estimated horizontal distance to the bird. Distance estimations utilized known landmark features (idle turbines, power poles and cleared forest areas) in addition to satellite imagery maps with known distance rings. I defined the study site as an area within 2 km of the crest of Johnson Col; birds observed beyond 2 km were noted but are not included in the analysis (Figure 1.2).

Weather data were collected at 2 m above ground by an Onset™ (Onset, Bourne, MA, USA) HOBO weather station located at the south end of Johnson Col in an exposed area without the influence of tree cover (Figure 1.2). Data were averaged and recorded every five minutes by an Onset data-logger. Weather parameters recorded were temperature (^{o} C), wind direction (degrees), wind speed (km/hr), barometric pressure (mbar) and relative humidity (%). Visual weather data collected in the field included percent cloud cover and ceiling height class (low [1000–2000 m], medium [2000–4000 m], and high [>4000 m]) at the start of every hour. Wind direction classes were created to analyze the circular data, and were consistent between seasons; a head-wind in the fall (spring tail-wind): 136–225^{o}; west cross-wind: 226–315^{o}; fall tail-wind (spring head-wind): 316–45^{o}; and an east cross-wind: 46–135^{o} (Figure 2.1a[i] & b[i]). I used Oriana (version 2.0) to average and plot circular wind

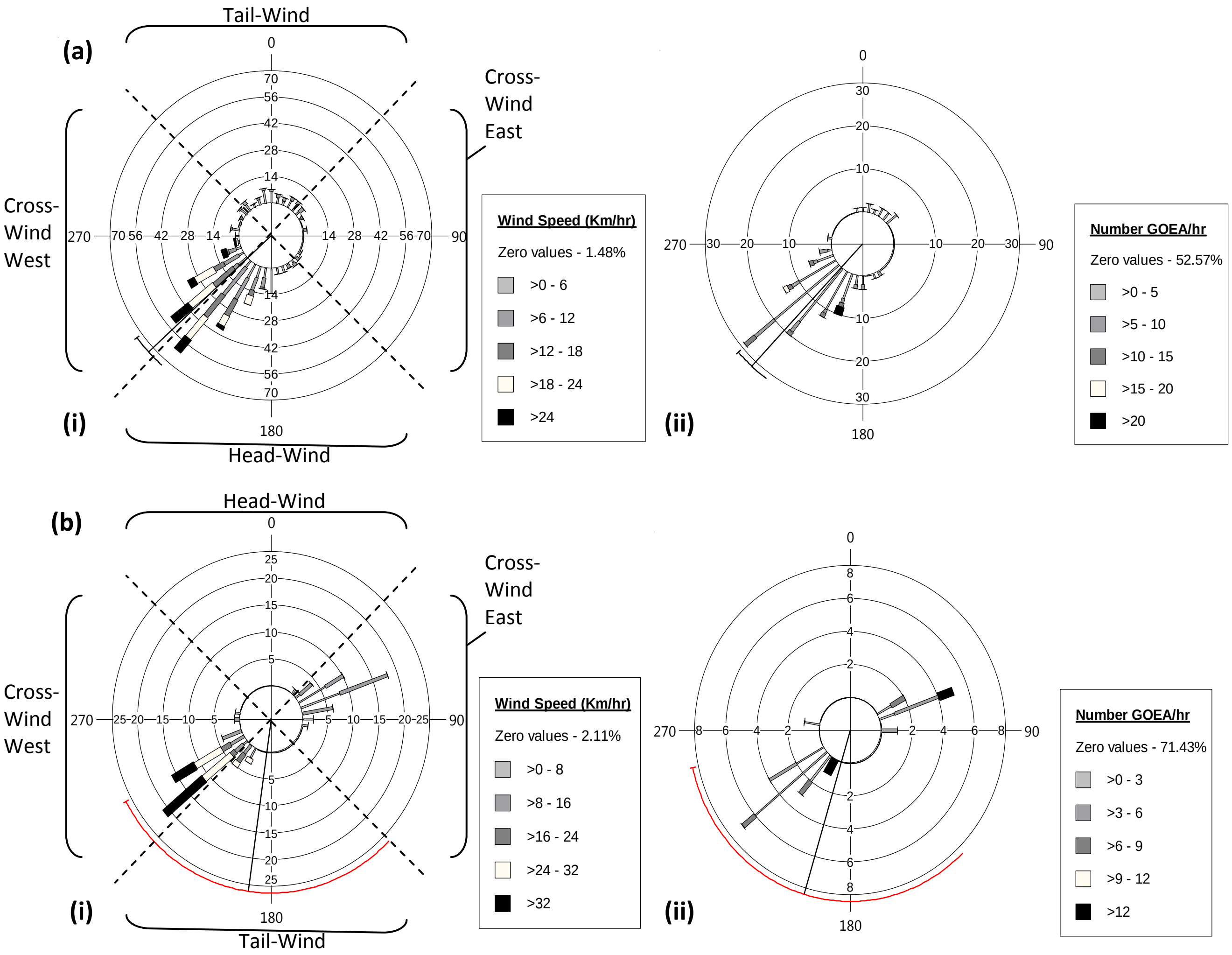

Figure 2.1 Stepped circular histogram of **(i)**, hourly wind speed by direction and **(ii)**, hourly golden eagle passage rates by wind direction for **(a)**, fall migrations seasons (1–10 Oct 2008 and 13 Sept–24 Oct 2009); and **(b)**, Spring (17–28 March 2010), between 0900 and 1530 hours Pacific Daylight Time. Mean with 95% confidence intervals are represented by line and side-bars. Note different scales between graphs.

direction data (Kovach Computing Services, Anglesey, Wales, UK).

2.2.3 Data Preparation

Bird locations were estimated using trigonometry equations that incorporated observer UTM coordinates. The equations used for the creation of bird locations are as follows:

Bird Easting (X) = Observer UTM E + (distance (m) (SIN(Radians(bearing angle)))),

Bird Northing (Y) = Observer UTM N + (distance (m) (COS(Radians(bearing angle)))).

Using bird location points, I created three-dimensional golden eagle flight tracks using ET Geowizard (ET Spatial Techniques, Pretoria, South Africa, www.ian-ko.com) in GIS. Using GIS, I identified golden eagle flight tracks that entered the proposed turbine string, which I refer to as the *risk-zone* – a 100 m buffer area surrounding the turbine string (Figure 1.2). Similar in concept to a risk-index developed by Barrios and Rodriguez (2004), the 100 m area represents a 50 m buffer beyond the length of the turbine blade to account for error due to distance estimations. The risk-zone is thus a contiguous area stretching the full length of the ridge top. All entries into the risk-zone are treated equally and do not take into account flight altitude.

I also classified migration route in relation to the study ridge (east, west or unknown) using GIS. A route was determined upon approach of the ridge for each migration season (Figure 2.2).Upon the completion of the farm, the northern extent (1 km) of Johnson Col will be undeveloped and could possibly serve as a control in future studies. Therefore, five ‘virtual turbines’ were placed along the north end of the Johnson Col to extend the

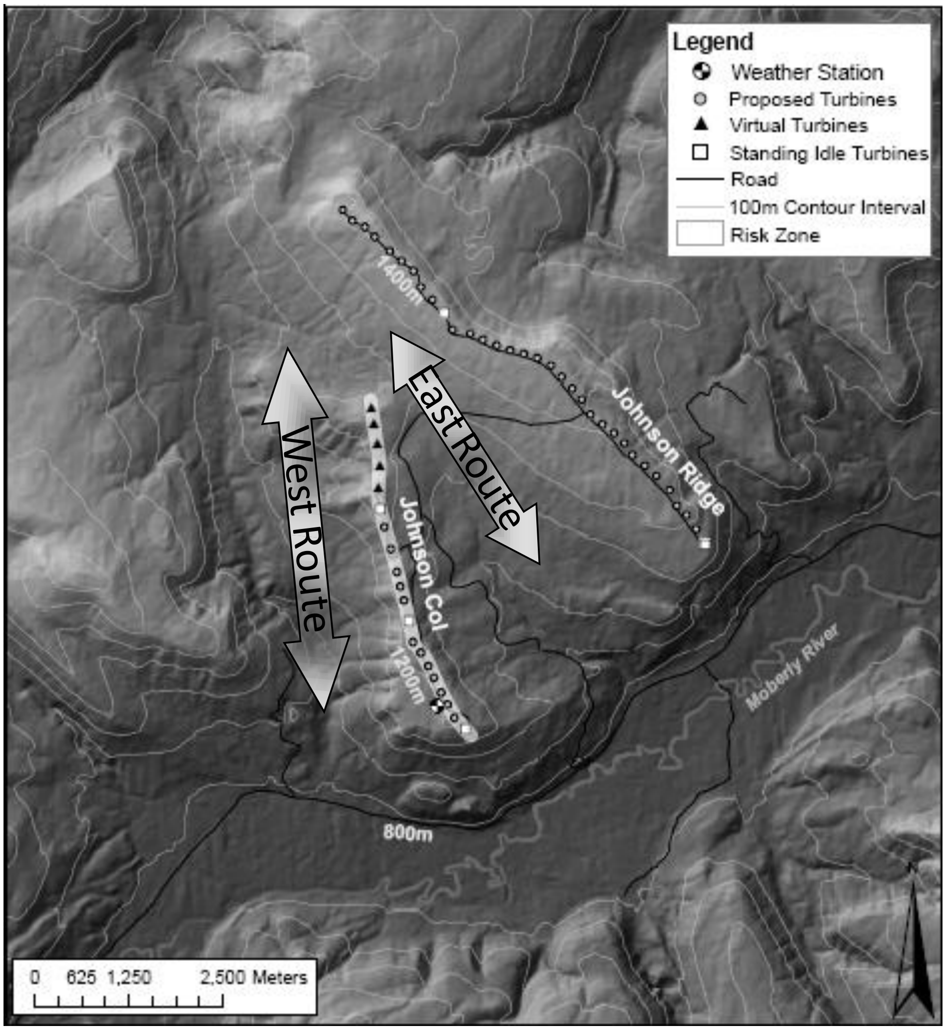

Figure 2.2 Golden eagle migration routes at the North Dokie site, east versus west of Johnson Col, for both spring (northward) and fall (southward) migration seasons.

hypothetical turbine ‘string’, and these were included in my analyses (Figure 1.2).

Although golden eagles are considered solitary in their migration strategy, aggregated passage of clustered individuals was observed in both migration seasons. I used field notes and GIS to classify individual eagles as migrating alone or in a cluster based on the criteria of travelling within 30 seconds of another bird and along a similar route for over 75% of the observed track length. These criteria result in a conservative estimate which excludes birds that were travelling along the same route but at distances greater than my cut-off. However, it should be noted that at any point in time, eagles could change their flight direction relative to the other birds in the group, and as such an individual migration route is considered independent from other birds (Omland and Hoffman 1996).

2.2.4 Statistical Methods

I ran separate spring and fall Poisson generalized linear regression models for the fall and spring to determine (1), what, if any, weather variables were associated with golden eagle hourly passage rates, and (2), if eagles that entered the risk-zone were correlated with hourly passage rates and/or weather conditions at the site. My response variable was (1), the number of birds observed per hour, and (2), the number of eagles that entered the risk-zone per hour. My predictor variables for depicting hourly passage rates (1) included the following: barometric pressure (mbar), relative humidity (%), wind speed (km/hr), wind direction (head-, cross-east and west, and tail-wind), temperature (^{o} C), and cloud cover (%), date, date squared, and hour. Weather variables represented hourly averages. The same variables, except for barometric pressure and relative humidity, but including hourly passage rates, were my predictor variables for (2), the number of entries into the risk-zone per hour. Fall 2008 data are incorporated into fall models except for analyses that include comparisons for clustered passage (section 2.3.3 B). Model selection for Poisson and negative binomial models used both forward and backward selection based on the Akaike Information Criterion (AIC) value of the model (Zuur et al. 2009). Final model covariates were checked for significance based on an analysis of deviance test as AIC selection has a tendency to over-fit (Zuur et al. 2009).

To confirm the presence of overdispersion observed in the frequency plots, I used a dispersion test that tests the null hypothesis of equidispersion in a Poisson model against the alternative of overdispersion or underdispersion (Crawley 2007, Kleiber and Zeileis 2008). If overdispersion was detected, a model based on a negative binomial distribution was used (Venables and Ripley 2002, Zuur et al. 2009). Zero-inflated models, to assist with the presence of both true (zero hourly passage) and false (zero hourly passage that missed a bird) zeros, were then used where excess zeros were observed in the frequency plots (Zeileis et al. 2008, Zuur et al. 2009). Final non-nested zero-inflated models were compared to their standard distribution model for best fit using the Vuong test (Vuong 1989, Golam Kibria 2006, Yang et al. 2007, Zuur et al. 2009). Final models were tested for their fit against the null model, and all covariates tested against the full model, using a likelihood ratio test (LR-test) (Zeileis and Hothorn 2002, Zuur et al. 2009).

Logistic regression models for route taken (east or west of the study ridge) and aggregated passage (clumped or dispersed movement through the site) were selected using backward and forward selection based on AIC values (Venables and Ripley 2002, Zuur et al.

2009). I used the ANOVA command to test the fit of final models against the null model, and for the significance of covariates by testing their removal against the full model (Bates et al. 2008, Zuur et al. 2009). Logistic regression models for route taken (east or west) and clustered passage included all weather variables except barometric pressure and relative humidity, while including date, hour, and age (adult [adult-looking], immature [juvenile-looking] and unknown age). Statistical significance was set to $\alpha = 0.05$ and all means reported are accompanied by their standard error.

I used Pearson's chi-squared tests to test the observed versus the expected frequencies of observations for: (1), the occurrence of aggregated passage within a season, and (2), route taken (east versus west) through the site within a season, and (3), to compare the proportion of risk-zone entries, aggregated passage, and use of the eastern route between seasons. I assigned a Yates correction to chi-squared contingency tests for comparisons with small sample sizes ($n \leq 50$) or with a value less-than 5. I used the statistical software R for all analyses (R Development Core Team, www.r-project.org).

2.3 Results

Golden eagle migration at the North Dokie site experiences similar patterns observed at other hawkwatch sites located in the Front Range to the south; fall migration occurs over a longer period of time and consists of a greater number of individuals (Figure 2.3a) compared to the spring (Figure 2.3b). Based on our sampling effort, I estimate that a minimum of 1000 eagles migrate through the fall each year (mid-September to mid-November) and approximately 200-300 each spring (mid-March to mid-April). These differences in passage are likely due

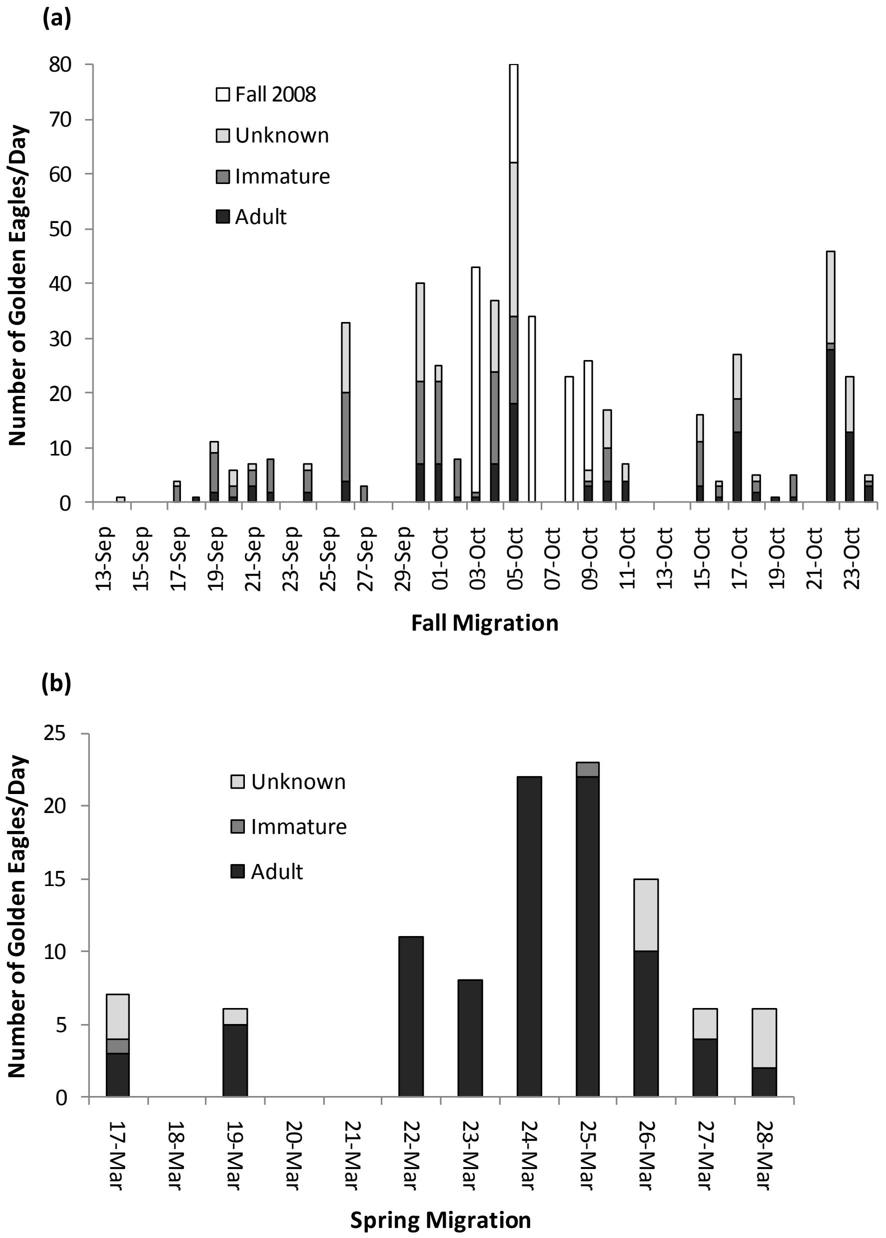

Figure 2.3 North Dokie daily site passage in (a), the fall of 2009 (*n*=417) and 2008 (*n*=139; white bars), and (b), the spring of 2010 (*n*=104) for adult and immature (juvenile appearance) plumage age-classes (2008 not shown). Note different y-axes between seasons.

to the mixed age-classes that augment numbers in the fall and additionally, the northward migration may be farther to the east into the foothills in the spring (Yates et al. 2001, Sherrington 2003).

2.3.1 Weather Patterns

During the fall eagle migration season the prevailing winds at the site originated from the southwest (SW: 90% of watch hours in 2009), equivalent to my classifications of head- and west cross-winds in the fall, with less common northeast (NE) winds – or tail-winds (5% of watch hours in 2009; September – October; Figure 2.1a[i]). NE winds were typically associated with weak wind speeds and/or poor weather and visibility conditions, and eagle migration was less likely under low-visibility conditions. The proportion of prevailing winds was similar for the fall 2008: 85% originated from a SW direction (*n* = 66 hours), with 10% (*n* = 6 hours) from the NE. During most of the latter periods, however, the weather was fogged-in and observations were not possible.

Wind direction was more variable during the peak of spring migration in 2010, with a greater proportion of NE versus SW winds compared to the fall migration seasons. The important difference between SW versus NE winds in terms of eagle migration is the difference in wind speed between the two general directions. Ground weather data collected on-site in all spring and fall seasons showed that winds from the NE did not reach speeds required for the movement of the turbine blades (turbine cut-in speed: 14 km/hr; Figure 2.4a&b). Weather data collected at nacelle height is needed to confirm this trend.

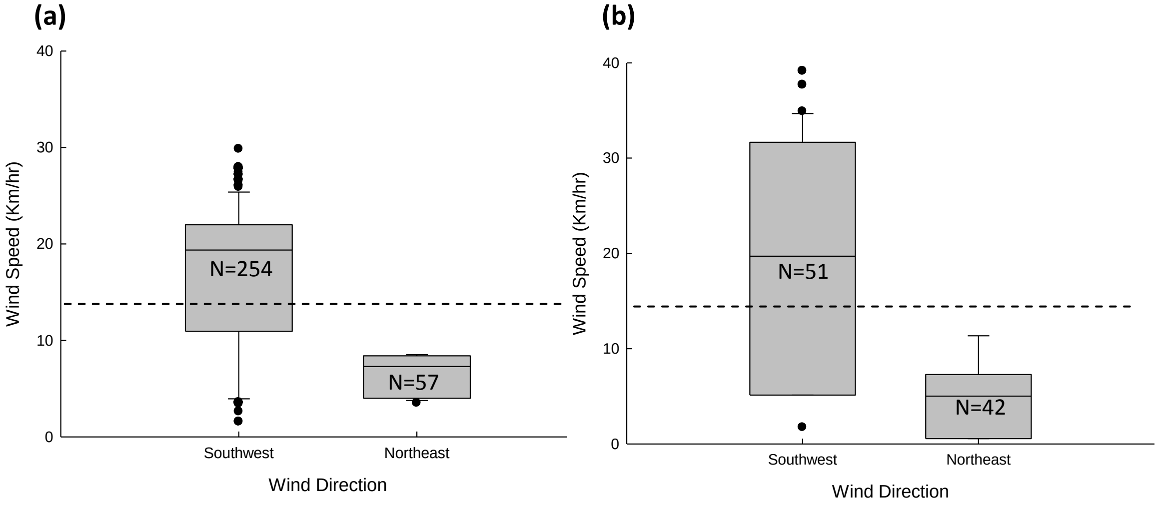

Figure 2.4 Average hourly wind speed (km/hr) by hourly wind direction class (southwest [SW] or northeast [NE]) for **(a)**, fall 2008 and 2009 (*n*=311 hours) and **(b)**, spring 2010 (*n*=93 hours). SW represents head- and west cross-winds in the fall (tail- and west cross-winds in the spring) and NE tail- and east cross-winds (head-and east cross-winds in the spring). NE winds never reached the turbine cut-in speeds of 14 km/hr (dotted-line). Southeast and northwest directions not shown for the fall (<10% of total hours each) and did not occur in the spring. Boxplots represent median and 25th and 75th percentiles, whiskers identify 10th and 90th percentiles, and dots represent outliers.

2.3.2 Migration Patterns

A. Factors associated with passage rates.

The number of eagles observed within the 2 km study area compared to birds detected with 4 km were: *n* = 139 (92%) in the fall of 2008; *n* = 417 (98%) in the fall of 2009; and *n* = 104 in the spring of 2010 (100%; Figure 2.1). The proportion of golden eagles that travelled in weak NE tail-winds in the fall of 2009 accounted for around 5% (*n* = 15) of the total number of birds observed (Figure 2.1a[ii]), compared to approximately 43% (*n* = 45) in the spring (Figure 2.1b[ii]). All fall 2008 hours of stand-watches occurred under SW winds. Daily passage in the fall was greatest under the prevailing SW wind direction, although a small amount of passage was also seen in NE conditions. Similar to the wind direction patterns observed in the spring, spring daily passage was more variable with greater numbers of birds observed under both SW and NE conditions compared to the fall (Figure 2.1a&b).

Fall passage rates increased with date ($\chi^2_1 = 25.41$, $P = 0.001$); decrease with date-squared (i.e. an upward peak) ($\chi^2_1 = 29.73$, $P \leq 0.001$); increased during the hours after midday ($\chi^2_1 = 29.12$, $P \leq 0.001$); increased with increasing temperature ($\chi^2_1 = 13.84$, $P \leq 0.001$); and increased with increasing wind speed (GLM $\chi^2_1 = 27.21$, $P \leq 0.001$; LR-test $\chi^2_1 = 87.03$, $P \leq 0.001$; Table 2.2). I did not find a difference between years.

A negative binomial model for spring passage rates revealed that no explanatory variables were significant (the best model contained date, which was not significant [LR-test $\chi^2_1 = 2.691$, $P = 0.101$]).

Table 2.2: Summary of multivariate negative binomial regression examining the association of temporal and environmental variables on the passage rates of golden eagles in the fall at North Dokie between 13 September and 24 October, 2009. Response is number of golden eagles per hour. For example, to estimate the number of eagles on October 1 (day 20) at a wind speed of 15 km/hr, at 1400 hours and at a temperature of 5^{o}C, $\log(y) = -4.456 + 0.307 \times 20 - 0.006^{\wedge}2 \times 20 + 0.092 \times 15 + 0.805 + 0.096 \times 5$; $\log(y) = 4.109$. Therefore, $y = \exp^{(4.109)} = 60.89$ eagles/hr.

Term	Estimate	SE	z	P
Intercept	−4.456	0.645	−6.910	≤ 0.001
Date[1]	0.307	0.051	6.003	≤ 0.001
Date^2	−0.006	0.001	−5.402	≤ 0.001
Windspeed[2]	0.092	0.016	5.694	≤ 0.001
Hour 11:00	0.078	0.392	0.200	0.842
Hour 12:00	0.461	0.381	1.210	0.226
Hour 13:00	1.097	0.370	2.967	0.003
Hour 14:00	0.805	0.377	2.136	0.033
Hour 15:00	0.335	0.387	0.866	0.386
Hour 16:00	0.473	0.385	1.229	0.219
Temperature[3]	0.096	0.025	3.840	≤ 0.001

[1] Day 1 is 13 September; [2] km/hr; [3] degrees Celsius

B. Factors associated with local migration route (east versus west of study ridge).

During both south-bound and north-bound migration, eagles were observed moving through the study area on both sides of Johnson Col, to the west over the Johnson river valley, or to the east between Johnson Col and Johnson Ridge (Figure 2.2). For the fall seasons, golden eagles were over 3-times more likely to take the eastern route (as opposed to the western route) under head-wind conditions rather than under west cross-winds (GLM $\chi^2_2 = 16.86$, $P \leq 0.001$). Furthermore, the use the eastern route decreased slightly (around 2%) with each unit increase in cloud cover (GLM $\chi^2_1 = 17.229$, $P \leq 0.001$; ANOVA: $\chi^2_3 = 29.19$, $P \leq 0.001$; Table 2.3). I did not detect a difference between years and wind speed conditions did not differ between routes (Figure 2.5a).

The use of the western route in the spring was not observed under eastern cross-winds. Cross-winds from the east resulted in a greater use of the eastern route, and the opposite was true under cross-winds from the west; a greater proportion of birds used the western route than expected (Chi-squared test $\chi^2_1 = 36.9$, $P \leq 0.001$). However, spring routes through the site were described by wind speed (LR-test $\chi^2_1 = 49.15$, $P \leq 0.001$; Table 2.4). Eagles used the eastern route 15% less often with each unit increase in wind speed (Figure 2.5b). Only adult birds were identified, which excluded age class from the model.

C. Factors associated with aggregated passage.

Compared to the number of individuals that migrated alone, I found greater clustering (or events of aggregated passage) of individuals in the spring of 2010 compared the fall of 2009

Table 2.3: Summary of logistic regression examining association of temporal and environmental variables on route choice of golden eagles in the fall at North Dokie between 13 September and 24 October, 2009. Response is east (1) or west (0) of the study ridge. For example, to estimate the probability of using the eastern route (as opposed to the western) under head-winds with a cloud cover of 40%, $log(y) = -1.091 + 1.422 - 0.025 \times 40$; $log(y) = -0.669$; $P(y) = exp^{(-0.669)} / 1 + exp^{(-0.669)}$; $P(y) = 0.339$ or 33.9%.

Term	Estimate	SE	z	P
Intercept	−1.091	0.738	−1.49	0.139
Wind Direction Head	1.422	0.364	3.906	≤ 0.001
Wind Direction Tail	0.388	0.844	0.460	0.646
Cloud Cover[1]	−0.025	0.006	−4.042	≤ 0.001

[1] Percent

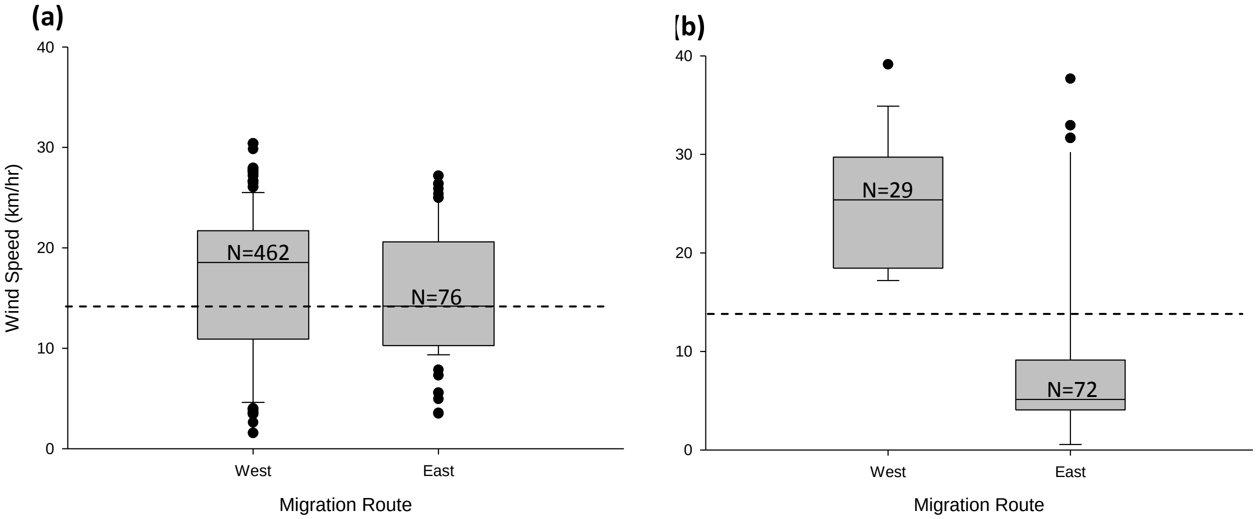

Figure 2.5 Proportion of golden eagles that used the west and east migration routes through the North Dokie site by average hourly wind speed for **(a)**, the fall 2008 and 2009 and **(b)**, spring 2010. Eagle tracks of unknown migration direction not included (*n*=18 and 3 respectively). Boxplots represent median and 25th and 75th percentiles, whiskers identify 10th and 90th percentiles, and dots represent outliers.

Table 2.4: Summary of logistic regression examining the association of temporal and environmental variables on route choice of golden eagles in the spring at North Dokie between 17−28 of March, 2010. Response is migration route to the east (1) or west (0) of the study ridge. For example, to estimate the probability of using the eastern route (as opposed to the western) with a wind speed of 15km/hr, $log(y) = 3.531 - 0.1599 \times 15$; $log(y) = 3.103$; $P(y) = exp^{(3.103)} / 1 + exp^{(3.103)}$; $P(y) = 0.7563$ or 75.6%.

Term	Estimate	SE	z	P
Intercept	3.531	0.6119	5.770	≤ 0.001
Wind Speed[1]	−0.1599	0.0293	−5.453	≤ 0.001

[1] km/hr

(Chi-squared test $\chi^2_1 = 13.33$, $P \leq 0.001$). This is likely a result of the larger group sizes observed in the spring (average 3.5; fall average 2.0). In the fall, an eagle was 2.17-times more likely to migrate in a cluster in the afternoon (noon-3pm) compared to the morning (9-noon; GLM $\chi^2_1 = 4.559$, $P = 0.033$), and was 5% less likely to migrate as a cluster with each unit increase in wind speed (GLM $\chi^2_1 = 12.19$, $P \leq 0.001$; ANOVA $\chi^2_2 = 13.01$, $P \leq 0.001$; Table 2.5).

Although clustering was more commonly observed in the spring (making up approximately 50% of all observed individuals compared to 25% in the fall) no explanatory weather variable was identified in the logistic regression model.

2.3.3 Factors Associated with Entering the Risk-Zone

Here I address golden eagle movement patterns in relation to flight tracks that entered the 100 m risk-zone area of the proposed turbine string. I found the number of birds that entered into the risk-zone in the fall increased by 16% with increasing hourly passage rates (ZINB $z = 3.945$, $P \leq 0.001$; LR-test $\chi^2_1 = 78.13$, $P \leq 0.001$; Table 2.6; Figure 2.6a). Hourly passage was also found to significantly contribute to the excess of zeros in the model; the probability of detecting a false zero decreased by 1% with an increase in hourly passage ($z = -2.213$, $P = 0.027$). In the presence of hourly passage no weather variable contributed significantly to the model, and I did not detect a difference between years.

Similar to the fall, I found that the number of golden eagles that entered into the risk-zone increased by 27% with increasing hourly passage (ZINB $z = 2.890$, $P = 0.004$; LR-test

Table 2.5: Summary of logistic regression examining association of temporal and environmental variables on aggregated passage golden eagles in the fall at North Dokie between 13 September and 24 October, 2009. Response is solitary (0) versus aggregated (1) movement. For example, to estimate the probability of an eagle migrating in close proximity to another eagle (aggregated as opposed to migrating away from other eagles) in the afternoon and at a wind speed of 15km/hr, $log(y) = -1.180 + 1.155 - 0.048 \times 15$; $log(y) = -0.745$; $P(y) = exp^{(-0.745)} / 1 + exp^{(-0.745)}$; $P(y) = 0.3219$ or 32.2%.

Term	Estimate	SE	z	P
Intercept	−1.180	0.435	−2.715	0.007
Time PM	1.155	0.400	2.887	0.004
Wind Speed[1]	−0.048	0.015	−3.251	0.001

[1] km/hr

Table 2.6: Summary of multivariate zero-inflated negative binomial regression examining the association of temporal and environmental variables on hourly entries into the risk-zone in the fall at North Dokie between 13 September and 24 October, 2009. Response is number of eagles that entered the risk-zone per hour. For example, to estimate the number of hourly eagle entries into the risk-zone at an hourly passage rate of 15 eagles, $log(y) = -0.919 + 0.145 \times 15$; $log(y) = 1.256$; $y = exp^{(1.256)}$; $y = 3.5$ eagles per hour.

Term	Estimate	SE	z	P
Intercept	−0.919	0.276	−3.326	≤ 0.001
Hourly Passage	0.145	0.037	3.945	≤ 0.001

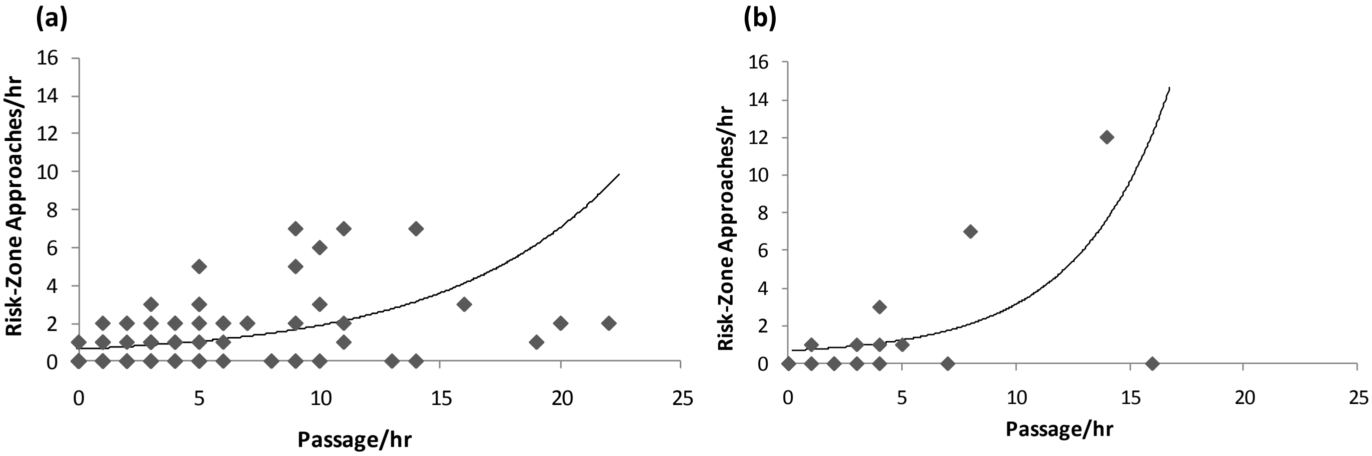

Figure 2.6 Number of golden eagles per hour that entered into the risk-zone versus the number of eagles that passed through the site per hour for **(a)**, fall 2008 and 2009 (*n*=283), and **(b)**, spring 2010 (*n*=84). Solid line represents predicted values based on a zero-inflated negative binomial model.

$\chi^2_1 = 8.424$, $P = 0.014$; Table 2.7; Figure 2.6b). Here, passage rates did not contribute to excess zeros in the response variable ($z = -0.26$, $P = 0.795$).

A. Associations with Route and Aggregated Passage on Entering the Risk-Zone.

Although most of the passage through the site occurred along the west side of the study ridge in the fall, I found entries into the risk-zone occurred more often than expected for birds that took the eastern route in 2009 (Chi-squared test $\chi^2_1 = 6.34$, $P = 0.012$), but was not significant in 2008 ($\chi^2_1 = 1.45$, $P = 0.229$; Figure 2.7). In the spring, I also found the proportion of golden eagle entries into the risk-zone was greater for the eastern route compared to the western route ($\chi^2_1 = 8.6$, $P = 0.003$; Figure 2.7).

In the spring of 2010, the proportion of passage to the east of the study ridge was higher than passage to the west ($n = 73$ and 29 respectively). In this case, however, the use of the eastern route occurred when the winds were weak and likely below turbine cut-in speed (14 km/hr; Figure 2.5b).

A greater proportion of birds entered the risk-zone in the spring compared to the fall (Chi-squared test $\chi^2_1 = 12.01$, $P \leq 0.001$). Whether a bird migrated close to other birds, however, did not affect the probability of entering the risk-zone in either season (fall $\chi^2_1 = 0.067$, $P = 0.795$; spring $\chi^2_1 = 0.831$, $P = 0.362$).

Table 2.7: Summary of multivariate regression examining association of temporal and environmental variables on hourly entries into the risk-zone in the spring at North Dokie between 17−28 March, 2010. Response is number of eagles that entered the risk-zone per hour. For example, to estimate the number of hourly eagle entries into the risk-zone at an hourly passage rate of 15 eagles, $log(y) = -1.387 + 0.240 \times 15$; $log(y) = 2.213$; $y = exp^{(2.213)}$; $y = 9.1$ eagles per hour.

Term	Estimate	SE	z	P
Intercept	−1.387	0.568	−2.441	0.015
Hourly Passage	0.240	0.083	2.890	0.004

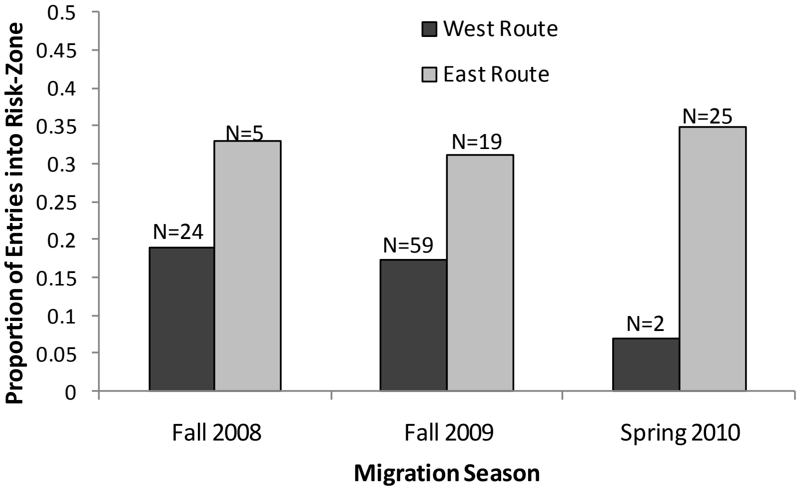

Figure 2.7 Proportion of golden eagle flight tracks that entered the risk-zone by migratory route (east versus west) for the fall of 2008, 2009, and spring of 2010 (total *n*=136, 402, and 101 respectively). East and west route signify the route taken in relation to the study ridge, Johnson Col. Individuals with unknown route not included (fall 2008 *n*=3; fall 2009 *n*=15; spring 2010 *n*=3).

2.4 Discussion

My main findings suggest that during migration golden eagles moved through the region under a variety of weather conditions, which highlights seasonality (i.e. the month of October in the fall and mid-March in the spring) as a leading association with migration though the area. For monitoring purposes, seasonality is a reliable and important variable in predicting general movement through the site. Eagle behaviour in terms of hourly passage rates and routes taken through the study area, however, were associated with variation in local weather conditions. Similar to findings by Yates et al. (2001), golden eagles appeared to opportunistically use the conditions available so long as visibility was not hampered by dense fog or precipitation. Hourly entries into the risk-zone were found to be associated with passage rates in both seasons and across years. In addition, eagles were two to three times more likely to enter the risk-zone when they used the eastern compared to the western route, however, the number of birds that used the eastern route in the fall was low. The greater use of the western route in the fall thus represented a larger number of entries into the risk-zone despite being proportionally smaller compared to the eastern route. Weak wind conditions were associated with increased aggregated passage in the fall and the use of the eastern route in the spring. Although weak wind conditions are associated with low risk of collision, our findings are based on wind speeds collected at ground level and are based on only one outbound and return migration season.

2.4.1 Migration Patterns

Heavier golden eagle passage through the site in the fall was likely due to the composition of mixed-age birds compared to mostly adult birds in the spring (Yates et al. 2001, Sherrington 2003). In addition to differences in age composition, lower spring counts compared to the fall have also been noted elsewhere in the Front Range, and are speculated to be a result of greater golden eagle passage in the foothills further to the east (Yates et al. 2001, Sherrington 2003). In addition to the difficulty of identifying golden eagle age-classes due to an overlap in identifying plumage features, age identification required a relatively close and good view of the bird. For these reasons, the large proportion of unknown-age individuals in the fall dataset does not allow for an age-structure comparison between seasons, which may have explained differences in movement patterns between seasons.

Similar to other watch locations (Yates et al. 2001, Sherrington 2003), hourly passage rates in the fall were highly tied to season, with peak migrations occurring between early- to mid-October and mid- to late-March at the Dokie site. In addition to time of year, I also identified weather variables, mainly wind speed and temperature, to be associated with passage through the site in the fall. Increased hourly passage with increasing temperature and in the hours after midday, likely highlighted the presence of favourable conditions for lift created by thermals. Increased passage with increasing wind speed is likely associated with increased lift through upward deflection from mountain slopes. Although I did not identify associations between hourly passage and barometric pressure in the fall, other studies on soaring raptors have. For example, some studies found daily raptor passage to be associated with the passage of cold fronts (Hall et al. 1992, Allen et al. 1996, Omland and Hoffman

1996), or hourly passage to be explained by a drop in barometric pressure (Millsap and Zook 1983, Thomas 2008). Others, however, found increased hourly passage to be associated with an increase in pressure (Allen et al. 1996, Yates et al. 2001).The absence of barometric pressure in my fall passage model could possibly be explained by the presence of wind speed. The positive relationship with passage and wind speed may be indirectly related to a change in regional barometric pressure since greater wind speeds are associated with the passage of cold front systems (Whiteman 2000). The lack of associating a single variable with hourly passage likely reflects the ability of eagles to utilise numerous sources of lift available in the complex terrain used during migration (Yates et al. 2001).

No patterns were identified that explained passage rates in the spring of 2010; however, the lack of significant variables may reflect the differing selective pressures between seasons. For example, there may be greater temporal pressure on adults to reach breeding versus wintering grounds, thus forcing birds to migrate under more varied, and unfavourable, conditions in the spring (Alerstam and Lindstrom 1990). The lack of explanatory variables may also be due to the shorter migration period in the spring compared to the fall (Sherrington 2003, McIntyre and Collopy 2006). Additional years of sampling may indicate that spring passage rates are positively correlated with date.

In addition to time of year, days with the highest passage (> 20 birds) were also observed under SW winds. Other than these two variables, the identification of specific conditions under which golden eagles migrated in the fall is difficult to identify due to the opportunistic ability of eagles to utilize a variety of weather conditions. For example, high daily passage was observed in both weak and strong SW wind conditions during peak migration, which reduces the ability to accurately predict days of high passage based on wind speed alone. This is supported by Thorup et al.'s (2006a) study with satellite-tagged ospreys, in which they did not detect a preference for wind speeds or direction during outbound and return migrations. Yates et al. (2001) in the eastern Rocky Mountains of Montana also found golden eagle migration to be opportunistic, and occurred under different combinations of weather conditions. Although stronger SW winds would provide lift by deflection along the western slopes of Johnson Col, golden eagles were able to utilize other sources of lift during peaks dates of migration. As long as visibility was not hampered by heavy precipitation or fog, migratory golden eagles can use deflected winds from mountain slopes to gain lift by soaring, and circle soared on rising thermals when the winds are weak (Yates et al. 2001, Mandel et al. 2008). Hence, the greater use of SW winds in the fall likely reflects the availability of good lift conditions through the Dokie site.

The ability to migrate under different conditions also enables raptors to migrate around local weather systems. At the Dokie site most of the low cloud originates from the mountains to the west, thereby forcing eagles to migrate further to the east (J.E. Bradley, UNBC, personal observation). In addition, the high-elevation terrain of the mountains compared to the foothills means that low cloud ceilings can completely obscure the mountain terrain. This can vary golden eagle passage through the site on an annual basis depending on the frequency and duration of poor weather at the site and in the region. In other words, weather systems can displace eagles from their migration route should the low-visibility weather system be localized (i.e. in the mountains but not in the foothills), or halt migration altogether should a large weather system obscure visibility over a region. Since the occurrence of peak movement can be altered by weather systems within a season, wind farm managers interested in applying preventative mitigation measures should consider a larger time frame other than peak migration dates to account for this within year variability (Leshem and Yom-Tov 1996, Bildstein 2006a).

2.4.2 Entries into the Risk-Zone

In both seasons, hourly passage rates through the site were the only variable correlated with the frequency of entries into the risk-zone. As hourly passage rates increased, hourly entries into the risk-zone was 11% greater in the spring compared to the fall. Approximately 20% of golden eagles observed within the study area in the fall entered the risk-zone, compared with 27% in the spring. However, since my definition of entering the risk-zone includes all heights, including those above rotor-swept height and thus not at risk of collision with turbines, further research is needed into the factors associated with low flight altitudes.

Given that eagle entries into the risk-zone were positively related to hourly abundance, the monitoring of passage rates will continue to be an important component of post-construction monitoring. However, caution should be used at the upper range of the datasets (> 15 birds/hr in the fall; > 10 birds/hr in the spring) due to few data points. This was particularly evident for the fall data, which suggested a positive trend at the upper values when none existed (Figure 2.6). Nevertheless, throughout October, and from mid-March to early-April, hourly entries into the risk-zone will likely increase with conditions that are favourable for lift; with increasing wind speed, temperature, and in the hours after midday.

2.4.3 Local Migration Routes and Aggregated Passage

Despite the greater prevalence, and thus greater potential, for bird crossings over the ridge-top when travelling along the western route under SW prevailing winds, I found the proportion of entries into the turbine risk-zone to be higher for individuals that travelled along the eastern route. It is important to note, however, that passage rates in the fall are much greater, and thus approaches from the western migration route were overall more numerous despite being proportionally low.

The use of the eastern route in the spring was negatively correlated with increasing wind speed, likely resulting in low risk because the turbines would have been idle. However, this is only based on one season and is also informed by weather data collected at ground level, which underestimates wind speed, since speed increases with increasing altitude. By comparison, the use of the eastern route in the fall increased by a few birds under head-wind conditions but did not vary from the western route with wind speed. An increased frequency of head-wind conditions in the fall may result in an increased use of the eastern route and should be considered in post-construction monitoring.

The seasonal differences between the routes used through the site also suggest that local movements change with the prevalence of weather variables that differ across seasons. The use of the eastern route in the spring is likely a result of the higher proportion of days with weak northeast winds compared to the fall. The eastern route overlies a valley at higher elevation than the deep river valley located to the west of the study ridge. Under low wind conditions in the spring, possibly when updrafts are less numerous, birds may be moving over higher ground to avoid losing altitude. When moving northward, eagles have to cross a deep valley before reaching the Dokie ridges. After crossing what is known to be a downdraft area (Ainsley, B., Alexander, N., Johnston, N., Bradley, J., Pomeroy, A., Otter, K., and Jackson, P., UNBC, unpublished data), eagles may be choosing the eastern route to gain altitude over higher ground. By comparison, the prevailing southwest winds in the fall, which is also the source of the strongest winds, provides lift through deflection along the western slopes of Johnson Col (Ainsley, B., Alexander, N., Johnston, N., Bradley, J., Pomeroy, A., Otter, K., and Jackson, P., UNBC, unpublished data). The presence of updrafts along the western route most likely explains the heavy use of this route in the fall compared to the spring when the winds were more often weak or originating from the northeast.

Furthermore, the increased probability that an eagle entered the risk-zone from the eastern route may be related to the narrower corridor of this route compared to the west, thereby increasing the likelihood that a bird will leave the constricted area and thus enter the risk-zone. More research is needed in the spring during post-construction to document flight behaviours under stronger southwest winds when the turbines will be spinning, especially as birds have been observed to travel in larger groups during this season. In addition, flight behaviours need to be contrasted to wind data collected closer to turbine height to better assess risk.

Although golden eagles are considered to be solitary migrants (Omland and Hoffman 1996), I observed clustered passage in both seasons; however, group size was larger in the spring and included a greater proportion of the total individuals observed (50% of all birds detected in the spring versus 25% in the fall). In the fall, the greater occurrence of aggregated passage in the afternoon and at lower wind speeds may be associated with the greater prevalence of thermal availability in the afternoon, which can slow down migration speed and aggregate birds (Spaar and Bruderer 1997, Klaassen et al. 2008). By comparison, no spring weather variables were identified to contribute to the clustered passage of birds. Here, aggregated passage may be in response to the more frequent occurrence of days with weak winds, or possibly due to more frequent migration delays due to large-scale weather systems, which further aggregates birds. In both cases, it is likely that aggregated passage may occur for the most part when wind speeds are below turbine cut-in speed (14 km/hr), although this needs to be verified with wind speed data collected at turbine height (80m). Lastly, although aggregated migration patterns were more prominent in the spring and were comprised of larger group sizes, this did not appear to be associated with the proportion of entries into the turbine risk-zone within a season.

The use of flight route analysis as used in this study may be useful at the planning stage of a wind farm development to identify areas of raptor use. My results indicate that ridges adjacent to deep valleys that also receive prevailing SW winds from the mountain range are used as a main corridor of golden eagle passage in the fall. More information is needed to document spring migration routes. Little information exists for proposed developments oriented perpendicular to the main lines of migration. For wind energy developments parallel to the main lines of golden eagle migration, micro-siting turbines away from the main slopes used during migration has proven to reduce collision impacts and should be part of the planning phase (Smallwood and Thelander 2005, Drewitt and Langston 2008, Whitfield 2009).

2.5 Conclusion

In both migration seasons, the number of golden eagles that entered the risk-zone – although proportionally low – increased with increasing passage rates through the site. Should mitigation measures be needed, I recommend that they be focused on the periods of condensed passage (the month of October in the fall and mid-March to early-April in the spring). Despite our short sampling period in the spring, it appears that golden eagle migration under northeast winds poses little concern for collisions with turbines since these winds have been found to be weak and below turbine cut-in speed. However, additional surveys, in addition to wind speed data collected at turbine height, are needed to confirm this trend. Post-construction monitoring should continue to document passage under southwest winds in both migration seasons when the turbines will be spinning. In particular, further attention is needed to document the use of the eastern route under head-wind conditions in the fall. Research into the factors that were associated with low flight altitudes at wind speeds above turbine cut-in speed are discussed in chapter 3.

CHAPTER THREE – THE ASSOCIATIONS BETWEEN WIND AND TOPOGRAPHY ON GOLDEN EAGLE FLIGHT ALTITUDE AT A PRE-OPERATIONAL WIND FARM IN THE CANADIAN ROCKIES

3.0 Abstract

The potential for wind energy developments in the Hart Range of the Rocky Mountains of northeast British Columbia, Canada, has raised questions regarding collision risk impacts to migratory golden eagles. The Dokie Wind Energy Project is the first for the region that is situated along a significant golden eagle migration corridor. I surveyed most of the fall migration period in the fall of 2009, and peak migration in the spring of 2010, to assess the factors associated with golden eagle heights as they entered a pre-defined area around the proposed string of turbines (also the ridge-top). Fall approach heights (above ground level) increased with increasing wind speed, were lower under head-winds compared to cross-winds, were lower over sloped compared to flat areas of the ridge-top topography, and decreased as the season progressed. Spring heights were positively correlated with wind speed and were higher in the hours immediately after midday. Most low entries (≤ 150 m) in the spring were under weak wind conditions when the turbines would likely have been inactive; however, additional years of research are needed. Low entries into the turbine string in the fall occurred at greater wind speeds, mostly under head-wind conditions and over sloped or ridge-end topography. Although avoidance rates are likely to be high post-construction, a cumulative impact assessment for the region is needed in order to take into account the potential synergistic effects of small impacts on eagles due to the growing number of new wind energy developments along this migration corridor.

3.1 Introduction

Birds of prey have been identified as being more vulnerable to collisions with wind turbines than other bird species (Erickson et al. 2001, de Lucas et al. 2004, Desholm 2009, Whitfield 2009). Where raptor collisions have occurred at wind farm developments, findings common among studies suggest that mortality events are aggregated by season, spatial location (some turbines killed more birds than others), and by taxonomic group (some species are affected more than others); a result of species-specific behavioural responses to regional wind – topography interactions (Hunt 1995, Barrios and Rodriguez 2004, Smallwood 2007, de Lucas et al. 2008).

Collision risk may be enhanced in raptors because this group relies heavily on energy-efficient soaring flight, which in turn is dependent upon interactions between wind and topography to generate lift (Alerstam and Lindstrom 1990, Yosef 2009). The reliance on wind for lift, especially for heavy-bodied species such as golden eagles (*Aquila chrysaetos*), potentially places them at greater risk of colliding with man-made structures under conditions not favourable for gaining altitude (Barrios and Rodriguez 2004, Smallwood et al. 2009). For example, griffon vulture (*Gyps fulvus*) mortality events were associated with weak wind conditions over gentle slopes. Under these conditions birds were forced to gain lift by slowly circle-soaring on thermals (rising warm air), often in airspace that overlapped with turbine locations (Barrios and Rodriguez 2004). Therefore, the documentation of species-specific flight behaviour is an important component in the assessment of mortality events at wind farm developments (Hunt 1995, Barrios and Rodriguez 2004, Smallwood 2007, de Lucas et al. 2008).

In addition to thermals, horizontal winds can also help to reduce energy costs; cross-winds can increase lift when deflected upward along mountain slopes, whereas horizontal tail-winds can reduce drag (Bildstein 2006a). Differences in drag resulting from different wind directions can also influence the altitude at which soaring migrants fly (Alerstam and Lindstrom 1990). Since wind speed increases with increasing altitude, migration altitudes are generally lower under unfavourable head-winds in an effort to reduce drag, and higher under tail-winds when the conditions are favourable (Alerstam 1990). Such patterns have been observed in migrating sharp-shinned hawks (*Accipiter striatus*) in eastern North America (Mueller and Berger 1967a). The reliance on topography-induced lift during migration potentially places migratory golden eagles at greater risk of collision mortality with wind farms in mountainous regions when conditions are not favourable for lift.

To date most collision mortality events have been documented with resident and overwintering species, although few developments are located within the direct line of a raptor migration route (Barrios and Rodriguez 2004, Lekuona and Ursua 2007, de Lucas et al. 2008). In addition, avoidance behaviour studies for migratory raptors are currently lacking (Band et al. 2007, Drewitt and Langston 2008). One exception involves research at a wind farm in Montana where migratory golden eagles were tracked (Whitfield 2009). Results indicated lower post-construction mortality than that predicted by a risk model based on pre-construction flight patterns, which suggests the ability to detect and avoid structures (Band et al. 2007, Whitfield 2009). However, the results of this study are based on carcass searching, which does not differentiate between the displacement of eagles from the site from close-proximity avoidance manoeuvres to turbines (Whitfield 2009). Despite the ability of eagles to see and avoid turbines, the identification of conditions associated with low flight altitudes at proposed wind farms may assist in informing managers interested in the application of mitigation techniques post-construction.

To date little is known regarding the behavioural responses of migratory golden eagles to wind farm developments, particularly in mountainous regions. For this reason, concerns arise when wind farm developments are introduced to narrow migration corridors used by golden eagles in mountainous regions (de Lucas et al. 2004, Katzner et al. 2006). Few studies assess risk based on observed flight behaviour, and most studies in North America solely involve carcass searches around the turbine base (Drewitt and Langston 2008, Smallwood et al. 2010). The mainly European studies that broadened their risk assessment methodologies to include other sampling methods (see Barrios and Rodriguez 2004, Lekuona and Ursua 2007, Smallwood et al. 2009) found species-specific differences in fatality events, which were not correlated with species abundance (de Lucas et al. 2008). Thus, in addition to understanding the interactions of weather conditions and topography on flight behaviour, it is imperative that risk assessments occur at the species level while incorporating a seasonal component (i.e. migration, breeding or overwintering).

In North America, golden eagles migrate in concentration along relatively narrow corridors of the major mountain ranges, in particular along the eastern Rocky Mountains (Sherrington 2003, McIntyre et al. 2008). The thrust-fault formation of the Rocky Mountains, particularly in Canada, results in ridges and foothills directed in a consistent southeast to northwest direction (Whiteman 2000), which in many areas along its length, is perpendicular to the prevailing winds and creates strong and consistent updrafts for migrants. The Hart

Range of the northern British Columbia Rockies, Canada, has consistently strong winds which have been identified by the BC government as favourable for wind farm development (Larson 2010). Also called the Front Range in Alberta and the USA, an estimated quarter of the eagle migration observed in southern Alberta passes though the Hart Range each fall (1000+ individuals) (Sherrington 2003). The first commercial wind installation under construction in the Hart Range is located on the North Dokie Ridges which are characteristic in both topographic orientation and exposure to weather patterns, including wind strength and direction, for the Range (Yates et al. 2001). This is the first Canadian study to document golden eagle flight altitudes in proximity to a pre-operational wind farm development in the Rocky Mountains along a significant migration route.

My study addresses these issues by focusing on the topographic and weather features associated with the altitude of golden eagle flights among individuals entering a ridge-top risk-zone, or the proposed string of turbines, over a fall and spring migration season. The research objectives for this study are first, to determine if weather, such as wind direction, wind speed, and temperature, flight behaviour (straight-line soaring, circle-soaring and powered flight) and ridge-top topography are associated with the heights of golden eagles over ridgelines; and second, if these same factors are associated with movement within the rotor-swept height of proposed turbines (≤ 150 m) and how these vary with wind speeds that would influence whether or not the turbine blades would be spinning (cut-in speed of > 14 km/hr or 4 m/s). Although the data are focused on behaviour associated with a single wind development, future developments in the region would be situated along topographically similar ridges experiencing similar weather patterns. My results could be used to inform future research regarding turbine and wind farm sitting decisions in the Hart Region, and as a baseline for post-construction comparisons.

3.2 Methods

3.2.1 Study Area and Sampling Regime

Located in the Peace River Regional District of British Columbia, Canada, the Dokie Wind Energy Project (55^{o}46’28.00”N, 122^{o}16’48.75”W) is only the second wind facility in the Province, and the first situated along a significant golden eagle migration route in Hart Range of the eastern Rocky Mountains (Figure 1.1).

The 144 MW project on the Dokie site consists of two ridges, Johnson Ridge (elevation 1400 m) and Johnson Col (elevation 1200 m) that run nearly parallel in a NE-SW direction (Figure 1.2). The study ridge is the smaller and more western of the two ridges, Johnson Col that runs in a more N-S direction and meets Johnson Ridge at the north end by a `col’ or low point between the ridges. Although the larger ridge, named Johnson Ridge, is part of the same project, it has proportionally low passage of birds during the fall (Pomeroy et al. 2009). Analysis of ridge-top approaching behaviour was restricted to the Johnson Col ridgeline, as too few crossings (< 5) were observed on Johnson Ridge to draw conclusions about general patterns of movement in either season (Chapter 2). Approximately 4.5 kilometres long, Johnson Col (herein referred to as the study ridge) will hold 15 of the 48 3-MW, 127 metre tall Vestas turbines that will be operating in early 2011. My study was conducted in the years following road and initial pad construction, but there was no active construction during the sampling period due to a change in ownership of the development.

Three widely-spaced turbines (1.5 km apart) had been erected on the study ridge but were not operational. The upper third of the ridgeline had no proposed turbines (Figure 1.2), and was sampled to provide additional information regarding topography use of the entire ridge, and could serve as a potential control area for post-construction monitoring. I considered the construction phase as essentially underdeveloped for the purposes of this study due to the few widely-spaced idle turbines and research indicates that birds do not exhibit avoidance to idle standing structures (de Lucas et al. 2007).

Previous field sampling in 2007 and 2008 also identified fall migration as having the greatest passage of eagles (Pomeroy et al. 2009), and thus our effort aimed to cover most of the fall migration season in 2009. Golden eagle observations during fall migration took place between the 13 September and the 24 October 2009. Of these 42 days in the fall, 33 days were sampled under weather conditions of sufficient visibility between the hours 900 and 1530 Pacific Daylight Time, for a total of 181 hours. Spring surveys took place between 17 and 28 March 2010 for a total of 12 days (72 hours). Although effort was considerably shorter in the spring, I managed to catch the peak movement of adult eagles. Our sampling methods followed that developed by the consulting firm Stantec Inc. (formerly Jacques-Whitford AXYS) and the University of Northern BC as part of the Environmental Assessment used in 2007–2008, although a few modifications were implemented to increase the accuracy of distance estimations and flight altitudes. For this reason, the analysis presented here is based on the 2009 fall and 2010 spring datasets, taken from three observation locations, two on Johnson Col and one on Johnson Ridge.

Observation sites were chosen based on the availability of good vantage points (i.e. radii of 2 km); this required a clear view of the study ridge top (Johnson Col) in addition to valley bottoms. Each site was surveyed for three hours, and a total of two sites were surveyed each day, weather or visibility permitting. The sampling regime accounted for time of day so that sites were sampled during the two different time blocks (am and pm) to account for variation in abundance due to time. The site on Johnson Ridge (JR27) provided a view of the northern half of the study ridge and overlapped with the more northern site on Johnson Col (JC11 fall; JC15 spring). The southern site (JC02) covered the southern half of the study ridge. Observations from JR27 were directed towards the study ridge, although birds travelling along the west side of Johnson Ridge (east of the study ridge) were also documented. The northern JC11 site (JC15 in the spring) provided closer and more accurate distance estimations of eagle movements in relation to ridge-top, while the JR27 location provided a different vantage of the same area. The fact that the northern portion of the study ridge has more complex topography meant that an additional observation location ensured that all migration paths were documented. Therefore, overlap did occur in the northern section in both seasons; however, minimal overlap between the southern and northern sections of the study ridge was achieved. For this reason I divided the fall sampling effort covering the northern portion of the study ridge between the two observation locations (JC11 [57 hours] and JR27 [38 hours]) to result in an effort of that equalled the southern portion (JC02 [86 hours]; Figure 1.2).

Lastly, the sites covered a variety of ridge-top topographical features such as ridge slopes (ridge ends and low points), and flat areas to help identify areas that may pose increased risk of collision with turbines (Figures 3.1 & 3.2).

3.2.2. Data Collection

For each golden eagle detected, three-dimensional points of their locations in space were collected using a compass for bearing, a clinometer for height angle relative to the observer, and visual estimations of horizontal distance to the bird from the observer. The same observer (James E. Bradley) estimated horizontal distances to eagles in both seasons to reduce observer-related error. Horizontal distances to eagles were estimated with the aid of known-distance landscape features (i.e. utility poles, idle turbines, and clear cuts) obtained from satellite imagery maps with known distance rings. Although birds were tracked up to 4 km away, only eagle movements within 2 km from an observation site are included in this analysis. This distance is within the range that provides both high certainty of visually detecting eagles and more accurate visual distance estimations to targets in relation to visual landmarks. From each observation site, six to eight proposed turbines and two idle standing turbines fell within a 2 km radius.

For birds detected outside of the study area, i.e. greater than 2 km away, minimal information (one-to-two data points) was recorded in order to keep our focus on areas surrounding the ridge-top. For birds that flew at distances of 2–4 kilometres away and were heading away or maintained their distance from the study ridge, data points were collected two-to-three times versus six-to-ten times for birds that came within 2 km and approached the ridge-top, thereby prioritizing birds that were exhibiting potentially higher-

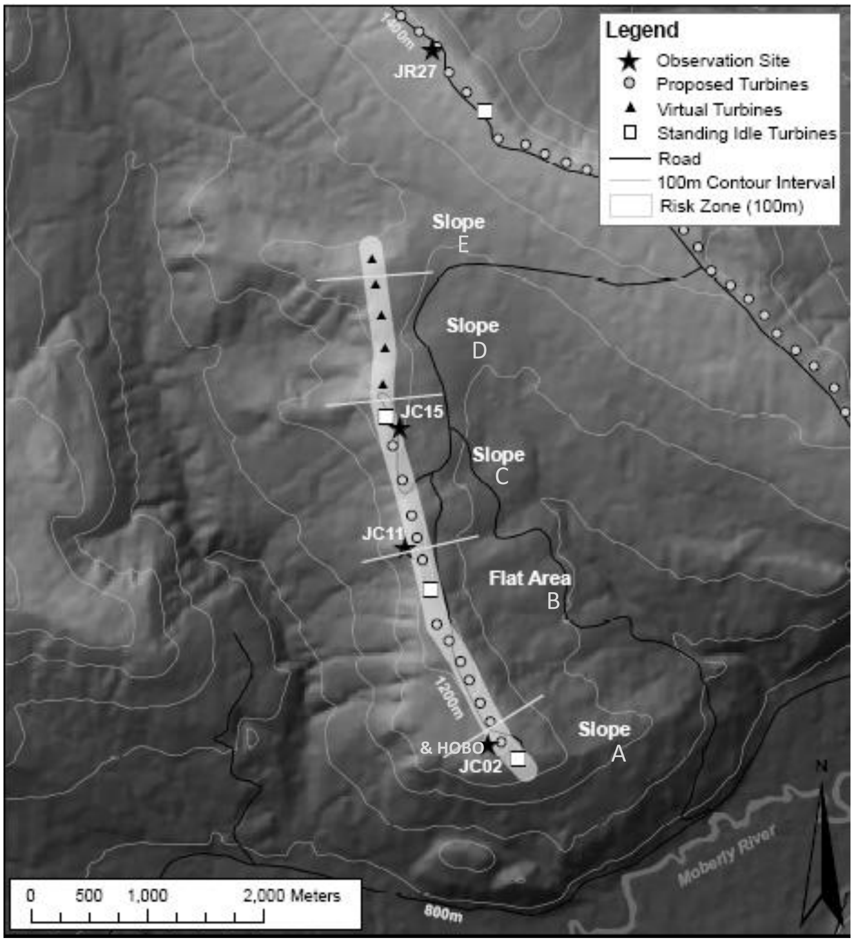

Figure 3.1 Study ridge (Johnson Col) topography type based on ridge-top grade: slopes =18–24%, flat area=1–2%. Letters A-E represents the various sections of the ridge.

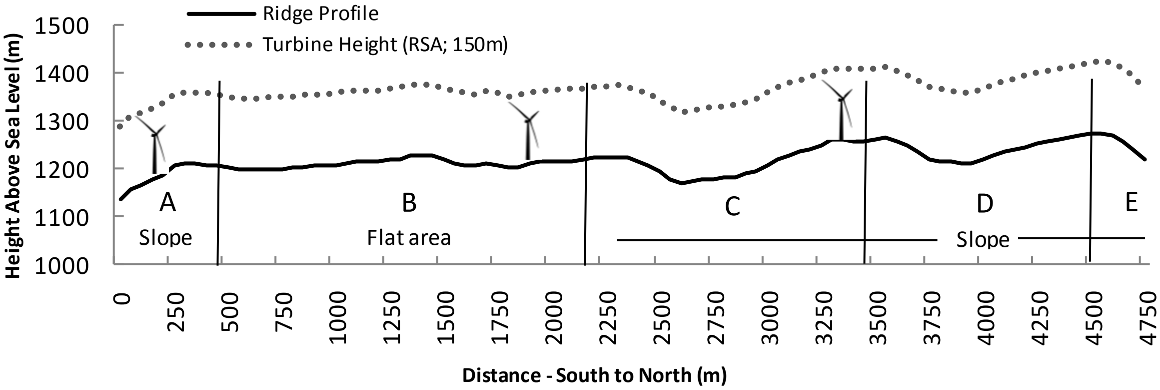

Figure 3.2 Study ridge (Johnson Col) profile, including ridge-top topography classifications and standing idle turbine locations, from South to North. Vertical exaggeration is 2. Letters A-E represents the various sections of the ridge as shown in Figure 3.1.

risk flight behaviour. A minimum of six points were collected for birds that approached the study ridge; where possible, points were collected upon first sight of the bird and subsequently for any changes in height, altitude or flight behaviour along the route. Additional points were taken as the bird approached and departed the ridge top area.

Flight behaviours noted included: soaring flight (non-flapping movement such as updraft soaring along a straight line, or kiting (a sideways movement in relation to the direction the bird is facing), circle-soaring (ascending on a rising on a thermal of air, or circle-soaring on deflected slope updrafts), and powered flight (flapping flight). The difficulty in age-group identification due to the overlap in plumage appearances at the different stages of development (juvenile, sub-adult and adult) resulted in a classification of age-appearance categories: adult-looking, juvenile-looking, and unknown age. In addition, for birds that crossed over the ridge top, a visual estimate of height category (above or below turbine height; 150 m) was made in the field for comparison with information extracted using Geographic Information System (see below).

Weather data were collected at 2 m above ground level every five minutes using an Onset™ (Onset, Bourne, MA, USA) HOBO weather station located at the south end of the study ridge (JC02; Figure 3.1). HOBO weather parameters of interest include wind speed (km/hr), wind direction (degrees), and temperature (^{o}C). Hourly field estimations for cloud cover (%), cloud ceiling height (low [≤ 2000 m], medium [2000–4000 m] and high [≥ 4000 m]) and cloud type were recorded manually.

3.2.3. Data Preparation

Trigonometric calculations were used to determine bird location, incorporating the observer's UTM coordinates and elevation in addition to distance and angle measurements taken in the field. The equations for bird location and altitude are as follows:

Bird Easting (X) = Observer UTM E + (distance (m) (SIN(radians(bearing angle)))),

Bird Northing (Y) = Observer UTM N + (distance (m) (COS(radians(bearing angle)))), and

Bird Altitude (Z) = Observer Elevation + (Distance (m) × (clinometer angle (%)/100)).

For each three-dimensional data point collected in the field, a spatial point was created in ArcGIS (version 9.3) accompanied with an altitude (above sea level). All GIS applications included a digital elevation model with a 50 metre by 50 metre resolution as the base layer. To create three-dimensional flight tracks, I converted golden eagle location points into three-dimensions using spatial analyst based upon the bird altitude data calculated from field measurements. Points were converted to three-dimensional tracks using ET Geo wizard (ET Spatial Techniques, Pretoria, South Africa, www.ian-ko.com). The result was a layer of individual three-dimensional tracks with a flight direction associated with each track.

The three-dimensional flight tracks were superimposed on top of a base map in GIS for visual and computational data extraction. Examples of data extracted from GIS includes: the number of entries into the risk-zone, the topographic features used while entering the risk-zone, and the corresponding flight altitudes for each entry. The extraction of spatial data using ArcGIS was exported for statistical computation.

To extract information for flight heights above the ridge-top, heights were obtained from flight tracks at a distance of 100 metres (m) from the string of turbines. Herein called the *risk-zone*, this 100 m buffer area represents a continuous area along the string of proposed turbines (and ridge top; Figure 1.2). Entries into the risk-zone were then categorized based on height. The rotor-swept height (RSH) refers to the height that will be occupied by the turbine blades once the turbines are erected and spinning. Here I have conservatively assigned the RSH at 150 m above ground level (agl) within the risk-zone (see Figure 3.2). Standing 80 m tall to the nacelle with 47 m blades, the height of a turbine is 127 m tall and the lower blade sweep reaches to 33 m above the ground. In actual space, the risk-zone represents a 53 m lateral buffer on each side of the 47 m turbine blades in addition to the space between turbines (150 m). Risk-zone entries at RSH included any birds that came within 23 m above or 33 m below a turbine blade. The added distance above and below the turbine blades, in addition to an extra 53 m upon approaching a turbine and the space between turbines allows for any errors associated with distance estimations, in addition to what I consider a trajectory of increased risk.

The risk-zone area was created by buffering the centerline at 100 m using the arctoolbox buffer tool, which was then employed to intersect approaching golden eagle flight tracks. I used the intersect tool twice to obtain bird heights; first to break the line, and then again to add a point. Next, I obtained height above sea level by using field calculator and a visual database script called `get Z’ (ET Spatial Techniques, Pretoria, South Africa, www.ian-ko.com). To obtain height (agl) I extracted ‘values to points’ using the arctoolbox extraction tool which resulted in a new geodatabase file that had a new field called rastervalue, which is ground elevation below the new point. To get height (agl), I then subtracted rastervalue from height above sea-level. For birds that entered the risk-zone more than once, only the first point of entry is included. First entry points were then selected for the type of topography based on selected criteria (see below).

Two ridge-top topography types were determined using ArcGIS: ridge slopes (includes ends/knolls and saddles) and flat areas. Topography type was defined by terrain grade; slopes are represented by a grade of 18–24%, and flat areas a grade of 1–2%. The designation of a slope feature included an extension of 200 m beyond the point at which the topography levelled (Figure 3.2). This enabled me to account for any possible variation in the position of the bird over slopes when birds utilized updrafts created by these features. The result places flat areas within the southern portion of the study ridge, and slopes in the north, with the exception of a slope at the south end of the ridge. Slopes accounted for just under twice as much topography length as do flat areas.

Wind direction categories were created to linearize the circular data. In the fall of 2009, golden eagle passage occurred under a southwest wind direction that ranged over 110 degrees, originating from bearings of approximately 170–280 degrees (Figure 2.1b[ii]). For eagles travelling along the steep western North-South oriented slope of Johnson Col, the 110 degree difference in wind direction presents itself either as a head-wind (winds from bearings 136–225 degrees) or a west cross-wind (bearings 226–315 degrees) (Figures 1.2 & 2.1a[i]). Although two cross-wind categories exist (east and west), in the fall only one eagle was documented to have approached the study ridge string of turbines (also ridge-top) under an eastern cross-wind (wind from bearings 46–135 degrees). This lone observation was lumped with tail-winds since the wind direction was on the edge of that division (Figure 2.1a[ii]). In the fall, tail-winds occurred when wind bearings were from 316–45 degrees. Spring wind direction categories are consistent with fall classifications except for the reverse designation of head- and tail-winds.

To further assure our estimations of distance, and thus of bird height, I compared GIS derived classifications of above versus below rotor-swept height against visual classifications noted for birds that crossed the ridge center in the field (73%; $n = 59$). Few discrepancies (5%, $n = 3$) were found for RSH classifications (above or below RSH), thus justifying the utilization of GIS track output for my analysis of risk-zone entry heights. Additionally, the average horizontal distance used for entries into the risk-zone from any observation site was less than 1 km (690 ± 59 m), which is within an accurate distance estimation range. Lastly, I used only one set of highly trained observers throughout the entire study period in both the spring and the fall to remove error due to differences between observers (Band et al. 2007). Hence for what error that does exist, possibly due to parallax, I believe that it is relative in scale, relatively low, and thus suitable for the analysis used in this study.

3.2.4. Statistical Analysis

I used a linear mixed-effects model to determine the temporal and environmental factors associated with golden eagle heights as they entered the risk-zone. I considered the following dependent variables: topography type (slope or flat area); average hourly wind speed (km/hr), wind direction (head-, cross- or tail-wind), temperature (^{o}C), relative humidity (%), cloud cover (%), and cloud ceiling height (low, medium and high); flight behaviour (soaring, thermalling or powered flight); date; hour; and age (adult- or juvenile-looking birds and unknown). I selected fixed-effects using step-wise model selection criteria using Akaike's Information Criterion (AIC) of the final models, and checked the significance of variables as AIC tends to over-fit (Zuur et al. 2009). I compared simple multiple regression models (i.e. no interactions) for ease of biological explanations. Where categorical data contributed significantly in a model, I used means comparisons using Tukey protected t-tests. Model assumptions were verified by visual inspection of residual plots both before and after random effects were assigned. I applied data transformations where linear models deviated from assumptions, mainly equal variance and normality of errors. Observation site was included as a random effect to account for any variation due to differing elevation and sampling effort between sites.

I used Pearson's chi-squared tests, using Yates correction for sample sizes ≤ 5, to compare observed versus expected frequencies for: (1), the number of observed entries into the risk-zone under different wind direction categories, and (2), the number of observed flight behaviour by topography type (sloped versus flat). I used a binomial exact test for comparisons between entries into the risk-zone and topography sections (A-E) that differed in length to account for successes that differed from an equal probability. Statistical significance was determined at $\alpha = 0.05$, and all means reported are accompanied by standard errors. I conducted all analyses using R (version 2.8.1; R Development Core Team, www.r-project.org). Circular wind direction data were graphed and averaged using Oriana, version 2.0 (Kovach Computing Services, Anglesey, Wales, UK).

3.3 Results

3.3.1. Site Passage

In 2009, golden eagle passage within the North Dokie study site peaked on 5 October and again, although to a lesser extent after a period of bad weather, on 22 October, for a total count of 417 birds. Due to the large number of birds of unknown age in the fall, trends in age were not possible to isolate. Spring 2010 counts consisted primarily of adult birds, in addition to some unknown age-classes, and peaked on 24–25 March, for a total count of 104 birds.

Fall passage through North Dokie in 2009 occurred mainly under southwest (SW) prevailing winds (head-winds and cross-winds), which was also the source of the strongest winds - average 14.24 ± 2.65 km/hr (Figure 2.1a[i]). Tail-wind passages, i.e. movement occurring during north-northeast winds, were associated with weak-wind conditions – average 5.21 ± 0.71 km/hr – and were relatively infrequent (5% of total passage versus 95% under SW winds; Figure 2.1a[ii]).

During spring migration in March 2010, a higher proportion of eagle passages (40%) occurred during northeast (NE) winds, which were also weak (5.11 ± 0.56 km/hr) compared to southwest winds (19.64 ± 1.54 km/hr; Figure 2.1b[i]). This resulted in a higher proportion of migration under both low wind speeds and northeast winds compared to the fall (Figure 2.1b[ii]).

Under the prevailing strong SW winds in the fall, the majority of migrating golden eagles were observed along the steep west-facing slopes of the study ridge (Chapter 2; Figure

1.2). The western flank of the study ridge is juxtaposed against a deep valley that receives prevailing southwest winds (arising on the eastern down-slope of the Rocky Mountains).

In the spring, however, birds used the west side of the study ridge more often when the winds were from the southwest, but in this case clearly used the route to the east of the study ridge under weak and northeast winds. Thus, in both seasons birds used lift from the west side of the study ridge more often when the prevailing SW winds were present.

3.3.2. Height Models for Risk-Zone Entry

Fall

Of the 417 golden eagles detected within 2 km centered around the study ridge (study area), approximately 20% ($n = 81$) entered the risk-zone area (100 metres from the turbine string). Using a square-root transformation of height above ground (m) and observation site as a random effect, I found the heights at which migrating golden eagles entered the risk-zone were positively correlated with wind speed ($F_{1,74} = 4.446$, $P = 0.038$), were lower under head-winds compared to cross-winds ($F_{2,74} = 8.402$, $P \leq 0.001$), were lower over sloped topography features compared to flat areas ($F_{1,74} = 8.627$, $P = 0.004$), and decreased as the season progressed ($F_{1,74} = 7.532$, $P = 0.007$; Table 3.1). Using a multiple means comparison with Tukey protected t-tests for differences in heights between wind direction classifications, I found risk-zone entries under head-winds were significantly lower than for cross-winds and tail-winds when wind speed, topography and date were held constant ($|t| = 4.065$, $P \leq 0.001$). The decrease in height within a season could not be accounted for by age structure, although my data is largely comprised of individuals of an unknown age-class.

Table 3.1: Summary of multivariate linear regression examining association of temporal and environmental variables on golden eagle flight heights as they entered the risk-zone in the fall at North Dokie between 13 September and 24 October, 2009. Response is golden eagle height[1] with square-root transformation. For example, to estimate the height of eagles as they entered the risk-zone on October 1 (day 20), at a wind speed of 15 km/hr, under head-winds and over sloped topography, $\sqrt{y} = 20.81 - 0.123 \times 20 + 0.154 \times 15 - 2.818 - 3.481$; $\sqrt{y} = 12.64$; therefore, $y = (12.64)^2 = 160$ m.

Term	Estimate	SE	z	P
Intercept	20.81	1.994	10.43	≤ 0.001
Date[2]	−0.123	0.045	−2.744	0.008
Wind Speed[3]	0.154	0.073	2.108	0.038
Wind Direction Head	−4.535	1.114	−4.071	≤ 0.001
Wind Direction Tail	−2.818	2.389	−1.180	0.242
Topography Sloped	−3.481	1.185	−2.937	0.004

[1] Metres above ground level; [2] Day 1 is 13 September; [3] km/hr

Spring

Of the 104 golden eagles detected, approximately 26% (*n* = 27) entered the risk-zone. Using a log10 transformation on the spring linear model, with observation site as a random effect, I found that heights as eagles entered the risk-zone increased with increasing wind speed ($F_{1,20}$ = 7.101, *P* = 0.016) and during the hours after midday ($F_{5,20}$ = 3.880, *P* = 0.015; Table 3.2). Here all approaches were made over sloped areas and all individuals were adult birds.

3.3.3. Risk-Zone Approaches within RSA height and Above Turbine Cut-In Speed

Based on the model outcomes for each season, I investigated the patterns of heights for birds that entered the risk-zone with respect to the significant variables, accounting for turbine height (150 m) and cut in speed (14 km/hr; 4 m/s).

A. Wind Direction

Fall

Approximately 31% (*n* = 25) of all initial approaches were made below RSH, and of these 40% (*n* = 10) were made above turbine cut-in speed (14 km/hr; Figure 3.3a). As identified in the model above, heights at which golden eagles entered the risk-zone were significantly lower under head-wind conditions (head-wind 170 ± 17.36 m [*n* = 40]; cross-wind 383 ± 32.15 m [*n* = 37]), and accounted for 83% (*n* = 8) of all entries at rotor-swept height (RSH) that were also above turbine cut-in speed (Figure 3.3a). Tail-wind approaches were also low, but were infrequent (94 ± 36.87 m; *n* = 4) and occurred when winds were weak and below turbine cut-in speed. Thus, despite the similar frequency of cross- to head-wind approaches,

Table 3.2: Summary of multivariate linear regression examining the association of temporal and environmental variables on golden eagle flight heights[1] as they entered the risk-zone in the spring at North Dokie between 17−28 March, 2010. Response is golden eagle height as it enters the risk-zone with log10 transformation. For example, to estimate the height of eagles as they entered the risk-zone at 1300 hours and at a wind speed of 5 km/hr, $\log 10(y) = 1.454 + 0.651 + 0.017 \times 5$; $\log 10(y) = 2.19$; therefore, $y = 10^{(2.19)} = 155$ m.

Term	Estimate	SE	z	P
Intercept	1.4541152	0.15454764	9.408848	≤ 0.001
Hour 1200	0.7148504	0.17015164	4.201255	≤ 0.001
Hour 1300	0.6519836	0.16362801	3.984548	≤ 0.001
Hour 1400	0.5736708	0.14412599	3.980342	≤ 0.001
Hour 1500	0.3661007	0.13978960	2.618941	0.2322
Hour 1600	0.1750224	0.08119731	2.155520	0.0442
Wind Speed[2]	0.0171627	0.00644039	2.664850	0.0153

[1] Metres above ground level; [2] km/hr

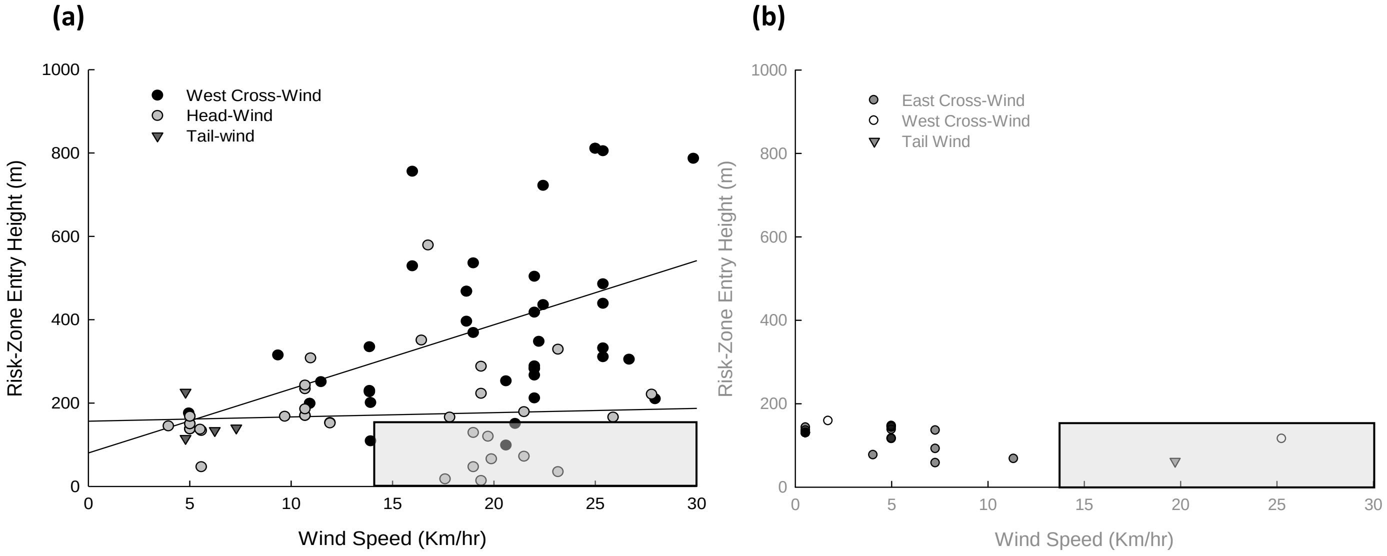

Figure 3.3 Height (m above ground) of golden eagles entering risk-zone versus wind speed (km/hr) by wind direction class for **(a)**, head-, tail- and cross-winds in the fall of 2009 (*n*=40 and 37 respectively; Regression line not shown for tail-winds due to low sample size [*n*=4]), and **(b)**, for east and west cross-winds and tail-winds in the spring of 2010 (*n*=24, 2 and 1 respectively). Grey box represents rotor-swept height (≤ 150 m) above turbine cut-in speed (14 km/hr).

head-wind conditions resulted in a greater proportion of approaches within RSH and at wind speeds above turbine cut-in speed (*n* = 8) compared to cross-wind conditions (*n* = 2; Chi-squared test $\chi^2_2 = 16.0$, $P \leq 0.001$; Figure 3.3a).

Spring

Golden eagle entries into the risk-zone in the spring were lower in height than the fall (120 ± 5 m versus 275 ± 21 m respectively), which resulted in 96% (*n* = 26) of risk-zone entries within RSH. However, despite the high proportion of entries within RSH, only 8% (*n* = 2) occurred at wind speeds above turbine cut-in speed (14 km/hr; Figure 3.3b).

B. Ridge-Top Topography

Fall

While taking into account the length of a topographic feature, I found that golden eagles were more likely to enter the risk-zone over areas of sloped topography than over flat areas of the ridge (Exact Test: P = 0.035; 71% over slopes; 29% over flat areas; *n* = 81; Figures 3.1 & 3.2). The trend was the same for the proportion of entries made within RSH (*n* = 25); far fewer RSH entries were made over flat areas (4%) compared to slopes (96%; Exact Test $P = 0.001$). Between the identified sloped topography features, a greater number of eagles entered the risk-zone at the south end of the study ridge (section A) compared to other identified areas (Figure 3.2; Exact Test $P \leq 0.001$). Although the middle section of the turbine string (section C) had similar sloped topography and the same number of approaches as section A, the density of entries into section C was more spread out along a longer section of the ridge (Exact Test $P \leq 0.001$).

In addition to the lower golden eagle heights over slopes than flat areas (Slopes 219 ± 17.47 m; Flats 455 ± 53.77 m), all (100%; *n* = 10) risk-zone entries within RSH and above turbine cut-in speed were over slopes (grey box of Figure 3.4a). Very few (4%, *n* = 1) approaches over flat areas occurred within RSH, and all of these occurred during weak winds that were below turbine cut-in speed (Figure 3.4a).

Spring

All risk-zone approaches occurred over slopes areas, and all approaches occured in the northen sections of the study ridge in equal proportions (Exact Test *P* = 0.23; Figure 3.4b).

C. Flight Behaviour

Fall

Among golden eagles that entered the risk-zone, there was no difference in flight heights between different flight behaviours (Figure 3.5a). However, soaring flight occurred more often than expected (80%; 291 ± 30.21 m) within RSH under winds above turbine cut-in speed (>14 km/hr) compared to below (Chi-squared test $\chi^2_2 = 11.3$, $P = 0.004$). However, for RSH entries below turbine cut-in speed – when the turbines would have been idle – circle-soaring was more commonly used (67%; 273 ± 31.17 m) than either soaring (20%) or powered flight (13%). Powered flight occurred at the lowest range of altitudes within my dataset (94 ± 36.86 m), and occurred within RSH both above and below turbine cut-in speed, although the sample size is low (*n* = 4). Lastly, I did not find an association between flight behaviour and topography type (Chi-squared test $\chi^2_2 = 4.24$, $P = 0.120$).

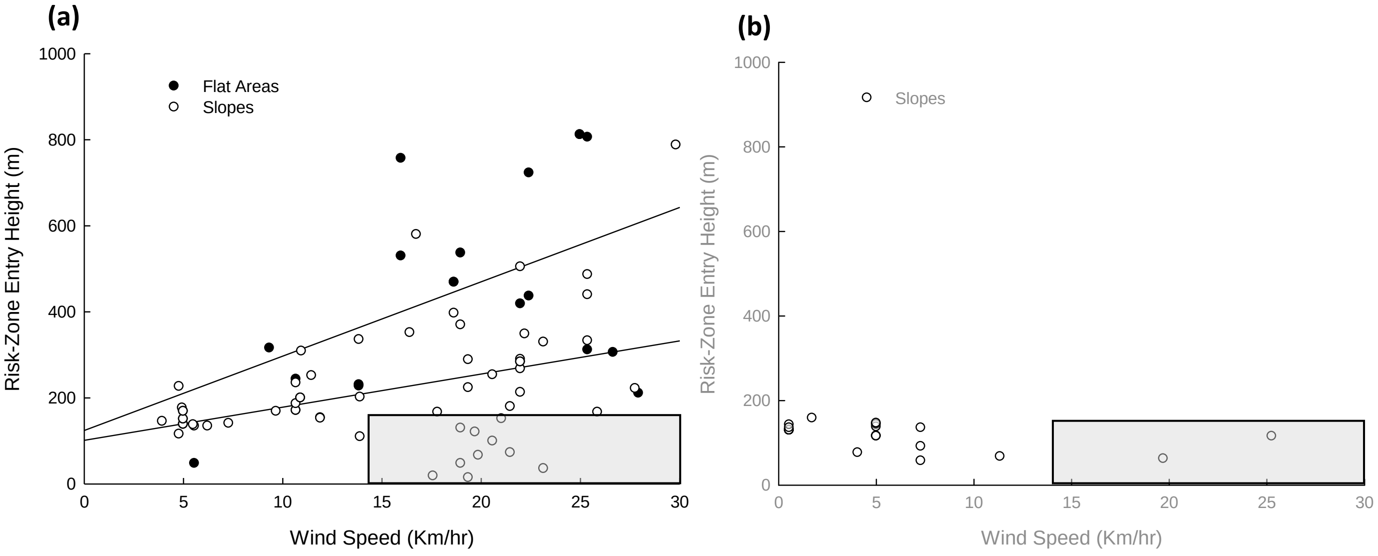

Figure 3.4 Height (m above ground) of golden eagles entering risk-zone versus wind speed (km/hr) by topography feature (sloped versus flat) for **(a)** fall 2009 (slopes *n*=56; flat *n*=25), and **(b)**, spring 2010 (slopes *n*=27). Grey box represents rotor-swept height (≤ 150 m) above turbine cut-in speed (14 km/hr).

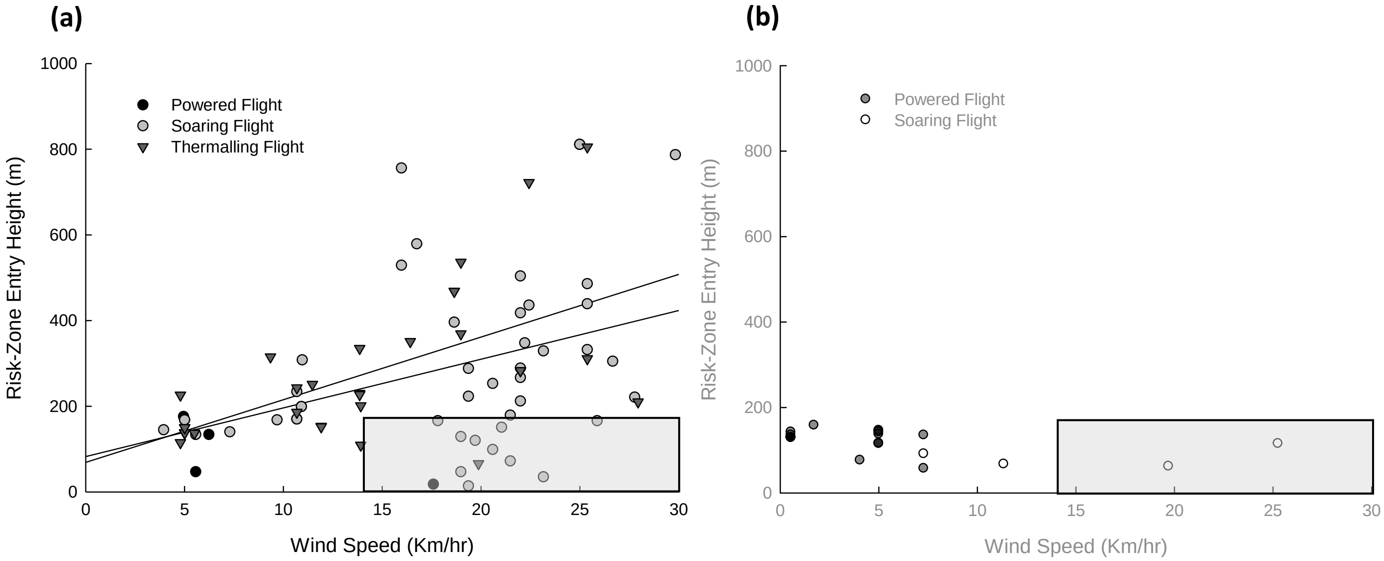

Figure 3.5 Height (m above ground) of golden eagles entering risk-zone versus wind speed (km/hr) by flight behaviour for **(a)**, fall 2009 (soaring *n*=46; circle-soaring *n*=31; and powered flight *n*=4 [no regression line displayed]), and **(b)**, spring 2010 (soaring *n*=4; powered flight *n*=23). Grey box represents rotor-swept height (≤ 150 m) above turbine cut-in speed (14 km/hr).

Spring

The majority of risk-zone approaches occurred under weak wind speeds (4.6 ± 1.2 km/hr), and correspondingly, I found that the majority of these approaches were made using power flight (85%; *n* = 23; Figure 3.5b).

3.4 Discussion

In both migration seasons, golden eagle flight heights in proximity to a proposed ridge-top wind farm were positively correlated with wind speed. In the fall, flight heights were also lower under head-winds, were lower over sloped topography, and decreased as the season progressed. In the spring, however, eagle heights also increased in the hours after midday. Although more golden eagles entered the risk-zone at rotor-swept height in the spring compared to the fall, a greater proportion in the spring were at weak wind speeds assumed to be below turbine cut-in speed. However, the results presented here are based on one season and rely on weather collected at ground level. Additional surveys are needed in addition to wind-speed data collected near nacelle height (80 m).

3.4.1 Wind Speed and Direction

Similar to my results of increasing flight altitudes with increasing wind speed, a study on griffon vultures in Spain found that low wind speeds (although still above turbine cut-in speed) in combination with gentle ridge slopes significantly increased collision mortalities with turbines (Barrios and Rodriguez 2004). This was due to vultures not getting sufficient lift to clear the structures. And similar to these findings, I observed entries into the risk-zone in the fall using circle-soaring flight under weak-wind conditions as birds attempted to gain lift on rising warm air. However, based on the weather data collected at 2 m above the ground, such flights were observed at wind speeds below turbine cut in speed (14 km/hr or 4 m/s). Since wind speed increases with altitude due to resistance from the ground, we are likely underestimating the wind speed at nacelle height, and potentially the risk posed by circle-soaring flight.

I also found that golden eagle flight height (above ground level [agl]) did not change with increasing wind speed under head-wind conditions, despite a trend toward higher flight heights with increasing wind speeds under cross-winds. Low altitude flights occurred under tail-winds but the sample size is low, and winds from this direction were always weak and likely below turbine cut-in speed. Irrespective of wind strength, previous research on the flight altitudes of sharp-shinned hawks found lower flight heights under head-winds compared to tail-winds (Mueller and Berger 1967a). It is possible that under head-wind conditions golden eagles chose to fly at lower altitudes to minimize drag, which decreases with decreasing elevation (Alerstam 1990).

Although the identification of head versus cross-winds may appear subtle as they are both from a southwest direction, the identification of head-wind conditions, particularly during peak migration, should be scrutinized in post-construction collision risk assessments. As noted in other research, the implications of strong winds could result in an increase in collision risk because turbine blades spin faster with increasing wind strength (Barrios and Rodriguez 2004).

3.4.2. Ridge-top Topography

In the fall, I found lower eagle flight heights over sloped compared to flat areas of the ridge-top topography, and all entries into the risk-zone in the spring were over sloped areas. Ridge-top topography is an important variable for assessing raptor collision risk because studies in North America and Spain have identified canyons and ridge ends (often also the end of a turbine string) as areas of increased collision risk for raptors (Barrios and Rodriguez 2004, Smallwood 2007). In addition to lower flight altitudes over slopes compared to flat areas, I also found a greater frequency of rotor-swept height (RSH; ≤ 150 m agl) movements over these features. Entries into the risk-zone over slopes represented 98% of all entries within RSH in the fall, and 100% of all entries in the spring. Thus, the combination of head-wind conditions and sloped topography appears to place golden eagles within the operating range of turbines.

The use of slopes under head-winds may represent golden eagles attempting to manoeuvre themselves out of unfavourable conditions (Alerstam 1979). At the same time, it may reflect the greater influence that topography imposes on birds when they fly at low altitudes. Compared to flights at higher altitudes, where birds can use their elevation to glide or find updrafts, migrating eagles at low altitudes likely have fewer options and are thus routed by winds deflected by sloped topography (Mueller and Berger 1967a). In addition to deflected winds, another possible explanation for the greater use of sloped areas may be due to increased exposure to the sun, especially for rocky cliff areas, which would create rising warm air or thermals.

Furthermore, I found heavier use of sloped areas located near the distal ends of the ridge (i.e. the ends before leaving the ridge) in both migration seasons. For example, a possible explanation for the large number of birds that entered the risk-zone at the south end of the ridge in the fall may be that this area represents a last opportunity for eagles to gain lift before they head out over a wide valley and reach the next ridge (Ainsley, B., Alexander, N., Johnston, N., Bradley, J., Pomeroy, A., Otter, K., and Jackson, P., UNBC, unpublished data). However, the southern area is also characterised by a steep rocky cliff, which is conducive to thermal creation. Nevertheless, should post-construction mitigation measures be required to reduce golden eagle impacts, a temporal shift in high-risk conditions should be considered; the south-end slopes on the ridge have higher potential for conflict in the fall, and the northern ends in the spring. Until proven otherwise, wind farm design should aim to avoid the placement of turbines from ridge ends or abrupt low points in the topography that are heavily used by golden eagles (Thelander and Rugge 2001, de Lucas et al. 2004, Smallwood 2007), or be prepared to idle such turbines during periods of high passage.

3.4.3. Flight Behaviour

Although I did not find circle-soaring to occur at rotor-swept height at winds above turbine cut-in speed, caution should be taken because the weather data are not able to take into account the increase in wind speed with increasing altitude (from 2 m to 80 m at nacelle height). I recommend that ground wind speeds be compared with wind data available in turbine nacelles or met-towers post-operation. Should eagles circle-soar near turbines at wind speeds close to turbine cut-in speed, an increase in cut-in speed from 14 km/hr (4 m/s) to 18 km/hr (5 m/s) would be recommended. This strategy has been proven successful in the reduction of fatalities with bat species (Baerwald et al. 2009) and does not significantly reduce profits made from power generation. Furthermore, circle-soaring should be reassessed post-construction to unsure that land use practices, such as the clear-cut logging along the ridge-top, does not change eagle flight behaviour patterns. Furthermore, circle-soaring should be reassessed post-construction to unsure that land use practices, such as the clear-cut logging along the ridge-top, does not change eagle flight behaviour patterns. Multi-year post-construction research is needed to identify conditions were avoidance may be reduced.

3.4.4. Potential for Avoidance Behaviour

Avoidance of turbines is believed to be high for diurnal raptor species, although differing results have been found and few studies manage to quantify the issue (Madders and Whitfield 2006). Ultimately, avoidance behaviours are difficult to ascertain due to the fact that collisions, even in areas of high annual mortality, have high spatial and temporal variance, making them a rare event to witness (Smallwood et al. 2009). At both the Altamont Pass Wind Resource Area in California, USA (Orloff and Flannery 1992), and at Tarifa, Spain (Barrios and Rodriguez 2004), the proportions of passes close to turbine blades (i.e. within 50 m) compared to site use (i.e. passes within 250 m) by raptors occurred more often than expected for some species, suggesting that turbines were not being avoided. However, the opposite was found in Europe for small raptors and sea ducks, suggesting high rates of turbine avoidance (Osborn et al. 1998, Guillemette and Larsen 2002). For golden eagles at a handful of wind farms across the USA, Whitfield (2009) found avoidance rates to be similar to those of other raptor species, at approximately 95–98%. Although this appears high, it is comparatively low to other avian species (99%). It is one of the reasons that raptors are considered more at risk of collision with turbines than other bird species.

Research regarding collision risk for migratory raptors, especially with regards to how they respond post-construction, is currently lacking (Drewitt and Langston 2008). Recent research on migratory golden eagles at a wind farm in Wyoming, USA, however, found lower mortality rates than expected (Whitfield 2009). Although this suggests that migratory golden eagles are at low risk of collision mortality, this may only be true for wind farms that are oriented parallel to the main lines of migration with turbines offset from the main slopes used. Much has yet to be learned regarding collision events by migratory raptors, especially for developments oriented perpendicular to the lines of migration.

The problems with collision risk assessments in North America is that post-construction assessments are based on carcass searches alone, which can result in an overestimation of avoidance behaviours due to crippling bias, where fatally injured individuals soar or walk away from the development (Barrios and Rodriguez 2007). This was found to be significant for griffon vultures in Spain that, like golden eagles, are highly skilled fliers (Barrios and Rodriguez 2007). Even though the vultures detected turbines, they flew comfortably close to them, which resulted in misjudgement and distal injuries to the wing. Secondly, carcass searches alone fail to document avoidance or displacement responses since this method does not include species abundance at the site. Hence, visual post-construction assessments, in addition to carcass searches, are needed to better quantify species-specific avoidance and displacement responses following the erection of turbines before collision risk models can be effective (Band et al. 2007, Drewitt and Langston 2008, Whitfield 2009).

Avoidance at the higher end of the scale is likely in this study due to the parallel alignment of the development with golden eagle movements. If I were to apply an estimated avoidance rate to the number of approaches within rotor-swept height and above turbine cut-in speed (2.5%), based on an estimated passage of 1000 individuals in the fall, a 98% avoidance rate would result in 0.5, or one, eagle entry into the risk-zone. However, since this is only based on one season, it is likely that annual variation in the proportion of weather conditions, such as head-wind conditions, could alter the proportion of collision risk events. For this reason, multi-year post-construction research is needed to identify conditions where avoidance may be reduced.

3.5 Conclusions

In the Hart Range, I have evidence to suggest that golden eagle mortality at a single farm is likely to be low; however, this finding is based on one season and concerns remain for cumulative effects along their migration route through the Hart Range. I identified head-wind conditions, in combination with the placement of turbines on slopes, or low points in the ridge-top topography, and at ridge-ends, particularly where deep valleys separate ridges from each other, as variables that could potentially increase risk of collision with turbines. My findings of low flight altitudes in the fall under head-winds, regardless of wind-speed, suggests that golden eagles are also potentially more vulnerable to collision with turbines under these conditions as wind speeds increase due to faster moving blades. Further research is needed to confirm identified associations between eagle heights in relation to wind speed at turbine height.

Since my study is one of the first for a region of BC that is used as a golden eagle migration corridor, and also has a large potential for wind farm development, I recommend a cumulative impact assessment for the region were numerous small impacts may occur. In addition, I recommend multi-year comparative pre- and post-construction risk assessments that use the same methodology, in addition to carcass searches post-construction, to document any changes in behaviour or abundance. Understanding the cumulative effects of numerous developments in a region used by a long-lived and slow-to-reproduce species such as the golden eagle is critical in managing the impacts of the wind energy sector on eagle populations.

CHAPTER FOUR – GENERAL DISCUSSION

The flight behaviours and routes used by golden eagles were not unexpected; in fact, many were anticipated given local conditions and topography of the area (Kerlinger and Moore 1989, Ainsley, B., Alexander, N., Johnston, N., Bradley, J., Pomeroy, A., Otter, K., and Jackson, P., UNBC, unpublished data). The findings of this study should be applicable to other areas in the Hart and Front Range due to the similarity of topographic orientation and wind conditions along the eastern Rocky Mountains (Yates et al. 2001).The use of updrafts created by the complex terrain of the Rocky Mountains by golden eagles during migration may put birds at risk of collision with turbines. This was evident by the witnessed movements into the risk-zone at the Dokie site. Wind speed and direction may be associated with the frequency of dangerous flight paths, but these predictions need to be verified and avoidance behaviours quantified post-construction with wind data collected at turbine height.

4.1 Trends in golden eagle flight behaviour

Golden eagle hourly passage through the site in the fall was positively correlated with date, and peaked in early and late October. Passage also increased in the hours after midday, and with increasing cloud cover and wind speed. Since the timing of golden eagle migration is innate and highly consistent, time of year is a key variable for estimating when the bulk of passage is likely to occur (i.e. early and mid to late October in the fall, and late March in the spring) (Leshem and Yom-Tov 1996). For this reason, seasonality will be an important consideration for the implementation of mitigation measures (Kerlinger and Gauthreaux 1985, Alerstam and Lindstrom 1990, Leshem and Yom-Tov 1996, Niles et al. 1996, Bildstein 2006a). Nevertheless, given the annual diversity in weather conditions (i.e.

visibility, wind speed and direction) within a migration period, peak migration dates may vary slightly as daily passage rates vary (Sherrington 2003). This variation in passage makes the prediction of peak migration dates difficult to pin-point exactly, and therefore, site managers should aim to broadly cover peak migration periods (i.e. the month of October versus specific peak dates) when considering the implementation of mitigation measures.

In all migration seasons monitored, hourly passage best explained the frequency of eagle entries into the risk-zone. This indicates that entries into the risk-zone did not occur under a select set of weather conditions, but rather, were more related to relative activity levels at the site. In the fall, increased passage in the hours after midday and as wind speed and temperature increased likely reflects the increased availability of lift. For example, as wind speed increased, sources of lift was likely available due to deflection along mountain slopes; as temperatures increased, thermal activity was likely more abundant along the ridge-top area, especially after midday. Thus, the increased passage under conditions favourable for lift was also reflected by an increase in the use of Johnson Col for lift, as shown by increased entries into the risk-zone. Therefore, determining the weather systems (although complex) and seasonal patterns associated with variation in abundance will also aid in defining the potential risk for collisions.

Migratory golden eagles that used the eastern migration route through the site were at least twice as likely to enter the risk-zone compared to individuals that used the western route. Compared to the western route, which is over a wide and deep valley, the eastern route represents a narrow corridor between the two site ridges, which may be associated with the increased likelihood of a ridge-top crossing. In the fall, the greater probability of using the eastern route under head-wind conditions, and as cloud cover decreased, may reflect the preference for the weaker wind speeds along this route to minimize drag. Since the eastern route would be partially sheltered by Johnson Col, head-winds would likely be dampened due to the downdraft created by passing over Johnson Col (Ainsley, B., Alexander, N., Johnston, N., Bradley, J., Pomeroy, A., Otter, K., and Jackson, P., UNBC, unpublished data). Furthermore, the greater use of the eastern route as cloud cover decreased, or as solar activity increased, may reflect a greater presence of thermal activity over the more gentle slopes found in this area. The use of the eastern route potentially posed a greater hazard to individual eagles; although fewer birds overall used this route, those that did had a higher probability of entering into the risk-zone. However, a greater proportion of eagles used the western route, and so total numbers of entry into the risk-zone were larger than for the eastern route. Nevertheless, the identification of head-winds as a potential hazard to migrating eagles provides information at the site level for mitigation measures, whereby site managers concerned with collision risk could idle turbines on days with high passage.

In the spring, the use of the eastern route was tied to low wind speeds, which posed little threat of collision since the turbines would not have been spinning. However, caution is required due to the use of ground weather data in this study, in addition results based on one migration season. The observed differences in routes used between seasons may be explained by: differences in age structure, with our patterns reflecting mixed-ages in the fall and adults in the spring; differences in weather conditions between seasons, especially the abundance and distribution of thermals available for lift, and whether birds are forced to rely on powered flight for lift; and lastly, differing pressures on adults, such as time-related pressures to arrive early on the breeding grounds in the spring compared to the fall. Hence, the greater use of the eastern route in the spring may represent a time constraint on birds forced to migrate when updraft creation is minimal – under such conditions the utilization of powered flight over higher ground allows birds to maintain their overall altitude.

Concerns over collision impacts in the fall exist due to the larger number of birds that pass through the site in the fall, particularly since most of the passage occurs at wind speeds above turbine cut-in speed, and often up to speeds that support maximum turbine blade rotation (29 km/hr; 16 revolutions per minute). However, additional spring and fall surveys are needed, along with weather data collected closer to turbine height, to assess risk under conditions when the turbines will be spinning.

4.2 The Association between Weather and Topography on Golden Eagle Flight Altitude

In the fall of 2009, heights at which eagles entered the risk-zone increased with increasing wind speed, were lower under head-winds compared to cross-winds, were lower over sloped areas of the ridge compared to flat areas, and decreased as the season progressed. Similar to research on migrating sharp-shinned hawks (Mueller and Berger 1967a), I found low golden eagle altitudes during entries into the risk-zone under head- and tail-wind conditions. In my study, however, entries into the risk-zone under head-winds were consistently low, even as wind speed increased. Thus, under head-winds, collision risk increased with increasing wind speed as the winds approached 8 m/s (29 km/hr), which is the maximum blade-tip speed. The low flight altitudes under head-winds are likely related to eagles attempting to reduce drag and increase flight speed, since wind speed decreases closer to the ground due to the friction with the terrain (Alerstam 1990).

As eagles entered the risk-zone, I also found lower average flight heights over sloped versus flat areas of the ridge-top topography, suggesting that eagles used breaks in the topography when flying at low altitudes. In addition, I found a greater use of slopes located at the south end of the ridge in the fall. While other studies have identified ridge-ends and canyons as areas of higher raptor use and collision mortality events (Thelander and Rugge 2001), the heavy use of the south end of the Dokie ridge in the fall likely represents an attempt by eagles to gain lift before heading over a wide valley, also a downdraft area (Ainsley, B., Alexander, N., Johnston, N., Bradley, J., Pomeroy, A., Otter, K., and Jackson, P., UNBC, unpublished data).

The spring of 2010 experienced a greater proportion of weak wind conditions, mainly from the northeast, and as such, all but two of the observed entries into the risk-zone occurred at wind speeds below turbine cut-in speed. However, wind speed at turbine height needs to be verified with data collected at ground level to confirm this finding. Nevertheless, based on ground data, the two approaches that did occur when the blades would have been spinning occurred during western cross-winds and at winds above turbine cut-in speed. In order to quantify risk, more research is needed with wind data collected at turbine height (80 m). In addition to the frequent use of powered flight in the spring, all entries into the risk-zone occurred over sloped areas at the north section of the ridge. The more frequent use of the northern slopes likely represents a means for birds to exit the narrowing valley of the eastern route as they reached the northern section of the study ridge. Hence, raptor use of the distal ends of the ridge in both seasons requires further attention at North Dokie post-operation, and should also be scrutinized at proposed developments in the Hart Range.

4.3 Conclusions

For the fall migration season I estimate around 20% of golden eagles that flew within 2 km of the focal ridgeline entered the 100m risk-zone around the proposed turbines strings. In terms of collision risk, 2.5% of all birds detected within 2 km of the ridge entered the risk-zone at both rotor-swept height (150 m) and when the winds were above turbine cut-in speed (14 km/hr). It is important to note that this 2.5%, however, does not include avoidance behaviours; birds detecting turbines and taking collision avoidance routes around them. A study in Wyoming estimated migratory golden eagles have up to 98% avoidance rates when encountering turbine strings, this includes both avoiding the strings or flying between turbines. Based on the results from this one study in Wyoming, golden eagle collisions are likely to be low for the Dokie site and for developments oriented parallel to the main lines of migration provided that turbines are micro-sited away from the main slopes used. However, further research is needed to describe and quantify golden eagle avoidance behaviour to ridge-top wind farms in the Rocky Mountains since current findings are based on carcass searching, which is riddled with biases. At the North Dokie site, which is oriented parallel to the main lines of migration, post-construction observations of golden eagle flight behaviour are needed to assess the degree to which the wind farm or individual turbines are avoided. Further research is especially needed for proposed developments oriented perpendicular to the corridors of eagle migration.

At a minimum, a Cumulative Impact Assessment (CIA) is needed to extrapolate local results within the Hart Range of British Columbia, Canada, since collision impacts are likely to be low at individual sites. Currently the provincial goals to meet green energy targets has resulted in a large number of proposed wind farm developments in the Hart Range, sequentially spaced along a known golden eagle migration corridor. Such sequential placement of installations could result in higher cumulative effects on eagle populations than is evident from the effect of each individual installation. Masden et al. (2010) proposes that a CIA should be undertaken prior to approval of new developments within areas where migration corridors occur, potentially placing upper limits to the number of new farms allowed within defined regions. In addition to a CIA, new Federal legislation for golden eagle `take' permits in the USA is requiring wind energy facilities to monitor mortality events (Pagel et al. 2010). The take permit process will be a part of the permitting process, and is intended to help document collision mortality events at individual developments. The information gathered could be used locally for mitigation strategies, or at a broader scale for the assessment of cumulative impacts (Pagel et al. 2010).

Currently, provincial and federal government agencies in Canada responsible for assessing environmental impacts do not have the capacity to assess impacts at regional or population scales, as no guidelines exist for the collection and assimilation of this data (see http://www.ceaa.gc.ca/43952694-0363-4B1E-B2B3-47365FAF1ED7/Cumulative_Effects_Assessment_Practitioners_Guide.pdf). The lack of government oversight leaves the responsibility of cumulative impacts to individual wind farm owners, without defined guidelines for the documentation of mortalities beyond the post-construction monitoring phase (Noble 2010). The data collected by the take permits could also allow government scientists to share impacts over Bird Conservation Regions (see http://www.bsc-eoc.org/international/bcrmain.html) for the assessment of impacts at the population level (Pagel et al. 2010). The implementation of a species-specific take permitting policy in Canada - to centralize the collection of eagle mortality data - would be especially important in regions that serve as migratory corridors between distant breeding and wintering grounds. For example, the Hart Range serves as a major corridor for movement between northern breeding populations and southern wintering grounds – collision mortality in this region could have significant impacts on breeding populations that are not only distant from the source of mortality, but may occur in different jurisdictional or national boundaries. Without understanding the potential impact of large-scale development in these corridor areas, there is the potential to decouple population losses from the source of disturbance.

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