

**MOVEMENT PATTERNS OF NOCTURNAL AVIAN MIGRANTS AT A WIND
ENERGY PROJECT IN NORTHEAST BRITISH COLUMBIA**

by

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ABSTRACT

In North America, the migration corridors of passerine birds between breeding and non-breeding grounds are relatively well documented, and along these corridors passerines generally move in a broad-front fashion interspersed with stopover periods in which to rest and replenish fuel stores. Understanding movement patterns at individual locations along these routes is required to identify whether anthropogenic developments, such as wind energy installations, can lead to disruption or collision risk during migrations. Wind energy installations are becoming more numerous in the corridors along migration routes as they use the same wind resources exploited by migratory birds. Documenting collision risk to nocturnal migrants, particularly passerines, through the collection of accurate data on the movement patterns and flight altitudes at wind energy sites during both pre-operational and operational phases is needed to correctly assess the level of risk to these birds.

Using standard marine radar units equipped with an inexpensive digital interface system, I automated the detection and extraction of radar echo signatures or target information for nocturnal migrants (Chapter 2) at a wind energy site in northeast British Columbia. Using the open source software program radR, I identified optimal values for input criteria to automatically detect and track these migrants with high accuracy from the digital radar data, when compared to known, manually-tracked targets ($R^2 = 0.94$). The program was also effective in reducing the amount of insects that were detected and tracked. Use of the auto-tracking software also increased the number of detected targets by over 500% compared to the real-time collection of radar data.

Using radR, I analyzed the micro-scale movements of nocturnal migrants during the pre-operational and operational periods of the wind energy project (Chapter 3). Despite

variations in wind conditions between seasons, migrants showed consistent directionality and general trends of broad-front migration at altitudes typically above the height of wind turbines. In the spring, migrants were predominantly utilizing favourable tailwinds, but when wind conditions changed, migratory direction at the micro-scale level appeared to remain constant. In the fall, migrants were rarely moving with favourable winds and were predominantly facing headwind or crosswind conditions. Regardless, at the micro-scale level nocturnal migrants were not significantly adjusting their movements around the wind energy facility during the operational period and their typical migratory behaviour was not placing them in potential collision risk situations.

Unfavourable weather and the influence of artificial lights have been identified as contributing factors in bird collisions with tall human-made structures. I used vertical radar data on the heights of migrating passerines to document the number of birds within 300 m height categories above ground per hour before and after 54 separate rain events. The number of birds did not increase in the lower height categories immediately before the rain event, suggesting that isolated rain events may not increase collision risk (Chapter 4).

Nocturnal migrants rely on rod-dominated vision at night and are likely sensitive to intense artificial light sources. I broadcasted lights at different wavelengths (blue, green, red and white) and flash rates (solid or flashing) from a portable spotlight and documented the response of migrants (trajectories and heights of migrants) as they travelled past the light source (Chapter 5). Migrants exposed to light colours at shorter wavelengths consistently displayed lower flight altitudes compared to migrants exposed to light colours at longer wavelength. My results strongly suggest that artificial light colours at shorter wavelengths may have a greater attraction effect on nocturnal migrants than other lighting regimes.

Overall, my results demonstrate that nocturnal migrants moving through northeast British Columbia are at a low risk of colliding with wind turbines under both favourable and unfavourable conditions.

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 this thesis. Despite the use of first person singular in writing within the thesis, I would like to acknowledge that this work was not conducted in isolation. The large scope of the analysis associated with Chapter 2 of this thesis was reliant on contributions and the expertise of Isobel Hartley at UNBC. This contribution was instrumental in the data management and analysis of the subsequent chapters. Finally, my supervisor, Dr. Ken Otter, contributed to experimental design; data analysis and writing on all studies included in this thesis, and is included in authorship on all resulting manuscripts.

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The data collection and results of my work has also contributed to additional papers.

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1 GENERAL INTRODUCTION

Accurately documenting how birds use the environments around wind energy installations and how they are affected by these developments could aid both in understanding the potential cumulative effects of wind energy development on bird populations, and in mitigating any negative effects. Although concerns that collisions between birds and wind turbines resulting in fatalities have been raised for several decades, avian behaviour and response to wind projects is still not fully understood and fatalities continue to occur at many wind projects (de Lucas et al. 2008, Drewitt and Langston 2008, Rodriguez and Rodriguez 2009, Loss et al. 2013, Zimmerling et al. 2013, Erickson et al. 2014). The goal of my research was to document movement patterns of nocturnal migrants before and after construction of a wind energy facility in northern British Columbia, as well as to determine the potential for weather patterns or turbine lighting to influence collision risk.

1.1 Passerine migration and energetic costs

Avian migration is a costly endeavour, both in terms of the energy required to traverse the distances between breeding and wintering grounds and the potential risks faced along the journey. Regardless, most birds undertake migration to: take advantage of seasonal increases of food (e.g., seeds, insects); to find better nesting and rearing habitat; and, to avoid unfavourable climates during winter (Able 2004). Most passerine species migrate in a broad-front fashion – meaning they travel long distances spread over a wide area – and will complete their journey in a series of stages of up to 300 km at a time interspersed with

stopover periods of two to three days (Able 2004). Passerines will spend significant portions of their migratory period foraging to restore energy reserves, and the rate at which they cover the migration distance is partially dependent upon both the quality of suitable foraging sites at stopover locations and how quickly these can be used to replenish fuel stores (Klaassen et al. 2008). The time required to replace fuel stores must also account for the energetic costs of anti-predator behaviour at stopover sites (Lank and Ydenberg 2003). Predation risk is lower during the day when passerines can be more vigilant (Able 2004), which may potentially account for the majority of passerine species migrating at night when pressure from predators is reduced. Nocturnal migration also has other advantages; there is typically less turbulence in the atmosphere at night, which is more favourable for reducing energy demands on birds in flight (Harmata et al. 1999, Able 2004). In addition, the cooler air at night reduces the stress from dehydration and overheating (Harmata et al. 1999, Able 2004). Migrants will select conditions that not only minimize energetic costs of travel, but may also facilitate greater ability to navigate. Decisions to depart stopover locations and to continue with migration are also influenced by weather conditions (Richardson 1978, Able 2004, Liechti et al. 2013), with the likelihood of departure from stopover locations being highest on nights with moderate winds and no rain (Schaub et al. 2004). At the broader spatial and temporal scale, migration movements are more predictable, but at the local scale particular movements on a given night or a particular hour are variable (Mabey 2004). The local movements of migratory birds are less understood, particularly in the Rocky Mountains (Pocewicz et al. 2013), because of the influence of weather and topography. Further, weather conditions can vary temporally and spatially across seasons and years at the site-level,

making local patterns and timing of migration less predictable than broad-scale patterns (Mabey 2004, Liechti et al. 2013).

1.2 Influence of weather and topography on migration

Nocturnal migration is initiated about an hour after sundown (Balcomb 1977) and peaks one to two hours thereafter (Bruderer 1997b, Able 2004, Mabee et al. 2006).

Movement then gradually declines until daybreak (Lincoln et al. 1998). Most nocturnal passerine migrants fly at altitudes relatively close to the ground – between 100 m and 750 m in height (Able 2004, Longcore et al. 2008, Liechti et al. 2013). This height distribution is influenced by the altitudinal profile of winds and the weather conditions (Bruderer 1997b). In the spring, northbound migrants prefer warmer temperatures and southerly winds. Such conditions typically occur when there is a high pressure system to the east of the migratory route (Bruderer 1997b, Able 2004). In the fall, southward migration through mountainous regions is heaviest after the passage of a cold front, as this results in a thermal inversion that produces favourable winds (e.g., 5 to 13 m/s) from the north over ridge tops (Gauthreaux 1991, Bruderer 1997b, Williams et al. 2001, Able 2004). Birds may time migration to coincide with such favourable conditions, as they would reduce energetics associated with long-distance movement.

Most flight paths of nocturnal migrants typically do not appear to be influenced by underlying topography until they descend for landing at stopover sites (Gauthreaux 1991, Bruderer 1997b, Williams et al. 2001). Birds do, however, use topographic features in the distance to aid navigation. Birds migrating across large bodies of water, for example, will utilize distant land features to guide their movements, such as Long Point peninsula in

Ontario (Jones and Francis 2003) and coastal promontories (Drewitt and Langston 2008). These features are preferred locations for lighthouses, the presence of which increases the collision risks for birds especially as these are also coupled with intense light sources known to attract birds (see subsection 1.5). In addition, under unfavourable weather conditions, when birds may be forced to fly below the cloud cover, local topographical features, such as mountain ridges, will have greater influence on the migratory stream (Bruderer 1997b). Winds above mountain ridges may also oppose the principal direction of migration; birds can compensate for this by flying closer to the ground where they can utilize visual cues from below to maintain directionality (Gauthreaux 1991).

The number of migrants varies from night to night as movements are influenced by rain, cloud, fog and strong winds (Able 2004). Cloud cover, particularly when associated with rain (Richardson 1978), often results in decreased migration densities (Erni et al. 2002, Nilsson et al. 2006), suggesting these weather conditions impede movement. Rain also wets plumage, which increases drag and thus the energy requirements and flight costs for migrants (Schaub et al. 2004, Gagnon et al. 2011). An increase in cloud cover and rain can also reduce the effectiveness of celestial cues that nocturnal migrants use to navigate (Pyle et al. 1993, Able and Able 1995) and can preclude migrants from detecting topographical features used to orientate during migration; such cues are often relied upon to compensate for wind drift (Pyle et al. 1993, Gagnon et al. 2011). Because of the relatively low flight altitudes, migrants can be exposed to both headwind and tailwind conditions, which can vary by night or season (Mabey 2004, Liechti et al. 2013). Under tailwind conditions, the range of migratory direction is typically narrower as birds are able to take a more direct flight to their migratory destination. Under headwind conditions, by contrast, migration patterns are more

scattered and migrants are typically flying at lower altitudes (Able 2004, Liechti et al. 2013), as wind speed is often reduced closer to ground level. There may be selective pressure for birds to alter or curtail activity during inclement weather, but these must also be balanced against energy costs and the need to time arrival at destinations for other purposes (e.g., to initiate breeding). Migration behaviour, thus, appears to be an interplay between balancing the timing of movement with both individual condition and environmental cues, so as to ensure arrival at future stopover sites, breeding or wintering grounds at time periods that maximize chances of survival or reproduction (Schaub et al. 2004).

1.3 Migratory behaviour and orientation cues

Migratory behaviour in birds has a strong genetic basis (Able 2004). Nocturnally-migrating birds exhibit restlessness – increased nocturnal activity orientated in the direction typical of the route of migratory movement – during the migratory period, which provides evidence of the instinctive desire to initiate movement (Berthold and Terrill 1991). Studies on hand-reared caged birds have examined various cues that birds use in nocturnal migratory orientation. These cues include those requiring visual detection, such as celestial cues and polarized light, as well as detection of magnetic fields. There are multiple magnetic field detectors (e.g., ferromagnetic crystals or magnetite) in the heads of birds, one of which is located in the eye (Edmonds 1976). Birds will orientate towards their migratory direction based solely on the influence of magnetic fields when all other stimuli are controlled (Wiltschko and Wiltschko 1976, Able 2004), but there is typically an interplay among sensory and visual detection used for migratory orientation. This allows birds to innately

develop migratory orientation without learned experience (Berthold and Terrill 1991), which may be subject to disruption by other stimuli.

Birds use a suite of orientation mechanisms/cues to establish migratory direction, including magnetic fields, celestial orientation, polarized light on the horizon and reference to the sun's position in relation to a bird's circadian rhythm (Able and Able 1995). Polarized light appears to be the most dominant visual cue (Wiltschko et al. 1998) and birds use their visual sense to discern diurnal patterns of polarized light to orientate themselves for night-time migration (Able and Able 1995). As the sun sets in the west, a band of polarized light, perpendicular to the setting sun appears which is visible at temperate latitudes up to 45 minutes after sunset. Birds detect changes in the polarization patterns during this period, which provides directional information to nocturnal migrants. This pattern of polarized light at dusk provides the primary source of orientation information for night-migrating species (Able 1989, Able and Able 1995, Able and Able 1997, Lincoln et al. 1998). Night-migrating species rely upon these visual cues to maintain directionality when movements are affected by local weather and topography. This in turn demands a visual system that is selectively attuned to these cues (Martin 1990, Hart 2001) and birds will shift between the various cues to derive directional information from whichever visual cue is available. This capacity allows them to continuously adjust their orientation as necessary to stay on their migratory course (Wiltschko et al. 1998). Thus, a bird's perception of visual cues and objects at night is critical for maintaining migratory direction.

1.4 Avian optic system and influence on orientation

A bird's perception of colour and luminance is important for detection and classification of objects. Visual information about surface reflectance, pigmentation and other material properties assists birds in making decisions about migratory direction (Osorio and Vorobyev 2005). Like most vertebrates, the avian retina is comprised of visual photoreceptors that are divided into two subtypes: rods and cones (Cuthill et al. 2000). Cones dominate the retina and are more sensitive at higher light levels (i.e. photopic conditions) (Hart 2001). Cones discriminate colour based on their ability to absorb different wavelengths of the visual spectrum. A bird's retina has four spectrally-distinct single cones, which are made up of visual pigment molecules called opsins, and are associated with colour discrimination on the basis of their peak wavelength sensitivity (Cuthill et al. 2000, Osorio and Vorobyev 2005, Ghim and Hodos 2006). Brightly coloured oil droplets (e.g., red, orange and bright yellow) on cones act as additional wavelength filters by broadening the spectral sensitivity and improving visual acuity (Hart 2001), making birds more sensitive to colour than are humans (Manville 2000, Ghim and Hodos 2006).

In addition to single cones, birds also have a class of double cones that are used for motion perception, luminance detection and form vision (Osorio and Vorobyev 2005). Double cones have two halves and comprise 50% of the cone photoreceptors in the retina (Bowmaker 2008), which reduces competing demands for spectral sensitivity and luminosity (Hart 2001). The double cones of the avian eye play a major role in spatial resolution since these receptors are more numerous than single cones and allow for high-contrast sensitivity (Osorio and Vorobyev 2005). Under scotopic conditions (i.e., during low light conditions), the eye shifts from cone- to rod-mediated vision (Hart 2001) since rods are 25 to 100 times

more sensitive to light than cones (Cuthill et al. 2000, Hart 2001). Rods are not used for colour distinction and are primarily responsible for achromatic vision (Hart 2001). This shift in vision under low light conditions, otherwise known as the Purkinje shift (Hart 2001), changes the eye from being more sensitive to colours at long wavelengths to being more sensitive to both colours at short wavelengths and more intense light (Hart 2001). Because of the Purkinje shift, the contrast sensitivity of the avian eye is affected. Typically, the detection of an object is ascertained by matching the visual sensitivity to the available background light. This would be greatest at twilight when both rods and double cones are functioning to detect brightness levels. As the night becomes darker, rod-mediated vision predominates. At these times of night when light levels diminish, longer wavelengths become more abundant due to the illumination from the moon and stars, and the rod-mediated vision is no longer optimal for contrast sensitivity. Thus under normal night-time conditions, a bird's ability to discriminate fine objects is relatively poor and they are likely only able to detect coarser details (Martin 1990). These aspects of the optic system allow birds to detect cues necessary for orientation, but also subject them to disorientation from false cues on the landscape arising from human-built structures and/or artificial light sources.

1.5 Bird responses to human-built structures

Human-built structures pose a collision risk to birds when these occupy the same airspace where birds fly. The most common structures include communication towers, wind turbines, buildings, lighthouses, smokestacks and oil platforms. Most collisions with these tall structures occur during migration periods, with the majority occurring at night and thus differentially impacting nocturnal migrants (Erickson et al. 2005, Mabee et al. 2006,

Kuvlesky et al. 2007). Past research on bird collisions and mortality has been primarily conducted at communication towers (Erickson et al. 2005), which vary in height and can exceed 305 m (Gehring et al. 2009). Due to the increase in popularity of cellular telephones and digital television, between 5,000 and 10,000 new towers are erected each year in the United States, and by 2015 approximately 600,000 communication towers will be in place throughout the US (Erickson et al. 2005). The study of mortality associated with communication towers may provide insight into the factors that will influence collision at other structures. Of particular interest is bird mortality events at wind turbines, as this is one of the most direct, visible and well-documented impacts of wind energy development on bird species (Loss et al. 2013).

The general consensus in the scientific community is that the potential for collision during the night increases if structures are lit. Yet, lighting is required on all structures over 60 m tall as a warning to aircraft pilots (U.S. Department of Transportation 2007; Transport Canada 2014). It is unclear if birds are being attracted to these light sources from a distance or whether birds become ‘trapped’ by the light as they pass illuminated structures. This trapping effect refers to birds flying into the illuminated area of a light source and becoming reluctant to leave the area (Evans Ogden 1996, Drewitt and Langston 2008). Verheijen (1958, cited in Evans Ogden 1996) suggested that the illumination of the environment around a light source interferes with the normal photopic orientation. As the avian eye shifts from photopic to scotopic vision at night, it becomes more sensitive to intense light. Birds are thus drawn to an artificial light source because it is more intense compared to the surrounding natural light (Evans Ogden 1996). Documentation of this type of effect dates back to the late

1800s when it was noticed that birds were killed by flying into the lights at lighthouses (Cochran and Graber 1958).

The colour of the lights, degree of polarization, light intensity and flash duration are the main factors associated with artificial lights that may affect collision risk. Structures are typically lit with white or red lights, and these lights may be solid (i.e., constantly on) or pulsating on and off (i.e., flashing). There is conflicting evidence regarding which light colour has the greatest effect on birds, but light intensity and flash duration appear to have more influence on collision risk than light colour (Drewitt and Langston 2008). The longer the duration between flashes the less likely birds are to be attracted to the light (Manville 2000); the interruption of the light may allow birds to either disperse from the illuminated area (Jones and Francis 2003) and/or view visual cues that will help to reorient themselves on the correct migratory path. Light intensity is a separate factor. A study at an Ontario lighthouse showed a decline in the number of birds killed after a less powerful light was installed (Jones and Francis 2003). Depending on the intensity of the light, birds may be confusing the artificial light sources with the moon or stars, which leads to disorientation (Martin 1990). Furthermore, on overcast nights, birds are more likely to become disoriented from lighted towers because other visual cues (e.g., stars) are obscured and artificial light reflecting off the clouds causes a large illuminated area (Avery et al. 1976). Thus, interactions between weather and lighting may impact collision risk of migrants, and needs to be addressed as wind farms continue to proliferate.

1.6 Wind energy development

Generation of wind energy has increased at a rapid rate in recent years due to social and economic pressures to develop alternative energy sources (Zimmerling et al. 2013, Erickson et al. 2014). In Canada, the installed capacity of commercial wind power increased exponentially from 137 megawatts (MW) in 2000 to over 9,200 MW in 2014 (Canadian Wind Energy Association 2014), and this amount is expected to increase tenfold over the next 10 to 15 years (Zimmerling et al. 2013). As of December 2014, there was over 3,000 wind turbines erected in Canada (Canadian Wind Energy Association 2014). In British Columbia, the provincial government is viewing wind energy as a means of meeting its goals of renewable energy sources (BC Hydro 2013). Currently there are four operating wind energy facilities in the province, with three concentrated in the northeast region of the province plus several others being proposed.

The environmental impacts of wind energy development are considered to be low relative to other sources of energy production (Marques et al. 2014), however, both the growth of wind energy in new areas and the development of new turbine technologies have implications for avian migration (Marques et al. 2014). Development of wind energy facilities into a variety of areas, which can differ greatly in topography and environmental conditions (National Wind Coordinating Committee 1999, Environment Canada 2005), could have varying impacts on local bird communities (Marques et al. 2014). Since local bird migration patterns may differ among areas (Richardson 1978, Akesson 1993, Williams et al. 2001), general assumptions about how wind projects will affect birds and bird movements cannot be made without examinations of individual sites (Environment Canada 2005).

Passerines are the most abundant group of species traversing past wind energy facilities during migratory periods (Marques et al. 2014), and collisions with wind turbines has been consistently raised as a main concern (Kingsley and Whittam 2005, Drewitt and Langston 2006, Barclay et al. 2007). Wind turbines pose a unique risk to birds because, in addition to being like other static structures that are tall and lit, they have a moving rotor (Drewitt and Langston 2008) and birds are killed by being hit by the turbine blades in the rotor-swept zone (Smallwood 2007). Past research indicates that passerines suffer the most collision fatalities and typically comprise 80% of all fatalities, most of which involve nocturnal migrants (Loss et al. 2013, Zimmerling et al. 2013, Erickson et al. 2014), however, mortality estimates in the past have been highly uncertain and are prone to bias because of variation in the protocols for monitoring and analysing mortality among sites (Smallwood 2007). Regardless, these fatalities of passerines at individual wind farms are likely proportional to relative species abundance, and are not necessarily thought to impact individual bird populations (Kuvlesky et al. 2007). Yet, data to confirm mortality rates relative to general passage rates are often lacking in making this assessment.

Bird collision risk at wind energy facilities is usually estimated during pre-construction surveys of migratory movement patterns and spatial use of the areas being considered for construction (Kunz et al. 2007, Marques et al. 2014). Studies of collision risk often assume a linear relationship between the frequency and abundance of observed birds and the predicted number of fatalities (Everaert 2014). A factor which further complicates the ability to determine risk is that many studies shift methodology during post-construction research; pre-construction work monitors movement patterns and spatial use, but post-construction research measures realized collision risk through carcass searching without

continuing to track movement patterns (Ferrer et al. 2012). The result is that pre- and post-construction datasets are only weakly comparable. Estimating collision risk is a complex interaction of factors such as movement rates and flight heights of birds, avoidance behaviour (if known) characteristics of the wind energy facility such as the number, size, configuration and lighting of wind turbines and additional factors including topography, food availability and weather (Band et al. 2007). Several of these measures (e.g., avoidance behaviour) require monitoring of movement during operational periods as well as pre-operational periods.

Patterns of avoidance by birds will have a strong influence on mortality rates but the degree to which birds exhibit avoidance behaviour to human-made structures is at present relatively unknown, particularly for passerine species which are migrating at night (Liechti et al. 2013). Birds are capable of detecting structures during the daytime, but detection ability is significantly reduced at night (Desholm and Kahlert 2005; section 1.4). Avoidance can be confounded if artificial lights placed on structures for aircraft navigation result in attraction of birds to these structures (Desholm 2006), but only a few studies have attempted to document bird behaviour around lit structures (Gehring et al. 2009). Finally, avoidance may be occurring at the larger or macro-scale levels, where birds may avoid an entire wind energy facility. Alternately, avoidance may occur at a finer or micro-scale, where birds adjust their movements around individual wind turbines (Marques et al. 2014).

Very few studies have attempted to calculate micro-avoidance rates in situ at wind energy developments, and those that have studied the proportion of diurnally-active birds that have taken avoidance action and not nocturnal migrants (Everaert 2014). The advancement of data collection techniques with radar and high performance computer hardware and

software can allow for a detailed understanding of fine-scale movements of nocturnal migrants.

1.7 Tracking bird movements by radar and current limitations

Radar has been used extensively to track nocturnal bird movements around wind farms (Bruderer 1997a, Harmata et al. 1999, Gauthreaux and Besler 2003, Desholm et al. 2006, Otter et al. 2014). Radar provide an advantage over other avian monitoring techniques (e.g., night vision and thermal imaging) because they cover large distances, collect data under low light conditions, and operate under moderately-inclement weather, such as fog (Bruderer 1997a). A basic radar is comprised of an antenna, a transmitter/receiver, a signal processor, a display unit (i.e., monitor) and a power supply (Toomay and Hannan 2004). Electromagnetic (radio frequency) waves are generated in the transmitter and are radiated through the antenna in the form of pulses. When the radio waves hits a target they are scattered in all directions, but in this action a small part of the scattered energy is reflected back to the radar, which is referred to as the echo signature of the target. The transmitter/receiver has an alternating switch which opens the antenna to receive the radio waves reradiated back from the object. This returned signal is routed through the receiver and measurements of the object are produced by the signal processor, and the size and intensity of this received signal are presented on the unit's visual display. In addition to the detection of a target, the radar system records the time from when the pulse was transmitted to when the returned signal is received. This allows for the calculation of the range to the target, which is also presented on the display unit (Bruderer 1997a, Toomay and Hannan 2004).

The pulses of energy emitted from the radar antenna typically form a single lobe-shaped pattern of radiation, although minor or side lobes can be included depending on the antenna design. The radar beam is defined by its horizontal and vertical beam widths, which are determined by the physical size and shape of the antennae itself. Beam widths are typically within the range of 1° to 60° and is the area in which the signal power is greatest (Toomay and Hannan 2004). A more focused beam width concentrates the radar system's energy in a narrower field of view, which increases the chance of detection of smaller, more distant objects. Energy from radar is emitted at wavelengths, typically in the range between 2 m and a few millimetres. Radar systems with longer wavelengths, such as L-band radars that have wavelengths in the range of 15 cm to 30 cm, have the advantage of being less disturbed by rain, but they would also suppress the echo signatures of small objects like passerines (Toomay and Hannan 2004). Decreasing the wavelength and beam width increases the detection capability of smaller targets, like passerines. Radars with these characteristics are also smaller, which increases their utility as mobile units. Shorter wavelength radar systems, such as X-band with wavelengths in the range of 2.4 cm to 3.8 cm are optimal for detecting smaller birds; however, the disadvantages of these units are that they have a decreased range ability and will also detect other small objects like rain and insects (Bruderer 1997a).

The actual power striking a target is the concentrated energy in the transmitted signal multiplied by the target area or radar cross section (RCS) (Toomay and Hannan 2004, Denny 2007). The RCS is a measure of the size of a target as presented to the radar pulse and influences the power that is intercepted and reradiated, at the same wavelength, by a target. The RCS of a target is a complex combination of multiple factors including its size, shape, aspect, material and edges. Simple targets, such as birds, have only a few edges or scattering

sources which would result in a smaller RCS for reflecting signals. Further if the size of the target is smaller than the wavelength of the electromagnetic signal being emitted by the radar system, then the radar system is unlikely to be able to resolve and detect the target. If a target is larger than the wavelength, however, the reradiated signal is proportional to its shadowing area – the area behind the target where there is no return signal.

The most commonly used radar antennas for measuring local bird movements are either the parabolic dish or the open array (i.e., t-bar). A parabolic dish produces a conical beam and the angular diameter of the beam is inversely proportional to the dish diameter. With a dish antenna, the geographic position of targets relative to the antenna location can be determined by the delay in the echo return; further, when the antenna is pointed at a defined angle above the horizon the approximate height of targets can also be determined using simple trigonometry (Taylor et al. 2010). In contrast, open array antennas generate a fan shaped beam that is narrow (focused) on the horizontal axis and wider on the vertical axis. The open array antenna provides data on distance of targets relative to the radar, but are not capable of providing information on height when used in the normal horizontal orientation (Bruderer 1997a, Taylor et al. 2010). Since open array antennas have smaller horizontal beam widths, compared to parabolic dishes, they can provide better azimuth resolution and are able to resolve targets that are closer together (Taylor et al. 2010). As the vertical beam width is also larger, each sweep of the antenna detects targets over a wider field of view, and sequential detection of targets on successive rotations of the antenna is less subject to slight changes in altitude of the target.

When an antenna rotates 360° (scanning mode) the radar signal will repeatedly hit the target and, as mentioned above, can provide information on the bearing and distance to the

target as the signal is reflected back to the radar. As the distance to the target increases, the power density of the transmitted signal power decreases. The power density is increased by adjusting the gain on the radar unit, which causes beamforming – defined as the focusing of the mainlobe of the radar beam – so as to concentrate more radar energy into the forward pulse, and less into sidelobes. Some of the target signal power reradiated back to the radar antennae is also lost from attenuation through the atmosphere. Atmospheric attenuation is the result of radiation being absorbed by atmospheric gases and/or being scattered by rain, aerosols or dust. The concentration of gases in the atmosphere is relatively constant, but the amount of water vapour and other airborne particles will vary over the globe (Denny 2007). In addition, receiver noise – unwanted power that contaminates the signal – will also affect the target detection. Some of this noise comes from the atmosphere and manufactured sources (e.g., other radars, power facilities), however, most of the noise is generated in the transmitter itself. The source of this internal noise is thermal heating of the electronic components (Toomay and Hannan 2004). Radar placement and tuning can also aid in minimizing signal loss from these confounding sources.

Marine surveillance X-band radars (i.e., those used for ship navigation) are typically used to monitor bird movement. These radars generate a small wavelength capable of resolving objects with small RCS areas, and so are effective at recording information on behaviour, passage rates, flight direction and flight altitudes of birds (Mabee et al. 2006, Taylor et al. 2010). These units are relatively inexpensive, readily obtainable from radar manufacturers, are relatively easy to operate, and with very little modification they can be configured for easy portability to survey locations for tracking bird movements (Cooper et al. 1991, Taylor et al. 2010). Unfortunately, a major limitation of these conventional radar units

is that they operate on analog signal processing, meaning that the results of radar tracking are presented in real-time on the display unit. Researchers must manually transcribe data on flight direction, behaviour and passage rates from the radar monitor as bird movements are occurring, which has become scientifically accepted as a standard method of radar ornithology (Beason et al. 2013). Accurately transcribing all data being presented on the radar monitor can be challenging, particularly during busy periods of migration activity (Cooper et al. 1991, Harmata et al. 1999). To address these challenges, researchers have developed methods for recording movement data for later analysis including: the use of time-lapse film (Richardson 1978); transcribing movements on top of acetate sheets placed on the radar monitor (Harmata et al. 1999, Desholm and Kahlert 2005); and, the use of raw video pictures (Bruderer 1997a, Taylor et al. 2010). These methods remain prone to errors and do not produce results that are comparable across studies (Taylor et al. 2010).

Newer radar technologies are now available that provide automated data collection solutions including high-definition digital radar units, high performance radar remote sensing and computer technologies specifically designed for avian tracking (Krijgsveld et al. 2005, Merritt et al. 2008) and advanced radar processing technologies (Rutter Inc. n.d.). The cost of these technologies, which can exceed \$100,000 per unit, is typically the limiting factor for their wide application in tracking bird movements. Development and testing of the potential low-cost or open-source signal digitization and tracking hardware/software would render greater options for research on avian movement, and is a focal area of my thesis. Such technology would allow greater resolution at determining the behavioural response of birds to landscape development, such as collision risk imposed by placement of tall structures on the landscape.

1.8 Study site

My study was conducted at the Dokie I Wind Energy Project (55°41'28"N 122°18'06"W), located approximately 40 km west of the town of Chetwynd, British Columbia. The site is located in the foothills of the Hart Range of what is considered the Northern Rockies, which lie in a north-northwest to south-southeast orientation (Fig. 1-1). The project is situated on two ridges ranging in elevation from 1200 m to 1400 m above sea level. The project underwent site construction (roads, turbine pads, etc.) from 2008-2009, turbine erection in 2010 and commenced energy production in 2011. The Dokie I Wind Energy Project is a 144 megawatts (MW) installation comprised of 48 Vestas V90 3MW wind turbines that have a tower height of 80 m, a rotor diameter of 90 m and a rotor swept area of 6,362 m². Fifteen turbines are placed on Johnson Col and 33 turbines are placed on Johnson Ridge. There are two meteorological towers located near turbines JC11 on Johnson Col and J17 on Johnson Ridge. Approximately 12 km of above-ground collector lines are distributed between wind turbines and run to a substation located in the valley to the immediate south of the project site.

Daily weather at the study site is influenced by middle-latitude cyclones that typically move from southwest to northeast British Columbia that respond to large scale features of the Rocky Mountains (Whiteman 2000, Klock and Mullock 2001). These lows tend to move over mountains and produce a widespread area of precipitation as well as unstable air where bands of clouds and showers develop. The middle-latitude cyclones dominate the weather during the fall through spring, while convection dominates during the summer months. The lows can become very slow moving and result in large amounts of precipitation in one place (Klock and Mullock 2001). Combined with moist air that originates over the Pacific Ocean,

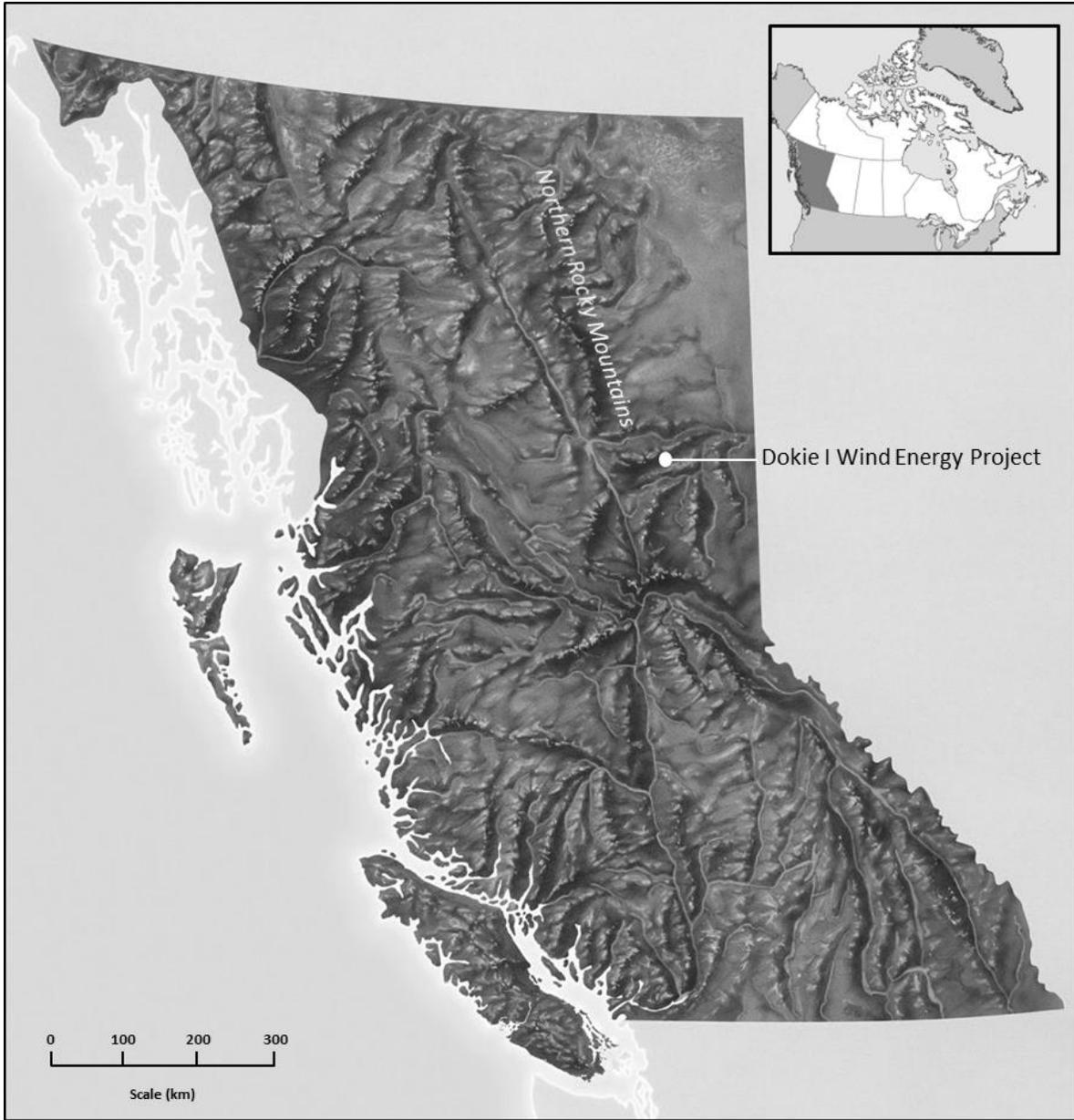


Fig. 1-1. Location of the Dokie I Wind Energy Project near Chetwynd in northeast British Columbia.

this makes its way eastward through the narrow and deep valleys that occur through the Rocky Mountains. Also, the Northern Rockies are lower in height compared to their southern counterparts, which allows this moist air to move into the northeast region of British Columbia bringing strong winds from the southwest, turbulence, increased cloud cover and precipitation (Vickers et al. 2001).

1.9 Outline of thesis

The goals of my research were to measure movement patterns and behaviour of nocturnal migrants and assess collision risk at the Dokie I Wind Energy Project in northern British Columbia. To monitor fine-scale movement and detect potential changes in relation to wind turbines, weather conditions and artificial light, I tested the capacity of X-band marine radar units equipped with signal interface systems, which digitally recorded raw radar signal data, to assess movement behaviour (Chapter 2). This technology was then used to compare the flight patterns of nocturnal migrants before construction to those following construction and operation of the wind energy installation. Here, I examined the passage and altitude of migrants in relation to the predominant wind patterns (Chapter 3). These data were collected under relatively clear conditions and would represent normal migratory behaviour from which general collision risk could be predicted. To test how collision risk changes under varying conditions, I examined the movement of nocturnal migrants as sporadic rain events occurred (Chapter 4) and how variation in artificial lighting of structures could affect these movements (Chapter 5).

2 ANALYTICAL PROTOCOLS FOR THE DETECTION AND AUTO-EXTRACTION OF AERIAL VERTEBRATE TARGETS FROM DIGITAL RADAR SIGNALS AT A WIND ENERGY PROJECT

Abstract - I tested an automated system for the detection and extraction of data on the movement of birds from digital radar data that can be used in a variety of contexts. Nocturnal migration was recorded using standard marine radar units equipped with an inexpensive digital interface system during the spring and fall migration periods from 2008 to 2012 at a wind energy project in northeast British Columbia. Using the open source program radR, the movement of birds was automatically detected and tracked from the digital radar data with high accuracy compared to known, manually-tracked birds ($R^2 = 0.94$). The program was also effective in reducing the amount of non-avian targets that were detected and tracked. Use of auto-tracking software increased the number of detected targets by over 500% compared to the real-time collection of radar data in the field. The employment of this system can provide a cost-effective option to assist in the conservation of species, as it can provide detailed information on movement behaviour of birds in instances where collision risks are a concern, such as migration behavior around proposed wind energy sites.

2.1 Introduction

Wind power has become an increasingly attractive energy source, and development of this capacity has grown exponentially over the past decade because of social and economic pressures for alternative energy options (Drewitt and Langston 2006). Mortality of birds and bats from collision with wind turbines continue to occur at many wind projects (Thelander and Rugge 2000, Erickson et al. 2001, Mabee and Copper 2004, Kerlinger et al. 2011) so the development of wind energy projects should proceed only with a complete understanding of

potential impacts to ecological systems (de Lucas et al. 2007). Understanding how migrants respond to wind turbines is crucial to the conservation of species (Ruth et al. 2005) and this understanding can only be obtained when data on the movement of birds are accurately collected from pre- and post-construction surveys.

To assess such movement patterns during pre- and post-construction there must be reliable and efficient technology that can be employed in avian tracking. Marine surveillance radars (X-band) are becoming an increasingly important tool in tracking the flight paths of birds (Gauthreaux and Besler 2003) and have been the primary means of documenting movements of nocturnal migrants around wind energy projects (Harmata et al. 1999, Gauthreaux and Besler 2003, Harmata et al. 2003, Desholm et al. 2006). Marine radar units are available from radar manufacturers at reasonable costs and can be easily transported to survey locations (Taylor et al. 2010). These radars emit short wavelengths (e.g., 2.5 cm to 3.75 cm) (Cooper 1995, Taylor et al. 2010) capable of resolving small targets, such as passerines and bats, at distances up to 1.5 km (Kunz et al. 2007). This not only allows researchers to detect the patterns of passerine movements at distances beyond those capable by visual observations, but also allows detection of movements during periods of low visibility, such as foggy and/or night-time conditions (Gauthreaux and Besler 2003). The critical factors involved in the quantification of migration by radar include the identification of discrete targets, which occupy small parts of the radar pulse volume (Bruderer 1997b, Schmaljohann et al. 2008). These data are collected from the detection and extraction of target information (position and heading) on successive scans of the radar's signal (Blackman 2004, Toomay and Hannan 2004, Denny 2007, Alter and Coleman 2008). Traditional radars operate on analog signal processing and this means data on the movement of birds are often

extracted in real-time from the radar monitor, which has become a standard method in the scientific literature (Beason et al. 2013). The analysis of radar movement data collected in real-time has a number of potential limitations that affect data accuracy: 1) there may be limited ability to record all targets on the radar screen during busy periods (e.g., during peaks of migration); and 2) there is the potential for observer bias in recording accurate distance and bearing information from the radar. The impact of these limitations is likely to increase with density of targets being tracked, and the result could compromise data on the patterns of passerine movements.

To counter these limitations, several authors have developed methods for recording the movement of birds from radars for later analysis, such as the use of time-lapse film (Richardson 1978), drawing movements on top of acetate sheets overlaid on the radar screen (Harmata et al. 1999, Desholm and Kahlert 2005) and the use of raw video pictures (Bruderer 1997a, Taylor et al. 2010). Recent advancements in radar software have provided affordable opportunities, when paired with marine radar units, to digitally-record raw analog radar signals. These latter advances have the highest potential for increasing accuracy of censuses. For example, by digitizing and recording the radar signal, researchers can obtain detailed information on the echo signatures of specific targets, which can aid in target identification (O'Neal et al. 2010). Yet, problems with tracking avian movement using radars still need to be addressed; targets of interest must be identified as aerial vertebrates (birds/bats) and discriminated from non-vertebrate targets (e.g., insects, radar noise and clutter) to quantify relative passage rates and heights (Blackman 2004). Further, this post-analysis must balance the additional data that can be gathered with the time and costs required to conduct such detailed assessment of recorded imagery. In this study I tested an automated system for the

detection and auto-extraction of information on aerial vertebrate targets from digital radar data. My goal was to determine whether an automated system can be cost-effectively used to increase tracking ability and discriminate aerial vertebrates from non-vertebrates, while retaining high reliability in the output. Such a system would expand the potential to track the movement of avian targets in a variety of contexts (e.g., movement patterns around tailings ponds, airfields, transmission towers, or wind energy facilities), and thus would improve accuracy of data on avian movements that could contribute to conservation strategies.

2.2 Methods

2.2.1 Study area

I collected radar data at the Dokie I Wind Energy Project (55°41'28"N 122°18'06"W) located in northeast British Columbia during the spring and fall migration periods from 2008 to 2012. This wind project is situated in the foothills of the Rocky Mountains approximately 40 km west of the town of Chetwynd, British Columbia. The project underwent site construction (roads, turbine pads, etc.) from 2008-2009, turbine erection in 2010 and commenced energy production in 2011. Wind turbines are situated on two ridges ranging in elevation from 1200 m to 1400 m above sea level. Data collection periods were timed to overlap with the peak in nocturnal passerine migration for the region, as determined through surveys in 2006 and 2007 (Jacques Whitford-AXYS Ltd. 2006, Pomeroy et al. 2007). In the spring this coincided with mid-May to the end of May and in the fall from late August to early September. I collected data beginning at or before sunset and continued until the following morning (after sunrise). I gathered radar data over a two week period each season with an average of 5.8 hrs and 8.5 hrs of radar data being recorded each night during the

spring and fall migration periods, respectively. Differences in the number of hours of data recorded between seasons were primarily a reflection of the length of the night period at the latitude of the study area. During each data collection period, I experienced unfavorable weather conditions and equipment issues when radar data could not be collected, however, these two issues combined accounted for only one to two nights during each season. Weather problems were primarily due to periods of heavy rain, which created sufficient clutter on the radar monitor where birds could not be reliably tracked. Equipment issues were primarily related to problems with power supplies and computer hardware early in the study period.

2.2.2 Radar data collection

I recorded movement patterns of nocturnal migrants around the wind project using two Furuno X-band marine radar units (model 1954C, 12kW, 9,000 MHz, 1.83 m open array antennas – Furuno Electric Company Ltd. Miki Japan). One radar was set in the surveillance position (antenna rotating on the typical horizontal axis) to track passage rates and the second unit was set in the vertical position (radar mounted at 90°, so that the antenna rotated through the vertical axis) to track heights of targets. The radar units were set in locations where minimal interference from ground clutter was present. The horizontal radar was mounted approximately 2.0 m above ground and oriented to true north. The vertical radar was mounted approximately 1.5 m above the ground and the antenna was aligned with the proposed/constructed turbine arrays (Fig. 2-1). The main beam of the horizontal radar unit scanned an arc of 22° (vertical) with a beam width of 1.9° (horizontal), rotating 360° every 2.5 secs. Likewise, the main beam of the vertical radar unit was 22° (horizontal) in width with an arc of 1.9° (vertical). For the horizontal radar unit, the wave guide was tilted to 25°

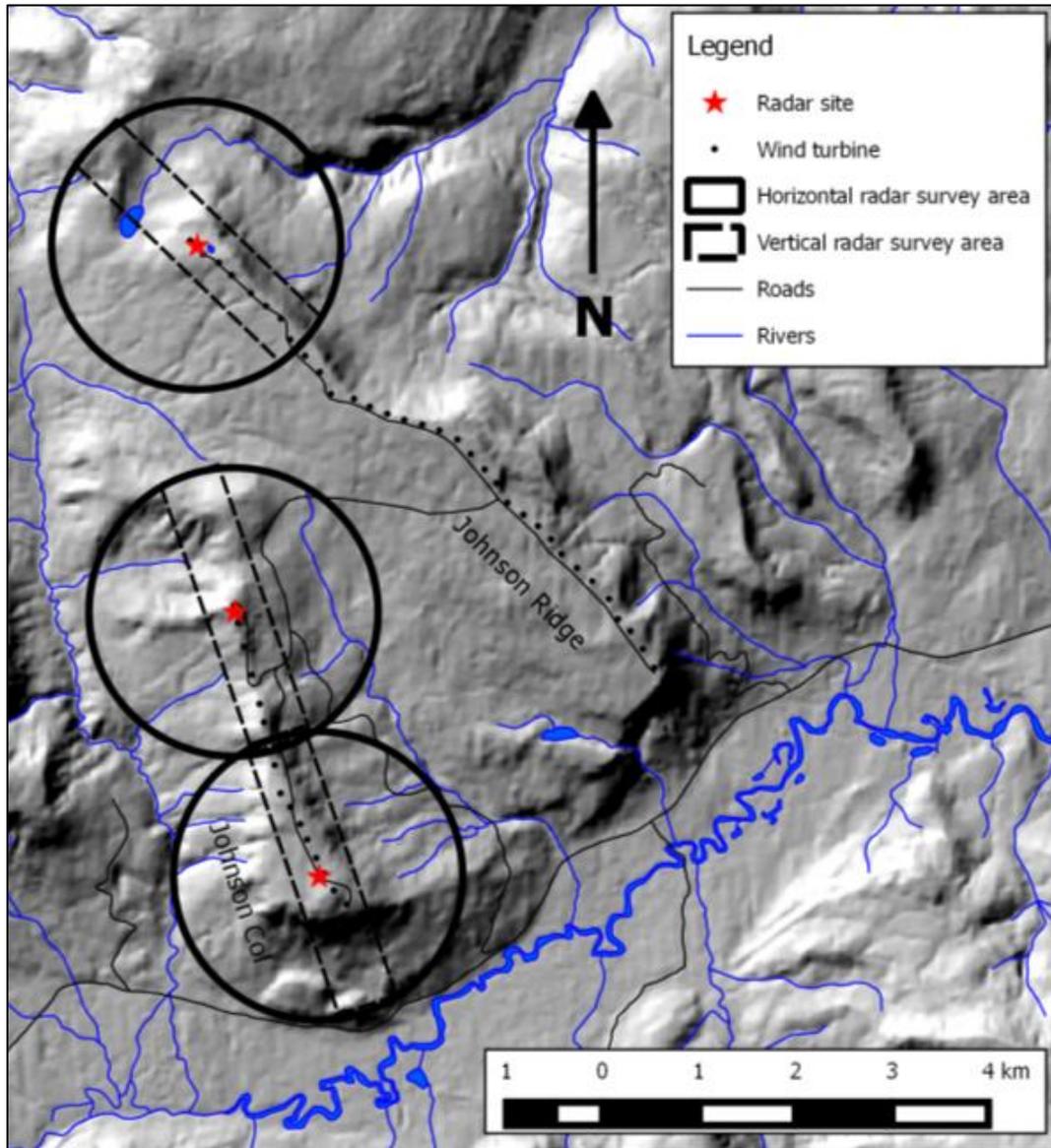


Fig. 2-1. Position and orientation of the radar sites surveyed from 2008 to 2012 in relation to the topography of the ridgelines at the Dokie I Wind Energy Project in northeast British Columbia. The 1.5 km radius circles represent the area of coverage for the surveillance (horizontal) radar. The dashed rectangular boxes represent the area of coverage for the vertical radars.

above horizontal to further reduce the amount of ground clutter and increase the amount of airspace surveyed (Harper et al. 2004). Both radar units were set on short-pulse length (80 ns at pulse repetition frequency [PRF] = 2100 Hz) with a range of 1.5 km. Rain and sea clutter suppression algorithms were turned off. The gain scale on the radars ranged from 0 to 99 and I used a setting of 76, which was the highest setting, determined during radar tuning, which maximized the information returned from targets while reducing the amount of radar noise. With the added influence of side lobes, this created a detection zone of approximately 500 m depth throughout the 1.5 km range, which was verified independently by recording movements of a training helicopter (Robertson R22 – Tech Helicopters Ltd.) and small remote model aircraft (Easy Star II Airplane Kit; 1.3 m wingspan; Model MPU214260 - Multiplex Modelsport USA) mounted with altimeters and GPS units that were flown at stratified altitudes across a flight grid within the 1.5 km detection zone (M.I. Hartley, K.A. Otter, unpublished data).

The same settings were used each year and the radar systems were set up in the same locations each season (Fig. 2-1). Each radar unit was equipped with an electronic interface system, including a signal digitizer (XIR3000B) and radar software (WinHorizon Version 1.5.0.13 – Russell Technologies Inc., North Vancouver, BC; <http://www.russelltechnologies.ca/>). The XIR3000B is an 8-bit digitization card that operated in slave mode whereby it transcribed the analog signals being passed from the transceiver to the radar master and digitized the return signals: video, trigger, ships heading marker and azimuth information. WinHorizon is a multi-purpose automatic radar plotting aid that offered a raster-scan radar with a 4096 scan line resolution display. The digitized raw radar signals from each scan were saved as individual files that represented one 2.5 sec scan of the radar

and were automatically saved into separate electronic folders for each data recording session. From the spring of 2008 to the fall of 2012, I recorded over 800 hrs from the horizontal radar and 744 hrs of data from the vertical radar.

2.2.3 *Target detection and tracking*

In my analysis, I attempted to discriminate aerial vertebrates from non-vertebrates (i.e., insects, ground clutter) and hereafter refer to each as “true targets” and “false targets”, respectively. In my data, it was likely that aerial vertebrate targets were predominantly birds since monitoring of bat activity in 2008 to 2010 indicated relatively low occurrences of bats (Jacques Whitford AXYS Ltd. 2009, Pomeroy et al. 2010). I detected and tracked true targets from the radar data in three separate ways: 1) direct observation/recording of targets from the radar monitor in the field (Real-time detection). This entailed scoring targets as they moved across the screen, without pausing or replaying imagery, as would occur from scoring a non-recorded analog image; 2) manual detection from recorded digital radar data where I was able to pause and replay imagery to ensure accurate detection and tracking of each target (Manual-detection); and 3) use of detection algorithms from software to automatically detect and track targets from recorded imagery (Auto-detection).

From 2008 to 2010, I had five observers record the nocturnal movement of migrants using the Real-time detection method as the radars were being operated on site, and simultaneous to digitizing radar imagery. Real-time detection was conducted in hourly segments, alternating between horizontal and vertical radar, during the first four hours after sunset. The spatial location of true targets relative to the radar, including the distance and bearing of when each first appeared were transcribed directly from the radar monitor. Observers recorded the size and number of times each target appeared on the monitor, along

with the distance and bearing of when it last appeared on the monitor. A total of 72 hrs of horizontal data and 67 hrs of vertical data were transcribed from the radar monitor using the Real-time detection method (during this same period over 405 hrs of horizontal data and over 385 hrs of vertical data were digitally recorded).

I conducted Manual-detection on 29 15-min periods of radar data from the spring migration between 2008 and 2011. I selected radar data nights where no rain was present and spanning the date ranges within each year; and from these, I selected the 15 min periods to balance the represented hours across all the samples. Manual-detection of each sample period of radar data was completed using WinHorizon where imagery could be paused and replayed. This allowed me to manually count the exact number of recorded true targets, summated on a per minute basis. True targets were discriminated from false targets based on relative flight direction and speed, aided with the trails function on moving targets and the high colour display in WinHorizon. The total number of true targets recorded using the Manual-detection method for the 15-min periods ranged from 6 to 887, with a median value of 153 targets. I used this median value as the cut-off between less intense movements and more intense movements to correlate the accuracy of the Auto-detection method (described below). Each target took approximately one minute to process using the Manual-detection method, so the time required to manually-score the 15-min periods ranged from 15 min to 14.75 hrs, depending upon the density of migrants within the recordings.

To extract target information from the digitally recorded radar data using the Auto-detection method, I employed the analysis program radR (Version 2.5.1, Taylor et al. 2010), which is an open-source platform with user-defined functions written in the R statistical programming language (R Development Core Team 2014) to process the digitized radar data.

I used the XIR3000arch plugin in radR to playback the files from the WinHorizon recordings. Program radR has built in algorithms to detect and track true targets and to also ignore returns from stationary clutter. The detection and tracking of targets in radR was summarized as a two-step process whereby the true targets (blips) were initially identified with the blip filtering plugin and were then tracked with the tracker plugin. The blip filtering plugin is a target-finding algorithm with user-defined variables that can be set to filter true targets within the radar signal. Each digital scan gets processed as a matrix of integers comprised of pulses (columns) and range cells (rows). The columns in the matrix are uniformly spaced around the radar's rotational plane (e.g., 0° through 360° azimuth) and represent the amount of energy reflected back from a target at increasing distance from the radar. Each row in the matrix corresponds to the energy received from a given range cell, while the radar was pointed at a particular direction. Each point in the matrix is known as a "sample" that represents the strength of the radar echo from a single pulse for a given range cell. radR uses a specified number of learning scans to compute a background intensity score for each sample across the scan, based on user-defined threshold values. An intensity score for each subsequent sample in the remaining scans was computed relative to the background score and groups of samples that exceeded the user-defined threshold were amalgamated into blips. For my data that were digitized with an 8-bit card at 4096 pulses per scan, each sample had a value between 0 and 4096.

The tracker plugin is based on a multiframe correspondence (MFC) algorithm (Shafique and Shah 2005) that builds active tracks by matching targets from two scans, based upon distance, velocity and blip characteristics (e.g., number of samples, area). When the third scan occurs, the algorithm predicts where that target will be, based on matching targets

of similar characteristics and trajectories from the first two scans. As with blip filtering, several user-defined variables are set in the MFC algorithm and within the tracker plugin controls. For detailed explanations of the blip filtering and tracker plugins refer to Taylor et al. (2010).

I determined through preliminary testing of the radar data and consultations with the radR design team that adjustment to four variables among the blip filtering and tracker plugins resulted in the greatest variability among the detection and tracking of true targets (J. Brzustowski, pers. comm.; Table 2 1). To determine the minimal values for each of these four variables for testing I examined radR outputs of known avian targets collected from paired radar and visual monitoring conducted at various airports in British Columbia (M. d'Entremont, unpublished data). I made visual observations of small birds (e.g., passerines), medium sized birds (e.g., waterfowl, gulls and crow) and large birds (e.g., eagles) at varying distances within the radar detection field. I cross-referenced the visual observation data with the radR output and the average values for the various variables were used to set lower limits for testing. Each variable is described below.

“Min blip samples” represented the minimum number of samples in a patch – essentially the minimum size and intensity of the target. In 2008 and 2009 the radar data were recorded with a version of WinHorizon that offered 1024 pulses per scan (i.e., lower resolution) resulting in a lower number of samples for each blip. For these years I tested the values 7, 8, and 9. The 2010 to 2012 data were recorded at a higher resolution (e.g., 4096 pulses per scan) resulting in a higher number of samples in each blip; therefore the values of 10, 15 and 20 were tested.

Table 2-1. Variables adjusted within radR for auto-detection and tracking of avian targets from radar recorded with the XIR3000B signal processor. Variation in the tested value for blip filtering is due to upgrades with the WinHorizon software from 1024 to 4096 scan lines in 2010.

Plugin	Variable	Description	Tested Value
Blip filtering	min blip samples	The minimum number of samples in a patch of hot targets.	7, 8, 9 (2008-2009 data) 10, 15, 20 (2010-2011 data)
Tracker	minimum number of blips required for a track	If a track does not meet the minimum number of blips required it is discarded.	4, 5
Tracker	number of scans to backtrack over in building tracks	The algorithm will look back at a specific number of scans when considering all possible connections to the next blip.	2, 3
Tracker	minimum gain for a blip to join a track	The gain function is used for evaluating the match between blips in an active track to a blip in the next scan.	10, 15, 20

“Minimum number of blips required for a track” was used to reduce or eliminate the number of false tracks that were logged. Values that were too low would result in the tracking of more false targets, whereas when values were too high, true targets with shorter trajectories (e.g., on periphery of detection zones) may fail to be tracked. Commonly, three to four successive returns are used to confirm a blip is a true target (J. Brzustowski, pers. comm., Krijgsveld et al. 2010), but in some studies more conservative approaches require five successive returns. I tested values of four versus five to determine which was more accurate for tracking true targets in the data.

“Number of scans to backtrack over in building tracks” was used to minimize the number of tracks that were dropped. If a value was too high there was a greater risk of including blips not associated with the active track thereby dropping an actual track of a true target. I tested whether backtracking two versus three scans gave greater reliability in target tracking.

“Minimum gain for a blip to join a track” – the MFC algorithm had a gain function that returned the quality of a match between each new blip and blips within an active track based on the proximity of the new blip to the next blip location predicted for the track. It did this by assuming both constant target velocity and the homogeneity of target velocity when determining if the new blip was statistically linked to the blips in an active track. This function reduced the chance of an active track selecting blips from an adjacent active track. I tested threshold values of 10, 15 and 20 for the variable “minimum gain for a blip to join a track” to determine where the optimal match between track and blip would lie.

To identify the best-suited values for the blip filtering and tracker variables to use for my radar data processing I subjected these 29 15-min recordings to Auto-detection using

radR. Each 15-min sample was processed under the 36 different permutations of the blip filtering and tracker variables (every combination of tested values in Table 2-1) for a total of 1044 individual outputs. Using the Auto-detection method in radR, each 15-min sample period took less than 1 min to be processed. I fitted a linear regression separately for each of the 36 trials using the number of targets detected from the Manually-detection method as the independent variable and the number of targets detected using the Auto-detection method as the dependent variable to identify which combination of blip-filtering and tracker variables provided the best relationship between Auto-detection method and the actual known targets from the Manual-detection method. Statistical analysis was completed using Statistica Version 12 (Statsoft Inc. 2014).

2.2.4 Field radar data analysis

To demonstrated the potential for additional information gathering afforded by the Auto-detection method, relative to Real-time detection method, I correlated the number of targets auto-tracked from 24 of the 15-min periods used above to the number of targets recorded by observers using Real-time detection in the field for the same time periods (Pomeroy et al. 2010). Observers in the field used conventionally-accepted methods of counting targets as they appear on screen (as described above), with neither the ability to pause or review recordings. These Real-time detections in the field took 15 mins, the length of the recording period.

2.2.5 Filtering for non-vertebrate aerial targets

Tracking of non-vertebrate aerial targets, such as insects or non-biological targets is a common issue that requires attention when processing radar data (Larkin 1991,

Schmaljohann et al. 2008). This was true for my data as I visually observed insects on nights when temperatures were 10°C or higher and wind speeds were low. I also calibrated the intensity of high and low periods of insect presence from observations with an iGEN 20/20 night vision scope (iGEN, El Paso, TX, <http://www.igen2020.com>; D. Walsh, M. d’Entremont and K.A. Otter, unpublished data). In most cases these non-vertebrate aerial targets were moving at a lower speed relative to other targets on the radar monitor and were often moving in a different trajectory, mirroring passive movement with wind currents characteristic of insects (Cabrera-Cruz et al. 2013). These targets were recorded by the radar as oblong-shaped, low-intensity targets and were detected primarily at closer ranges (e.g., <750 m). I used the flexible blip filtering controls in radR, where an R logical expression was used to further refine the blip filtering criteria (Taylor et al. 2010), to test radR’s ability to filter out these false targets in the radar data. I applied an R expression to filter patches where the perimeter of the detected blip was disproportionately large compared to its area (Equation 1) these characteristics were indicative of false targets, such as insects, but tend not to be

$$\frac{perim^2}{area * (4 * pi)} < 5 \quad [Eq. 1]$$

associated with the desired true targets, such as birds and bats. Using this expression a true target was assumed to be circular in shape and was measured as a scale invariant index by squaring its perimeter. True targets of similar shape will have a similar index regardless of their size. Targets that were at least five times as irregular as a circle were filtered out. I also tested the addition of an intensity filter ($int > 0.3$) to the above area expression equation to eliminate targets with both diffuse area and low signal-return intensity.

I assumed that aerial vertebrate targets were predominantly birds, and refer to them as such hereafter for simplicity. I ran a paired analysis from 12 nights where 15 min periods of

radar data were gathered during three time periods within each night where visual and night-vision data confirmed: 1) insects were predominant (twilight period; n = 12); 2) both birds and insects were present (post-twilight to midnight; n = 12); and, 3) where birds were predominant (midnight to approximately 02:00; n = 12). For each grouping I determined the total number of targets using the full logical expression filter (Equation 2) the logical

$$\frac{perim^2}{area * (4 * pi)} < 5 \& int > 0.3 \quad [Eq. 2]$$

expression filter without the intensity expression (Equation 1) and with no logical expression filter. I anticipated that the number of tracked targets should not only decrease when the filters were applied (as false targets are being eliminated), but that the magnitude of this target reduction should be greatest during periods of the nights where the majority of targets were known to be false (twilight period) and target reduction should be lowest during periods of the night where most of the targets were aerial vertebrates (midnight to 02:00). I tested these predictions using a repeated measures General Linear Model with the number of targets detected under the various filters as the dependent variables and the different categories (predominately birds, insects and birds combined and predominantly insects) and date as categorical factors. I then calculated the proportion of targets retained between filtered versus non-filtered trials among the different categories and compared these using a Friedman ANOVA.

2.3 Results

2.3.1 Comparison of the number of targets from Auto-detection versus Manual-detection

Using the range of tested values for blip filtering and tracker processing in radR, I ranked the various permutations of values based on the linear relationships between the

number of targets that were tracked using Manual-detection versus the number of targets that were tracked using the Auto-detection method (Table 2-2), and used this to identify the best combination of radR settings for auto-detection and tracking of data. The best permutation (equated as having the highest R^2 value) had a “min blip samples” value of 9 for the 2008 and 2009 data and a value of 20 for the 2010 and 2011 data. The other variables of the best permutation included a “minimum number of blips required for a track” value of 4; a “number of scans to backtrack over in building tracks” value of 2 and a “minimum gain for a blip to join a track” value of 20 ($R^2 = 0.94$; $intercept = -61.38$, $slope = 1.56$). This combination of values had a strong linear regression between manual and automated-tracking (Fig. 2-2).

I compared the radR output for the 15 min periods where movement was less intense to those where movement was more intense. In both instances, the protocol had similar and very strong relationship between number of Manual-detected targets and the number of Auto-detected targets (higher-intensity movement periods: $R^2 = 0.93$, $F_{1,13} = 83.5$, $P < 0.001$, $n = 14$; lower-intensity movement periods: $R^2 = 0.89$; $F_{1,12} = 47.6$, $P < 0.001$, $n = 13$).

2.3.2 Comparison of auto-tracked versus real-time field analysis

Overall, there was a 300% increase in the number of targets detected using the Auto-detection method compared to the number of targets using the Real-time detection method in the field (Table 2-3). For less intense movement periods the number of targets detected when transcribing target data in real-time were moderately correlated to the number of targets detected using the automated methods ($r = 0.69$, $P < 0.01$, $N = 17$), although the number of targets detected increased by an average of 176%. Under the higher-intensity movement periods the number of targets detected when transcribing target data in real-time showed low

Table 2-2. Ranking of performance, based on R^2 , between the number of targets auto-detected versus the number of targets manually detected, from the 36 different trials used for determining the best-suited values for blip filtering and tracking in radR.

Rank of Variable Setting Combinations	Variables				R^2
	Min Blip Samples	minimum number of blips required for a track	number of scans to backtrack over in building tracks	minimum gain for a blip to join a track	
1	9 (2008/2009) 20 (2010/2011)	4	2	20	0.938
2	8 (2008/2009) 15 (2010/2011)	4	2	15	0.936
3	9 (2008/2009) 20 (2010/2011)	4	3	20	0.932
4	7 (2008/2009) 10 (2010/2011)	4	2	15	0.929
5	9 (2008/2009) 20 (2010/2011)	5	2	10	0.928
6	9 (2008/2009) 20 (2010/2011)	5	3	15	0.924
8	8 (2008/2009) 15 (2010/2011)	4	2	20	0.921
8	8 (2008/2009) 15 (2010/2011)	4	3	20	0.921
8	8 (2008/2009) 15 (2010/2011)	4	3	20	0.921
10	9 (2008/2009) 20 (2010/2011)	5	3	20	0.920

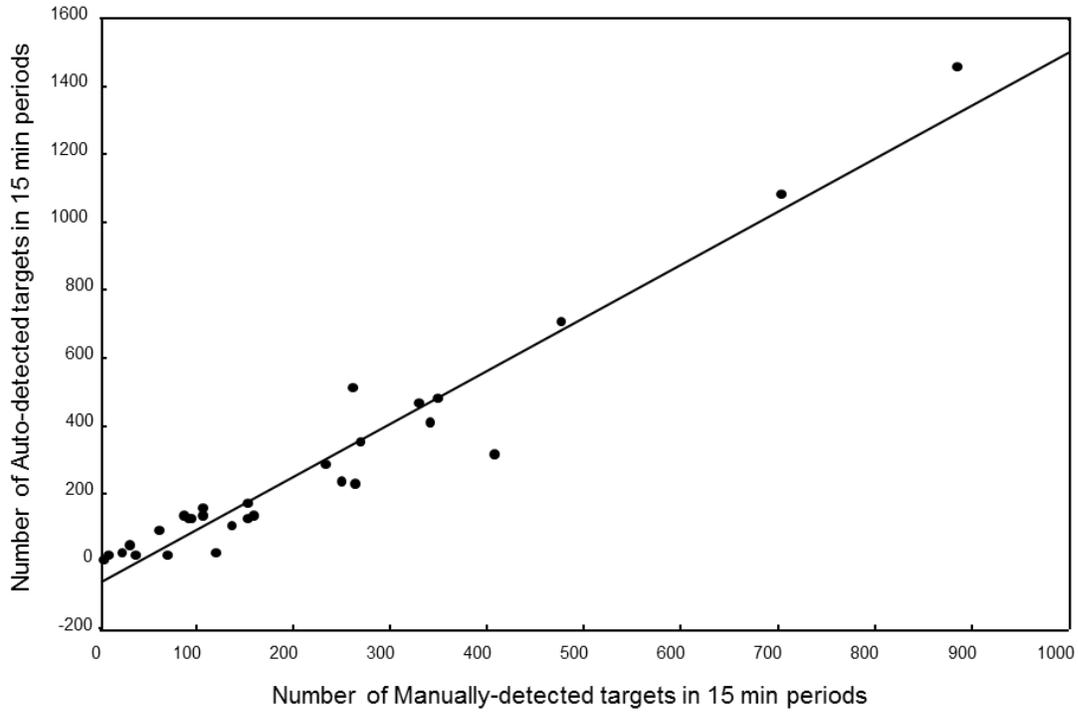


Fig. 2-2. Relationship between the estimated number of targets detected from 29 15-min sample periods of radar data processed in with the Auto-detection method compared to the number of nocturnal migrants identified using the Manual-detection method of the same data. Estimated numbers were established through auto-tracking functions in radR using the using the highest-performing combination of values for blip filtering and tracking tested ($R^2 = 0.94$, *intercept* = -61.38, *slope* = 1.56). All data were collected at the Dokie I Wind Energy Project from 2008 to 2011.

Table 2-3. Effect of using the automated tracking methods in radR compared to the manual collection of radar data for nocturnal songbird movements collected at the Dokie I Wind Energy Project in northeast British Columbia from 2008 to 2010..

Sample Dates	Time Period	Real-time Counts	Automated radR Counts	Increase with automation (%)
13 May 2008	21:46 to 22:00	10	16	60.0%
13 May 2008	22:01 to 22:15	17	43	152.9%
13 May 2008	22:16 to 22:30	24	153	537.5%
17 May 2008	22:30 to 22:44	45	511	1035.6%
17 May 2008	22:45 to 22:59	92	462	402.2%
17 May 2008	23:00 to 23:14	51	234	358.8%
17 May 2008	23:15 to 23:29	41	229	458.5%
18 May 2008	23:30 to 23:44	24	93	287.5%
18 May 2008	23:45 to 23:59	35	129	268.6%
18 May 2008	00:00 to 00:14	35	132	277.1%
18 May 2008	00:15 to 00:29	41	129	214.6%
14 May 2009	22:40 to 22:54	50	136	172.0%
14 May 2009	22:55 to 23:09	40	108	170.0%
14 May 2009	23:10 to 23:24	44	126	186.4%
14 May 2009	23:25 to 23:39	56	136	142.9%
15 May 2009	21:45 to 21:59	10	5	-50.0%
15 May 2009	22:00 to 22:14	21	15	-28.6%
15 May 2009	22:15 to 22:29	39	17	-56.4%
15 May 2009	22:30 to 22:44	39	24	-38.5%
22 May 2010	22:11 to 22:25	11	28	154.5%
22 May 2010	22:26 to 22:40	58	166	186.2%
22 May 2010	22:41 to 22:55	65	314	383.1%
23 May 2010	01:50 to 02:04	45	288	540.0%
23 May 2010	02:05 to 02:19	42	352	738.1%
OVERALL		935	3846	311.3%

correlation to the number of targets detected using the automated method ($r = 0.40$, $P < 0.01$, $N = 12$). During these higher intense periods the number of Auto-detected targets was an average 563% higher than those recorded via Real-time detection.

2.3.3 *Filtering for non-vertebrate aerial targets*

The use of the R logical expression in the blip filtering reduced the number of tracked targets between the three biological target categories (predominately birds, insects and birds combined and predominantly insects). In all cases, there is a significant reduction (all $P < 0.01$) in the number of targets tracked when the full filter and filter without the intensity factor are applied compared to when no filter is applied (Fig. 2-3), but the filter effect between the three different target-type categories was not quite significant ($F_{4,44} = 2.44$, $P = 0.06$). There was a significant difference among different biological target categories in the proportion of targets remaining between filtered and non-filtered data (Friedman ANOVA: $\chi^2 = 15.0$; $P = 0.001$). To determine where this difference lay, I conducted a multiple comparison following a Friedman test (Conover 1999) of the three treatment types (predominately birds, predominantly insects or mixed insects/birds). The reduction in proportion of targets tracked was significantly greater in periods of the night where targets were predominantly insect-like returns, compared to periods that were predominantly avian targets ($P < 0.05$) or when both insects and birds were present ($P < 0.05$). There were no differences in target reduction between periods of mixed insect/bird versus predominantly birds.

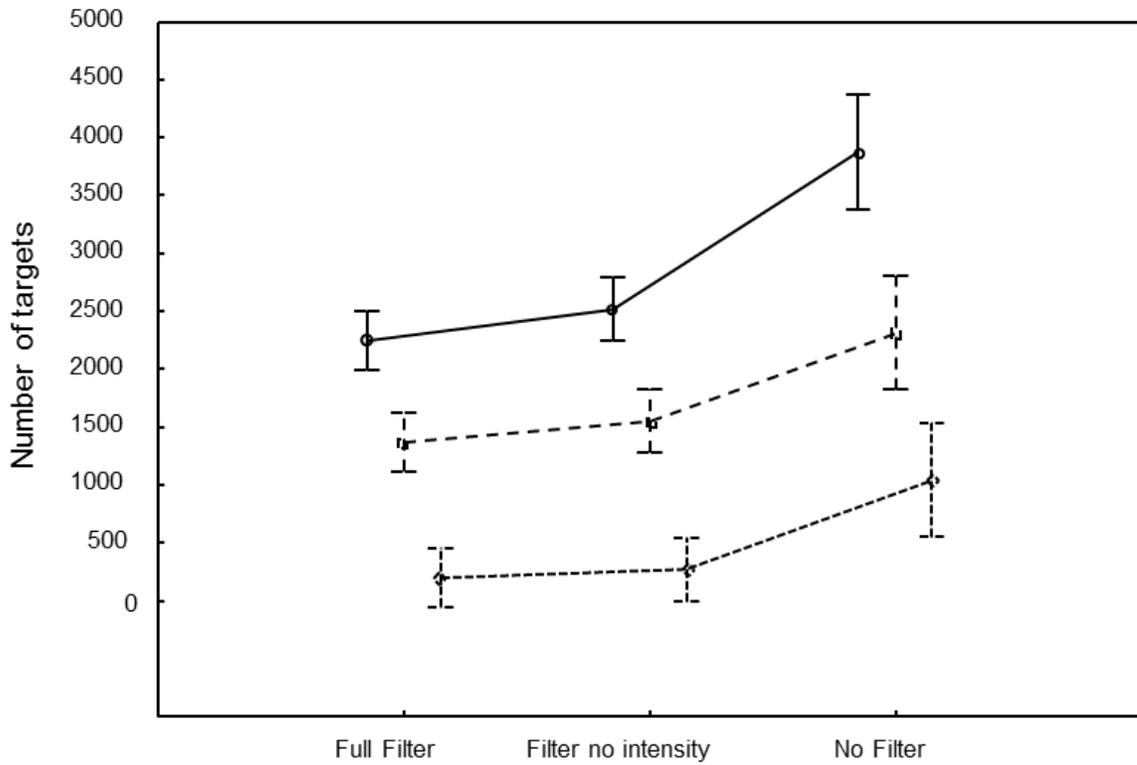


Fig. 2-3. The repeated measures General Linear Model revealed an almost significant effect in the number of tracked targets when comparing unfiltered radar data to the two levels of filtered data (with and without intensity expression added) for the 12 nights of data where 15 min periods were extracted on the predominantly insect samples (dotted line), the predominantly bird samples (dashed line) and the bird and insect samples (solid line). Data was collected at the Dokie I Wind Energy Project from 2008 to 2012. The Friedman ANOVA showed that the reduction in targets tracked was significantly greater in periods of the night where targets were predominantly insect-like, compared to periods that were predominantly bird targets or when both insects and birds were present.

2.4 Discussion

My results showed that digitization of radar imagery and use of available open-source processing software to auto-track aerial vertebrate targets can effectively increase the ability to accurately census the movement patterns of birds without necessarily increasing post-analysis time. First, I found that birds were detected and tracked with high accuracy using the Auto-detection method, when compared to known birds that were Manually-detected and tracked from recorded data. Second, the Auto-detection and tracking of targets from recorded imagery using radR software increased the number of detected targets by over 500% during periods of intense movement compared to the Real-time detection and tracking of live radar imagery, suggesting a much greater potential accuracy in censusing by making use of digital recordings and auto-tracking targets from recorded data. This accuracy, though, does not come at a cost of increase personnel time – while Manual-detection and tracking in post-analysis greatly exceeds the time required to census live imagery in real-time, Auto-detection and tracking of recorded data required the least amount of personnel time. Third, recording radar imagery allowed the application of target filter features which appeared to be highly effective at reducing the number of non-vertebrate aerial targets. This allows potentially more accurate assessment of avian movement patterns in relation to wind installations or other structures of interest. Using this system, the radar operator can invest less time overall in the field on the collection of radar data by letting the system autonomously record data, then use the Auto-detection and tracking of aerial vertebrate targets from the digital radar data to expedite the analysis component.

The system I used for automating target detection and tracking is comparable to other, more expensive, commercial systems that offer radar and computer techniques developed

specifically for detecting and tracking the unique behavioural characteristics of birds (Krijgsveld et al. 2005, Merritt et al. 2008). These other systems also employ target-finding algorithms that follow the basic steps of suppressing or eliminating stationary clutter and then tracking moving targets where at least three echoes are required to make a track, however, issues remain with regard to the identification and tracking of false targets and the splitting of an automated track from a single target into two or more tracks (Krijgsveld et al. 2010). Using filters designed to exclude targets that had diffuse shapes and intensity characteristic of insects; the system I tested appeared to be highly effective at excluding false targets. Further, I was able to optimize settings associated with target size, return intensity and persistence between successive radar scans to have a high degree of congruence between auto-detected targets to those manually-detected targets. While the application of filters and the use of auto-detection and tracking in my recorded data likely excluded some true targets, and integrated some false targets, my results suggest that this system still represents a significant advance in the accuracy of avian movement censusing than is offered by real-time analysis.

The auto-tracking of aerial vertebrate targets with digital radar data greatly increases the number of targets that are detected compared to real-time recording of data from the radar monitor in the field. The digitized raw radar scans also provide considerably more information about aerial vertebrate targets than is typically displayed on standard radar screen (Taylor et al. 2010) such as precise locations that can be used to calculate speed and flight direction. Further, by digitally recording radar data, the entire night of aerial vertebrate movements can be sampled while eliminating biases from observer fatigue or multi-observer variability. It can also combat the inability of real-time observers to record all targets during

periods of more intense movements, thereby allowing for a more complete understanding of the nightly nocturnal movement behaviour. This improvement in data accuracy is likely to improve assessment of potential impacts of wind installations on migratory bird populations.

The auto-detection approach I used is effective when comparing relative passage rates (typically measured as birds/km/hr), that are used in reporting the movement of birds around wind energy projects (Harmata et al. 1999, Mabee et al. 2006). Comparing changes in the altitude of birds can be presented in a Before-After-Control-Impact design approach for measuring the impact on birds from wind energy projects (Chapter 3). This approach is also flexible if the required objective is to document daily or seasonal counts of birds in a defined area. When an accurate estimate of passage rate is desired, the application of a linear regression equation to automated counts can be used as a correction factor to achieve this outcome.

The auto-detection analysis also addresses the common issue of differentiating aerial vertebrates from insects and/or non-biological targets when processing and tracking radar data (Larkin 1991, Schmaljohann et al. 2008). Typically, differentiation between bird and insect targets in radar data is carried out by calculating respective airspeeds (Schmaljohann et al. 2008, Cabrera-Cruz et al. 2013), however, at wind energy sites wind speeds may be sufficiently high to cause the passive movement of insects to overlap flight speeds associated with birds. I have demonstrated that a high proportion of insect contamination can be filtered based on the target characteristics measured by radR. The insects present in my study were those that are common in northern latitudes including large, soft-bodied insects such as moths. In other locales where insect targets may have similar return signatures as bird targets,

additional filtering for insects would be possible using the output from radR to calculate speed and direction of travel relative to the local winds.

The detailed biological data on the movement of birds collected using digital recordings and auto-detection will provide opportunities to learn more about the spatiotemporal patterns of movement (Ruth et al. 2005, Fijn et al. 2015) and can allow for informed decisions for the placement of wind turbines (Ruth 2007). This system could also have broad application in other situations where spatiotemporal analysis of movement patterns is of primary concern in avian conservation, such as movement of birds around airfields and potential for collision risk, or in relation to collisions around transmission lines or towers.

3 MICRO-SCALE MOVEMENTS OF NOCTURNAL MIGRANTS AROUND A WIND ENERGY FACILITY IN NORTHEAST BRITISH COLUMBIA, CANADA DURING PRE-OPERATIONAL AND OPERATIONAL PERIODS

Abstract - I investigated the passage of nocturnal migrants at the Dokie I Wind Energy Project in northeast British Columbia during the pre-operational and operational periods using two open array marine surveillance radars from 2008 to 2012. Micro-scale movements were examined as the deviation between average hourly track bearings of nocturnal migrants and the average wind vector on a nightly basis, the average hourly altitude of migrants and the average hourly number of migrants flying in the airspace closest to the wind turbines. In general, passage rates and flight trajectories did not significantly change between the pre-operational and operational periods, suggesting there was little effect on migratory directionality from the presence of wind turbines. Despite variations in wind conditions between seasons, migrants showed consistent directionality and general trends of broad-front migration patterns. The altitude at which migrants flew did differ with development phase of the wind facility, with migrants flying at higher altitudes during years when the turbines were operational. In general, though, the overall altitudes used by migrants were typically higher than turbine height, so the adjustments I documented were further reducing the current low levels of collision risk. In conclusion, at the micro-scale level nocturnal migrants were not significantly adjusting their movements around the wind energy facility during the operational period and their typical migratory behaviour did not place them in potential collision risk situations.

3.1 Introduction

In North America, passerine birds migrate in a broad-front fashion between breeding and non-breeding grounds along relatively well-documented corridors, stopping for periods in which to rest and replenish fuel stores (Gauthreaux 1991, Able 2004, Liechti et al. 2013). At this broad spatial and temporal scale (macroscale of 100s of km), directionality of migration movements are predictable (Mabey 2004). The site-specific timing and spatial patterns of movements of migratory birds at individual locations (microscale of 1-10km) along these corridors are less understood, particularly because variation in weather and topography can influence these patterns (Mabey 2004, Liechti et al. 2013, Pocerwicz et al. 2013). Understanding movement patterns on these small microscales is required to identify whether anthropogenic developments, such as wind installations or other tall structures built along migration corridors, can lead to disruption of migration or collision risk.

While nocturnally-migrating passerines have been recorded at a range of altitudes up to 5,000 m, most appear to migrate at relatively low heights between 100 m and 750 m above the ground (Able 2004, Mabee et al. 2006, Longcore et al. 2008) during both spring and fall movements (Bruderer 1997b). Migrants will typically climb to altitudes where they encounter favourable winds, which are used to maximize flight ranges on a given amount of fuel stores (Schaub et al. 2004, Klaassen et al. 2008, Marques et al. 2014). Wind layers at greater heights above ground are less subject to surface friction, and thus create more stable and predictable winds to facilitate migration (Klaassen et al. 2008, Dokter et al. 2013), however, altitude choice must be balanced with limitations on exceeding altitudes where extreme cold and lower oxygen for respiration occur (Able 2004). This results in nocturnal migrants settling their movement each night within the most profitable wind layer available

that balances these factors (Schaub et al. 2004). Flight altitudes generally peak early in the evening and are typically higher than those observed later in the evening/early morning (Mabee et al. 2006); this altitudinal profile of nocturnal migrants during a night, though, is influenced by topography and wind (Bruderer 1997b). Because of the relatively low flight altitudes, migrants can be exposed to terrain forced winds when moving over mountain ranges that may oppose the principal direction of migration (Bruderer 1997b, Liechti et al. 2013). Under such conditions, the flight paths of migrants may be scattered and subject to topographic features and structures on the landscape (Mabee 2004), further adding to the unpredictable patterns of movement at a fine-scale.

Understanding of fine-scale movement patterns, and the factors that govern them, may prove a useful tool in determining the potential impact of wind power development on the patterns of migration for passerines. During the spring and fall migration periods nocturnally-migrating passerines are the most abundant avian group encountering wind energy facilities (Marques et al. 2014), which is reflected in the high proportion of passerine carcasses that are typically found at wind projects (Johnson et al. 2002, Zimmerling et al. 2013, Erickson et al. 2014). Passerines typically comprise 80% of all fatalities at such installations, most of which involve nocturnal migrants (Mabee et al. 2006, Kuvlesky et al. 2007). While this likely constitutes a small fraction of overall population sizes (Loss et al. 2013, Zimmerling et al. 2013), effects on birds remains among the forefront of environmental assessments for wind energy developments (Zimmerling et al. 2013). The general knowledge of the interactions between birds and wind turbines has substantially increased since the infancy of the wind energy industry (Marques et al. 2014), but before-and-after development

studies on how wind facilities affect the migratory behaviour of passerines are still sparse (Kuvlesky et al. 2007).

Avoidance behaviour by nocturnal migrants will strongly influence the mortality rates observed at wind energy projects (Chamberlain et al. 2006), but the scale of avoidance to wind turbines for nocturnally migrating birds is almost unknown (Liechti et al. 2013). Two levels of magnitude are expected for the avoidance of wind turbines: 1) macro-scale avoidance where birds alter their flight path to circumnavigate an entire wind energy installation; and 2) micro-scale avoidance where birds alter their flight movements while they are passing within the boundaries of a wind energy installation (Marques et al. 2014). In this study, I documented the micro-scale patterns of nocturnal migrant movements through a 144 MW wind energy project in northeast British Columbia, Canada. Using X-band marine radar units, equipped with an electronic interface system, I recorded the movement patterns and altitudes of migrants to determine if spatial patterns of flight differ between pre-operational and operational periods of the wind energy facility.

3.2 Methods

3.2.1 Study area

I collected radar data on nocturnal migrants at the Dokie I Wind Energy Project located in northeast British Columbia, Canada during the spring and fall migration periods from 2008 to 2012 (Fig. 1-1). Site details are provided in section 1.8. For the analysis in this chapter, the first three years of the study (2008 – 2010) represent the pre-operational period for the wind energy facility and the final two years (2011 – 2012) represent the operational period.

3.2.2 *Data collection*

I recorded movement patterns of nocturnal migrants around the wind project using two Furuno X-band marine radar units (model 1954C, 12kW, 9,000 MHz, 1.83 m open array antennas – Furuno Electric Company Ltd. Miki Japan). One of the radar units was set in the surveillance position (antenna rotating on the typical horizontal axis) to record passage rates and the second unit was set in the vertical position (radar mounted at 90°, so that the antenna rotated through the vertical axis) to record heights of targets. The radar units were set in locations where minimal interference from ground clutter was present. The horizontal radar was mounted approximately 2.0 m above ground and oriented to true north. The vertical radar was mounted approximately 1.5 m above the ground and the antenna was aligned with the proposed/constructed turbine arrays (Fig. 2-1). Beam angles and radar settings are described in detail in section 2.2.2. Radar settings were standardized among years and the radars were set in the same locations each season (Fig. 2-1). Radars were generally operational from 21:00 to 05:00 each night in the spring and 20:00 to 06:00 in the fall. Recording dates varied slightly among years, but surveys were timed to coincide with the previously documented peak periods of spring passerine migration (mid- to late-May) and fall migration (late-August to early September) each year (Jacques Whitford-AXYS Ltd. 2006, Pomeroy et al. 2007).

Each radar unit was equipped with an electronic interface system (signal digitizer [XIR3000B] and WinHorizon software [Version 1.5.0.13 – Russell Technologies Inc., North Vancouver, BC; <http://www.russelltechnologies.ca/>]). Recorded radar imagery was analyzed using radR (Taylor et al. 2010), which distinguishes moving targets from stationary objects. Targets were identified in radR by establishing user-defined criteria to initially discriminate

moving bird targets as blips based on their size and shape (Chapter 2). These were then tracked with the tracker algorithm. Output data from radar for the tracked targets was further processed in the statistical program R (R Development Core Team 2014) to extract specific data on track location, length, bearing and speed (horizontal radar data) and specific height data and position within four height categories (0-300 m, 301-600 m, 601-900 m and 901-1200 m above ground level [agl]) (vertical radar data) for each target.

3.2.3 Wind data

I obtained wind vector data from the National Centres for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR) dataset using the three hour composite data for the zonal wind (U wind) and meridional wind (V wind). The latitude and longitude of the study site was matched with the nearest NARR 32 km by 32 km grid cell centre, which was approximately 10 km from the study site, and I obtained data from the 825 mb pressure level, which corresponds to approximately 500 m above ground level at the study site. This altitude was chosen as it corresponded to average heights of migrants detected during preliminary analysis. I calculated the wind vector as the direction, with respect to true north, towards which the wind was blowing; this allowed for the direct comparison with the direction to which migrants were moving. I used the two-argument arctangent function to calculate the inverse tangent of zonal wind / meridional wind and converted the output radians into degrees with Equation 3.

$$\text{Wind vector} = \text{atan2}(U, V) * r2d + 180 \quad [\text{Eq. 3}]$$

In Equation 3, U is the zonal velocity or the component of the horizontal wind towards the east and V is the meridional velocity or the component of the horizontal wind towards the north. The function $r2d$ represents the conversion from radians to degrees and

equals $45.0/\text{atan}(1)$. Nightly three hour composite wind vectors were calculated for the hours 20:00-22:00, 23:00-01:00 and 02:00-04:00. Composite wind vectors were used to calculate an average nightly wind vector, which I used in conjunction with the average nightly track bearing to determine if migrants were moving in relation to tailwind, headwind or crosswind condition. I considered tailwind conditions to be where the deviation between nightly average wind vector and nightly average track bearing was between 0° and 45° and headwind conditions to be where a deviation was between 135° and 180° . Finally, I considered crosswind conditions to be where deviations range from 45° to 135° . Average hourly wind vector and track bearing were calculated for each night of data collection. These data were analyzed with basic circular statistics (Oriana Version 4.02) to test for seasonal directionality of both wind vector and migration.

3.2.4 Migratory directionality relative to wind

I decomposed migration into the micro-scale movement represented by the 1.5 km radial range of the radar I used. From the horizontal radar data, the average hourly track bearings were calculated for each night of data collection. Given the length of the day-time period at the latitude of my study site, nightly nocturnal migration typically commenced an hour later in the spring compared to the fall. Direct comparisons between the spring and fall seasons were made by organizing the data into the hourly movement of birds starting from sunset. Subsequent hours were identified as sunset plus one hour, sunset plus two hours, etc., up to sunset plus seven hours.

I analyzed bird movement based on the deviation of the hourly average of flight trajectories (measured as track bearing based on the trajectory calculated from the location of the first and last detection of the target on the radar) from the corresponding three hour

composite wind vector calculated from the NARR data for each night of data collection. I measured deviation on an absolute scale from 0° to 180°, which assumes that nocturnal migrants would attempt to utilize favourable winds and that the deviation to wind vector can never be greater than 180°. I selected deviation between track bearing and wind vector as the metric to linearize the data and avoid biases of circularity, particularly as this relates to wraparound issues when analysing compass bearing data.

I used general linear mixed models (GLMM) to compare the average hourly deviation between track bearing and wind vector across different hours of the night (within-subject response). I added operational phase of the wind project (Pre-operational [2008-2010] vs Operational [2011-2012]) to the models as a between-subjects response to determine whether this affected deviations between track bearing and wind vector across the night.

3.2.5 *Migratory altitudes*

I determined the average hourly flight altitudes (above ground level [agl]) for each night of data collected using the vertical radar data. I ran a GLMM comparing the average hourly height of nocturnal migrants across the different hours of the night (within-subject response), and whether this differed between operational phase of the wind project (between-subject response).

I used a GLMM to compare the average hourly number of targets within the different height categories (0-300 m, 301-600 m, 601-900 m and 901-1200 m agl) for each night of data collection (within-subject response) and compared this between operational phases of the wind project (between-subject response).

3.3 Results

3.3.1 Overall passage rates of migrants

Over the five year survey period I auto-tracked a total of 2,293,814 aerial targets with the horizontal radar and a total of 598,834 aerial targets with the vertical radar (Table 3-1 and Table 3-2) with the radR processing. Periods of poor weather were excluded from the survey effort, which partially explains the variation in annual and seasonal survey effort. Technical difficulties with the radar equipment also caused minor gaps in the collection of data and these periods were excluded from the survey effort. In general, more targets are detected by the horizontal radar due to the larger detection area being covered by the radars in their respective orientations. Finally, a higher number of targets were consistently detected in the fall migration.

3.3.2 Migratory Directionality Relative to Wind Vector

Across the survey period the predominant wind vectors at the study site were generally to the northwest. The average wind vector in the spring was 353.13° with a circular standard deviation of 52.01° and the average wind vector in the fall was 335.89° with a circular standard deviation of 42.67° . The average target track bearing for the spring was 341.69° with a circular standard deviation of 38.03° (Fig. 3-1) and the average target track bearing for the fall was 136.98° with a circular standard deviation of 42.48° (Fig. 3-2). Thus, most transit during the northward spring migration occurred during tailwind conditions, while southern migration in the fall is predominantly under headwind conditions. In the spring, movements of birds were made under either tailwind ($n = 34$) or crosswind ($n = 14$) conditions, with no observation of movement under headwind conditions. In contrast, fall movements occurred under either headwind ($n = 23$) or crosswind ($n = 14$), but not tailwinds,

Table 3-1. The total numbers of tracked avian targets detected by the horizontal radar, by season and year, across the survey period from 2008-2012 at the Dokie I Wind Energy Project in northeast British Columbia. Variation in the number of nights surveyed between season and years reflected both problems encountered with weather and equipment. Target numbers shown reflect exclusion of non-avian targets through application of filter expressions in radR.

	2008		2009		2010		2011		2012	
	Spring	Fall*	Spring	Fall	Spring	Fall	Spring	Fall	Spring	Fall
Targets detected	120,934	-	8506	655,103	28,199	158,750	150,334	379,968	164,665	617,355
Number of nights surveyed	16	-	5	12	7	10	9	10	13	11
Date range over which sample collected	May 11 – May 31	-	May 12 – May 18	Aug 26 – Sep 7	May 19 – May 26	Aug 25 – Sep 3	May 19 – May 28	Aug 24 – Sep 2	May 18 – May 30	Aug 19 – Aug 29
Hours surveyed	99.9	-	34.3	112.5	23.0	83.6	57.6	70.7	91.6	94.0

*Fall 2008 -horizontal radar was non-operational in the fall of this first year of data collection.

Table 3-2. The total numbers of tracked avian targets detected by the vertical radar, by season and year, across the survey period from 2008-2012 at the Dokie I Wind Energy Project in northeast British Columbia. Variation in the number of nights surveyed between season and years reflected both problems encountered with weather and equipment. Target numbers shown reflect exclusion of non-avian targets through application of filter expressions in radR.

	2008		2009		2010		2011		2012	
	Spring	Fall								
Targets detected	23,875	45,125	3149	135,780	21,426	98,202	55,268	82,667	164,665	85,674
Number of nights surveyed	16	16	5	13	7	10	9	8	13	11
Date range over which sample collected	May 11 – May 31	Aug 21 – Sep 5	May 12 – May 18	Aug 26 – Sep 7	May 19 – May 26	Aug 25 – Sep 3	May 19 – May 28	Aug 24 – Sep 2	May 18 – May 30	Aug 19 – Aug 29
Hours surveyed	97.4	119.4	24.8	119.1	27.0	43.4	54.5	73.2	91.6	93.6

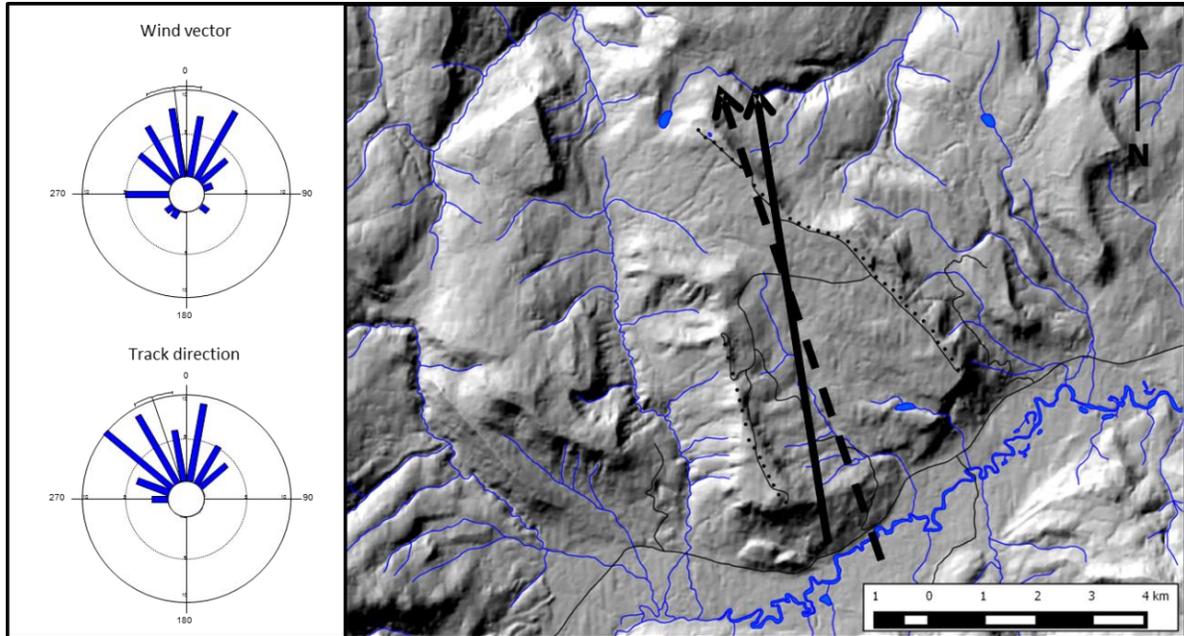


Fig. 3-1. The average wind vector across the study period (2008-2012) at the Dokie Wind Energy Project in northeast British Columbia during the spring is 353.13° (s.d. 52.01°), represented by the solid black arrow. The average direction of nocturnal migrants in the spring is 341.69° (s.d. 38.03°), represented by the dashed arrow. The circular histograms represent the relative variation in wind vector (top) and track bearing (bottom). The bars represent the number of values (e.g., tracks) in 20° intervals (e.g., 0° to 20° , 20° to 40° , etc.) and the length of the bars is proportional to the frequency of occurrence in each grouping. Mean vector/bearing with standard error are displayed by black lines.

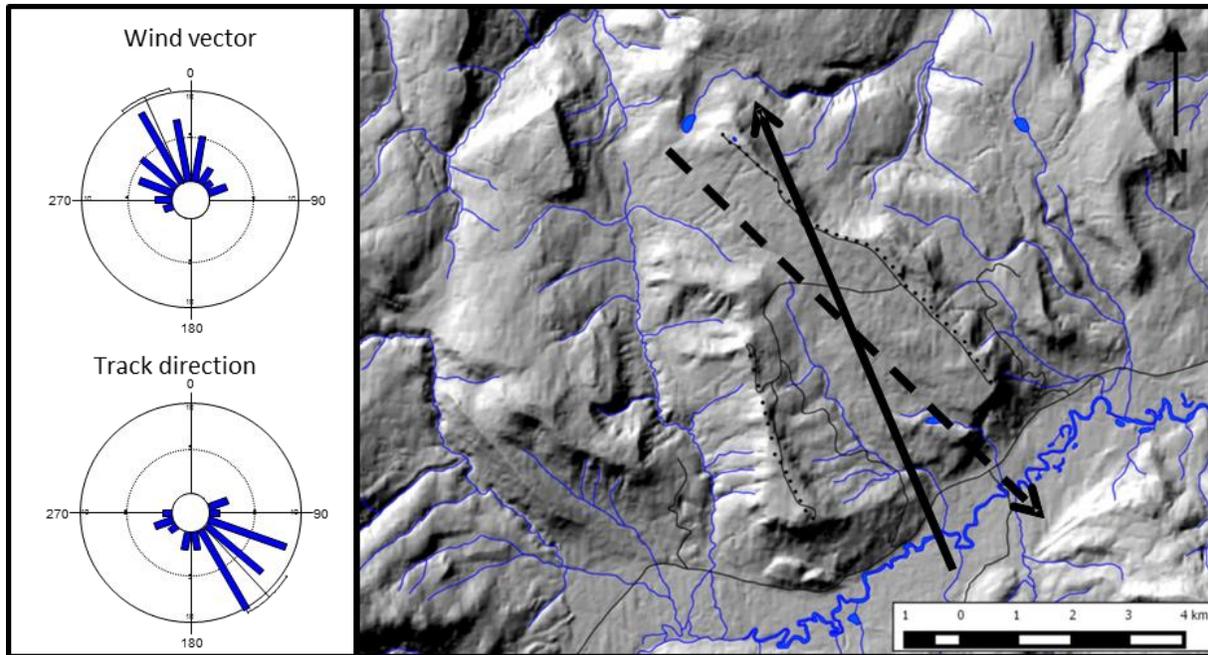


Fig. 3-2. The average wind direction across the study period (2008-2012) at the Dokie I Wind Energy Project in northeast British Columbia during the fall is 335.87° (s.d. 42.67°), represented by the solid black arrow. The average direction of nocturnal migrants in the fall is 136.98° (s.d. 42.48°), represented by the dashed arrow. The circular histograms represent the relative variation of wind vector (top) and track bearing (bottom). The bars represent the number of values (e.g., tracks) in 20° intervals (e.g., 0° to 20° , 20° to 40° , etc.) and the length of the bars is proportional to the frequency of occurrence in each grouping. Mean vector/bearing with standard error are displayed by black lines.

creating significant differences between the wind conditions birds faced between migratory seasons (Chi-squared test: $\chi^2 = 56.6$, $df = 2$, $P < 0.0001$). Given these differences in the nightly wind conditions birds encounter between seasons, I analysed the bird movement and height data separately for each season, which is consistent with other studies (Thomas 2008).

There was no differences in the average track bearings (relative to wind vector) across hours of the night ($F_{7,105} = 0.75$, $P = 0.63$) during spring migration, and no effect of either operational phase on overall track bearing ($F_{1,15} = 0.93$, $P = 0.35$) or the interaction between operational phase and deviation between track bearing relative to wind vector across nightly passage ($F_{7,105} = 1.69$, $P = 0.12$). The overall tailwind/crosswind conditions faced in the spring (above) are also reflected in hourly average deviations between track bearing and wind vector, but appeared to oscillate between predominantly tailwind conditions at the start of migration periods within a night and switching to occasional crosswind conditions later in the night (Fig. 3.3).

During fall migration, I found a significant difference in the variation across hours of the night in the deviation between track bearing versus wind vector ($F_{7,140} = 12.79$, $P < 0.01$). Again, however, there was no overall effect of operational phase on relative track bearing ($F_{1,20} = 1.10$, $P = 0.30$) or the interaction between operational phase and the deviation between track bearing versus wind vector across nightly passage ($F_{7,140} = 1.78$, $P = 0.10$). Upon embarking on movement each night, birds tended to face stronger crosswinds or headwind conditions as evidenced by relatively lower deviations, but on hourly inspection these quickly switched to predominantly headwind conditions through the night (Fig. 3.3).

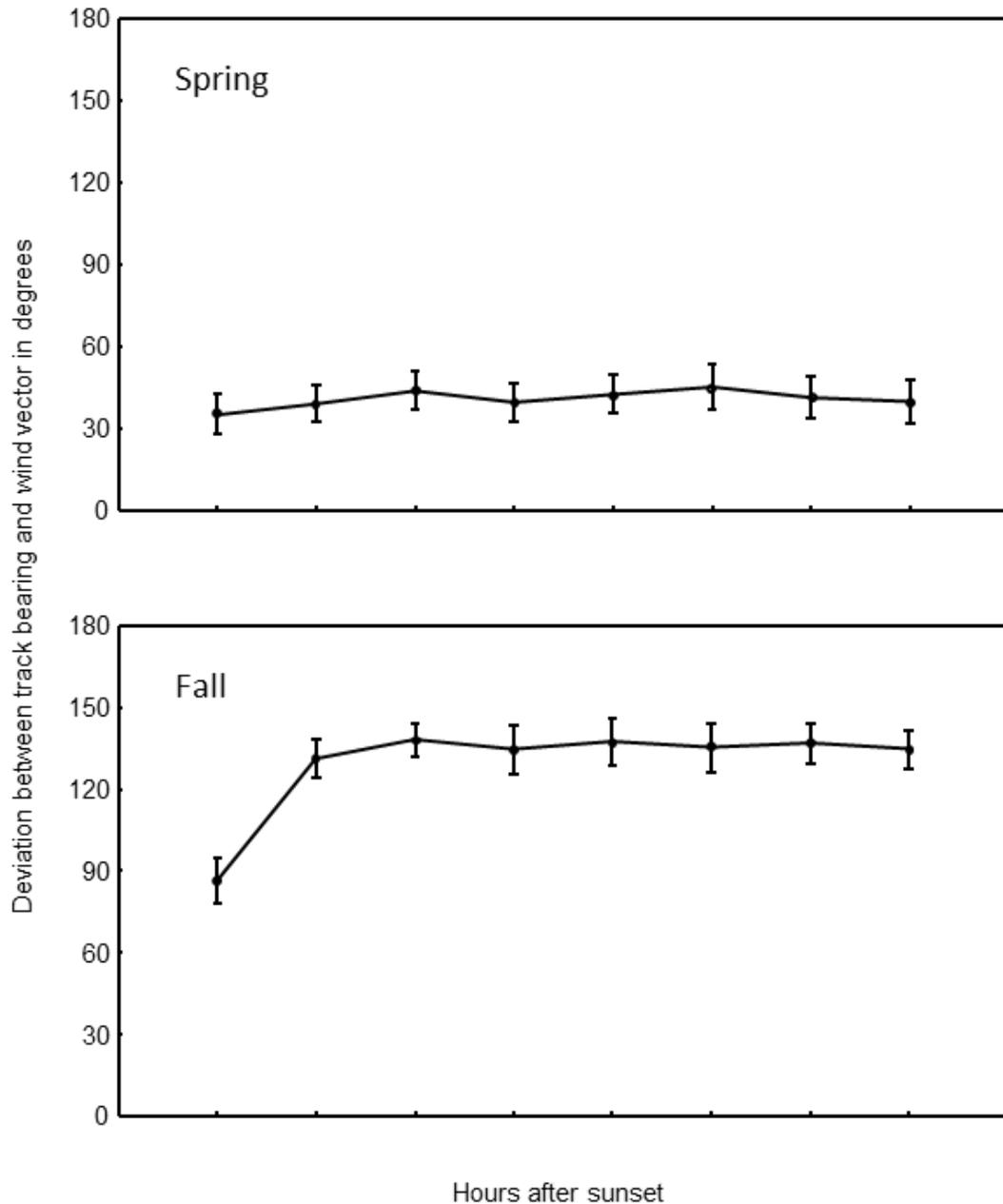


Fig. 3-3. Relationship between average hourly deviations (\pm SE) across the night between the track bearing of nocturnal migrants and wind vector in spring and fall recorded at the Dokie I Wind Energy Project in northeast British Columbia from 2008 to 2012. Values represent the absolute difference between track bearing and mean wind direction (0-180°), with 0-45° representing tailwinds, 45-135° crosswinds, and 135-180° headwinds. Migrants in the spring face tailwind conditions at the onset of nightly movement, but then face crosswind conditions as the night proceeds. In the fall, migrants start out facing crosswind conditions, but this quickly changes to headwind conditions for the remainder of the night.

3.3.3 Average heights of targets

During spring migration, the average height of targets varied significantly across hours of the night ($F_{7,119} = 5.72, P < 0.01$). Overall heights across nights were not affected by operational phase ($F_{1,17} = 3.30, P = 0.08$), but there was a significant interaction between operational phase and hour of the night ($F_{7,119} = 9.80, P < 0.01$). Because of this interaction, I analysed the data separately by operation phase.

Average hourly heights during the night were approximately 300 m to 350 m during the pre-operational period and did not significantly change across hours of the night ($F_{7,49} = 0.90, P = 0.51$). In contrast, average heights during the operational period changed significantly across hours of the night ($F_{7,30} = 17.81, P < 0.01$), beginning significantly lower (approximately 250 m agl) at sunset (Fishers LSD posthoc test: $P < 0.05$), but then increasing rapidly across the first three hours of migration to average between 400 m to 500 m agl by two hours after sunset and remaining at this level for the remainder of the night (Fig. 3-4).

Similar to the spring, the average heights of targets varied significantly across hours of the night in the fall ($F_{7,189} = 16.34, P < 0.01$). Again, the overall heights averaged across the night were not significantly affected by operational phase ($F_{1,27} = 3.54, P = 0.07$), but there was a significant interaction between operational phase and hour of the night ($F_{7,189} = 2.02, P = 0.05$). During the pre-operational period, the heights of migrants were approximately 250 m above the ground at the onset of nightly migration and then significantly increased to approximately 380 m agl two to three hours after sunset followed by a slight decline to approximately 325 m ($F_{7,119} = 4.97, P < 0.01$). Likewise during the first hour of the night in the operational period the heights of migrants were at approximately 250

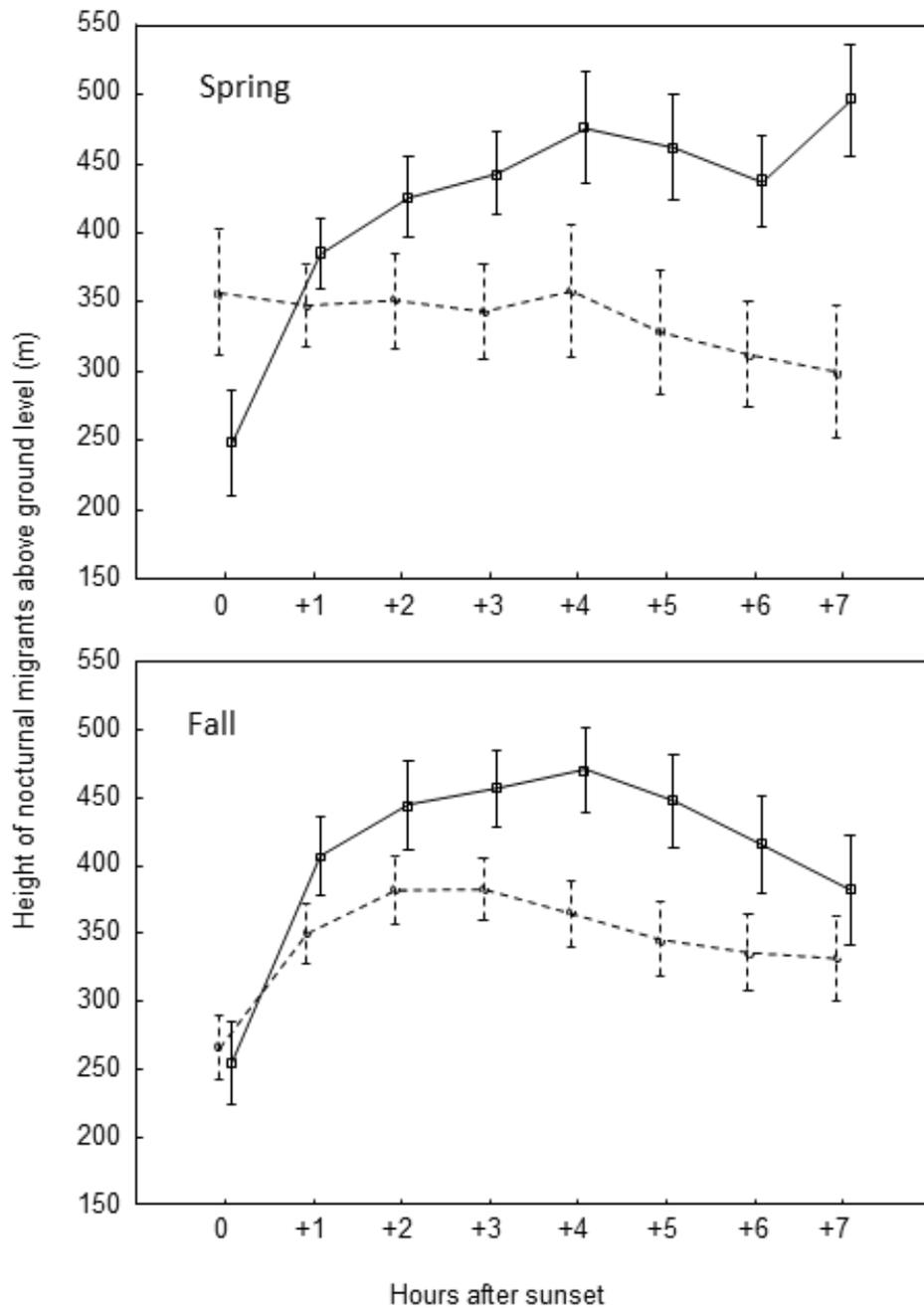


Fig. 3-4. Variation between the average hourly heights of nocturnal migrants (\pm SE) and operational phases in spring and fall at the Dokie I Wind Energy Project in northeast British Columbia from 2008 to 2012. Heights during the operational period (solid squares and lines) were approximately 120 m higher than heights recorded during the pre-operational period (dashed squares and lines) at peak heights in the spring and approximately 90 m higher during the operational period in the fall compared to the pre-operational period.

m, but significantly increased to approximately 470 m agl four hours after sunset and then declined to approximately 375 m ($F_{7,70} = 14.61$, $P < 0.01$) (Fig. 3.4)

3.3.4 *Number of targets by height category*

In both spring and fall, there were higher numbers of birds in the two lower height categories compared to the higher height categories, with this difference being far more marked in the fall ($F_{3,132} = 18.37$, $P < 0.01$) compared to the spring migration ($F_{3,111} = 20.24$, $P < 0.01$) (Fig. 3-5). There was no overall effect of operational phase ($F_{1,37} = 1.35$, $P = 0.25$) or an interaction between operational phase and height category ($F_{3,111} = 0.11$, $P = 0.95$). In the fall, operational phase did not have an effect ($F_{1,44} = 0.37$, $P = 0.55$) nor was there an interaction between operational phase and height category ($F_{3,132} = 0.08$, $P = 0.97$).

3.4 Discussion

The micro-scale movements of nocturnal migrants around the Dokie I Wind Energy facility vary by season, with higher passage rates in the fall than in the spring. This is expected since both adult and juvenile birds are moving during the post-breeding season in the fall (Harmata et al. 2000, Otter et al. 2014). Further, some fall migrants may have been bats, which are more prominent in the fall migration (Kunz et al. 2007). If migrants were making micro-scale adjustments in height in response to the presence of wind turbines, I expected to see a reduction in the number of targets at the lowest height category during operational phases of the wind farm. The number of targets detected in the lower height categories was, however, not affected by operational phase, but did show noticeable differences between seasons with a greater number of detected targets in the 0-300 m and

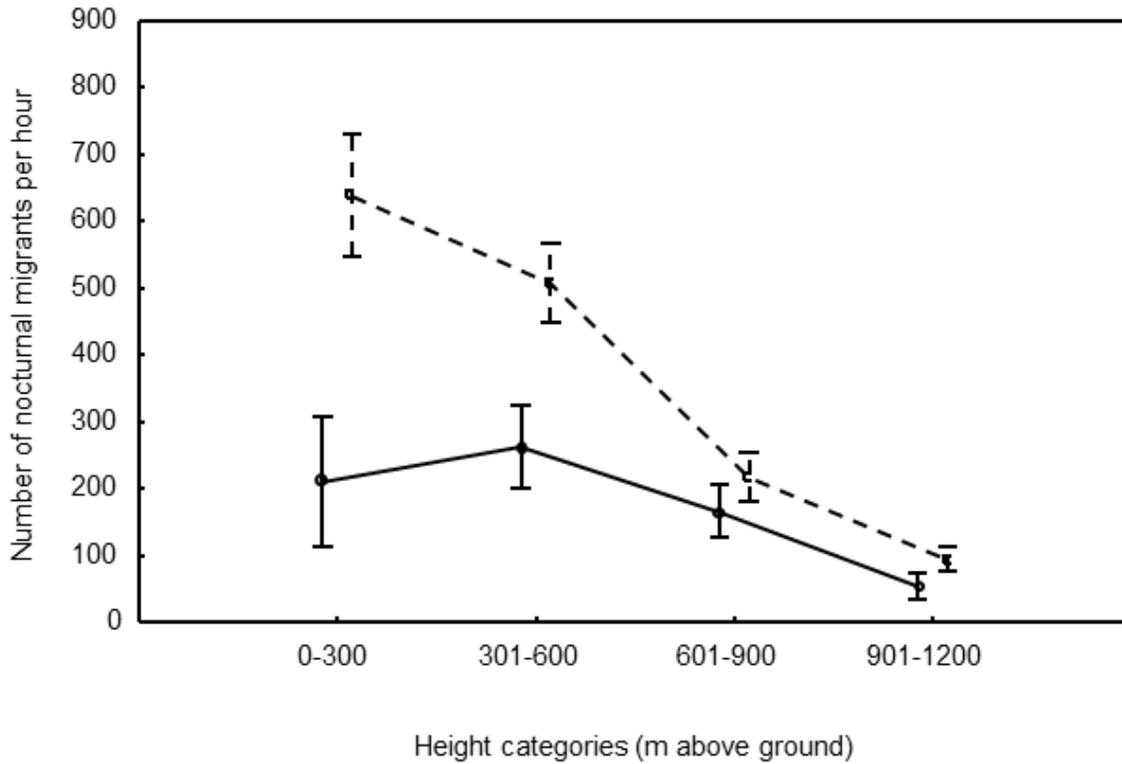


Fig. 3-5. Average number of birds (\pm SE) detected during the survey period (2008 to 2012) at the various height categories at the Dokie I Wind Energy Project in northeast British Columbia during spring (solid circles and line) and fall (dashed squares and line). There were significantly higher numbers of birds recorded in the two lowest height categories in each season, with this pattern being more marked in the fall compared to the spring.

301-600 m heights in the fall than spring. This suggests that migrants were not responding to the presence of wind turbines by avoiding these lower height regions. There was, however, a higher average hourly altitude of migrants tracked during the operational period, which suggests that nocturnal migrants may respond to the presence of the wind project by making minor adjustments to their heights.

The increase in altitude across the hours of the night during the operational period was not matched by a decrease in the number of targets detected at the lowest height category. The wind turbines in my study site were 120 m tall and migrants may have been making small-scale adjustments in altitude that affects the overall average of target heights while remaining within upper or lower bounds of the height categories. Further, the average altitude of migrants was higher than the height of wind turbines in both the pre-operational and operational periods, which suggests that migrants will typically avoid wind turbines under normal migratory conditions. Thus, while I found support for micro-scale adjustments in migratory behaviour in response to the presence of wind turbines, these adjustments were minor and would serve to further reduce already low collision risk with this facility. As the vast majority of nocturnal migrants were already moving above turbine height during pre-operational surveys, this suggested the impact of development from this particular wind energy project was low. This was consistent with post-construction carcass searching on the site that yielded very low estimated collision rates of <0.01% (Stantec Consulting Ltd. 2012a, Stantec Consulting Ltd. 2012a, Otter et al. 2014).

Despite variation in wind conditions between seasons, migrants showed consistent overall directionality and general trends of broad-front migration patterns. In the spring, migrants predominantly used favourable tailwinds, but when wind conditions changed,

migratory direction at the micro-scale level still appeared to remain fairly consistent. The smaller deviations between migratory track bearings and wind vector under tailwind compared to larger deviations under crosswind conditions in the spring and the larger deviations measured under headwind conditions provide an indication of this. Tailwind conditions are most favourable in the spring, but when the winds change to crosswind conditions birds appear to compensate for this as evidenced by the greater deviations between track bearing and wind vector. Likewise in the fall, despite facing headwind conditions, the large deviations between track bearing and wind vector suggest that the southward trajectory was fairly consistent. So despite encountering unfavourable winds, other factors, such as energy requirements or timing constraints to reach breeding or wintering grounds (Klaassen et al. 2008) appeared to be influencing migratory decisions at northern latitudes, which appeared to influence the overall avoidance rate of nocturnal migrants to wind turbines at northern latitudes.

Avoidance rates of nocturnally migrating species have not been extensively studied, but conservative estimates of 98% to 99% have been used in collision-risk models (Chamberlain et al. 2006, Liechti et al. 2013). Nocturnal migrants are primarily comprised of passerine species that are relatively abundant and widespread so subtle changes in avoidance rates can have large implications on the accuracy of collision-risk models (Chamberlain et al. 2006). Micro-scale avoidance at our study site seems restricted to minor adjustments in altitude during the operational phase of the wind installation, however, quantifying the degree of micro-scale avoidance remains a challenge as some migrants are flying below the heights of turbines and may be taking evasive actions at individual turbines. Preliminary results from night vision cameras set up at and between wind turbines in the study site

suggested that there may have been a slight decrease in the number birds moving near turbines compared to the number of birds detected between turbines, which would influence avoidance rates (Walsh 2012).

In conclusion, at the micro-scale level, nocturnal migrants showed some indications of adjusting their movements around the wind energy facility during the operational period, yet their typically migratory behaviour was also not placing them in collision risk situations for the most part. Subtle adjustments in altitude may be occurring, which would further reduce collision risk at the wind project level. Changes at the macro-scale level may be occurring to avoid wind energy facilities, although I found little evidence suggesting fewer detected targets during migratory seasons during the operational phase of the installation.

3.4.1 Management implications

The radar data from this study showed that there was high nocturnal migration movement through the northeast British Columbia region in both spring and fall, providing context to the number of migrants potentially exposed to collision-risk situations (Otter et al. 2014). At the Dokie I Wind Energy Project, during two years of post-construction mortality monitoring an estimate of 35 fatalities (birds and bats combined) were found during the periods when I was conducting radar surveys (Otter et al. 2014). After correcting these numbers for searcher efficiency and scavenger impact, the estimated annual mortality rate was <0.01%. Conversely, under normal migratory conditions, the avoidance rate of nocturnal migrants to wind turbines would be predicted to exceed 99.99%. As mentioned above, conservative estimates of avoidance rates have been used in collision-risk models. These estimates are based on migrant passage rates documented using conventional methods for the collection of radar data (see Chapter 2). The passage rates I recorded are not comparable to

other studies, particularly those that record radar data in real time. Using conventional methods, accurately recording all targets during periods of high migration traffic is challenging. Further, given the variability in the altitude of migrants, particularly at the beginning of the night, survey designs that do not consider all hours of the night are likely to inaccurately estimate passage rates and average altitude of migrants, which would affect the predictions of avoidance rates and collision risk. The detailed data on nocturnal migration from this study reduces the level of uncertainty in estimating passage rates and eliminates the need for conservative estimates of avoidance rates. These high avoidance rates may, however, reflect regional variation in collision risk, so I recommend using similar methodology to detail passage rates in relation to mortality rates in post-construction years to derive accurate, local collision risk estimates.

4 NOCTURNAL BIRD MOVEMENTS AT A WIND ENERGY PROJECT IN RESPONSE TO RAIN

Abstract - Unfavorable weather has been identified as a contributing factor in bird collisions with tall human-made structures. The increase in collision risk often results from birds descending to fly below the cloud cover during periods of rain. When human-made structures are placed in high-elevation sites, they may overlap in airspace with lower altitude migrants. In British Columbia, mountain ridges are increasingly being developed for placement of wind energy turbines; understanding whether night-migrating birds respond to adverse weather by reducing their flight altitudes relative to underlying topography is important for assessing collision risk. I collected digital radar data on the heights of migratory passerines over a wind energy project in northeast British Columbia and extracted specific data of bird movements at 300 m stratified height categories from ground level to 1200 m above ground. I documented the number of birds within each height category during two minute periods for up to one hour before and after 54 separate rain events. If birds are forced to fly lower or be grounded by rain events, I expected to see an increase in the number of birds in the lower height categories immediately before the rain event. I did not find evidence in support of this, suggesting that isolated rain events may not increase collision risk. Birds appeared to resume normal migratory behavior within 30 minutes after rain events suggesting that birds maintain migratory movements by flying around isolated rain events.

4.1 Introduction

Nocturnal migration by passerine bird species is a costly endeavour, both in energy expenditure and risk of exhaustion (Able 2004). This typically requires birds to spend

significant portions of their migratory period foraging to replenish fuel stores (Gauthreaux 1991, Able 2004). The rate at which they cover the migration distance is partially dependent on the quality of suitable foraging sites at stopover locations, and how quickly these can be used to replenish fat loads (Klaassen et al. 2008). Yet, decisions to depart stopover locations and to continue with migration are also influenced by weather conditions (Richardson 1978, Able 2004, Liechti et al. 2013), with the likelihood of departure from stopover locations being highest on nights with moderate winds and no rain (Schaub et al. 2004).

Cloud cover, particularly when associated with rain (Richardson 1978), often results in decreased migration densities (Erni et al. 2002, Nilsson et al. 2006), suggesting these weather conditions affect migratory decisions. Rain wets plumage, which increases drag and thus the energy requirements and flight costs for migrants (Schaub et al. 2004, Gagnon et al. 2011). An increase in cloud cover and rain can also reduce the effectiveness of celestial cues that nocturnal migrants use to navigate (Pyle et al. 1993, Able and Able 1995) and can preclude migrants from detecting topographical features used to orientate during migration; such cues are often relied upon to compensate for wind drift (Pyle et al. 1993, Gagnon et al. 2011). Thus, there may be selective pressures for birds to alter or curtail activity during inclement weather, but these must also be balanced against energy costs and the need to appropriately time arrival at destinations during seasonal movements.

Throughout their migratory journey, birds pass through varying local weather conditions and are forced to react to unsuitable flight conditions that they encounter after departure (Schaub et al. 2004, Shamoun-Baranes et al. 2010). For example, increased precipitation may lead to the gradual suppression of migratory movement (Gauthreaux 1971, Gagnon et al. 2011). Under these conditions, birds may change their migratory movements to

avoid rain and cloud cover (Richardson 1978) by either flying above or below the cloud ceiling height (Blokpoel and Burton 1975, Kemp et al. 2013) or around isolated rain events; although such options may not always be advantageous. Nocturnal migrants with larger fuel stores may be more successful at continuing migration through bad weather (Arizaga et al. 2011, Bulyuk 2011). Alternately, birds may be making decisions to migrate through bad weather based on either low availability of suitable stopover habitats along migration routes (Karlsson et al. 2011), or constraints on the timing and energy requirements required for reaching breeding or wintering grounds (Klaassen et al. 2008). Thus, nocturnal migrants that are constrained to migrate through or around rain may make strategic decisions on departure timing or briefly curtailing activity to minimize lost flight time (Gauthreaux 1971, Richardson 1978, Erni et al. 2002), but such decisions may subject migrants to other hazards during migration.

Unfavourable weather has been identified as a contributing factor to higher mortality of birds associated with migration (Schaub et al. 2004) and increased collisions with obstacles, including buildings and communications towers (Johnson et al. 2002). Under inclement conditions, movements of nocturnal migrants that fly at lower altitudes below the cloud cover are more influenced by topographic features, such as mountain ridges (Bruderer 1997b). Because of the decrease in visibility and the potential for disorientation, the combination of flying at lower altitudes, navigating through or around rain events and flying over mountain ridges can increase the probability of mortality (Richardson 1978, Schaub et al. 2004), especially when tall structures, such as wind turbines, buildings and communication towers are placed on the landscape (Nations and Erickson 2009). Furthermore, when flying under cloud cover, nocturnal migrants are more likely to become

disoriented from lighted towers because natural visual cues (e.g., stars) are obscured and artificial visual cues are enhanced (Avery et al. 1976). Thus, a combination of lower-altitude flying, reduced visibility and attraction to artificial lighting has led to speculation that low cloud cover and rain events will increase collision mortality at wind energy developments (Smallwood and Thelander 2004, Sovacool 2009).

In British Columbia, Canada, mountain ridges are increasingly being used for placement of wind turbines. If the onset of rain events decreases flight altitudes of migrants in these regions, it could increase the risk of collision with these large structures. I tested the hypothesis that the onset of localized rain events will result in migrants decreasing flight altitudes, causing them either to land or fly below cloud cover. I used an X-band marine radar to track the number of migrants at various heights before and after rain events during the pre-operational and operational phases of a wind energy project in northeast British Columbia. I examined the number of birds aloft in different sectors of the airspace above wind turbines before and after rain events. My null hypothesis was that rain causes birds to either land or fly at lower altitudes. In this case I expected to see a spatial shift in the densities of migrants within each height category. As migrants encountered rain, I predicted there would be an increase in the number of birds detected in lower height categories as migrants descend to lower heights. Following the passing of rain, I expected to see the number of migrants increase in lower height categories as birds shift their movement patterns and gain altitude as they redistribute their heights with better wind conditions. If rain was not grounding birds, migrants may either flying above or around rain events. For the former (flying above rain events), I would expect to see a reduction in the numbers of migrants in lower height categories preceding rain events, but a simultaneous increase in the numbers detected in

upper height categories as migrants moved upwards. If birds are flying around rain events, then I would expect a simultaneous decline in detections in all height categories with the onset of rain, and simultaneous resumption following its end.

4.2 Methods

4.2.1 Study area

I collected radar data on nocturnal migrants at the Dokie I Wind Energy Project located in northeast British Columbia (Fig. 1-1). Details of the site and turbine placement have been previously described in section 1.8, so I focus descriptions here on influence of weather patterns at this locality. Daily weather in this region is influenced by cold moist air from the Pacific Ocean resulting in an unstable atmosphere with bands of clouds and showers (Whiteman 2000, Klock and Mullock 2001). Due to the prevailing weather pattern in the region, the migratory corridor on the foothills of this section of the Northern Rocky Mountains is subject to high winds, turbulence, extensive cloud cover and precipitation (Vickers et al. 2001).

4.2.2 Radar data collection and analysis

I collected data on the movement of birds at this facility during the peak of nocturnal passerine migration in the spring and fall periods (mid- to late-May and from late-August to early-September, respectively) over five years, from 2008 to 2012. The first three years of the study (2008 – 2010) represent the pre-operational period for the wind energy facility when roads and turbines were being constructed and erected. The final two years (2011 –

2012) represent the operational period when wind turbines were functioning and generating power.

The movement of birds was tracked with a Furuno X-band marine radar unit (model 1954C, 12kW, 9,000 MHz, 1.83 m open array antennas – Furuno Electric Company Ltd. Miki Japan) that was orientated in the vertical position to collect data on the heights of nocturnal migrants. The vertical radar was mounted approximately 1.5 m above the ground and scanned an arc of 1.9° (vertical) with a beam width of 22° (horizontal) every 2.5 seconds. The radar antenna was set up in three separate locations within the study area and was aligned with the proposed/constructed turbine arrays (Fig. 4-1), so as to provide vertical height information for birds navigating along or traversing the ridgelines. The radar unit was set on short-pulse length (80 ns at PRF=2100 Hz) with a range of 1.5 km. I gathered radar data, on average, over an 11-day period each season with an average of 5.8 hrs and 8.5 hrs of radar data being recorded each night during the spring and fall migration periods, respectively.

Recorded radar images were visually scanned in radR (Taylor et al. 2010) to identify periods of rain. To be suitable for my analysis a rain event had to start after the nightly migration movements began and had to finish before nightly migration movements ended. Where this occurred, I extracted data on the movement of bird targets from the radar data for one hour before the rain event and one hour after the rain event. Identified targets (Chapter 2) were tallied for two minute periods, following methods similar to Hassler et al. (1963), and I processed this output to extract specific height data for each target and organized all data into four height categories (0-300 m, 301-600 m, 601-900 m and 901-1200 m above ground level

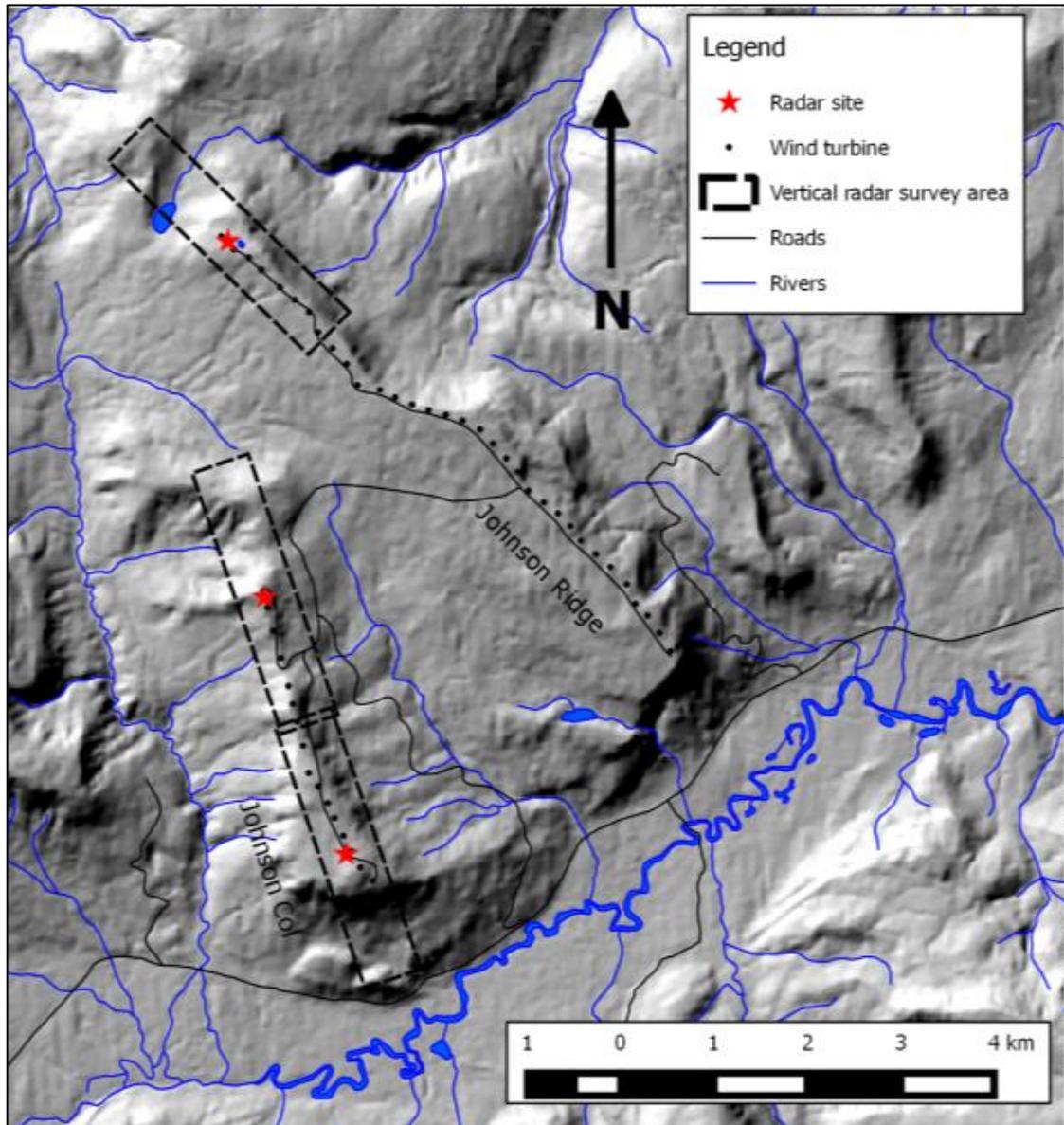


Fig. 4-1. Position and orientation of the radar sites in relation to the topography of the ridgelines at the Dokie I Wind Energy Project in northeast British Columbia.

[agl]). I ran a general linear mixed model comparing the number of migrants aloft in each individual height category across eight of the two minute periods of 58-60, 28-30, 8-10 and 0-2 minutes prior to and following rain events. I added the severity of the rain event and the operation phases (pre-operational versus operational, described above) of the wind project as between-subject factors to determine if they influenced patterns of migrants aloft in different time periods before or after rain events. I determined the severity of the rain event based on three factors; 1) the coverage of rain on the radar monitor - a light rain event was considered to be one where rain was visible on the radar and covered < 50% of the radar monitor, conversely, a heavy rain event was considered one where >50% of the radar monitor was not visible due to the rain; 2) the daily regional accumulation of rain recorded at the nearest Environment Canada climate station at the Chetwynd airport 40 km away; and 3) the duration of the rain event, which ranged in length from 1 minute to over 4 hours. I performed a cluster analysis using these three factors to determine appropriate groupings for severity. Statistical analysis was completed using Statistica (Version 12 – Statsoft Inc. 2014).

4.3 Results

I used data from a total of 54 rain events over the five-year collection period. The cluster analysis separated the dataset into two distinct clusters with the level of rain observed on the radar monitor having the highest unweighted pair-group average (0.96) followed by the regional accumulation of rain (0.60) and finally the duration of the rain event (0.08). The cluster analysis resulted in the dataset being fairly evenly split between the two clusters with 30 events in cluster one (predominantly light rain) and 24 events in cluster two (predominantly heavy rain). Thirty seven rain events were documented during the pre-

operational period (22 under light rain, 15 under heavy), and 17 were recorded during the operational period (8 under light rain, 9 under heavy). Higher numbers of birds were detected at the lower height categories compared to the upper height categories, so all subsequent comparisons of change in target detections in relation to weather patterns are made within individual height categories.

Within the lowest height category (0 – 300 m agl), there was no significant difference between the number of birds aloft between 60, 30, 10 and 2 minutes before a rain event ($F_{3,66} = 0.140$, $P = 0.25$). There was also no effect of operational phase ($F_{1,22} = 0.16$, $P = 0.69$) or rain severity ($F_{1,22} = 0.10$, $P = 0.75$) on the number of birds aloft before the rain event, nor any interaction of operational phase ($F_{3,66} = 1.03$, $P = 0.38$) or rain severity ($F_{3,66} = 1.10$, $P = 0.36$) on the number of birds across the comparison times leading up to the rain event. There was, however, a significant difference in the number of birds aloft between 2, 10, 30 and 60 minutes after rain events ($F_{3,75} = 2.74$, $P = 0.05$) showing a significant increase in numbers by 30 minutes after the rain has passed compared to the numbers at two minutes ($P < 0.01$), and staying consistent after this (no other significant pairwise comparisons) (Fig. 4-2). Similar to the period before the rain event, there was no effect of operational phase ($F_{1,25} = 0.46$, $P = 0.50$) or rain severity ($F_{1,25} = 2.03$, $P = 0.17$) on the number of birds aloft after the rain event and no interaction of operational phase ($F_{3,75} = 0.42$, $P = 0.75$) or rain severity ($F_{3,75} = 0.95$, $P = 0.42$) on number of birds across time periods after a rain event.

At the second lowest height category (301 – 600 m agl) there was also no significant difference in the number of birds aloft between 60, 30, 10 and 2 minutes before rain events ($F_{3,66} = 1.70$, $P = 0.17$), nor was there an overall effect of operational phase ($F_{1,22} = 0.002$, $P = 0.96$) or rain severity ($F_{1,22} = 0.00$, $P = 1.0$). There was also no interaction of operational

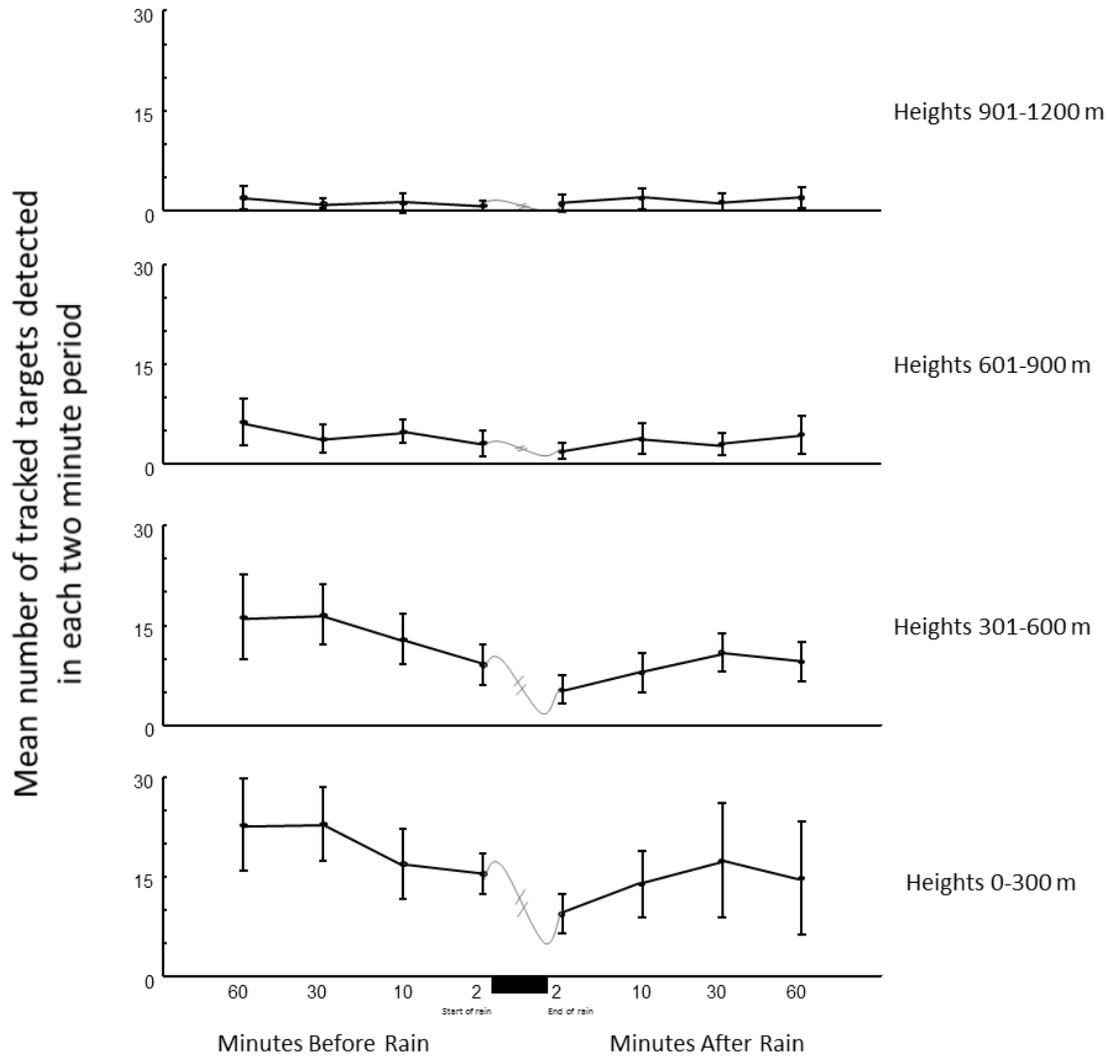


Fig. 4-2. Mean number of tracked targets (\pm SE) detected in the 2 min periods at 60 minutes, 30 minutes, 10 minutes and 2 minutes before and after 54 separate rain events at the Dokie I Wind Energy Project from 2008 to 2012. At the two lowest height categories there is a decrease in the number of nocturnal migrants before rain events.

phase ($F_{3,66} = 0.03$, $P = 0.99$) or rain severity ($F_{3,66} = 0.32$, $P = 0.81$) on the number of birds across time periods before rain events. There was a significant difference in the number of birds aloft in the 301-600 m agl height category in the time periods after rain events ($F_{3,75} = 4.04$, $P = 0.01$). Again, the number of birds steadily increases until 30 minutes after the rain compared to the starting point two minutes after rain had ended ($P < 0.01$) and remained at this level at the 60 min mark. There was no effect of operational phase ($F_{1,25} = 1.15$, $P = 0.29$) or rain severity ($F_{1,25} = 0.55$, $P = 0.46$) on the number of birds aloft in this height in the 60 minutes following rain, as well as no interaction of operational phase ($F_{3,75} = 0.19$, $P = 0.90$) or rain severity ($F_{3,75} = 0.81$, $P = 0.49$) on the number of birds across time periods after rain events.

At the third height category (601 – 900 m agl) I detected a significant difference in the number of birds moving between 60, 30, 10 and 2 minutes before rain events ($F_{3,66} = 2.67$, $P = 0.05$). There was no overall effect of operational phase ($F_{1,22} = 1.97$, $P = 0.17$) nor of rain severity ($F_{1,22} = 0.87$, $P = 0.36$), plus there were no interaction between operational phase ($F_{3,66} = 0.77$, $P = 0.52$) or rain severity ($F_{3,66} = 0.64$, $P = 0.59$) on the number of birds in the four time periods before rain events. At this height category there was a significant drop (Fisher LSD post-hoc analysis $P = 0.02$) in the number of birds from 60 minutes to 30 minutes prior to a rain event, followed by a non-significant increase in the number of birds at 10 minutes before another significant decrease in the final 2 minutes before the rain (Fisher LSD post-hoc analysis $P = 0.01$). Unlike the lower height categories there was no significant difference in the numbers of birds across the time periods after rain events ($F_{3,75} = 2.08$, $P = 0.11$). There was also no effect of operational phase ($F_{1,25} = 0.96$, $P = 0.34$) or rain severity ($F_{1,25} = 0.002$, $P = 0.97$) on the number of birds aloft in this height category across the 60

min period post-rain, as well as no interaction of operational phase ($F_{3,75} = 0.48$, $P = 0.70$) or rain severity ($F_{3,75} = 0.71$, $P = 0.55$) on the number of birds across time periods after rain events.

Finally, at the highest height category (901 – 1200 m agl) overall, there was no significant difference in the number of birds aloft between two minute periods before ($F_{3,66} = 2.36$, $P = 0.08$) or after ($F_{3,75} = 1.54$, $P = 0.21$) rain events. There was an effect of operational phase on the number of birds aloft in this height category before ($F_{1,22} = 4.15$, $P = 0.05$) but not after ($F_{1,25} = 1.71$, $P = 0.20$) rain events. There were no overall effects of rain severity before ($F_{1,22} = 0.008$, $P = 0.93$) or after ($F_{1,25} = 0.08$, $P = 0.78$) rain on the number of birds aloft. Similarly, there were no significant interaction between these variables and the number of birds aloft across times leading up to the rain event, or following the rain event (all $P > 0.07$) in this highest height category.

4.4 Discussion

I found little evidence for an increase in the number of birds aloft in the lowest height category (0-300 m agl) just prior to rain events, which would suggest that nocturnal migrants were not reducing their altitude from higher levels in response to rain. Thus, within my study area there was little evidence to suggest that nocturnal migrants were at a higher risk of collision by the potential for grounding and ceasing their nightly migration in response to onset of rain events. The distribution of birds before and after rain events in this lowest height category were also not affected by the operational phase of the wind project or the severity of rain, which suggests nocturnal migrant behaviour was influenced by other factors.

The slight declines in the number of birds detected two minutes before a rain event at all the height categories (and significantly lower in the third height category) might suggest that a proportion of nocturnal migrants were being grounded by rain. If this were the case, I would have expected there to be a greater amount of clustering at the lower height categories. Rather the consistent declines in the number of birds detected two minutes before a rain event in almost all height categories suggest that migrants were likely avoiding rain events by flying around them on the lateral plane, which is a similar behaviour observed in other studies (Blokpoel and Burton 1975, Kemp et al. 2013). This pattern could explain the low numbers of birds recorded two minutes before and after rain events as birds moved away to avoid the rain and ultimately moved out of the 500 m detection range of the vertical radar system. By expanding the research to include horizontal radar data, one might be able to determine whether there is evidence showing an increase in the concentration of migrants in the regions opposing the direction of the incoming rain immediately prior to the rain appearing in radar imagery.

After rain events, birds appeared to be re-adjusting their movements, presumably to correspond with more profitable winds or visual cues to aid in continued migration (Richardson 1978, Schaub et al. 2004). This would be evident by the increase in the numbers of birds aloft as time progresses after the rain. Ultimately, birds returned close to their pre-rain numbers within 30 minutes, which is likely a result of the broad-front migration trends as they spread out to take advantage of favourable conditions (Able 2004). Nevertheless, the risk to nocturnal migrants colliding with wind turbines during the onset of rain events appeared unlikely to increase. Further, independent carcass searching, completed on site during the operation phase of this installation, failed to find increased collision rates during

nights containing rain events (Stantec Consulting Ltd. 2012a, Stantec Consulting Ltd. 2012b), which supported my assessment from radar tracking. Only three bird mortalities were observed during the overlapping period when I was tracking nocturnal migrants by radar (Stantec Consulting Ltd. 2012b). Two of these mortalities occurred on nights when rain events were present and one was from a clear night. Overall these numbers were very small compared to the total number of tracked nocturnal migrants that were recorded (Otter et al. 2014).

While the severity of rain appeared not to have an effect on the behaviour of nocturnal migrants, I suggest that the reactions of migrants were similar across these periods due to the topographic nature of the site. Under light rain events the average ceiling height, measured at the nearest weather station 40 km to the east at the Chetwynd airport, was approximately 950 m above ground and under heavy and moderate rain events was between 450 m and 500 m above ground, respectively. When these ceiling heights were extrapolated to the study area, the ceiling height under light rain events was estimated to be between 0 m and 350 m above the ridgeline. For moderate and heavy rain events the cloud layer would be at ground level. Because of the mountainous terrain, birds would be at a disadvantage if they decided to fly at a lower altitude in response to the rain. Attempts to fly under low clouds would either force migrants to be grounded or restrict them to the valleys neighbouring the ridges where turbines are located, which might not be oriented in the direction of their desired migration (Blokpoel and Burton 1975, Beason 1978), so flying around rain events may be more advantageous.

Most nocturnal passerine migrants fly at altitudes between 100 m and 750 m above the ground (Able 2004, Longcore et al. 2008). This height distribution is influenced by the

altitudinal profile of winds, weather conditions and topography (Bruderer 1997b). At my study site, higher numbers of nocturnal migrants were recorded in the two lowest height categories (Chapter 3). This may partially reflect a detection bias; at the higher height categories, the radar beam samples a smaller section of the sky compared to the lower height categories, based on the 1.5 km detection radius I had chosen. There is also a reduction in radar energy further away from the radar, which affects the ability to detect smaller targets at larger distances (Toomay and Hannan 2004, Denny 2007). My analysis controls for this, however, by making comparisons within the four height categories, rather than among them. The similar response pattern observed at each height category suggests that migrants are maintaining their altitudinal profile, but moving away from rain events as they approach.

Several authors have speculated that weather events may cause birds to decrease altitude and thus put them at greater risk of collision with land-based structures (Johnson et al. 2002, Schaub et al. 2004), however, my data suggest that this pattern is not occurring among migrants traversing the ridgelines within the northern Rocky Mountains. Site-specific studies of nocturnal migrant movements at proposed wind energy facilities are still warranted since collision risk is dependent on several factors including: passage rates; the altitudinal profile of migrants; the number and size of wind turbines, and; the lighting configuration of wind energy facilities (Band et al. 2007). I, therefore, recommend that before-and-after studies on migratory movement patterns in response to local topography and under varying weather conditions be conducted within regions undergoing wind energy development; this will provide information for various combinations of factors to understand collision risk for migrants in the regional-context in which development is occurring.

5 RESPONSE OF NOCTURNAL MIGRANTS TO VARIATION IN ARTIFICIAL LIGHTING AROUND WIND TURBINES

Abstract - Nocturnal avian migrants rely on rod-dominated vision at night and are likely sensitive to intense artificial light sources, such as those placed on top of wind turbines. This could result in disruptions of normal migratory behavior, the magnitude of which could be influenced by the intensity and colour of lights, and the flash rate. I tested how wavelength and flash rates of artificial lighting affect fine-scale flight paths of birds traversing a wind energy facility in northeast British Columbia. I broadcasted individual colours (white, red, green and blue), either solid or flashing, from a portable spotlight in a randomized order for 20 minute periods, followed by a 10 minute period of no light between trials during the peak spring and fall nocturnal migration in 2012. The response of migrants was recorded with an X-band radar unit equipped with a signal digitization card that recorded the trajectories and heights of migrants as they travelled past the light source. Nocturnal migrants exposed to light colours at short wavelengths consistently displayed lower flight altitudes compared to migrants exposed to other colours. This pattern was seen in the altitude of birds as they passed immediately above the spotlight's position and the overall change in altitude from when tracks were first detected to their heights when directly over the spotlight. My results strongly suggest that light colours at shorter wavelengths may have a greater attraction effect on nocturnal migrants than other lighting regimes.

5.1 Introduction

Passerine species use powered flight to migrate between breeding and non-breeding grounds, with the majority of species moving at night. Nocturnal migration typically exposes

birds both to less turbulence in the atmosphere and wind patterns that are generally favourable for reducing energy demands (Harmata et al. 1999, Able 2004, Liechti et al. 2013). During nocturnal migration, birds are known to use a suite of cues, including magnetic fields, celestial positions, polarized light and topographical features (such as coastlines and mountain ranges) as orientation mechanisms to maintain migratory directionality (Able and Able 1995, Liechti et al. 2013, Chapter 1). Night-migrating passerines prefer celestial cues over magnetic cues in hierarchical preference, and among celestial cues, polarized light on the horizon appears to be the dominant cue for orientation (Wiltschko et al. 1998). Birds will continuously recalibrate as necessary to stay on their migratory course (Wiltschko et al. 1998) and will ultimately rely on visual cues to aid migration (Martin 1990); therefore, the visual sense of a bird plays a large part in its ability to effectively navigate during migration. Since most nocturnal migrants are generally diurnally-active outside of the migration period, it is important to consider just how much their visual acuity is affected by low-light (i.e., night-time) conditions (Evans Ogden 1996).

Avian visual systems influence orientation behaviour by both detection of directional cues and calibration of other sensory cues with visual data. A bird's perception of wavelength and achromatic vision is key for adjusting migratory directionality (Osorio and Vorobyev 2005). Birds use their visual sense to discern diurnal patterns of polarized light, which permits them to orient themselves for night-time migration (Able and Able 1995). As the sun moves across the sky, birds detect changes in the polarization patterns of natural light, which allow determination of migration direction, however, the pattern of polarized light at dusk only provides the primary source of orientation information for night-migrating species (Able 1989, Able and Able 1995, Lincoln et al. 1998). Birds also use the earth's

magnetic field as a navigational aid (Edmonds 1976, Hart 2001). There are multiple magnetic field receptors (e.g., ferromagnetic crystals or magnetite) in the head of birds, one of which is located in the eye (Edmonds 1976), which appear to be sensitive to the wavelength of light (Wiltschko and Wiltschko 1995, Beason 2003). Early visual experience by birds also plays an important role in the development of orientation abilities (Emlen 1970). The combination of genetically-based magnetic field orientation and visually-learned experience of celestial rotation establishes a reference system of the cues that birds use on their nocturnal migrations (Francz Sauer and Emlen 1971, Able and Able 1995).

Night-migrating species must correctly interpret these visual cues to maintain their migratory direction (Martin 1990) and will rely on their complex visual sense to gather information about their surrounding environment (Hart 2001). They use this sense to discriminate objects on the basis of wavelength and intensity (Hart 2001) and have separate sets of photoreceptors: cones for colour vision and rods for achromatic vision or luminance (Cuthill et al. 2000, Osorio and Vorobyev 2005). Cones dominate visual perception under higher light levels or photopic conditions, but under low light or scotopic conditions there is a shift to rods due to their increased sensitivity to luminance (Hart 2001). This shift in vision under low light conditions, otherwise known as the Purkinje shift, changes the eye from being more sensitive to short versus long wavelengths to being more sensitive to intense light (Hart 2001). As a result, under scotopic conditions, birds are unable to deduce a high degree of spatial resolution and predominantly use rod-dominated vision for the detection of objects at night (Martin 1990).

As birds predominantly use achromatic vision at night, they are likely more sensitive to intense light, which results in birds being attracted to artificial light sources – these being

more intense than the surrounding natural light (Evans Ogden 1996). Depending on the intensity of the light, birds may also confuse artificial light sources with the moon or stars, which can also lead to disorientation (Martin 1990). It is unclear, however, whether birds are indeed being attracted to these light sources from a distance or whether birds become ‘trapped’ by the light. Such trapping effects refer to birds flying into the illuminated area of a light source and becoming reluctant to leave the area (Evans Ogden 1996, Drewitt and Langston 2008). Verheijen (1958 cited in Evans Ogden 1996) suggests that the illumination of the environment around a light source interferes with the normal photopic orientation.

The potential for nocturnal migrant fatalities increases if structures are equipped with artificial light sources (Gehring et al. 2009), although the assessment of relative impacts of different light sources on attraction and collision risk are still mixed. In North America, obstruction lighting is required on all structures over 60 m in height as a warning to aircraft pilots (U.S. Department of Transportation 2007; Transport Canada 2014). Structures are typically lit with white or red lights and these lights may be solid (i.e., constantly on) or pulsating on and off (Erickson et al. 2001). This artificial lighting appears to be the single-most influential factor affecting collision of nocturnal migrating birds with tall structures (Erickson et al. 2001) and the reactions to artificial light appear largely determined by the wavelength characteristics of the light source (Poot et al. 2008). Light intensity and exposure (i.e., continuous or flashing) are also major factors that influence collision. For flashing lights, the period between flashes and the length of the flash can influence the ability of birds to avoid wind turbines (Drewitt and Langston 2008). Some studies have shown that lights with long wavelengths (e.g., red) tend to cause a greater disturbance in birds than lights with shorter wavelengths (e.g., green and blue) (Poot et al. 2008). This disturbance may be related

to the fact that red lights interfere with the avian magnetic compass and may cause birds to become disorientated (Manville 2000, Hart 2001, Osorio and Vorobyev 2005), which does not necessarily relate to attraction. Other studies suggest that birds are less sensitive to red lights and may be less attracted by it (Evans 2010). Studies in New York showed that under dense cloud cover, the aggregation of birds was higher when white, blue or green lights were used compared to red lights (Evans et al. 2007). Kerlinger et al. (2010) also demonstrated that flashing red lights on wind turbines are associated with fewer bird collisions.

The goal of my research was to determine how wavelength and flash rates of artificial lighting affect fine-scale flight paths of birds traversing a wind energy facility in north eastern British Columbia. I tested lighting of similar intensity and patterning to those used to illuminate towers for air-safety measures. The response of migrants was recorded under clear conditions with an X-band radar unit equipped with a signal digitization system that recorded the trajectories and heights of migrants as they travelled past the light source. This novel approach allowed for the recording of movement patterns in response to light and differs from other studies (Evans et al. 2007, Poot et al. 2008) that looked at the point-source attraction within the lights beam.

5.2 Methods

My study site was located at the Dokie I Wind Energy Project (55°41'28.00"N 122°18'06.00"W) in northeast British Columbia, Canada (Fig. 1-1). This wind project is situated in the foothills of the Rocky Mountains approximately 40 km west of the town of Chetwynd, British Columbia. Wind turbines are situated on two ridges ranging in elevation from 1200 m to 1400 m above sea level. I used a Chauvet COLOURado™ 1-Tri IP light-

emitting diode (LED) spotlight, powered with three 12-volt deep cycle batteries connected in series and a 300 Watt power inverter. The spotlight had high power (3 watt) tricolour red-green blue (RGB) LEDs with an adjustable strobe feature to control flash rate that was of similar intensity to the obstruction lighting required on wind turbines. I ran light trials on 10 nights from 18 – 30 May 2012 and eight nights from 19 – 28 August 2012. The spotlight was situated away from the actual turbine string (approximately 1 km distant – Fig. 5-1), so as not to increase collision risk if trials resulted in attraction. The light was mounted on the top of a vehicle (~ 2.0 m above the ground, angled at 45°) and pointed in the direction of the oncoming migrants in spring (spotlighted directed at 195°) and fall (spotlight directed at 15°). The survey period corresponded with the peak period of nocturnal passerine migration for the area (Otter et al. 2014). Data collection was carried out under relatively clear nights that provided uniform natural light and high cloud conditions.

Light trials were comprised of projecting individual colours at different wavelengths (white, red, green and blue) and flash rates (solid or flashing) for 20 minute periods, followed by a 10 minute period of no light between trials. Flash rate was set at 49 flashes per minute (on time flash period of 0.6 seconds), which was within the range of recommendation flash rates by Transport Canada (2014). Light trials commenced approximately 30 to 45 minutes after local sunset, which corresponded to approximately 22:30 in the spring and 21:45 in the fall. All of the various colours and flash rates tested were played each night, with the sequence of light trials being block randomized across the trial period. This ensured that each colour/flash rate was represented equally during each respective time of night, so as to control for order effects and temporal variation in the nightly bird migration and to also

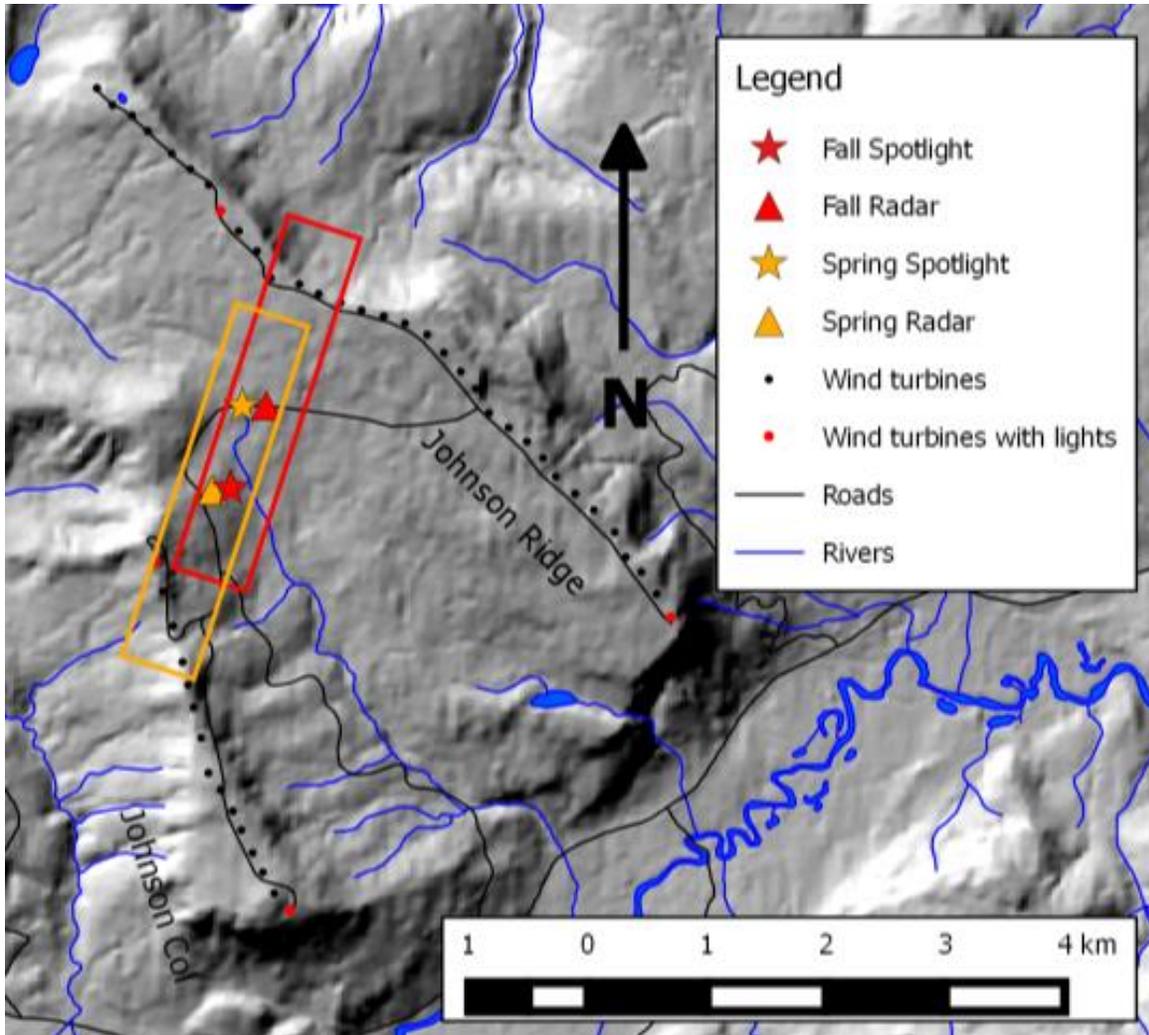


Fig. 5-1. Location of the spotlight and radar during the spring and fall seasons of 2012 at the Dokie I Wind Energy Project in northeast British Columbia. The rectangular boxes represent the area of detection for the fall radar (red) and spring radar (gold).

control for night-to-night variation in weather and relative timing of the trials during the migratory period.

Responses of nocturnal migrants to the light trials were recorded by a Furuno X-band marine radar unit (model 1954C, 12kW, 9,000 MHz, 1.83 m open array antennas – Furuno Electric Company Ltd. Miki Japan) orientated to rotate in the vertical axis, thus monitoring heights of migrants as they traverse the wind project. The radar was positioned approximately 750 m from the spotlight (Fig. 5-2) and was mounted approximately 1.5 m above the ground and scanned an arc of 1.9° (vertical) with a beam width of 22° (horizontal) every 2.5 seconds. The radar was set on short-pulse length (80 ns at PRF=2100 Hz) with a range of 1.5 km. Rain and sea clutter options were turned off. The gain scale on the radar ranged from 0 to 99 and I used a setting of 76, which was the highest setting that maximized the information returned from targets while minimizing the introduction of radar noise. With the added influence of side lobes, this created a detection zone of approximately 500 m width throughout the 1.5 km range (Chapter 2). In this orientation, the radar was able to track movements of individual migrants up to 1500 m away and travelling within a 500 m wide path intersecting the spotlight. As migrants were detected, their position as they crossed directly above the light, and changes in height along flight paths were recorded (Fig. 5 2).

The digital raw radar files were analyzed using radR (Taylor et al. 2010). Nocturnal migrants were identified as targets in radR by establishing user-defined criteria to initially discriminate targets as blips based on their size and shape (Chapter 2). Output data for the tracked targets was further processed in the statistical program R (R Development Core Team 2014) to convert sequential locations into a single track per individual target, to extract

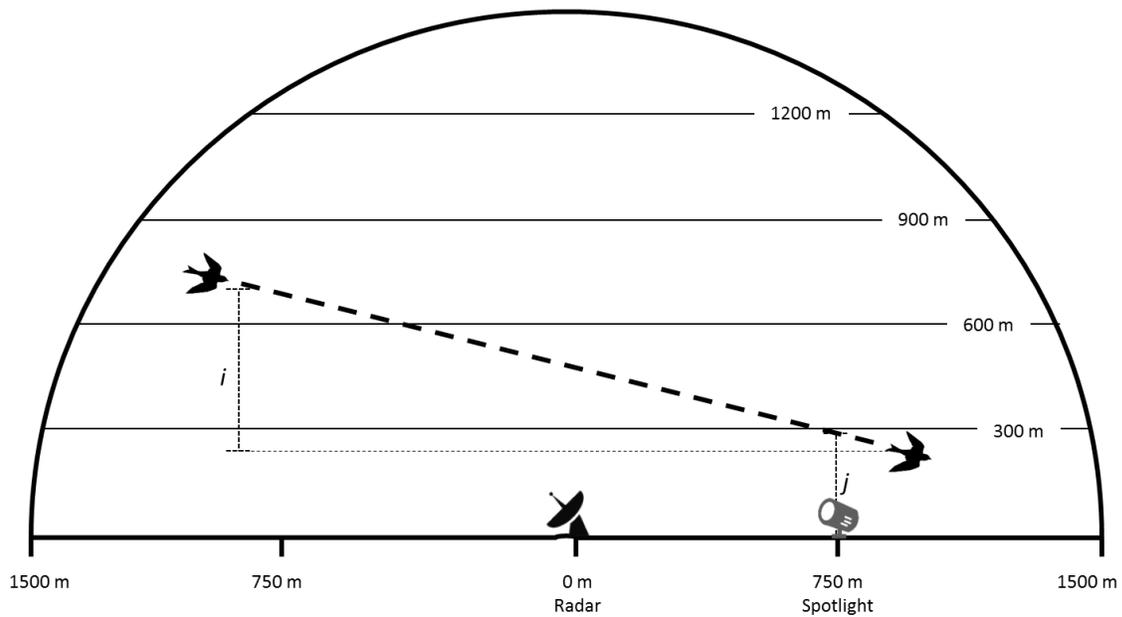


Fig. 5-2. Schematic drawing of the survey design showing the radar and spotlight set up, range of detection of the radar and the height categories. An example of a bird track is depicted: i represented the change in altitude of the bird in response to the spotlight; j represents the altitude of the bird above the ground as it passes over the spotlight.

specific height data for each tracked target and to determine its relative position within one of four height categories (0-300 m, 301-600 m, 601-900 m, and 901-1200 m above ground).

Data for tracked targets was organized into the 20 minute light trial sessions for each night. I ran a general linear mixed model using Statistica Version 12 (Statsoft Inc. 2014) with the dependent variables being the average height of tracked targets and the change in the altitude along a track – height difference between the start of each track to the position the target was in when directly above the spotlight – categorical predictors being light colour and flash rate. Night (date) and time of night (hour) were included as random effects to account for seasonal and temporal variability in the movement patterns. The model included the main effects and all possible interactions among the categorical predictors. I also selected the number of tracked targets in the lowest height category (0 – 300 m) above the ground and performed a repeated measures general linear model to determine which light trial resulted in the greatest number of birds aloft in this height category (indicating potential concentration of low-flying birds attracted by illumination pattern). I used the number of targets detected for each light trial per night as the dependent variable and season as a categorical predictor. The number of targets detected under no light conditions was corrected for survey effort to align with the effort allotted to the individual lights trials (e.g., 20 minutes).

5.3 Results

5.3.1 Altitude of targets in relation to artificial lighting

During the survey period, I collected data from 18 nights, which amounted to ten 20 min trials for each individual colour and flash rate in the spring and eight 20 min trials for individual lights and flash rates in the fall (Table 5-1). A total of 23,653 targets were tracked

Table 5-1. Summary statistics of the data collected for each light trial during the spring and fall of 2012 at the Dokie I Wind Energy Project. Ten trials were conducted in the spring whereas eight were conducted in the fall. Results are presented as the number of targets per minute to standardize across seasons.

Light Trial	Spring (<i>n</i> = 10)		Fall (<i>n</i> = 8)	
	Total # of targets/min	# of targets/min in lowest height category	Total # of targets/min	# of targets/min in lowest height category
White Solid	1.61	0.75	13.18	2.59
White Flash	1.59	0.80	12.57	2.47
Red Solid	1.70	0.83	8.96	2.48
Red Flash	1.62	0.64	8.74	1.89
Green Solid	1.36	0.65	11.58	3.78
Green Flash	1.52	0.75	8.68	2.76
Blue Solid	1.45	0.71	13.57	3.41
Blue Flash	1.31	0.49	11.32	1.99
No Light	1.51	0.69	10.71	2.49

across all light trials combined. The average altitude of tracked targets varied by night ($F_{19, 23623} = 133.57, P < 0.01$) and hour of the night ($F_{5, 23623} = 19.67, P < 0.01$), justifying controlling for these variables via random factors. Overall, there was a significant difference in the heights of migrants by light colour ($F_{3, 23647} = 38.07, P < 0.01$) and by flash rate ($F_{1, 23647} = 13.58, P < 0.01$), plus there was a significance interaction among the heights of migrants between light colour and flash rate ($F_{3, 23644} = 16.36, P < 0.01$). To explore this interaction, we separated the analysis by solid versus flashing lights to determine the effect of light colour on flight altitude.

Under solid light conditions, migrant heights were significantly lower compared to when flashing lights were broadcasted (Fisher LSD post-hoc analysis $P < 0.01$). Migrants exposed to solid white lights were significantly higher than migrants moving under no light conditions (Fisher LSD post-hoc analysis $P < 0.01$) and were also significantly higher than migrants exposed to red, green and blue lights (all Fisher LSD: $P < 0.01$). Migrants exposed to red solid lights were not significantly higher than migrants moving under no light conditions (Fisher LSD: $P = 0.74$), but were significantly higher than migrants exposed to green and blue lights (both Fisher LSD: $P < 0.01$). Migrants exposed to green and blue solid lights were significantly lower than the average height of migrants under no light conditions (both Fisher LSD: $P < 0.01$) (Fig 5-3).

Under flashing light conditions, the heights of migrants exposed to white flashing lights were not significantly different from the heights of migrants recorded under no light conditions (Fisher LSD: $P = 0.85$), but were significantly lower than migrants exposed to red and blue flashing lights (both $P < 0.01$). Migrants exposed to red flashing lights were significantly higher than migrants recorded under no light conditions ($P < 0.01$), were not

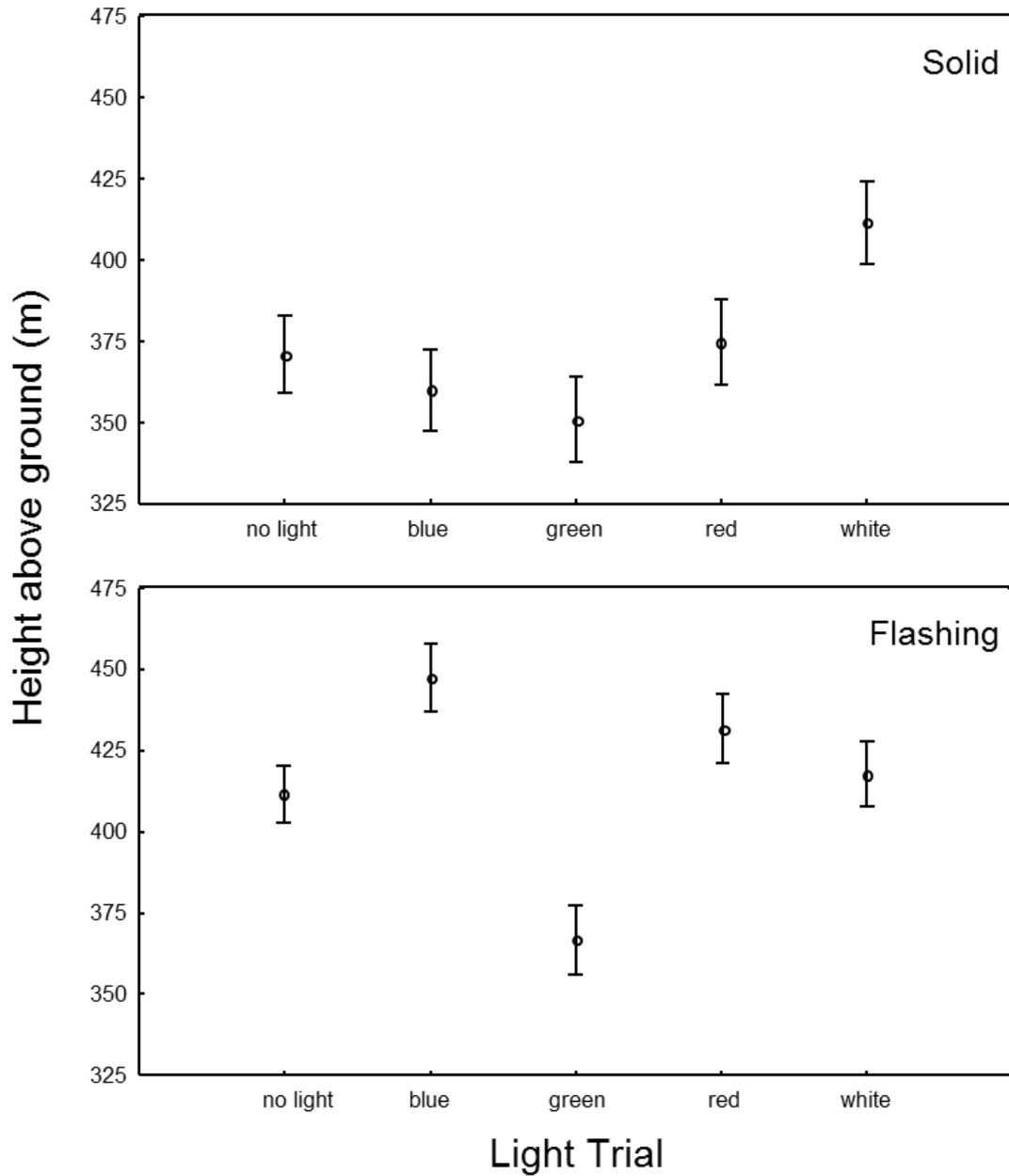


Fig. 5-3. Average height (\pm SE) of nocturnal migrants exposed to the solid and flashing light trials at the Dokie I Wind Energy Project in 2012. The altitudes of migrants exposed to both solid and flashing green lights were significantly lower than all other light trials.

significantly different than migrants exposed to blue flashing lights ($P = 0.11$), but were significantly higher than migrants exposed to green flashing lights ($P < 0.01$). Migrants exposed to green flashing lights were significantly lower than migrants moving under no light conditions ($P < 0.01$) and were significantly lower than migrants exposed to blue flashing lights ($P < 0.01$). Finally, migrants exposed to blue flashing lights were significantly higher than the heights of migrants moving under no light conditions ($P < 0.01$) and, as mentioned above, were significantly higher than all other light colours except for red flashing lights (Fig 5-3).

5.3.2 *Change in altitude of targets in response to artificial lighting.*

I then examined the magnitude of the altitude change across the length of each track under all light trial scenarios and compared these to conditions with no lighting. All migrants, regardless of whether or not lights were broadcasted, showed a general decrease in altitude across the length of their tracks (possibly reflecting contour flying with landscape features). There was no effect of flash rate on the magnitude of altitude change ($F_{1,1} = 1.91$, $P = 0.17$), but there was a significant effect of colour on the magnitude of altitude change ($F_{3,3} = 24.70$, $P < 0.01$). Plus there was a significant interaction between colour and flash rate on the magnitude of altitude change ($F_{3,3} = 3.58$, $P = 0.01$). Data were separated by flash rate for further analysis.

Under solid light conditions, the drop in altitude along the flight track was greatest under white lights, but was not significantly different than the drop in altitude of migrants under no light conditions (Fisher LSD: $P = 0.12$) or migrants exposed to blue lights ($P = 0.78$). This decrease in altitude was also significantly greater than the drop experienced by migrants exposed to green and red lights (both $P < 0.01$). The drop in altitude was lowest for

migrants exposed to solid red lights and this decrease in altitude was significantly lower compared to no light conditions and all other light trials (all $P < 0.01$). Under green light conditions, the drop in altitude was no significantly different than the decrease experienced by migrants under no light conditions ($P = 0.07$), but was significantly smaller than the decrease when migrants were exposed to blue and white lights (both $P < 0.01$) and significantly greater than the decrease when migrants were exposed to red lights ($P < 0.01$) (Fig 5-4).

Under flashing light conditions, blue lights resulted in the highest drop in altitude along the flight track, being significantly greater than under no lights (Fisher LSD $P < 0.01$) as well as greater than all other light colours (all $P < 0.01$). The change in altitude was smallest under red light conditions; the reduction in altitude was significantly less in response to red lights than the change in altitude experienced under no light conditions ($P < 0.01$) and all other light colours (all $P < 0.01$). The change in altitude of migrants exposed to white and green lights did not differ significantly from the drop in altitude under no light conditions (both $P > 0.10$) or from each other ($P = 0.51$) (Fig 5-4).

5.3.3 *Numbers of targets detected in near-ground airspace.*

There was no significant difference among the number of migrants detected in the lowest height category (0 – 300 m) during the various light trials ($F_{8, 120} = 1.51, P = 0.16$). There was a significant effect of season ($F_{1, 15} = 9.87, P < 0.01$) with higher numbers of migrants detected in the fall in the lower height bin; but there was no interaction between season and light trials on the number of migrants detected in the lowest height category ($F_{8, 120} = 1.42, P = 0.19$).

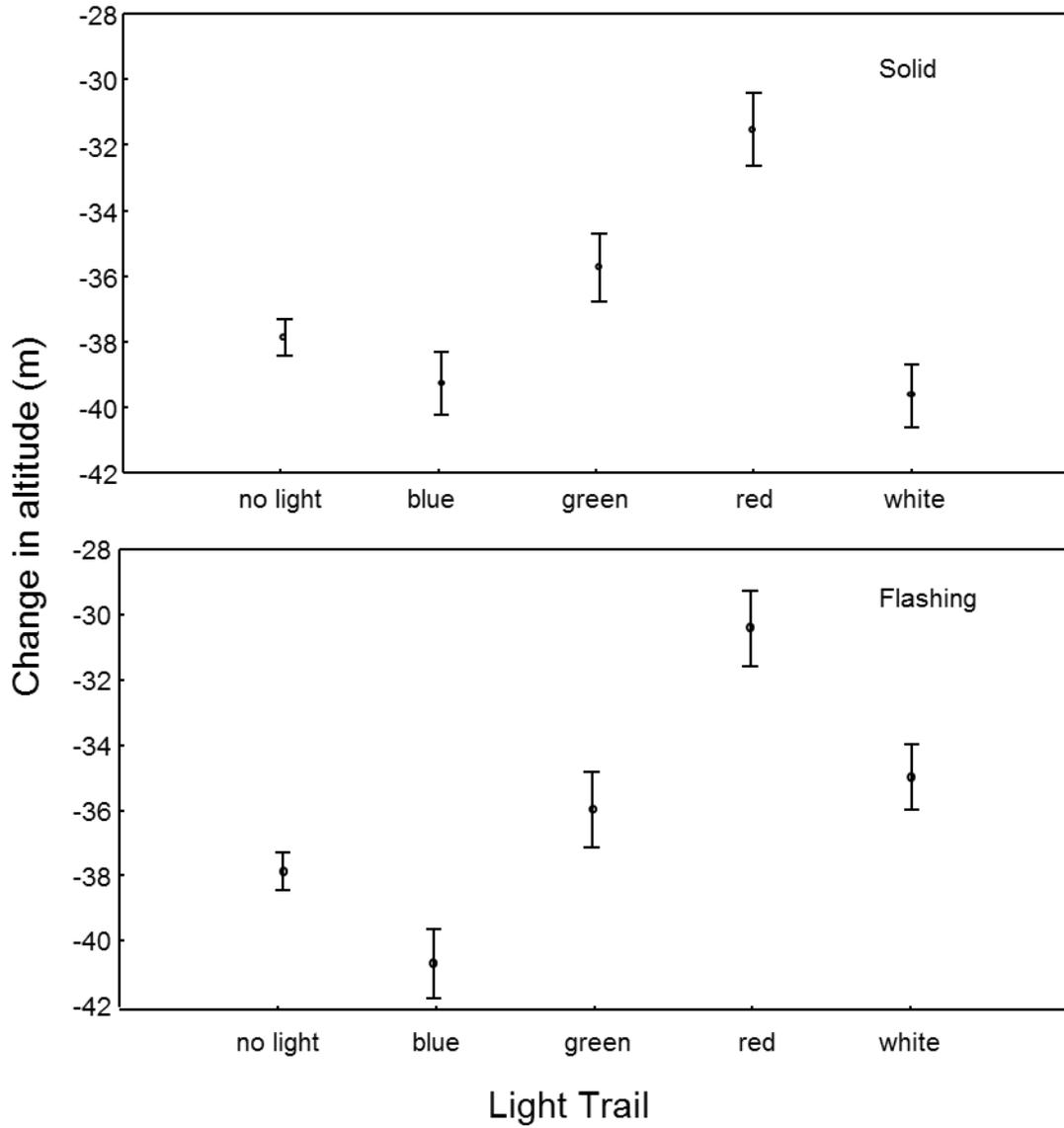


Fig. 5-4. Average change in altitude along the length of the tracked flight path of nocturnal migrants exposed to the various light colours among solid and flashing light conditions at the Dokie I Wind Energy Project in northeast British Columbia during the spring and fall season in 2012.

5.4 Discussion

Under clear conditions, nocturnal migrants exposed to green lights consistently display lower flight altitudes during movement across the ridgeline as compared to migrants exposed to periods of either no artificial lights or broadcast of other light colours. Migrants exposed to flashing blue lights displayed the larger altitudinal changes (change in height from when migrants were first detected to their heights when directly over the spotlight) compared to most other light colours. This strongly suggests lights at shorter wavelengths may have a greater attractant effect on nocturnal migrants than other lighting regimes, similar to the results found by Evans et al. (2007). In their study, bird aggregation at night occurred during periods of white, green and blue light (Evans et al. 2007). Contrary to previous studies, Poot et al. (2008) suggested that migrating birds were less disorientated by blue and green light compared to disorientation caused by red and white light. In both of these other studies, survey conditions were under cloudy skies and observations were made by observers at ground level and restricted to only those birds illuminated within the spotlight's beam. Through the use of radar tracking and auto-detection of migrants, I was able to collect data from a larger number of migrants over a broader spatial area compared to other studies, thus allowing me to determine both exact heights of migrants and changes in track altitude originating from areas beyond the spotlight's beam width to when migrants crossed over the spotlight. My data were also collected under relatively clear nights where I expected migratory orientation and navigation was primarily influenced by polarized light (Wiltschko et al. 1998) and other visual signals including natural light, celestial cues or topographic features (Martin 1990). Under these conditions, artificial lighting is considered to have less potential for attraction (Richardson 1978, Kerlinger et al. 2010), yet I still witnessed

significant changes in migrant behaviours, particularly during broadcast of light colours at short wavelengths. My results were also not likely influenced by other artificial lighting sources as the only other artificial light sources in our study area was obstruction lighting on the wind turbines; this is comprised of a CL-864 medium intensity, simultaneous flashing red lighting system consistent with the Obstruction Marking and Lighting Standard (CAR 621.19) for wind turbines and of similar intensity to the spotlight used in my trials. A total of four wind turbines were equipped with obstruction lights (Fig. 5-1), and the closest of these were 1.0 km to 1.5 km away from my focal light. These wind turbines were outside the 500 m wide side-to-side detection zone of the vertically-oriented radar. There were no other artificial light sources within 20 km of the study area.

The observed changes in migration patterns of birds exposed to artificial green and blue light in my study may have been a function of the sensitivity of birds' vision at night. The bird's eye becomes more sensitive to lights at short wavelengths (e.g., green, blue) under low light conditions (Hart 2001, Evans 2010), when rod-mediated vision predominates. The visual pigment, rhodopsin, in avian rod photoreceptors is known to have a peak sensitivity of ca. 500 nm, which is in the green range of the colour spectrum (Maier 1992, Beason 2003). As a result, birds are likely more sensitive to artificial light colours at shorter wavelength at night compared to other colours (Evans 2010). When a nocturnal migrant is presented with a green or blue light that is more intense than the natural background light, prior visual cues that the migrants had been using to orient themselves might be disrupted.

Another factor leading to disorientation could be attributed to magnetic orientation and the pattern of polarized light. There are light-dependent, wavelength-sensitive magnetic receptors within the avian eye that assist magnetic orientation (Ritz et al. 2000, Beason

2003), and laboratory experiments have shown that migratory birds require light from the blue-green part of the spectrum for magnetic compass orientation (Wiltschko and Wiltschko 1995). During the day and particularly as sunset approaches, birds observe changes in the polarization patterns of the sky (Able 1989, Able and Able 1995, Lincoln et al. 1998); during sunset, light becomes linearly polarized predominantly at shorter wavelengths due to atmospheric scattering (Kreithen and Keeton 1974). This polarized light is believed to stimulate the blue or green receptors located within the avian eye (Pomozi et al. 2001). This interaction of polarized light and magnetic reception provides the primary source of orientation information for night-migrating species (Able 1989, Able and Able 1995, Lincoln et al. 1998). When nocturnally migrating birds are presented with artificial light sources at short wavelengths, as in my study, the heightened sensitivity to colour in this range of the spectrum may override other directional stimuli (Able 1989) and result in the disorientation or attraction to artificial light sources, such as I observed in the altitudinal changes of tracked birds.

Despite showing a higher sensitivity to colours at shorter wavelengths, most birds are sensitive to all colours within the visual and UV spectrum (Wiltschko and Wiltschko 1995). Overall, the responses of nocturnal migrants in my study to white and red lights are similar to those shown by others, whereby towers equipped with red and white flashing lights had significantly fewer bird fatalities compared to towers with continuously illuminated lights (Gehring et al. 2009, Kerlinger et al. 2011). The average altitude of birds exposed to solid white lights in my study was among the highest of the light trials; however, the decrease in altitude over the course of the targets' tracks was also the greatest for this colour/flash combination. For white flashing lights, the response of birds was similar to that recorded

when no light was broadcasted. These results are consistent with Evans et al. (2007) where bird aggregations within spotlight beams were recorded under periods of white light, but not red light or flashing white light. Poot et al. (2008) suggested that white lights may interfere with the visual orientation of celestial cues, and in my study this may be evident in the observed altitudinal change in tracked migrants as they passed immediately above the spotlight; however, as my data were collected under relatively clear nights when other celestial cues would remain present and may have allowed migrants to maintain their higher flight altitudes and trajectories under white lights. Regardless, my results do suggest that flashing, rather than solid, white lights seemed to create less disruption to flight patterns of migrants, as suggested by Evans et al. (2007).

The altitude of migrants exposed to red lights in my study were higher than migrants exposed to no lights and the decrease in flight altitudes was also smallest compared to all other light trials and no-light conditions. This response of migrants to the red lights may be partially explained by the birds' vision being less sensitive to red wavelengths under scotopic conditions compared to blue or green wavelengths (Evans et al. 2007). In laboratory experiments, captive birds showed no directional preference when subjected to red lights (Wiltschko and Wiltschko 1995) and recent studies at large-scale wind turbine installations showed that there was no detectable difference in bird fatalities at wind turbines deployed with red, strobe-like CL-864 lights compared with turbines with no obstruction lighting (Gehring et al. 2009, Kerlinger et al. 2010). I found parallel responses in avian flight paths to red solid and red flashing lights, which is contrary to others who reported continuously illuminated red lights appearing to attract migrants, whereas flashing red lights do not (Gehring et al. 2009). In the latter case, light intensity, flash duration and the placement of

lights may be confounding factors (Drewitt and Langston 2008). Gehring et al. (2009) examined collision rates associated with non-flashing incandescent lights (L-810) placed on communication towers ranging in height from 116 m to over 305 m. The red incandescent lights have a higher irradiance or intensity than red LED lights (Manville 2000) and if placed at higher altitudes on towers are also closer to the average migration altitudes for nocturnal migrants (Able 2004, Longcore et al. 2008, Chapter 3). Light intensity was an influencing factor at one lighthouse in Ontario; when a less powerful light was installed, there was a reduction in the number of bird fatalities (Jones and Francis 2003). The intensity of my spotlight was similar to the CL-864 flashing red lighting system that has become the standard obstruction lighting used on towers greater than 60 m, so the response to migrants to red lights in my study was expected to be similar as those reported at recent wind turbine fatalities studies. My results add support to the use of flashing red lighting as a non-attractive illumination source on tall structures, due to the somewhat neutral effect it had on tracked flight paths.

My results from migrants being exposed to flashing blue lights were somewhat unexpected; I anticipated similar results to those observed for migrants exposed to green lights, as birds are more sensitive to light at short wavelengths under scotopic conditions. Migrants exposed to solid blue lights flew significantly closer to the spotlight than birds exposed to no light; however, the altitude of migrants exposed to flashing blue lights was significantly higher than migrants when no artificial lights were broadcast. My results are similar to Poot et al. (2008) who showed that birds generally followed seasonally appropriate migratory direction and there was little observable effects on the birds' orientation when exposed to blue light. Evans et al. (2007); however, observed an increase in aggregation of

birds within spotlight beams when subjected to blue light. Both of these earlier studies were conducted under cloudy conditions, whereas I collected data under relatively clear conditions. On overcast nights, birds are more likely to become disoriented from artificial lights because other visual cues (e.g., stars) are obscured and artificial light refracting off the clouds causes a larger illuminated area (Avery et al. 1976). This can be exacerbated by the trapping effect, where birds are reluctant to leave the illuminated area (Evans Ogden 1996, Drewitt and Langston 2008). As my study was conducted under clearer night conditions, the main differences between the observed effects of green and blue light may be the result of the peak sensitivity of photoreceptors in the avian eye. As mentioned, birds are optimally sensitive to the green part of the spectrum under low light (Maier 1992), which appears to be enough to cause different responses compared to other light colours under clear conditions.

In conclusion, it is evident that artificial lights interfere with migratory orientation, but the degree of interference varies depending on the light colour and flash rate. My study confirms that red flashing lights had less of an effect on nocturnal migrant flight paths compared to other light colours. When these or white flashing lights are used as obstruction lighting the collisions of migrants with structures may be minimized.

6 GENERAL DISCUSSION

Millions of birds move through northern British Columbia during annual migrations to breeding and wintering grounds (Environment Canada 2013). During these movements, migratory species must find sufficient stopover habitat and food, and avoid several hazards including pollution, severe weather and collisions with human-built towers and buildings (North American Bird Conservation Initiative Canada 2012). Many species of neotropical migrants are currently in decline (North American Bird Conservation Initiative Canada 2012), while at the same time the number of above ground structures, like communication towers and wind turbines, is increasing (Loss et al. 2013, Zimmerling et al. 2013, Erickson et al. 2014), which raises concerns over the conservation of migratory species due to a potential increase in the number of mortalities from collisions with structures (Ruth et al. 2005).

Conservation of migratory birds requires an understanding of these threats faced by birds during migration, and the movement behavior of birds in response to these threats, so as to reduce potential collisions with above-ground structures (Mabee and Copper 2004, Pocewicz et al. 2013). Nocturnal passerine migrants are the most abundant group of species that typically encounter wind energy facilities (Marques et al. 2014). Direct impacts from collisions is the most documented impact of wind turbines on avian species, although, migrants may also be avoiding important stopover habitats if these locations are anthropogenically disturbed (Able 2004, Pocewicz et al. 2013). Understanding how migrants respond to wind turbines is crucial to the conservation of species (Ruth et al. 2005) and this understanding can only be obtained when data on the movement of nocturnal migrants are accurate. Recent investigations on the of migrating birds in response to wind turbines has focused on diurnally migrating, large-bodied species like waterfowl and raptors, and have

been performed in low altitude and topographically uniform areas, where reported avoidance rates exceed 99% (Chamberlain et al. 2006). There are very few studies that have calculated micro-avoidance rates of nocturnal migrants at wind energy facilities and because these species are moving at night, avoidance of turbines may be more difficult to determine compared to large diurnal birds (Liechti et al. 2013). Further, avoidance of individual wind turbines is not the same as avoidance of wind energy facilities and would affect the understanding of collision risk and the data required for collision risk models. Regardless, better field information is needed to understand collision risk (Everaert 2014).

6.1 Bird movements and collision risk

My thesis presented a new methodology for the collection and analysis of radar data to provide accurate information on the movement of nocturnal passerine migration. Radar has been used for decades to study the movements of biological organisms, particularly due to its ability to detect targets under night time conditions (Taylor et al. 2010). Despite this long period of use, the lack of an automated, cost-efficient systems for the collection of digital radar data has been a major barrier to its general application in studies that require the knowledge on the movement of nocturnally migrating birds, such as those required for assessing collision risk at wind energy facilities. The results of my study showed that digitization of radar imagery and use of available open-source processing software to auto-track aerial vertebrate movements effectively increased the ability to accurately census avian movement patterns without necessarily increasing post-analysis time (Chapter 2). In addition, the system I tested is not cost-prohibitive compared to other more expensive commercial radar systems.

I showed that pairing X-band marine radars outfitted with open array antennas and a radar signal digitizer collected raw radar signals at a high enough resolution to resolve individual avian targets at site-specific spatial scales (1.5 km radius). When these data were processed with an open-source program capable of reading the radar data, aerial vertebrate targets were automatically detected and tracked with high accuracy, compared to known targets that were manually-tracked from recorded data. This allowed for the detailed detection of a greater number of targets compared to what could be transcribed by the radar operator in real-time, the conventionally accepted technique (Beason et al. 2013). This proved to be highly advantageous during periods of high migration traffic, which can result in more accurate measurements of migration rates, and exposure to collision risk. It can also provide context to the relative exposure compared to numbers of known collisions, thus providing detailed assessment of avoidance rates that can be used in collision risk models (e.g., Band et al. 2007). Further, the auto-detection and tracking of avian targets eliminated observer bias and errors associated with the real-time transcription of live radar data. Factors such as the inability to transcribe all targets during high migration traffic, observer fatigue and/or the reliance of multiple observers can lead to errors and biases in the radar data collection, which can then be difficult to account for in the post-analysis of the data. The capture and processing of these digital radar data also allowed for the collection of detailed information on timing of occurrence, target location and size from which variables such as speed, trajectory and bearing can be determined. Size estimates can be used to discriminate avian targets from non-avian targets, such as insects or other radar clutter that may be present (Larkin 1991, Cabrera-Cruz et al. 2013). In addition, size estimates may also be used to differentiate targets into different avian taxa. These types of additional detailed analysis of

the radar data can be conducted after the collection of data, which provides additional advantages over the real-time collection of avian radar data.

While other studies have used real-time analysis to track migrants in western North America (Harmata et al. 1999, Mabee et al. 2006), in Chapter 3 I applied the auto-detection and tracking methodology to assess the general patterns of nocturnal migrant movements in northeast British Columbia. Automation of the system provided an exceptional number of tracks, compared to other similar studies, upon which I could base my analysis. These detailed data on individual tracks allowed for the analysis of the behavior of migrants in response to weather variables and/or the presence of wind turbines on the landscape. Also, with the detailed altitudinal data, avian targets were separated into various height categories. Analyzing data at the level of the individual height category level eliminates errors from the detection bias of the radar since both the volume of airspace surveyed and the power of the radar signal decrease as the distance from the radar increases.

Nocturnal migrants in my study area were moving in a broad-front fashion in both the spring and fall migratory seasons. A significantly higher number of migrants were moving in the fall season, which was expected since both adult and juvenile birds were moving (Otter et al. 2014) and this trend has been observed at migration studies elsewhere (Harmata et al. 1999). The prevailing weather patterns for the region resulted in migrants moving under tailwind conditions in the spring and conversely, in the fall migrants were moving under predominantly headwind conditions. It was expected that the migration rates and movement of birds under headwind conditions would be more sporadic and scattered (Liechti et al. 2013), potentially leading to higher collision risk. The micro-scale movements of migrants through the Dokie I Wind Energy facility, based on the difference in the deviations between

track bearings of migrants and the seasonal wind vectors and altitudes of migrants did not suggest any potential increase in collision risk associated with wind energy development. Rather, the typical migration paths and altitudes of migrants in the region suggest little overlap with the airspace of turbines.

6.2 Influence of rain

In Chapter 4, I showed that nocturnal migrants appear to be adjusting their flight paths in response to rain. The ability to segregate the radar data at a fine temporal scale allowed for the analysis of detailed interactions between the behavior of migrants and response to rain events. By analyzing differences in the number of targets at various height categories in two minute intervals, I showed that there was a reduction in the number of migrants at lower height categories before a rain event rather than an increase, which suggests that some migrants were not being forced to lower altitudes or to the ground by rain. It would be more advantageous for birds to fly over or around a rain event, as oppose to through it to maintain orientation from visual cues used for navigation, such as the moon and stars. Migrants also would avoid wet plumage, which would increase drag and the energy requirements for migration (Schaub et al. 2004, Gagnon et al. 2011).

My results also showed that after a rain event the number of migrants in the various height categories is lower than pre-rain numbers. Although, the overall number of migrants appeared to reach pre-rain numbers within 30 minutes of the rain passing, which suggests that migrants that may have been grounded are resuming migration or those avoiding the rain are resuming normal trajectories in the typical broad-front fashion. I showed that there was a decrease in the number of migrants immediately before the onset of rain and concluded that a

proportion of the migrants were either being forced to the ground due to the rain or adjusting their flight trajectory laterally to avoid the rain. But again, with the number of migrants after the rain being close to pre-rain numbers, the proportion of birds exposing themselves to flight paths within rotor swept areas of the turbines appeared to be relatively low.

My results are counter to theories that rain events would cause migrants to descend from higher altitudes and concentrate in low altitudes (Gauthreaux 1971, Richardson 1978, Erni et al. 2002) thereby placing themselves in a higher collision risk situation with wind turbines (Johnson et al. 2002, Schaub et al. 2004). In my study, collision risk during inclement weather did not appear to increase, which was verified by independent mortality surveys during the operation phase of the wind energy project that failed to find increased collision rates during nights containing poor weather (Stantec Consulting Ltd. 2012a, Stantec Consulting Ltd. 2012b).

My results from Chapter 3 and Chapter 4 suggest that some nocturnal migrants respond to varying conditions they encounter along their migratory path, such as inclement weather and tall structures, by increasing altitudes to avoid these situations; although, the altitudinal profile of nocturnal migrants varies and some were flying at lower altitudes and at heights below turbines (Walsh 2012). Where migrants are moving at lower altitudes, either in response to rain or due to wind conditions, they would be at a greater risk of collision with wind turbines. This risk would increase if other factors are present that would disorient their patterns of movement, such as the presence of artificial light sources.

6.3 Influence of lighting

In Canada, certain turbines on wind energy facilities are required to be equipped with medium intensity CL-864 simultaneous flashing red lighting system (Canadian Aviation Regulation 2014). The specific turbines that must be equipped with these lights are dependent upon the number of turbines within the facility, turbine location and layout. My results in Chapter 5 showed that artificial light interferes with migratory flight paths, but the degree of this interference varies depending on the light colour and flash rate. I showed that red flashing lights have less of an effect on nocturnal migrants compared to other light colours, such as white, green or blue. The response of nocturnal migrants in my study to flashing white and red lights were parallel to those shown by others where towers with red and white flashing lights had significantly fewer bird fatalities (Gehring et al. 2009, Kerlinger et al. 2011). The reaction of migrants to solid white lights in my study varied. While the average altitude of birds exposed to solid white lights was the highest among the light trials, the recorded decrease in altitude over the course of the targets' tracks was also the greatest for solid white lights. These results were similar to those observed by Evans et al. (2007), where bird aggregations within spotlight beams were recorded under periods of white solid light. It has been suggested that the presence of white artificial lights may interfere with visual orientation of celestial cues (Poot et al. 2008). Regardless, my results validate that flashing lights, rather than solid lights; cause less of a response in nocturnal migrant flight paths.

Overall, I found that light colours at shorter wavelengths had the greatest disruption on flight paths of nocturnal migrants. Birds showed both the greatest drop in altitude along flight paths, and closest approach to the spotlight, under blue and green lights. The observed

change in altitude of migrants exposed to artificial blue and green light in my study was likely a function of the sensitivity of birds' vision at night. At night, the visual receptors in a bird's eye shifts from being cone dominated, that function most effectively under higher light levels, to being rod-mediated, which are more sensitive under low light conditions (Hart 2001). Rods are also more sensitive to artificial light, especially at shorter wavelengths (Beason 2003). My results (Chapter 5) showed that the flight paths of birds appeared to be affected by artificial blue and green light, which would likely appear more intense than natural background light and thus potentially disrupt other visual cues that birds were using to orientate themselves during migration.

Given the strong response of nocturnal migrants to artificial green lights, a potential mitigation strategy for wind energy development could be to install green lights in locations some distance (e.g., 1-2 km) from the turbine string. Broadcasting these lights under peak migration periods could steer migrants away from collision risk situations with turbines and could be used to support changes in lighting policy for wind farms. This presents another mitigation option for wind energy developers that differ from curtailment or shut down of turbines during high risk periods. This methodology is as yet untested and may have unpredicted effects on the flight paths of migrants, so further research is needed.

My research has provided detailed biological data on the movements of nocturnal migrants in a mountainous region of northern British Columbia as well as around a wind energy facilities comprised of industrial wind turbines. This information on the spatiotemporal patterns of bird movement can allow for informed decisions on the placement of wind turbines (Ruth et al. 2005, Ruth 2007). As mountain ridges are increasingly being

developed for placement of wind turbines, the risk to migrating birds will increase and more research is required to understand cumulative impacts on bird populations and habitat.

6.4 Cumulative effects

The patterns of movement of nocturnal migrants that I observed at the Dokie I Wind Energy facility represent a low collision risk for this species group. This risk level was confirmed by detailed assessments of carcass searching that was conducted for the first two years (2011 and 2012) of the operational period. During this time an estimated 35 total mortalities (birds and bats combined) were reported during the same nights in which 853,585 targets were tracked migrating through the study site. Based on these numbers the combined mortality rate at the Dokie I Wind Energy facility was estimated at approximately 0.0041% (Otter et al. 2014). Most passerine species have high reproductive potential (i.e., r-selected species) and are abundant and widespread (Chamberlain et al. 2006) so levels of mortality of this magnitude do not likely impact individual bird populations as most species are able to compensate for minor losses during migration (Kuvlesky et al. 2007, Arnold and Zink 2011, Erickson et al. 2014).

As development of wind energy in northern British Columbia continues, the potential for cumulative effects from direct mortality exists and is of concern to resource managers (Chamberlain et al. 2006, Zimmerling et al. 2013). In northeast British Columbia over 50 ridgelines hold wind energy development tenures and it is a reasonable expectation that one third of these will likely be developed into operating projects. If the observed number of collisions at the Dokie project are applied to future project scenarios, it has been estimated that the cumulative mortality rate from multiple wind projects in northeast British Columbia

would still remain below 0.5% (Otter et al. 2014). This level of mortality still remains relatively small compared to other sources of bird mortality and are not expected to affect population levels of migrating species (Arnold and Zink 2011, Erickson et al. 2014), but as wind energy development increases across North America the monitoring of cumulative mortality will be important. Several passerine species are already experiencing population declines as a result of habitat loss, climate change and direct mortality from multiple sources (North American Bird Conservation Initiative Canada 2012). When direct mortality from human activities becomes additive to natural mortality, the total losses of individuals may exceed the resiliency of populations to compensate.

Habitat loss from wind project development is relatively small compared to other types of development (Zimmerling et al. 2013) so the direct loss of foraging stopover habitat is likely low at an individual wind projects. This direct impact is rarely examined as most studies focus on the loss of nesting habitat from project development. Further, nocturnal migrants may avoid stopover habitats in the vicinity of wind turbines as a function of micro- or macro-scale avoidance, which would impact their ability to rest and replenish energy requirements. This displacement of birds to other habitats is likely of little consequence to migrating passerines in regions such as the northern Rocky Mountains, where there is currently relatively little wind energy development. As wind energy development continues to grow in the region and habitat loss and displacement from other sources of development, such as mining and oil and gas projects, accumulate along the migratory corridor of these species, the cumulative effects to migrating passerines remains a concern. Large-scale approaches to studying the movements of nocturnal passerines, the identification of stopover habitats in western North American, similar to those conducted in eastern North America

(Buler and Dawson 2014), and the understanding of the impacts of cumulative sources of mortality on nocturnal migrants will be essential for directing management and conservation actions.

6.5 Mitigation

Mitigation measures implemented to date to reduce mortality on nocturnally migrating passerines have primarily focused on avoidance of migratory paths through the placement and layout of wind projects (Marques et al. 2014). On-demand turbine shutdown has been targeted for certain species, such as raptors, at high collision wind projects and has proven to be effective while minimizing the reduction in energy production (de Lucas et al. 2012). The implementation of such mitigation requires a detailed understanding of the movement of birds through the area since non-rotating wind turbines still represent a potential collision risk, although this risk is lower than a turbine with spinning blades (Liechti et al. 2013). Further, mitigation measures cannot be broadly applied to wind energy installations because the factors that influence collision risk vary by project and depend on a wind project's location and spatial configuration, as well as the characteristics of migratory species moving through the site (Marques et al. 2014). This complex interaction of factors may require multiple mitigation strategies to address the specificities of each project and target species. The mitigation measures mentioned above are proving to be effective for particular affected taxa, but further research is needed to fully understand how applied mitigation is reducing impacts (Marques et al. 2014). For nocturnal migrating passerines, the study of collision fatalities in combination with height-specific and flight path movements around wind energy facilities can be used to improve collision risk models and mitigation

strategies for individual sites (Liechti et al. 2013, Everaert 2014, Otter et al. 2014, this study). Further, as the density and distribution of wind energy developments increase, an acceptable level of bird fatalities by wind turbines needs to be determined.

6.6 Future research

As mentioned above, X-band radars are typically used for tracking bird movements since they emit small wavelengths and are capable of resolving small objects (such as passerines) at distances up to 1.5 km (Taylor et al. 2010), making them useful for avian monitoring on a local scale (Kunz et al. 2007). Current studies often do not differentiate between targets of varying size, and identification to lower taxonomic levels (family or species) is rarely attempted, nor often possible (Cooper 1995, Williams et al. 2001). Many studies simply accept this ‘limitation’, and do not even attempt to determine whether size differences affect detection rates, or whether data could be differentiated for various taxonomic groups (Schmaljohann et al. 2008). Such discrimination; however, may be feasible using variation in the signal detection capacity of most of marine radars and signal digitization kits. In consideration of the radar cross section (RCS) of a target, the distance the target is from the radar and its position within the radar beam, the echo signature of the target can be attained (Schmaljohann et al. 2008). Particular groups of species (e.g., passerines as opposed to waterfowl) may have sufficiently different echo signatures when controlling for distance from the radar that broad classification into taxa may be possible. This could stratify the data into size classes that may aid in identifying groups at higher collision risk, providing more opportunity to target mitigation to particular species or families.

The limitation in pursuing such studies is often cited as the difficulty of ‘calibrating’ the detection signals with known target species (Schmaljohann et al. 2008). Visual confirmation of radar observations is typically achieved by paired radar surveys with visual observations, but many radar studies on wind farms have been criticized for neglecting this step (Schmaljohann et al. 2008). In nocturnal surveying, such confirmation of target identity often requires techniques such as moon watching (tracking the silhouettes of birds as they are backlit by the moon) and/or using ceilometers – high powered lights cast into the sky to spotlight migrants for identification (Gauthreaux 1991, Harmata et al. 1999). Few studies; however, have taken advantage of calibrating radars by operating these in daylight hours in areas of high bird density to study the characteristics of signal returns of known species at varying heights and distances from the radar, and using these to create discriminate models for classification.

Discriminating radar targets into bird groups will provide better information on the diversity of bird species encountered at wind energy project and can be used to improve collision risk models (Everaert 2014) as avoidance rates may vary among species groups. With the added ability to derive detailed bird movement information, as demonstrated in my study (Chapters 2 and 3), and coupling this with carcass monitoring data, updated collision risk models can be created to accurately assess potential risk to species groups from proposed wind energy development. Detailed models from individual projects can be extrapolated to the regional level to identify low risk versus high risk movement corridors for wind energy development to address potential cumulative effects.

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