J. Raptor Res. 46(3):000–000

DETERMINATION OF RAPTOR MIGRATORY PATTERNS OVER A LARGE LANDSCAPE

HEIDI M. SEELAND AND GERALD J. NIEMI[1]
Natural Resources Research Institute and Department of Biology, University of Minnesota, Duluth, MN 55811 U.S.A.

RONALD R. REGAL
Department of Mathematics and Statistics, University of Minnesota, Duluth, MN 55812 U.S.A.

ANNA PETERSON AND CARLY LAPIN
Natural Resources Research Institute and Department of Biology, University of Minnesota, Duluth, MN 55811 U.S.A.

ABSTRACT.—Each autumn, tens of thousands of raptors pass over Hawk Ridge in Duluth, Minnesota, on their southbound migration, but migratory pathways leading to Hawk Ridge are unknown. To address this issue, we counted migrating raptors between mid-August and mid-November 2008 from 24 observation points along eight transects perpendicular to the shoreline between Duluth and the Minnesota-Canadian border. Our goals were to determine migratory pathways over a large area (>2000 km^2) and identify how these movements were affected by weather, time of day, season, and characteristics of the landscape. A total of 4303 raptors of 14 different species were counted during the 2008 migration season. Exploratory analyses suggested that migratory raptors concentrated near the northern shoreline of Lake Superior, particularly during midday when winds are westerly. Average migration height differed between soaring raptors (buteos and eagles) and accipiters, with >40% of soaring raptors observed higher than 100 m above the tree canopy and ≥30% of accipiters observed lower than 100 m above the tree canopy. Mixed models analysis identified the significant factors ($P < 0.05$) associated with total raptor migration: wind direction, time of day, temperature, and antecedent wind (number of days in which the wind did not have a westerly component prior to the observation days; $R^2 = 0.23$). Significant factors associated with soaring-raptor migration included wind direction, time of day, temperature, and seasonal interval (e.g., early or late in the migration season; $R^2 = 0.17$) and those associated with accipiter migration included time of day, temperature, antecedent wind, wind direction, and seasonal interval ($R^2 = 0.29$). With the increasing popularity of wind power development, information is needed regarding avian migratory pathways to avoid bird-turbine conflicts. The methodology and design of this study provided a means to quantify the magnitude, timing, pathways, and weather conditions associated with raptor migration over a large landscape.

KEY WORDS: *autumn; birds; migration; raptors; timing; weather; wind power.*

DETERMINACIÓN DE PATRONES DE MIGRACIÓN DE RAPACES EN UN PAISAJE EXTENSO

RESUMEN.—Cada otoño, decenas de miles de rapaces sobrevuelan Hawk Ridge en Duluth, Minnesota, en su migración hacia el sur, pero las rutas migratorias que llevan a Hawk Ridge son desconocidas. Para resolver este tema, contamos rapaces migratorias entre mediados de agosto y mediados de noviembre de 2008 en 24 puntos de observación a lo largo de ocho transectas perpendiculares a la línea de costa entre Duluth y la frontera entre Minnesota y Canadá. Nuestros objetivos fueron determinar las rutas migratorias sobre un área extensa (>2000 km^2) e identificar cómo estos movimientos se vieron afectados por el clima, la hora del día, la estación y las características del paisaje. Un total de 4303 rapaces de 14 especies diferentes fueron contadas durante la época migratoria de 2008. Análisis exploratorios sugirieron que las rapaces migratorias se concentraron cerca de la línea de costa norte del Lago Superior, particularmente durante el mediodía cuando los vientos tienen dirección oeste. La altura media de migración difirió entre rapaces de vuelo planeado (especies de *Buteo* y águilas) y accipitéridos, con >40% de rapaces de vuelo planeado observadas a

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[1] Email address: gniemi@umn.edu

alturas mayores a los 100 m sobre el dosel de los árboles y ≥30% de accipitéridos observados a alturas menores a los 100 m sobre el dosel arbóreo. Modelos de análisis mixtos identificaron los factores significativos ($P < 0.05$) asociados con la migración de rapaces total: dirección del viento, hora del día, temperatura y viento antecedente (número de días en los que el viento no tuvo un componente oeste previo a los días de observación; $R^2 = 0.23$). Los factores significativos asociados con la migración de rapaces de vuelo planeado incluyeron dirección del viento, hora del día, temperatura e intervalo estacional (ej., temprano o tarde en la estación migratoria; $R^2 = 0.17$). Aquellos asociados con la migración de accipitéridos incluyeron hora del día, temperatura, viento antecedente, dirección del viento e intervalo estacional ($R^2 = 0.29$). Con la creciente popularidad del desarrollo de la energía eólica, se necesita información respecto de las rutas migratorias para evitar conflictos entre las aves y las turbinas. La metodología y el diseño de este estudio proveyeron medios para cuantificar la magnitud, las fechas, las rutas y las condiciones meteorológicas asociadas con la migración de rapaces sobre un paisaje extenso.

[Traducción del equipo editorial]

Each autumn, millions of raptors migrate from their breeding grounds to wintering areas following a number of established migration corridors across North America (Bildstein 2006). Within each of these corridors, raptors concentrate in several migratory pathways (Goodrich and Smith 2008). These pathways are generally defined by weather conditions (Titus and Mosher 1982, Hall et al. 1992, Allen et al. 1996) and geographical features, such as large bodies of water and ridgelines (Kerlinger 1985, Bildstein 2006). Decades of systematic raptor counts have been recorded at sites (including Cape May Point on the Atlantic Coast, Hawk Mountain in the Appalachian Mountains, and Hawk Ridge at the western end of the Great Lakes) located within known migration corridors (Farmer et al. 2008). However, information about the pathways used by migrating raptors between such sites is limited.

With increasing interest in wind power development, a detailed understanding of migratory pathway use is needed. Conflicts between migrating raptors and wind power development, such as mortality from collisions, migration path barriers, habitat conversion, and habitat fragmentation, may be avoided if the migratory pathways of raptors are better understood (Johnson et al. 2002, U.S. Fish and Wildlife Service 2003, Smallwood and Thelander 2008).

Corridors used by migrating raptors have been assessed using a number of methods, including annual counts at individual sites along major corridors (McCarty and Bildstein 2005), raptor banding (Henny and Van Velzen 1972), the use of hydrogen isotopes to determine the origin of migrating birds (Meehan et al. 2001, Hobson et al. 2009), and tracking with telemetry, satellites, or radar (Kerlinger and Gauthreaux 1985a, Bruderer et al. 1994, McClelland et al. 1994, Alerstam et al. 2006). Although site counts, banding, and isotope studies provide good broad-scale overviews of migratory pathways, many are based on observations or recoveries from a few sites, providing little or no information on where birds are traveling within migration corridors. Radio- and satellite telemetry provide more detailed data on the paths used by migrating birds; however, these methods result in very small sample sizes, and the paths taken by individual birds vary within and between years (Martell et al. 2001, Alerstam et al. 2006). Niles et al. (1996) used multiple observation points to examine the influence of habitat on raptor migratory pathways. There is a need for a methodology in the study of raptor migration that covers a large geographical area in great detail, while maintaining a large sample size and accounting for year to year variation.

The north shore of Lake Superior provided an ideal location to test the use of a series of observation points to obtain information on specific raptor migratory pathways within this migration corridor. Although migrating raptors are known to concentrate along the northwestern shore of Lake Superior (Hofslund 1966), the autumn migratory pathways they use are not well known. Encounters of Sharp-shinned Hawks (*Accipiter striatus*), Northern Goshawk (*Accipiter gentilis*), and Northern Saw-whet Owls (*Aegolius acadicus*), the three most common species banded at Hawk Ridge, during the breeding season have primarily been north or northwest of Hawk Ridge (D. Evans pers. comm., Goodrich and Smith 2008, Evans et al. 2012). The most plausible explanations for the concentration of raptors at Hawk Ridge are the prevailing westerly wind drift and the leading line created by the shoreline of the north shore of Lake Superior. Hence, raptors migrating in a broad front from northerly and northwesterly directions encounter Lake Superior and are diverted southwesterly along the shoreline and concentrate at Hawk Ridge in Duluth,

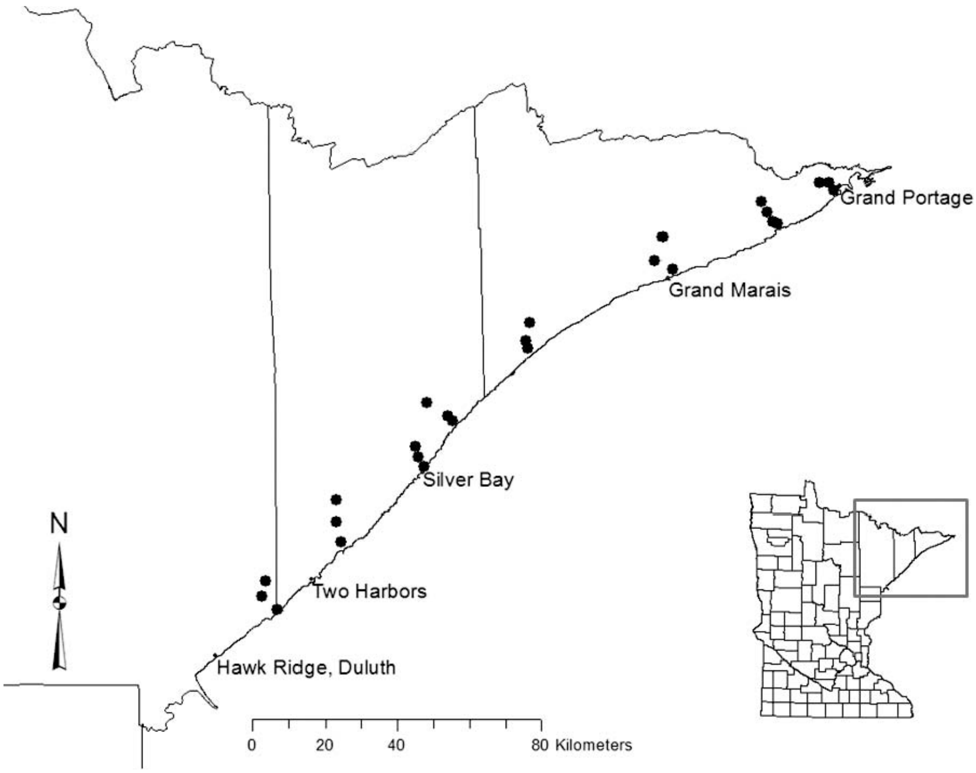

Figure 1. Fall 2008 raptor migration observation sites along the Minnesota portion of the north shore of Lake Superior. Study sites indicated by black dots, the nearest town by an open diamond.

Minnesota (Hofslund 1966, Mueller and Berger 1967a). The combination of many natural (ridgelines) and human-made (clearings) observation points, as well as a reliable raptor migration along the north shore, provided the opportunity to document the specific pathways used by migrating raptors approaching Hawk Ridge.

Our goals were to determine migratory pathways over a large area and identify how these movements were affected by weather, time of day, season, and characteristics of the landscape. These data will be useful to aid in future conservation planning and for the protection of raptor migration pathways from negative effects associated with potential future development of wind turbines, communication towers, or residential housing in the Great Lakes region.

METHODS

Study Sites. We counted and recorded migrating raptors from 24 observation points along eight transects located perpendicular to the Lake Superior shoreline between Duluth, Minnesota and the Minnesota-Canadian border (approximately 270 km) from 29 August to 11 November 2008 (Fig. 1, Appendix 1). Sites were selected based on their views of the surrounding landscape and proximity to the shore. We used prominent ridge tops, clear-cuts, gravel pits, roadsides, U.S. Forest Service fire towers, and other open spaces to obtain the best possible view.

Within each transect, the three observation sites were located within 2 km, between 2 and 8 km, and between 8 and 14 km from the Lake Superior shore, respectively. Sites were spaced as evenly and as perpendicularly as possible to the shoreline to provide a continuous view of the landscape from the shore to the site furthest inland. If views of the surrounding landscape were obscured by shrubs or young trees, observers used deer stands to elevate themselves from the ground. Views from the observation sites ranged from 190° to 360° as allowed by the terrain. From each observation site, birds were visible up to 3.2 km or more within the viewing angle from each site. The numbers of raptors observed from each site were standardized by time and area (see below) for data analysis by using the number of birds per ha per hr.

Transects were numbered 1 through 8 beginning with the southwestern-most transect near Duluth, Minnesota, and ending near Grand Portage, Minnesota. Sites were lettered a though c beginning with the site located closest to the shore of Lake Superior and ending inland.

Counting of Raptors. Three observers simultaneously conducted hourly raptor counts with one observer stationed at each of the three observation sites (sites a, b, c) within one transect on each sampling day. Observers used radio or cell phone contact. Counts began approximately 1–1.5 hr after sunrise and continued for 7 hr, with a minimum of 5 hr of data collected each observation day. Counts were delayed or stopped during inclement weather. Data were not collected in heavy fog (visibility limited to within 1.6 km of observation site) or rain heavier than drizzle or mist. Transects 2, 4, 5, 7, and 8 were sampled on three days. Transects 1, 3, and 6 were sampled on four days over the fall 2008 migration season.

To record migrating raptors, each observer used a topographic map of the landscape that included approximately 4 km surrounding the observation site. Migrating raptors were recorded by placing a dot on the map approximately where the bird was first sighted over the landscape. Observers scanned the sky for migrating birds using 8 × 42 or 8.5 × 32 binoculars. Once spotted, birds were identified to species or as specifically as possible using Swarovski STS-80 HD spotting scopes. Observers were conservative in identifying distant birds to genus or species when light or weather conditions compromised visibility. Observers recorded the number of individuals, bird identification, and approximate flight height on the topographic map. They estimated flight height relative to the canopy and categorized it as below canopy, canopy to 100 m, 100 m to 500 m, and more than 500 m above canopy. All data were recorded in 1-hr increments.

Observers took several precautions to avoid double-counting migrating raptors. Transects were grouped into three sets: transects 1 through 3, 4 and 5, and 6 through 8. Sets of transects were sampled in a random order. Because fall migrating raptors in this region are moving in a southwesterly direction and reportedly move an average of 170 to 175 km/d (Fuller et al. 1998, Kjellen et al. 2001), transects within each set were sampled in a northeasterly direction on any successive days to avoid double-counting the same individuals. If observers moved to a set of transects to the southwest, a delay of a least one day was taken. Observers used radio or cell phone contact to avoid double-counting raptors visible from multiple sites within each transect. If a raptor was spotted by multiple observers, the first observer to see the bird recorded it. If double-counting was suspected, data sheets were compared at the end of the day to discuss any potential overlap in observations.

Weather Monitoring. Observers recorded weather conditions, including sky cover (cloud cover or precipitation), temperature (°F), visibility (maximum distance at which birds were visible), wind speed (Beaufort wind speed scale), and wind direction in degrees at the beginning of each hour of observation. If precipitation occurred for more than 15 min within 1 hr, the appropriate designation was used regardless of the sky conditions at the beginning of the hour. Observers also estimated wind direction; however, this was not always accurate due to the sheltered position of several sites. For more accurate estimates, we retrieved wind direction records from the National Climatic Data Center (NCDC) website maintained by the National Oceanic and Atmospheric Administration (NOAA) from the regional airport nearest each site (NCDC 2009). Weather data retrieved from the NCDC were used in analysis. We also retrieved antecedent weather conditions, including wind direction and precipitation on the day prior to observations from NCDC.

Geographic Information. All observations were entered into a geographical information system (GIS) using ArcMap, version 9.3 (ESRI 2008). U.S. Geological Survey digital raster graphic maps were used as a base to create both the topographic map data sheets and to enter observations into ArcMap. All observations were entered as point features into a shapefile to calculate the coordinates for each raptor observation (NAD 1983 UTM Zone 15N). A single point was used for each bird or group of birds observed. An attribute table was used to record site, date, time of day (hr of observation), number of individuals (if all birds within a group were the same species), identification, and flight height for each observation. We also entered all weather and temporal (hr and date) data into an attribute table in ArcMap.

We estimated the total land surface visible within 4.8 km of each observation site using the Viewshed and Solar Radiation Graphics tools in ArcMap. Viewshed was used to calculate the land surface visible from each observation site using 10-m digital elevation model data. Calculating the viewshed alone was insufficient because many birds were observed over land surface that was not visible from the observation site. To include all land surfaces over which migrating raptors were sampled, we calculated hemispherical viewsheds for each site using the Solar Radiation Graphics tool in Solar Analyst to represent the area of the sky visible from each site (Fu and Rich 1999). Hemispheres were limited to 4.8 km as no birds were sighted beyond that distance. The hemispherical viewsheds were also insufficient because they did not account for areas of the sky blocked by trees, thereby including an area larger than that actually visible to the observer. To correct for obstructions, we modified the hemispherical viewsheds to more accurately reflect the area visible, and we excluded any areas where the sky was not visible. The land surface over which we sampled birds was added to the land surface calculated using the Viewshed tool for the remainder of analysis.

Data Analysis. We analyzed raptors in two groups, soaring raptors and accipiters, according to flight style to examine any differences in their migratory pathways. Soaring raptors included species that rely primarily on soaring flight, including Red-tailed Hawks (*Buteo jamaicensis*), Broad-winged Hawks (*B. platypterus*), Rough-legged Hawks (*B. lagopus*), Bald Eagles (*Haliaeetus leucocephalus*), and Golden Eagles (*Aquila chrysaetos*). Any unidentified buteos or eagles were also included in the soaring raptors group. Accipiters, species relying on flapping flight with intermittent gliding as opposed to soaring, included Sharp-shinned Hawks (*Accipiter striatus*), Cooper's Hawks (*A. cooperii*), Northern Goshawks (*A. gentilis*), and any unidentified accipiters. A third group consisted of all raptors observed (''all raptors'') regardless of flight style. This included Turkey Vultures (*Cathartes aura*), Osprey (*Pandion haliaetus*), Northern Harriers (*Circus cyaneus*), American Kestrels (*Falco sparverius*), Merlin (*F. columbarius*), Peregrine Falcons (*F. peregrinus*), unidentified falcons, and any unidentified raptors in addition to those listed above. Sampling days were grouped into four seasonal intervals. Interval 1 lasted from late August to mid-September; interval 2 from mid-September to mid-October; interval 3 from mid- to late-October; and interval 4 from late-October to mid-November. Each transect was sampled once per interval, with the exception of interval 4 in which only transects 1, 3, and 6 were sampled.

We performed exploratory data analyses and summaries for the 2008 migratory season using SAS version 9.2 (SAS Institute 2002–07). All data tables were exported from ArcMap into Microsoft Excel and then imported into SAS. We merged the data tables containing raptor, landscape, and weather data into a single table organized by site, date, and time of day. We calculated the total number of each species of raptor, total soaring raptors, total accipiters, and all raptors for each site during each hr of observation. Descriptive statistics, including the means and proportions of raptors observed at various locations were calculated using the number of raptors observed per hour. Hourly raptor totals were $\log_{10}$- transformed (count + 1) for analysis, and we calculated descriptive statistics, including the means and proportions of raptors observed under various conditions.

We conducted mixed models analyses to examine the relationship between migrating raptors, weather factors, and time of day using the Mixed Procedure (Littell et al. 2006). We chose a mixed model analysis to account for correlations between data collected at the same sites and on the same dates. Random effects considered were transect, date * transect, and site * transect. When random effects had estimates of zero for their variance components, those random effects were not included in the model. The fixed effects factor with the highest *P*-value was eliminated and the models run again until all remaining factors were significant at $P \leq 0.05$.

Mixed models do not include true partial R^2 values, but we provide analogous values to quantify the improvement in fit from including the fixed effects. These ''R^2'' values used the sum of squared errors including only random effects and using random effects plus fixed effects. For the overall models, these partial R^2 values give reasonable measures of the efficacy of the fixed effects. Calculating these sorts of values for individual terms in the models were in some cases misleading, particularly for the fixed effect of period when including dates as random effects. To quantify the effects of each variable, we calculated a ratio of expected counts for each variable comparing the most favorable level and the least favorable level of the variable. Because these data were analyzed as $\log_{10}(y + 1)$, the ratios of y + 1 will be smaller than the corresponding ratios of counts. To adjust for this bias, we used a

Taylor series expansion approximation ln(y) and converted to the relationship between $\log_{10}(y)$ and $\log_{10}(y + 1)$ as

$$Log_{10}(y) \approx Log_{10}(y+1) - \frac{1}{Ln(10)*(y+1)} - \frac{1}{Ln(10)*2*(y+1)^2}.$$

''Abundance ratios'' were estimated as back-transformed approximations for differences of Ln(y) with all other variables fixed at their best conditions. For example for wind direction, if $\text{direction}_{\text{Best}}$ and $\text{direction}_{\text{Worst}}$ are the best and worst wind directions, then the abundance ratio estimates

$$\frac{\textit{Birds for Best wind direction}}{\textit{Birds for Worst wind direction}}$$

where a ratio of 2.0 means there are twice as many birds seen at the best wind direction than at the worst wind direction.

We also examined distance from shore using the Mixed Procedure. We used the total number of accipiters, soaring raptors, and all raptors observed per ha per hr for the entire 2008 season to account for differences in the amount of area visible and the total hours spent at each observation site. The number of birds per ha per hr was $\log_{10}$-transformed for analysis.

RESULTS

Observers counted a total of 4303 raptors of 14 different species during the 2008 migration season. Bald Eagles were the most commonly observed species, followed by Sharp-shinned Hawks, Broad-winged Hawks, Red-tailed Hawks, Rough-legged Hawks, and Turkey Vultures (Table 1). From each transect, an average of 4.18 (±1.19 SE) accipiters, 9.09 (±3.14 SE) buteos, 4.35 (±0.82 SE) eagles, and 21.75 (±3.78 SE) total raptors per hour were observed with no consistent pattern in the numbers seen closer or further away from Duluth, Minnesota. Results discussed here from 2008 include four sample days for transects 1, 3, and 6 and three sample days for the remaining transects.

Weather and Temporal Factors. Mixed models analyses identified significant weather and temporal factors for all three groups (soaring raptor, accipiter, and all raptors). Significant factors ($P < 0.05$) for all raptors included wind direction (in degrees), time of day, temperature, and antecedent wind ($R^2 = 0.22$, $n = 564$ hourly observations). For the soaring raptor group, significant factors included wind direction, time of day, temperature, and seasonal interval ($R^2 = 0.26$, $n = 564$). For the accipiter group, significant factors included time of day, temperature, antecedent wind, wind direction, and seasonal interval ($R^2 = 0.29$, $n = 564$; Table 2).

Table 1. Total number of each raptor species observed in fall 2008, north shore of Lake Superior, Minnesota, U.S.A.SPECIES.

SPECIES	TOTAL
Turkey Vulture (*Cathartes aura*)	107
Osprey (*Pandion haliaetus*)	24
Northern Harrier (*Circus cyaneus*)	22
Sharp-shinned Hawk (*Accipiter striatus*)	539
Cooper's Hawk (*Accipiter cooperii*)	6
Northern Goshawk (*Accipiter gentilis*)	23
Unidentified accipiter	204
Broad-winged Hawk (*Buteo platypterus*)	375
Red-tailed Hawk (*Buteo jamaicensis*)	370
Rough-legged Hawk (*Buteo lagopus*)	160
Unidentified buteo	976
Bald Eagle (*Haliaeetus leucocephalus*)	822
Golden Eagle (*Aquila chrysaetos*)	24
Unidentified eagle	14
American Kestrel (*Falco sparverius*)	87
Merlin (*Falco columbarius*)	19
Peregrine Falcon (*Falco peregrinus*)	9
Unidentified falcon	16
Unidentified raptor	506
TOTAL	4303

The soaring raptors and all raptors were similarly affected by wind direction. For these two groups, we observed most birds when winds were from the northwest, north, and southwest, and we observed the fewest when winds were from the northeast, southeast, and south. Differences in wind directions were smaller for accipiters than for the other groups. Most accipiters were observed when winds were from the southwest and almost none were observed when winds were from the northeast, east, and south (Fig. 2a).

Daily counts were highest near midday for all three groups. The number of raptors observed increased through the third hour of observation (late morning) and then slowly decreased throughout the remainder of the day (Fig. 2b). Over the course of the migration season, most of the soaring raptors and all raptors groups were observed during the third survey interval, from mid- to late-October.

Table 2. Significant ($P \leq 0.05$) independent variables for weather and timing (time of day and seasonal interval) from a mixed model analysis of total of all raptors, total accipiters, and soaring raptors. Abundance ratios are the estimated ratios of birds seen at the best and worst conditions of that variable.

GROUP	FIXED EFFECTS PARTIAL R^2	VARIABLE	P-VALUE	ABUNDANCE RATIO
All raptors	0.23	Time of day	<0.01	2.96
		Temperature	<0.01	3.04
		Antecedent wind	0.02	4.16
		Wind direction	<0.01	1.89
Accipiters	0.17	Time of day	<0.01	1.31
		Temperature	<0.01	3.72
		Antecedent wind	<0.01	7.05
		Wind direction	<0.01	1.50
		Seasonal interval	<0.01	1.74
Soaring raptors	0.17	Time of day	<0.01	2.92
		Temperature	0.02	2.75
		Wind direction	0.01	2.18
		Seasonal interval	0.05	2.68

Overall, the number of raptors steadily increased during the third interval, and then dropped sharply during the fourth interval, from early to mid-November. The number of soaring raptors observed per hr peaked during interval 3 and was steady throughout intervals 1, 2, and 4. The number of accipiters peaked during the second interval, from mid-September through mid-October, with fewer observed during the first and third intervals and very few observed during the fourth (Fig. 2c).

Geographical Patterns. Within transects, we observed most raptors from one of the two sites located closest to the shore; however these results were not significant (Fig. 3). Among all three groups, accipiters showed the most fidelity to the shoreline sites. In transects 1, 2, and 4, most soaring raptors and all raptors were observed from site a, and in transects 3, 7, and 8 from site b. Transect 5 was an exception, for which we observed most soaring raptors and all raptors from site c. In transect 6, the number of raptors was evenly distributed among all three sites (Fig. 3). The number of raptors observed per hour at each transect varied widely (Fig. 4); however, when standardized by observable area, no significant patterns among transects emerged. Most accipiters were observed midway between Duluth and Grand Portage. Soaring raptors and all raptors were more variable (Fig. 4).

Flight Height. We rarely observed raptors flying below the tree canopy, with the exception of the accipiter group at transect 7. Most of the all raptors group was observed from 100 to 500 m and more than 500 m above the tree canopy. Accipiters were more frequently observed flying at lower altitudes than soaring raptors. This was particularly evident for the canopy to 100 m above canopy range: ≥30% of accipiters was observed flying within this range compared to <30% of soaring raptors at each transect. Most soaring raptors (>40%) were observed more than 100 m above the canopy (Fig. 5).

DISCUSSION

Patterns of Migration Along Lake Superior's North Shore. Exploratory analyses using this method provided insight into the effect of the shoreline and the use of ridgelines by migrating raptors. Westerly wind drift pushes southbound raptors along a broad front toward Lake Superior's north shore coast (Hofslund 1966, Mueller et al. 2004). The land-water interface of the north shore coast is a diversion line and results in a diversion of raptors along the shoreline (Bildstein 2006). Therefore, we tended to observe most migrating raptors from a or b sites located closest to Lake Superior.

We observed considerable variation in numbers of migrating raptors with respect to the shoreline. For instance, at transects 3 and 8, we observed higher numbers of raptors at the intermediate b sites which was the first major ridge from shore. On these transects, the site closest to the shore was not on a ridge yet provided the best view of the shoreline and inland to the intermediate site (Fig. 3). Raptors are known to rely on updrafts that form along the ridges running parallel to the shore

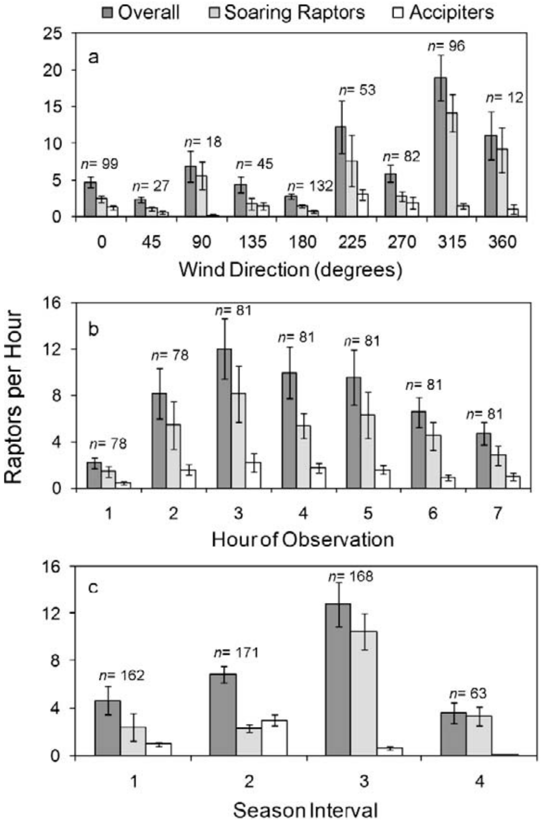

Figure 2. Raptors observed per hr related to wind direction, time of day, and seasonal interval of the migratory season (mean ± SE, *n* = total hours of observation). Hours of observation corresponds to hours after sunrise during each observation day. Seasonal interval corresponds to timing over the 2008 migration season, one sampling day at each transect per interval (with the exception of interval 4, in which only transects 1, 3, and 6 were sampled). Interval 1: late August to mid- September; interval 2: mid- September to mid- October; interval 3: mid- to late-October; interval 4: late- October to mid- November.

for efficient migratory flight (Hofslund 1966, Mueller and Berger 1967b, Bildstein 2006). Transect 6 in particular lacked well-defined ridgelines, which likely contributed to the relatively even distribution of raptor observations at all three sites (Fig. 3).

This pattern of changes in the number of raptors migrating along the north shore of Lake Superior with distance from the shoreline contrasted with descriptions of the Kittatinny Ridge in the Central Appalachians (Bildstein 2006). Whereas the Kittatinny Ridge is one long ridgeline, the north shore of Lake Superior from the Canadian border to Duluth is a series of ridgelines that vary considerably in elevation with their continuity disrupted by numerous stream valleys. Hence, the north shore on a smaller scale has a series of ridgelines and a series of ''water gaps'' (sensu Bildstein 2006 for the Kittatinny Ridge with the Lehigh River) that disrupt a continuous diversion line for raptor movement along the north shore of Lake Superior. More data for additional years will be necessary to discern more specific migratory pathways along the north shore of Lake Superior. In addition, local weather patterns also contribute to birds being pushed inland on days when winds were from the south or east (Mueller and Berger 1961).

One potential anomaly during the 2008 fall migration was the lack of a major flight by Broad-winged Hawks that typically occurs during the last two weeks of September (Hofslund 1966, Hawk Ridge Bird Observatory 2011). Presumably, weather patterns during the peak migration season for Broad-winged Hawks in 2008 were not amenable to a large migration in 2008; in addition, our sampling days did not include a major Broad-winged Hawk migration. The average number of Broad-winged Hawks over the past twenty years at Hawk Ridge has been 48 270, but only 35 781 were observed in 2008. Future studies may need to be modified to account for migrations by this species because of the large numbers that can overwhelm the numbers of the other soaring buteos.

Influence of Wind Direction, Daily Timing, and Seasonality. Raptors migrated in the highest numbers along the north shore of Lake Superior when winds had a westerly component, consistent with observations from Hawk Ridge (Hofslund 1966). Most raptors were strongly influenced by passing cold fronts, with most birds observed just after the passage of a front when winds had a westerly component (Mueller and Berger 1961, Allen et al. 1996). The timing of daily peak flights was consistent with other studies, with most raptors observed during the middle part of the day (Mueller and Berger 1973, Maransky et al. 1997). Red-tailed, Rough-legged, and Broad-winged hawks, Bald and Golden eagles, and Turkey Vultures all rely on thermals and updrafts for soaring flight, which are strongest around midday (Kerlinger and Gauthreax 1985a, 1985b, Maransky et al. 1997). The high number of Turkey Vultures in addition to *Buteo* species included in the all raptors group likely contributed to the high number of raptors observed midday (Fig. 5). Mueller and Berger (1973) noted that

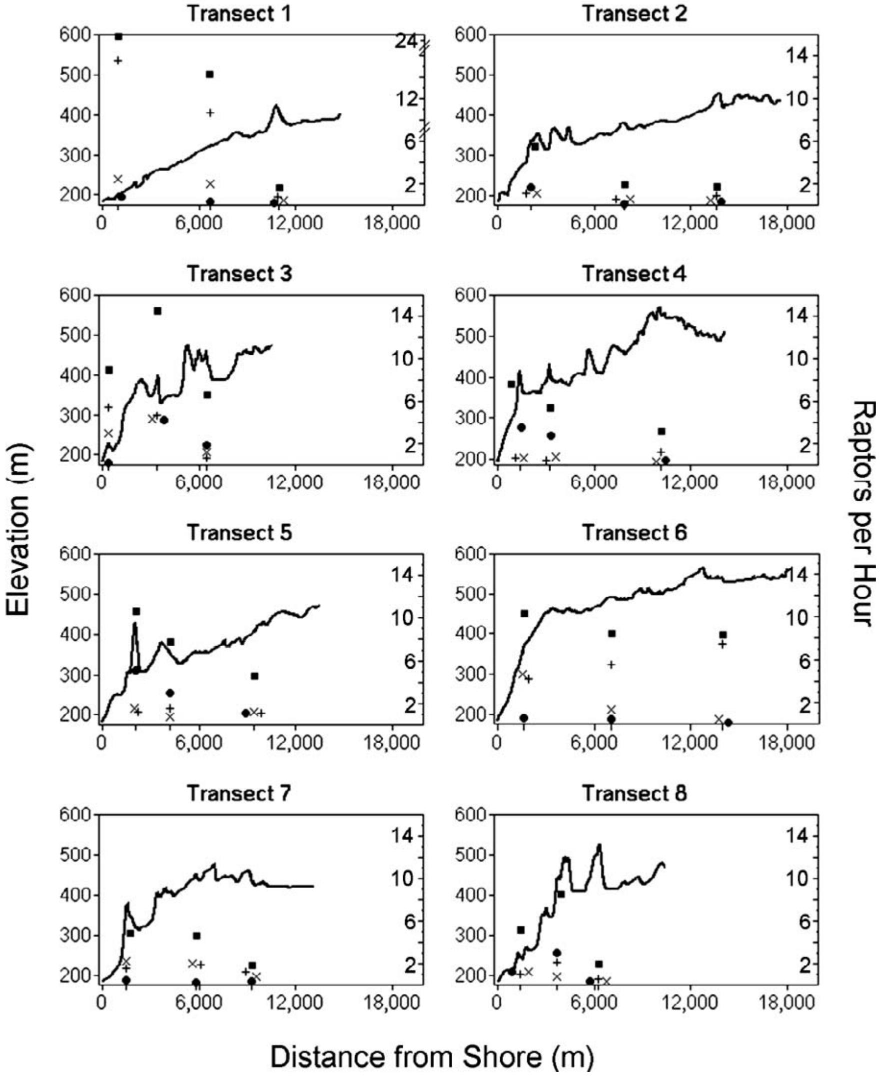

Figure 3. Cross-sectional elevation profile of each transect illustrating the position of major ridgelines, the position of each observation site, and the number of Accipiters (●), Buteos (+), Eagles (×), and total raptors (■) observed per hour. Symbols and dashes on the x-axis correspond to sites a, b, and c within each transect.

accipiters migrating along Lake Michigan tended to be seen more often in the morning than buteos and falcons. The tendency of this group to fly earlier in the day may have led to the lack of a distinct midday peak in the all raptors group, as compared to the soaring raptors.

Seasonal peaks were consistent with those recorded at Hawk Ridge (Hofslund 1966). The mid-to late-October peak in the soaring raptors group coincided with several late-season migrant species, including Red-tailed Hawks, which typically peak in October, Rough-legged Hawks, and Bald and Golden eagles, which peak from mid-October to early November. Peak accipiter migration occurred from mid-September to mid-October, with very few observed by late October and November. Several studies have documented a similar pattern in accipiter seasonal timing, which is likely associated with suitable weather conditions early in the fall (Mueller and Berger 1967b, Titus and Mosher 1982, Hall et al. 1992).

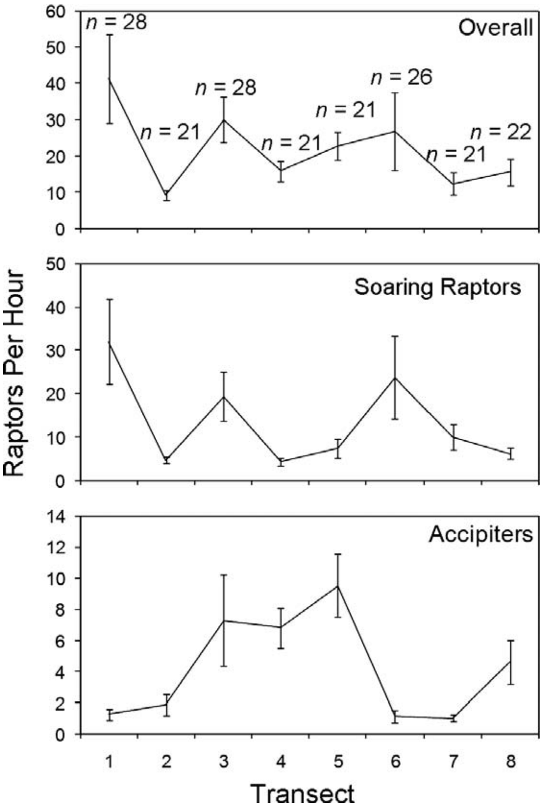

Figure 4. Raptors observed per hr at each transect over the fall 2008 migratory season (mean ± SE).

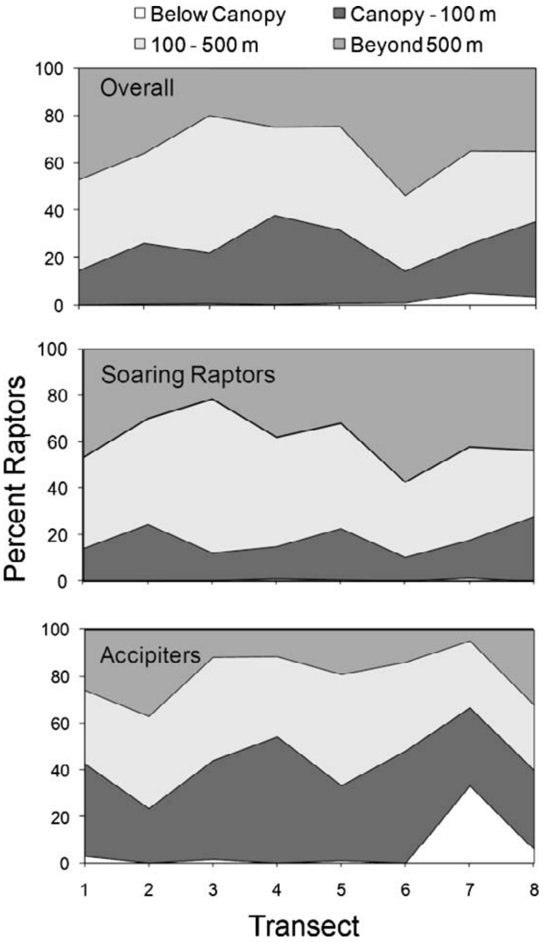

Figure 5. Proportions of raptors observed at each flight height category out of the total observed at each transect.

Flight Height. The most noticeable pattern in flight height was the difference between the accipiter and soaring raptors groups, with higher proportions of accipiters observed flying between the canopy and 100 m above as compared to the higher-flying soaring raptors (Fig. 5). Niles et al. (1996) found that raptors fly lower when over habitats they occupy during the year, perhaps foraging while migrating. The majority of the landscape along the north shore is forested, and accipiters, which occupy forested habitats, are likely taking advantage of foraging opportunities during migration (Niles et al. 1996). Accipiters also frequently rely on updrafts created along ridgelines rather than on the stronger thermals used by soaring raptors to gain altitude (Mueller and Berger 1967b).

Several species in the soaring raptors group, including Golden Eagles, Rough-legged Hawks, and Red-tailed Hawks, occupy open habitats that are sparse throughout the region, and they are less likely to be foraging. Buteos and other soaring raptors are also more often observed either gaining altitude on thermals or gliding from high altitudes between thermals (Kerlinger and Gauthreax 1985b). The lack of raptors observed flying below the canopy may have been due to several factors. Distant birds are difficult to see against tree cover or below the canopy, and we only observed birds flying beneath the canopy when they were very close to the observation sites.

Future Research. The methodology we used to determine the effects of weather, temporal, and landscape factors on raptor migration pathways over a large landscape allowed us to sample this large area and gain insight on the magnitude of migration and factors associated with migratory raptor movements. Additional years of bird movement data, in combination with more weather and landscape information, will likely provide a better understanding of the migratory pathways along the north shore of Lake Superior.

Visual methods of studying migratory raptor movements are useful where suitable observation sites exist; these methods allow the gathering of large sample sizes of birds. Other techniques for monitoring migration have various advantages and disadvantage. The use of radar is limited by the topography of this region because the southeast-facing ridgelines block radar beams from the Doppler radar tower in Duluth, Minnesota. Radar also has limited capacity for detecting low-flying birds, which is a concern with *Accipiter* species. Conventional telemetry methods are labor-intensive and more expensive than visual methods, and provide information on fewer individuals but with more detail. Telemetry studies have limitations in this area because of the rugged topography and the limited number of roads in the area. However, telemetry might be useful along the north shore of Lake Superior for confirming the pathways used by migrating raptors, especially those flying below the canopy. Satellite transmitters with global positioning systems (gps) offer many advantages for future use in studies of migratory pathways, especially since their degree of spatial resolution has greatly improved in recent years. Their greatest limitations are the current cost of transmitters.

The observation methods presented here can be tailored to any region where a more detailed understanding of the migratory pathways used by raptors is desired. A series of vantage points with a wide view of the landscape is required and can be obtained by using topographic features, lifts, towers, and other structures. Factors specific to each region, such as prevailing weather patterns, the orientation of ridges, shorelines, or other geographic features, and the flight styles of predominant species should be considered (U.S. Fish and Wildlife Service 2003). It is important to note that these methods are not intended to be used to determine the total number of migrating birds but rather to determine the factors affecting the pathways in which they concentrate. By examining the relative concentration of birds, locally heavily used areas can be identified. This can be especially useful in planning and locating new wind turbines or communication towers to avoid conflicts with migrating raptors (U.S. Fish and Wildlife Service 2003).

Several sets of guidelines on the construction of new wind power developments emphasize the importance of identifying potential bird conflicts and avoiding development in migratory pathways and other areas important to birds (U.S. Fish and Wildlife Service 2003, Michigan Department of Labor and Economic Growth 2007, Washington Department of Fish and Wildlife 2009). Using the methods described here, regional maps of migratory pathways can be produced and used to identify the areas where migratory birds may be most sensitive to potential wind energy development. Because direct mortality resulting from collisions has been documented at wind farms (Johnson et al. 2002, Smallwood and Thelander 2008), it is vital that migratory pathways be identified in detail over large regions to avoid large-scale negative effects on migrating birds.

ACKNOWLEDGMENTS

We are grateful to the following individuals for their contributions and support: Paul Dolan-Linne for his contributions in the field, Tom Hollenhorst and Paul Meysembourg for assistance with GIS work, Janelle Long and January Green for support from Hawk Ridge Bird Observatory, and constructive comments from David Evans, Allen Fish, and Laurie Goodrich. This project was funded in part under the Coastal Zone Management Act, by NOAA's Office of Ocean and Coastal Resource Management, in cooperation with Minnesota's Lake Superior Coastal Program. Matching funds were provided by the Natural Resources Research Institute, University of Minnesota Duluth. Housing during data collection was donated by the U.S. Forest Service. Finally we would like to thank the Grand Portage Band of Lake Superior Chippewa, Northshore Mining Company, Robert Slater and the Minnesota Department of Natural Resources, and the many private landowners who allowed access to observation sites. This paper represents contribution number 535 of the Center for Water and the Environment, Natural Resources Research Institute, University of Minnesota Duluth.

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Received 6 June 2011; accepted 29 March 2012
Associate Editor: Chris Farmer

Appendix 1. Latitude, longitude, and altitude of each observation point. Observation points were arranged in eight transects numbered 1 through 8. Each transect contained three study sites lettered a through c in increasing distance from the Lake Superior shoreline.

Transect	Site	Latitude	Longitude	Altitude (m)
1	a	46°56′51.139″N	91°47′33.295″W	201
	b	46°58′53.453″N	91°50′46.611″W	319
	c	47°1′9.709″N	91°50′1.754″W	419
2	a	47°6′49.788″N	91°33′28.610″W	303
	b	47°9′57.789″N	91°34′31.449″W	381
	c	47°13′2.399″N	91°34′22.797″W	449
3	a	47°17′44.159″N	91°15′3.884″W	231
	b	47°19′15.967″N	91°16′7.836″W	387
	c	47°20′49.688″N	91°16′40.233″W	454
4	a	47°24′34.317″N	91°8′21.727″W	417
	b	47°25′13.863″N	91°9′29.304″W	430
	c	47°27′22.718″N	91°13′55.762″W	572
5	a	47°35′5.542″N	90°51′22.566″W	430
	b	47°36′11.096″N	90°51′46.135″W	355
	c	47°38′59.079″N	90°50′53.595″W	402
6	a	47°46′14.099″N	90°19′0.108″W	361
	b	47°47′39.649″N	90°22′46.267″W	490
	c	47°51′13.416″N	90°20′48.117″W	538
7	a	47°52′36.279″N	89°55′13.225″W	372
	b	47°54′19.759″N	89°57′33.903″W	452
	c	47°55′53.025″N	89°58′42.471″W	457
8	a	47°57′10.729″N	89°42′26.569″W	256
	b	47°58′17.484″N	89°43′25.632″W	441
	c	47°58′28.447″N	89°45′33.521″W	520