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Topography drives migratory flight altitude of golden eagles: implications for on-shore wind energy development

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Summary

1. Wind power is a fast-growing industry with broad potential to impact volant wildlife. Flight altitude is a key determinant of the risk to wildlife from modern horizontal-axis wind turbines, which typically have a rotor-swept zone of 50–150 m above the ground.

2. We used altitudinal GPS data collected from golden eagles *Aquila chrysaetos* tracked using satellite telemetry to evaluate the potential impacts of wind turbines on eagles and other raptors along migratory routes. Eagle movements during migration were classified as local (1–5 km h^{-1}) or migratory (>10 km h^{-1}) and were characterized based on the type of terrain over which each bird was flying, and the bird's distance from wind resources preferred for energy development.

3. Birds engaged in local movements turned more frequently and flew at lower altitude than during active migration. This flight behaviour potentially exposes them to greater risk of collision with turbines than when engaged in longer-distance movements.

4. Eagles flew at relatively lower altitude over steep slopes and cliffs (sites where orographic lift can develop) than over flats and gentle slopes (sites where thermal lift is more likely).

5. Eagles predominantly flew near to wind resources preferred by energy developers, and locally moving eagles flew closer to those wind resources with greater frequency than eagles in active migration.

6. *Synthesis and applications*. Our research outlines the general effects of topography on raptor flight altitude and demonstrates how topography can interact with raptor migration behaviour to drive a potential human–wildlife conflict resulting from wind energy development. Management of risk to migratory species from industrial-scale wind turbines should consider the behavioural differences between both locally moving and actively migrating individuals. Additionally, risk assessment for wind energy–wildlife interactions should incorporate the consequences of topography on the flight altitude of potentially impacted wildlife.

Key-words: flight altitude, GPS telemetry, landform, migration, migratory behaviour, wind energy resources, wind turbines

Introduction

Wind power is the world's fastest growing energy technology (USEIA 2011). Globally, this development is occurring in areas that are also heavily used by flying wildlife, including many species of great conservation concern. This juxtaposition has a range of possible conservation consequences because wind turbines may have consistent, detrimental effects on avian survivorship (Hunt 2002), they can cause highly variable and site-specific mortality (Barrios & Rodriguez 2004), or they may result

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in minimal mortality because of behavioural responses by at-risk species (Desholm & Kahlert 2005).

Wind turbines present risk to birds when they are foraging (as occurs at Altamont Pass, CA; Hoover & Morrison 2005; Smallwood & Thelander 2008), when they are on nesting grounds (as occurs at Smøla, Norway, for white-tailed sea eagles *Haliaeetus albicilla*; Bevanger *et al.* 2009) or generally when they are in flight (Barrios & Rodriguez 2004). There is growing evidence that birds of prey are at highest risk of turbine collision when using orographic lift (slope soaring; Barrios & Rodriguez 2004; Hoover & Morrison 2005; Madders & Whitfield 2006). However, there has been little published evaluation of the risk from wind turbines to individual raptors when on inland migratory routes. Furthermore, existing risk assessment inadequately predicts actual mortality of birds at wind plants, suggesting important room for improvement in such studies (Ferrer *et al.* 2011).

In principle, the risks birds face during migration should be similar to those when engaged in other types of flight. However, long-distance directional migratory flight is different than shorter-distance winter or summer flight, and furthermore, birds engaged in migratory behaviour often are aggregated to a greater extent than are individuals at other times of the year. For example, in the Appalachian region of eastern North America birds often follow and thus concentrate around leading lines (linear topographic features) that can produce updrafts that facilitate migration (Mueller & Berger 1967; Brandes & Ombalski 2004) and hawk counting (e.g. www.hawkcount.org).

Turbines placed on leading lines therefore pose a potentially serious but under-studied risk to migratory birds that fly at or below ridge lines (NWCC 2010). Risk on migration is further complicated because, in addition to directed flight, migratory behaviours also include stopovers, foraging and roosting (Klaassen *et al.* 2008; Newton 2008). Moreover, avian flight is not context independent and birds are expected to change their flight altitude in response to the different habitats or landforms over which they are flying (McLeod, Whitfield & McGrady 2002). Although risk during each of these behaviours is highly unlikely to be uniform, risk assessments only occasionally account for flight behaviour.

A recent US Department of Energy study suggests the USA has the capability to produce 20% of its energy from wind by 2030 (DOE 2008). Achieving that goal will involve installation of 300 GW of new wind capacity. Because of their proximity to large human population centres with mandated renewable energy targets, the Appalachian Mountains of eastern North America are a focus for this development. Through this growth, the middle Atlantic and New England regions could see approximately 10 000 new wind turbines. Similar development is projected in Québec and Ontario (CANWEA 2011).

The scale and pace of this development has important implications for understanding and mitigating risk to flying wildlife, especially as this area is also a key migratory corridor for multiple avian species of conservation concern. The greatest concern raised has been regarding the large number of species of migratory birds of prey that use soaring flight. Of these migratory raptors, golden eagles are among the rarest species regionally and, based on studies of wind energy impacts in other sites (e.g. Hunt 2002; Smallwood & Thelander 2008), potentially at the greatest risk from turbines. Golden eagles in eastern North America are geographically separate from all other populations of this species (Millsap & Vana 1984, Kochert *et al.* 2002) and most routes between breeding and wintering grounds follow the Appalachian Mountains (Morneau *et al.* 1994; Brodeur *et al.* 1996; Miller *et al.* 2009). This species, which is protected at the US federal and state levels, also serves as a potential umbrella enabling the conservation of a suite of other raptors with similar flight behaviour (Katzner *et al.* 2012).

We used GPS-based satellite telemetry to quantify flight altitudes and behaviour of migratory golden eagles to evaluate potential risk to soaring migratory birds from wind turbines. Flight altitude is important because modern horizontal-axis wind turbines present a lethal collision risk to birds in the rotor-swept zone, usually between about 50–150 m in height.

Most previous work on flight altitude of migrating birds, especially raptors, uses radar to focus on species that use convective thermals to power flight (Kerlinger, Bingman & Able 1985; Kerlinger & Gauthreaux 1985; Kerlinger 1989; Leshem & Yom-Tov 1996; Spaar & Bruderer 1996; Spaar, Liechti & Bruderer 2000; Shamoun-Baranes *et al.* 2003; Dokter *et al.* 2010). Such flight typically occurs at 300–1200 m, well above the height of most turbines. Conversely, visually based studies of flight altitude along mountain ridges and hawkwatch data suggest that slope-soaring raptors often migrate much closer to the ground surface, exposing them to risk from turbines.

To understand this rapidly emerging human–wildlife conflict, our research had the following objectives. First, we evaluated behaviours within the migration period to understand the extent to which different flight modes could be characterized by different flight altitudes. Second, we measured the degree to which flight altitude changed in response to the type of landform over which birds were moving, for each of the two flight modes we considered. Third, we analysed eagle use of wind resources also preferred by energy developers. Finally, we considered the implications for assessment of risk to soaring species from wind turbines in light of the linkages between terrain, flight altitude and movement behaviour.

Materials and methods

STUDY AREA AND FOCAL SPECIES

Golden eagles in eastern North America breed in Québec, Labrador and Ontario and most migrate south through the Appalachian Mountains and winter in the central and southern parts of this range (Fig. 1; Katzner *et al.* 2012). Wind power development is currently underway throughout much of that area. As of 31 December 2010, the USA had 40 GW of installed wind energy capacity. New York had the greatest installed capacity of any state in the northeast, with 1275 MW. Pennsylvania follows with 748 MW. West Virginia had 431 MW, Maine 266 MW, Maryland 70 MW, New Hampshire 26 MW, Vermont 6 MW, and Virginia 0 MW (AWEA 2010, http://www.awea.org/learnabout/publications/factsheets/factsheets_state.cfm). Southern Québec has over 600 MW installed as of 2011 (CANWEA 2011).

TELEMETRY

Eight golden eagles ranging in age from nestling ($n = 2$) to adult ($n = 6$) were fitted with Microwave Telemetry Inc. (Columbia, MD, USA) solar GPS PTT-100s (henceforth PTT) from November 2006 to May 2009. Birds were captured on migration (Pennsylvania, $n = 2$), wintering grounds (West Virginia, $n = 1$) or on the breeding grounds (Québec, $n = 5$). Gender of eagles ($n = 7$M, 1F) was determined by genetic analyses (Fridolfsson & Ellegen 1999). Age was estimated based on moult patterns (Bloom & Clark 2001). Details on the sex, age, capture location and period tracked for each eagle are provided in Appendix S1 of the Supporting Information. PTTs were programmed to collect GPS data at 1-h intervals, with the exception that data were collected every 4 h during spring for four birds (Nos. 60, 62, 67 and 69).

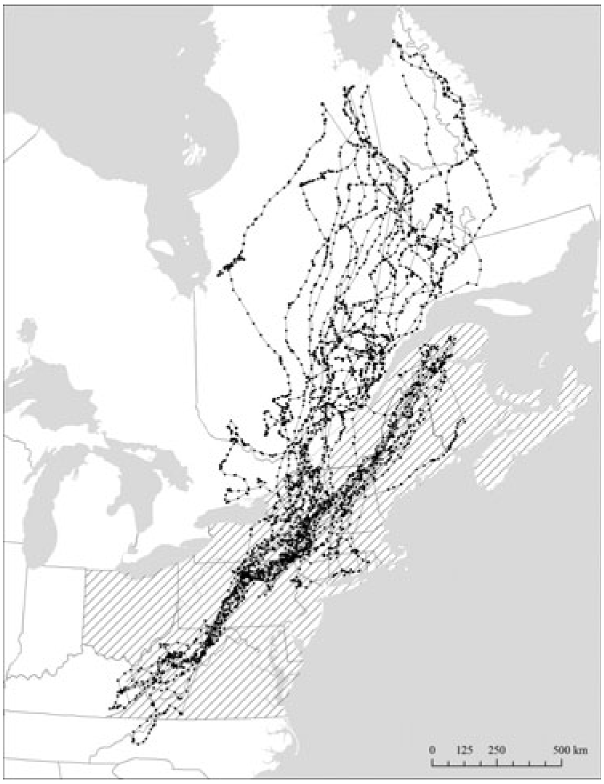

Fig. 1. Large scale movements of eight satellite-tagged golden eagles migrating through eastern North America. Data for this study were collected along these migratory tracks in all types of landform. Movement tracks are overlaid on cross hatching showing the extent of The Nature Conservancy's (TNC) Ecological Landform Units (ELUs) considered (Anderson *et al.* 2006). Details on data coverage are provided in the methods section.

Although our sample of birds in this study was sex biased, there is no indication from other sources that sex of eagles dramatically impact flight altitude and we saw no trends in the data set that were not consistent across genders. We analysed eagle migration data from both spring and fall. The beginning of migration was estimated as that date on which we could identify a consistent southbound or northbound movement corresponding to departure from breeding or wintering home range, respectively. The end of migration was approximated as that time at which the bird entered the core of its future seasonal home range and long-distance linear movements ceased.

SPATIAL DATA

We used three publically available habitat and meteorological data sets for this analysis. First, ground elevations within the USA were estimated using 30-m resolution National Elevation Dataset (NED; Gesch 2007). Within Canada, ground elevation was estimated using the 90-m resolution Shuttle Radar Topographic Mission data (SRTM; Jarvis *et al.* 2008). Second, land form classifications were determined using The Nature Conservancy's 30-m resolution ecological land unit (ELU) database, extending from Virginia north-eastward to the Gaspe Peninsula (Anderson *et al.* 2006). Finally, we estimated wind potential from Wind Resource Assessment maps produced by the US National Renewable Energy Laboratory (NREL; http://www.nrel.gov/wind/resource_assessment.html; accessed 20, 27 February and 02 March 2009 and 27 July 2010). These maps characterize wind speed at 50 m AGL, within the rotor-swept zone of modern horizontal-axis turbines and have an estimated maximum error of 200 m. Map data were publicly available for the mid-Atlantic and New England regions of the USA with the exception of NY state.

LINKAGES AMONG DATA SETS

Elevation at ground level below each GPS datum was determined using the Intersect Point Tool, one of Hawth's Tools for ArcGIS 9·2 (Beyer 2004). Golden eagle flight altitude above ground level (AGL) was subsequently determined for each point by subtracting the ground surface elevation (determined from the elevation data sets noted above) from the GPS-determined PTT altitude.

Error in calculation of flight AGL is the sum of errors in elevational data, in GPS estimated elevation and location, and in rectification and interpolation of the two data sets. The NED has an overall absolute vertical RMSE of ±2·44 m (Gesch 2007). The manufacturer's reported GPS accuracy is ±15 m, although this likely varies with unrecorded fix quality (commonly called dilution of precision or DOP). Errors in interpolation will vary with terrain and are scaled to the resolution of the data (30 m in this case). The largest magnitude errors can be expected in regions of steep terrain where ground surface elevation is highly variable, and smallest magnitude errors over flat terrain where resolution will have minimal impact on estimated ground surface elevation. In the steepest terrain, if a bird's location is off by one pixel then trigonometry suggests that the vertical error would be roughly equivalent to the pixel size (e.g. 30 m). In less steep terrain, vertical errors would be smaller.

By adding the maximum expected values of the three sources of error (NED = ±2·44 m, GPS = ±15 m, interpolation = ±30 m), conservatively we estimate that the combination of errors in accuracy could result in flight AGL errors of ±50 m. Consequently, prior to analyses we removed as outliers the 160 data points with calculated AGL values <−50 m (approximately 1·8% of all data points). Because we do not remove any apparent high outliers from the data set, our mean results are inherently upward biased – meaning that the actual flight altitudes of eagles are likely to be slightly less than the estimates we present here.

We used the Intersect Point Tool to link GPS telemetry data to underlying landform cover types from the 30 m ELU database (Anderson *et al.* 2006). Landform types were grouped into five main categories: cliffs and steep slopes, hills and gentle slopes, summits and ridgetops, flats and sideslopes (Fels & Matson 1995).

Wind resource assessment maps divide wind potential into seven classes, with wind power development generally seen as economically feasible in classes three and greater (i.e. 'high-class' or '3+' winds). We used these data and created a 30-m resolution grid showing distances to high-class winds and then using the Intersect Point Tool we captured the distance from each GPS datapoint to the nearest high-class wind resource. Because wind speeds are inherently variable, the estimated distance to wind resource should be interpreted in the context of behavioural trends rather than as precise behavioural estimates.

DATA ORGANIZATION

On any particular day during the migration period, birds may move either short or long distances. Because these two types of movements probably reflect fundamentally different flight goals, our initial data management step was to separate them from each other; this is conceptually similar to the approach used by Klaassen *et al.* (2008). We chose to characterize separately the movements that represented 'migratory' flight behaviour (hourly data points separated by ≥ 10 km) and those that represented 'local' movements (distances between hourly data points of 1–5 km). Because data points between 5 and 10 km apart could represent either local or migratory movements, we excluded these intermediary movements from our analyses. Likewise, we considered hourly movements of <1 km as indicative of either GPS error or other types of behaviour (e.g. roosting) and we excluded these from our analyses.

STATISTICAL METHODS

To evaluate behavioural differences between migratory and local movements, we compared (i) flight altitudes and (ii) change in bearings at sequential GPS data points (Batschelet 1981) between the two movement classes. Because these data are not normally distributed, we used a nonparametric two-tailed paired Wilcoxon signed-rank test to compare average change in bearing and average flight altitude for each bird in local and migratory flight (PROC NPAR1WAY; SAS v. 9.2).

We evaluated differences in flight AGL among landform types with a mixed model ANOVA (function lme; R Development Core Team 2011). Fixed effects in the model were the landform types and random effects were the eight individual birds with a repeated year effect. We log transformed our response variable (flight AGL) so that it more closely approximated a normal distribution. When the overall statistical test showed significant differences, we evaluated differences among groups with a multiple comparison (Tukey's test; function glht, package nmle; Pinheiro *et al.* 2011).

We evaluated differences in flight AGL between local and migratory movements within each of the five landform types with separate mixed model analysis of variance (PROC MIXED; SAS v. 9.2). We log transformed our response variable (flight AGL) so that it more closely approximated a normal distribution. Fixed effects in our model were the category of flight behaviour (migratory vs. local) and random effects were the eight individual birds with a repeated year effect.

We took two approaches to understand the frequency with which eagles flew close to winds suitable for development of wind energy. First, we created 31 equally sized bins of 500 m, from 0 to 15 500 m, which was the maximum distance observed, from high-class winds. We then calculated the average frequency with which the eight birds flew in each bin. We then evaluated the characteristics (mean, skew and kurtosis) of this binned distribution (PROC UNIVARIATE; SAS v. 9.2) and matched it against a normal distribution with a Kolmogorov–Smirnov test.

Second, we compared the frequency with which eagles moved near 3+ winds when in local and migratory movements within six frequency bins at a scaled interval. By scaling the bins, we ensured sample sizes large enough for statistical comparison with a Wilcoxon signed-rank test (PROC NPAR1WAY; SAS v. 9.2) within each of the bins. Bins were 0–250, 251–750, 751–1750, 1751–3750, 3750–7750, 7751–15750, and >15750 m from 3+ winds.

Results

CATEGORIZING MIGRATORY VS. LOCAL BEHAVIOUR

The majority of our data points were collected from roosting golden eagles (60·53 ± 2·45%; $\bar{\chi}$ ± SE; n = 8). Of the time spent moving, 21·13 ± 1·70% of the data points were from birds in migratory movements and 12·5 ± 0·93% were locally moving birds. The remainder of data points collected (5·80 ± 0·43%) were from birds moving 5–10 km per hour.

Our classification of migratory and local movements was supported by analysis of changes in bearing and flight altitude. When golden eagles were making migratory movements, hourly changes in flight bearing (28·49 ± 1·72°; $\bar{\chi}$ ± SE; n = 8) were less than those by the same eagles moving locally (99·83 ± 2·11°; n = 8; W = 100, z = 3·31, P = 0·0048). Similarly, average AGL was also higher during migratory movements (284·12 ± 7·63 m; n = 8) than during local movements (108·74 ± 4·87 m; n = 8; W = 36, z = −3·31, P = 0·0048). These differences suggests that eagles making migratory movements were, not surprisingly, flying in a more linear fashion and at higher altitudes than those making local movements.

DIFFERENCES IN FLIGHT ALTITUDE BY LANDFORM TYPE

Golden eagles exhibited clear responses in AGL to the landform types over which they flew (Table 1, Fig. 2; $F_{4,1322}$ = 20·59, P = <0·001). In general, eagles flew at the lowest elevations (~150 m) when over cliffs and steep slopes or summits and ridgetops. The highest average flight altitudes were observed over flats and gentle hills (~300 m). Finally, birds over gentle slopes showed

Table 1. Sample sizes, effect estimates and significance tests for a non-zero effect for differences in altitude above ground level (AGL) for each of five landform types, for eight golden eagles moving through the central Appalachian region of the eastern USA. Mean flight altitude is given in Fig. 2

Landform type	*N* birds	N Obs	Effect Est. ± SE	*t*-stat	*P*
Summit	8	96	2·02 ± 0·043	t_{1322} = 46·58	<0·0001
Cliff	7	150	2·03 ± 0·036	t_{1322} = 55·88	<0·0001
Side slopes	8	630	2·22 ± 0·023	t_{1322} = 97·13	<0·0001
Hills	8	352	2·30 ± 0·027	t_{1322} = 85·63	<0·0001
Flats	8	106	2·32 ± 0·042	t_{1322} = 55·69	<0·0001

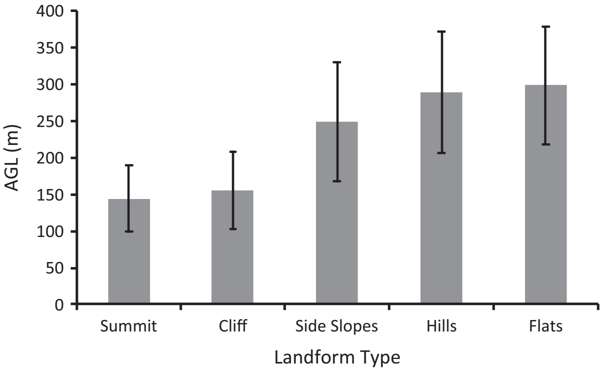

Fig. 2. Altitude above ground level (AGL in metres ±95% CI) used by golden eagles during the migratory period. Landform types are summit and ridgetops, cliffs and steep slopes, sideslopes, hills, and gentle slopes and flats. For details on classification, see text. Statistical tests for a non-zero effect are provided in Table 1.

intermediate flight altitudes (~250 m). These trends are consistent, implying that eagles typically use different types of lift when over different landforms.

DIFFERENCES IN FLIGHT ALTITUDE BY LANDFORM AND BEHAVIOUR TYPE

Golden eagles making local movements varied flight AGL in response to landform types ($F_{4,424}$ = 2·44, P = 0·047; Table 2, Fig. 3). *Post-hoc* comparisons suggested that the only differences in flight AGL among landform types was between summit and side slopes (Tukey's test, z = −3·062, P = 0·018).

Golden eagles making long-distance migratory movements also flew at different flight altitudes when over different landform types ($F_{4,858}$ = 12·63, P < 0·001; Table 2, Fig. 3). In this case, pairwise comparisons detected substantial differences between flats and cliffs (z = 5·886, P < 0·001), side slopes and cliffs (z = 5·786, P < 0·001), summits and cliffs (z = 4·452, P < 0·001), side slopes and flats (z = −3·265, P = 0·009), summits and flats (z = −3·986, P < 0·001) and summits and hills (z = −3·371, P = 0·006).

Within each landform type, flight altitude of migrating eagles was always greater than that of locally moving eagles (Table 2). When in local movements, AGL averaged 63–83 m, with SEs ranging from 10 to 23 m. When movements were migratory in nature, AGL averaged 135–341 m, with SEs ranging from 12 to 24 m. The pattern of AGL response to landform type was similar in each category to the overall trend (above), with the lowest altitudes over steep slopes and ridgetops and the highest when above flats and hills (although locally moving birds on side slopes flew at higher altitudes than expected based on this pattern).

CLASSIFYING DIFFERENCES IN DISTANCE TO HIGH-CLASS WINDS

The distribution of frequencies of distances to high-class winds was non-normal (D = 0·334, P < 0·010; Fig. 4), with a mean of 0·032 ± 0·011 (±SE), a rightward (positive) skew of 4·345 and kurtosis of 21·139. This distribution suggests a strong tendency for flight near high-class winds.

On average, locally moving eagles flew close to high-class winds with greater frequency than did eagles in active migration (Fig. 5). Statistically significant differences were observed only in the closest distance category, 0–250 m from high-class winds, where 35·50 ± 15·04% of locally moving birds flew 0–250 m from 3+ winds but only 21·74 ± 6·62% of migratory birds flew that close to

Table 2. Test for differences among local and migratory movements by golden eagles during the migration period in the central Appalachian Mountains, eastern USA. Effect estimates and significance tests on log-transformed data for a non-zero effect are provided, as are *F*-statistics for the difference between local and migratory movements

Landform	Movement category	Birds	*N* Obs	Effect Est. ± SE	*t*-stat	*P*	*F*-stat	*P*
Summit	Local	8	52	1·87 ± 0·42	t_{87} = 44·15	<0·0001	$F_{1,87}$ = 29·99	<0·0001
	Migratory	8	44	2·21 ± 0·05	t_{87} = 48·28	<0·0001		
Cliff	Local	7	75	1·97 ± 0·049	t_{142} = 40·41	<0·0001	$F_{1,142}$ = 7·01	0·009
	Migratory	6	75	2·12 ± 0·049	t_{142} = 43·17	<0·0001		
Side slope	Local	8	207	2·01 ± 0·03	t_{621} = 67·35	<0·0001	$F_{1,621}$ = 104·56	<0·0001
	Migratory	8	423	2·32 ± 0·02	t_{621} = 96·83	<0·0001		
Hills	Local	8	81	1·97 ± 0·04	t_{343} = 48·22	<0·0001	$F_{1,343}$ = 84·32	<0·0001
	Migratory	8	271	2·40 ± 0·02	t_{343} = 107·34	<0·0001		
Flats	Local	6	34	1·97 ± 0·05	t_{97} = 36·16	<0·0001	$F_{1,97}$ = 61·29	<0·0001
	Migratory	8	72	2·49 ± 0·04	t_{97} = 66·45	<0·0001		

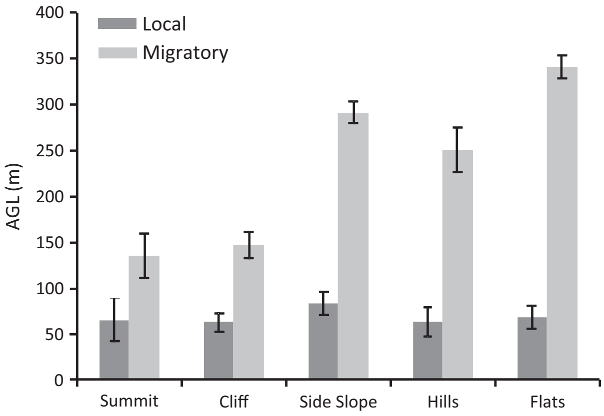

Fig. 3. Altitude above ground level (AGL in metres ±95% CI) used by golden eagles in local and migratory movements during the migratory period. Landform types are summit and ridgetops, cliffs and steep slopes, sideslopes, hills, and gentle slopes and flats. For details on classification, see text. Statistical tests for differences between movement types are provided in Table 2.

high-class winds ($z = 2{\cdot}31$, $P = 0{\cdot}035$) and in the 3750 –7750 m category (9·70 ± 6·77 (local) vs. 16·89 ± 5·05 (migratory); $z = -2{\cdot}15$, $P = 0{\cdot}048$). In all other distance categories, locally moving and migrating eagles used wind resources with similar frequency ($P > 0{\cdot}35$).

Discussion

Our work identifies patterns in use of flight altitudes by golden eagles during their migration period. This is important for conservation management because flight altitude is a key component of risk to birds from modern horizontal-axis wind turbines, which have a rotor-swept zone of typically 50–150 m above the ground.

Our sample was sex biased, but the body size of golden eagle males and females overlaps (Watson 2010) and there is no known difference in flight strategies for the two sexes. Thus, our findings characterize potential risk and suggest risk management strategies for the protection of migrating golden eagles of both sexes. Furthermore, as flight of golden eagles is representative of flight by other soaring birds of prey, this work has broad implications for conservation of other migratory avian species.

FLIGHT BEHAVIOUR IN MIGRATION

An unexpected outcome of this analysis was the degree to which we observed clear behavioural differences between local and migratory movements. Our original classification of migratory and local was based on knowledge of eagle biology and of their migratory movements. Nevertheless, this classification also has an arbitrary component. The strong differences we observed among classes in our response variable (AGL) therefore highlights the substantially different flight strategies that eagles employ when making long and short distance movements.

The existence of these differences has important consequences for the understanding of migration in general and for the management of risk to birds from turbines. The vast majority of analyses of bird migration distinguish only between stopover and flighted behaviour. Our work, and that reported in one similar study (Klaassen *et al.* 2008), suggests that within the flighted period are at least two, and possibly more, identifiable categories of behaviour. As these behaviours are manifested in the altitude at which birds fly, this strongly impacts the relative risk they experience from turbines.

EAGLE ALTITUDINAL RESPONSE TO TOPOGRAPHY

Golden eagles showed remarkably non-random flight altitude patterns in response to characteristics of the

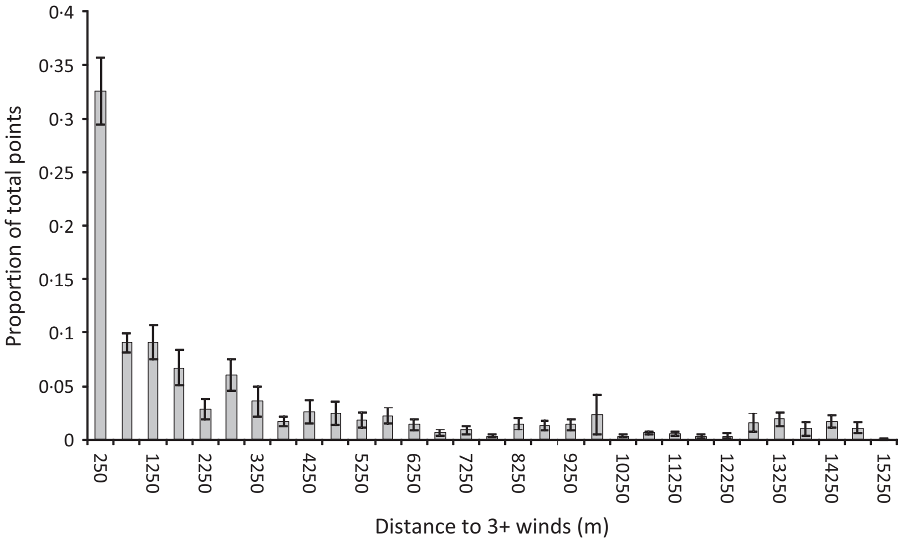

Fig. 4. Average frequency (±95% CI) with which golden eagles were found at distances to 3 + winds. Distances were binned at regular 500 m intervals, from 0 to 15 500 m. Statistical tests for normality of the distribution as well as distributional characteristics (skew, kurtosis) are given in the text.

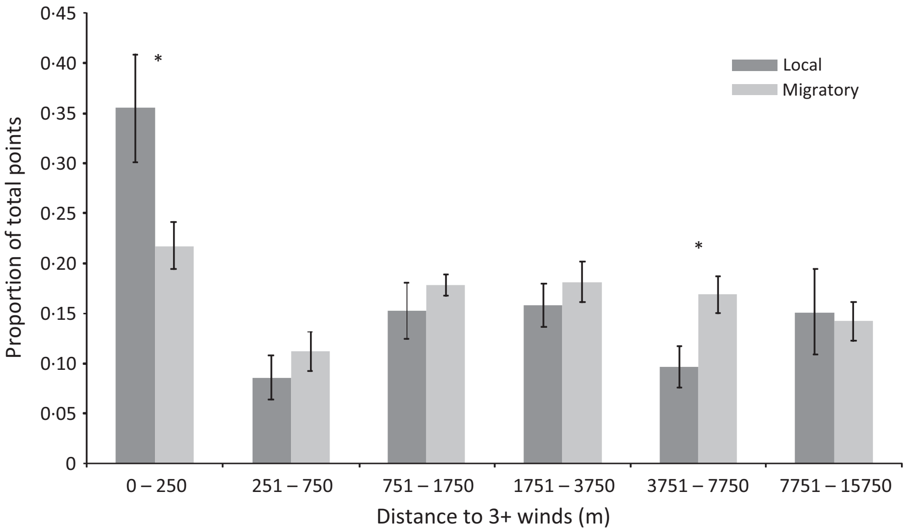

Fig. 5. Average frequency (±95% CI) with which locally and migratory moving golden eagles were found at distances to 3+ winds. Distances were binned at scaled intervals as noted on the figure. Statistically significant differences between locally and migratory moving birds were only at two lowest distance categories (marked by*)

landform over which they were flying (Fig. 2). As risk is altitude specific, it follows that risk to birds is also specific to the landform over which birds are flying. From these flight patterns and a basic knowledge of meteorology, we can also characterize the likely types of flight behaviours and sources of lift that eagles are using. Cliffs and steep slopes are the landscape features most conducive to generating orographic lift, a low-altitude energy resource (Kerlinger 1989). Correspondingly, eagles flew at lower altitudes over these features than over any other type of topography, suggesting they were slope soaring. Flatter areas and areas of gentle slopes are unable to generate orographic lift but may produce thermals, which extend to higher altitudes, often over 1000 m. On average, eagles flew at higher altitudes over such terrain, consistent with use of flight powered by convectively heated air.

These trends in telemetry data are corroborated by visual observations of raptors migrating in the Appalachians. Golden eagles and other raptors often are observed gliding at low elevations along ridgetops, particularly late in the autumn season and early spring when thermals are relatively weak (Maransky, Goodrich & Bildstein 1997). Eagles are less frequently reported in migration over flat regions, in part likely because they fly higher and are rarely near to established hawk count sites, where they can be counted.

Our analysis also identified consistent differences in flight AGL by birds engaged in local and migratory movements. Regardless of the landform over which they were flying, birds engaged in active migration flew at higher elevations than locally moving birds (Fig. 3). This pattern is probably explained by the tendency of locally moving birds to focus on behaviours such as foraging, perching and roosting that, by their very nature, occur at low altitudes. In contrast, birds engaged in long-distance movements have a greater need to search out and utilize the lift to minimize energy expenditures for long-distance flight.

PATTERNS IN USE OF HIGH-CLASS WINDS

Golden eagles also used areas that wind energy developers characterize as having high-class wind resources in a non-random manner. Areas close to good quality winds were more frequently used by birds than more distant locations, and locally moving birds were more likely to use high-quality winds than birds engaged in active migration.

In north-eastern North America, location of on-shore high-quality winds is strongly correlated to elevation, with highest winds typically on the tops of mountains, ridges and high plateaus. As most human-driven development is concentrated in fertile valley bottoms, high elevations also tend to have the most extensive forest cover. Thus, it is likely that eagles use these habitats not only because they provide lift but also because the remoteness and forest cover is especially conducive to foraging and roosting. Regardless of the reasons for use of these landscapes, their closeness to areas targeted for wind energy development suggests both the potential for consequences to eagles from wind energy development and strategies for management of that risk.

MANAGEMENT IMPLICATIONS FOR WIND ENERGY DEVELOPMENT

Globally, wind energy development is proceeding quickly and, in some areas, with little careful study of potential impacts on wildlife. This analysis focuses on one specific and often short time period where birds and wind power may interact (migration), and a single behavioural response variable (AGL). As such, our work has several implications for managing wind energy development and provides a concrete framework to predict and mitigate risk to migratory birds of prey.

First, potential risk to migrating raptors is clearly linked to terrain structure in ways that have not previously been explored. Eagles flying over summits, ridgetops, cliffs and steep slopes, whether in active migration or moving locally, flew at altitudes that put them at risk from modern horizontal-axis industrial wind turbines. Conversely, eagles flying over flat and gentle slopes spend a greater proportion of time above the rotor-swept zone, and thus, potential risk is relatively lower. Turbine development on ridgetops and near steep slopes over which eagles fly at lower altitudes should therefore proceed with extreme caution and careful attention to possible mitigation measures (e.g. setbacks; Erickson *et al.* 2002). This is especially important where and when migratory flight is geographically bottlenecked, as is the case in south-central Pennsylvania in late fall and early spring (Brandes & Ombalski 2004).

Second, our work suggests that birds may be at greater risk during local movements (when foraging or searching for roosts) than when in active migration. This is because when moving locally they fly at lower elevations and they have a greater likelihood of making multiple passes through a site, regardless of the habitat over which they are flying. This finding is also consistent with observed mortality at other sites (e.g. Altamont Pass Wind Resource Area; Smallwood & Thelander 2008), where birds appear to be at greater risk when foraging than when engaged in other behaviours. Thus, pre- and post-construction surveys conducted at proposed and existing wind sites should focus on documenting flight paths of locally moving individuals as well as the more common practice of counting birds in active migration through or past the site.

Third, when golden eagles are impacted by wind turbines, other species are also influenced. At the Altamont Pass Wind Resource Area (APWRA) in California, golden eagle blade strike occurs in conjunction with mortality of large numbers of red tail hawks, American kestrels and burrowing owls *Athene cunicularia*; (Smallwood & Thelander 2008). In the Appalachian Mountains, some of the same bird species are in abundance, as are several other soaring species – osprey, bald eagles and several *Buteo* hawks – that are uncommon at APWRA. All of these encounter some level of blade-strike risk that is impacted by topography and flight behaviour. Thus, management that protects golden eagles also should reduce risk to these species as well as many other soaring raptors worldwide (Bildstein 2006). However, mitigation for golden eagles may not ameliorate risk for species with different flight styles. For example, peregrine falcons *Falco peregrinus* commonly use flapping flight during migration, thus typifying a species whose risk profile is dramatically different than that of golden eagles.

Conclusions

Golden eagles are an important focus for research because their populations are small, they are at risk from development of wind energy and they are an umbrella species for conservation. Owing to the spatial correspondence of high wind resources with landforms used extensively by migrating eagles, there is real potential for conflict between eagles and wind turbines. Furthermore, it is likely that the frequency of collisions or displacement of raptors away from their usual migratory pathways will increase as wind energy projects grow in number along traditional leading lines for flight. Species that have small populations and low reproductive rates may be particularly at risk if siting of wind turbines proceeds without consideration of scientific studies designed to identify site-specific risk from variable flight behaviours.

The US Fish and Wildlife Service has recently published 'Land-based wind energy guidelines' and 'Eagle management plan guidelines' (USFWS 2011a,b). Both of these documents stress the consequence to raptors from development of wind energy and the 'Eagle management plan guidelines' identify a number of inadequacies in our understanding of biology and risk to eagles. Our analysis is a first step towards addressing these deficits and provides general themes that can be used to guide broad-based management approaches to mitigate risk to migratory raptors from industrial-scale wind energy development.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Appendix S1. Gender, estimated age at capture, trap location, time period followed, and number of migration data points collected for eight golden eagles studied in eastern North America.

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