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Approach Distances of Scottish Golden Eagles *Aquila chrysaetos* to Wind Turbines According to Blade Motion Status, Wind Speed, and Preferred Habitat

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Abstract: Understanding drivers underlying birds' responses to operational wind turbines is essential for robust wind farm proposal assessments, especially for large raptors with life history traits engendering sensitivity to impacts from two potential adverse effects: fatality through collision with rotating turbine blades and functional habitat loss through avoidance of turbines. The balance between these two potential effects represents opposing extremes on a continuum and is influenced by several factors. Collisions have an obvious impact on survival, but the impacts of avoidance may be more insidious and potentially more significant for a population. It is reasonable to conclude that collisions are less likely when blades are motionless. Consequently, turbine shutdown systems (TSSs, "shutdown on demand" or "curtailment"), instigated as raptors approach operational turbines, may provide mitigation against collisions. By contrast, if avoidance is most likely, this could be independent of blade motion, and TSSs/curtailment would provide no mitigation against habitat loss. For birds tending to wariness of turbines, therefore, it is important to understand if it is conditional on blade motion. Scottish golden eagles show a strong propensity to avoid (be wary of) turbines, subject largely to the suitability of habitat at and surrounding turbine locations. A previous Scottish study found that approach distances to turbines by non-territorial eagles were unaffected by blade motion but were closer at higher wind speed. Here, we analyse movement data from a GPS-tagged territorial eagle and non-territorial eagles responding to the motion status (and wind speed) of turbines at another Scottish wind farm. Eagles' approach distances to turbines were only weakly affected by blade motion but were closer at higher wind speed. We again found that habitat suitability in and around turbine locations was strongly influential on eagles' approach distance to turbines. Our confirmation that blade motion had little effect on Scottish golden eagles' wariness of turbines suggests that for eagles that are prone to avoid turbines, their wariness is a response to turbines *per se*, and not blades' movement. In our study system, and others where avoidance is the predominant response, curtailment of turbines' operation on birds' close approaches, or making turbine blades more obvious, should, therefore, have little material influence on functional habitat loss impacts. If true, this has important implications for wind farm designs and any proposed mitigation.

Keywords: renewable energy; wind farm; raptor; GPS-telemetry; turbine curtailment; risk assessment

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1. Introduction

The potentially negative impacts of wind farms on birds are an oft-highlighted consequence of wind farm development and policies to capture wind power, which otherwise provide a sustainable contribution to electrical grid energy demands [1–5]. Wind farm development continues to increase as a counter to reliance on fossil fuels' detrimental effects on climate change [3,6,7]. Understanding the drivers behind birds' responses to operational wind farms is essential if further wind farm development proposals are to be assessed robustly (and potential adverse impacts either avoided, minimised, or mitigated) [8–15].

Large raptors are often a focus of avian research surrounding such potentially adverse impacts, and the golden eagle *Aquila chrysaetos* is a frequent study species [16–18]. This focus is through life history traits, including extended longevity and prematurity, low reproductive rates and population size, and geographically extensive habitat requirements [19].

These traits engender sensitivity to impacts from the two potential adverse effects of wind farms: fatality through collision with rotating turbine blades and functional habitat loss through avoidance of turbines [9,13–15,20]. The balance between these two potential effects represents opposing extremes on a continuum and is influenced by several factors [8,9,13–15,20]. Collisions may be relatively common [18,21] and thereby impact survival rates [22–26], but the impacts of avoidance may be more insidious and potentially more significant for some populations [15,24,27].

It is reasonable to conclude that collisions are less likely when blades are motionless. Consequently, turbine shutdown systems (TSSs), "shutdown on demand", or "curtailment", instigated as raptors approach operational turbines, may provide mitigation against collisions and their impact through fatalities [9,28,29], although see [30]. This potential solution to minimising collision fatalities may be enhanced if turbine blades are made more visible [12]. These mitigation measures have often met with success in situations where the background evidential balance of large raptors' response to turbines is against avoidance and when the wariness of turbines seems weak [12,28,31–37]. This is even when displacement—an outcome of avoidance—may also occur [38] and when some avoidance may be implicated [37]. The efficacy of some TSSs has also been called into question [30] under practicalities for observer-based systems [39] or possible problems with analysis of relevant data in automated curtailment systems [40], although see [35].

If, rather than propensity to collision, the fundamental response of large raptors is towards avoidance through wariness of turbines, as has also been shown repeatedly [13–15,27,41–45], it is possible that this could be independent of blade motion. Birds may avoid the structure itself without being conditional on its moving parts [13]. Hence TSS/curtailment may provide no mitigation against functional habitat loss [13]. For birds tending to wariness of turbines, it is important to understand if it is conditional on blade motion.

Scottish golden eagles show a strong propensity to avoid (be wary of) turbines, subject largely to a repeated finding of habitat suitability at and surrounding turbine locations as influential [13–15]. Territorial birds were as wary of turbines, if not more so, than non-territorial birds [15]. Another Scottish study found blade motion had no effect on approach distances to turbines by non-territorial golden eagles [13]. When prone to wariness of turbines, as in Scotland, the response of territorial golden eagles to blade motion remains a research gap (see an incidental observation: [46]).

Our primary objective was to fill this gap by examining the response to turbines' blade motion at a Scottish wind farm by a territorial eagle and non-territorial eagles. If eagles were more wary of and "perceptive" of turbines with turning blades, the expectation was that approach distances would be greater when blades were in motion. Our study was conducted at a different wind farm from previous relevant research [13]. For our secondary objectives, we included examinations of responses to wind speed at turbines [13] and habitat suitability at and surrounding turbine locations [13–15].

2. Methods

2.1. Study Wind Farm

Scotland has substantial potential for terrestrial wind farm development [47], which has been exploited through numerous turbines [14]. Cruach Mhor Wind Farm (CM) is in the southwestern Highlands of Scotland (central point X 203815, Y 687683 UK Ordnance

Survey coordinates, latitude 56.041° longitude −5.151°). Construction was completed in January 2000, and it became fully operational by February 2004. Its nominal output is 1.0 MW from each of the 35 turbines, with hub heights of 45 m and three 26 m blades.

The pre-operation period (several years before 2004) included the removal of exotic conifer plantations within the site and its immediate surroundings and the encouragement of heather *Calluna vulgaris* moorland [48], which was predominant and well-established during our study period (commencing late 2015; see below). Thus, the site had been converted from unsuitable to potentially suitable vegetative habitat for golden eagles [49]. Hence, habitat management initiatives associated with CM's development could not have drawn eagles away from turbines during operation (*cf* [46]); rather, the opposite was more likely.

2.2. Study Species

Scotland supports over 500 resident territorial pairs of golden eagles [50] at globally high densities in several western regions [50,51]. Territory densities in some eastern regions are held below capacity by persistent illegal persecution associated with intensive management for driven shoots of red grouse *Lagopus lagopus scotica* [52–54].

Golden eagles occupy upland habitats in Scotland, which vary substantially in geology, vegetation, topography, and climatic influences [51,53]. As a result of greater oceanicity and a higher temperature lapse rate, characteristic upland vegetation is found near sea level in the west, closer to the Atlantic Ocean and the North Atlantic Current. Further east, increased continental influences restrict upland habitats to higher altitudes [55]. Despite this geographic variability, a robust predictor of preferred spatial use involves a simple topographic model combining measures of slope, distance to ridge, and altitude: the Golden Eagle Topography (GET) model [15,56].

2.3. Trapping and Tagging

Field methods for tagging golden eagles in Scotland have been repeatedly described elsewhere, as have specifications, accuracy, and performance of deployed tags, and the absence of any adverse effects of deployment on tagged individuals (e.g., [54,57–59]). The present study used data only from birds tagged with solar-charged 70 g GPS/GSM (PTT) models manufactured by MTI (Microwave Telemetry Inc., Columbia, MD, USA). Transmission is over the mobile phone (GSM) network, and the GPS fix rate is dependent on battery charge (dynamically adjusted fix rate dependent on battery charge from 1 per minute to 1 every 2 h). Transmissions are attempted to the GSM network twice daily.

Our study's resident territorial female was ringed as a nestling in 2009 and hence was in her seventh calendar year when trapped and tagged in early 2015 as an occupant of the territory encompassing CM (see also [15]). Subsequent data from her tag included the period when we had data from CM on turbine motion status and wind speed (1 December 2015 to 9 August 2019; see below). In this period, three tagged non-territorial birds were recorded during natal dispersal as intruders in the study territory and were also consequently exposed to the same CM turbines. These were tagged as nestlings in 2015 (male), 2016 (female), and 2017 (female).

2.4. Tag and Turbine Data Treatment

The high temporal frequency of fixes from GPS/GSM tags (see above and [60]) allowed flight lines to be approximated between consecutive records. The accuracy of such approximations depends on the time between consecutive fixes, and all consecutive records > 5 min apart were excluded. The derived flight line could indicate greater proximity to a turbine location than its composite start–endpoints alone by estimating the shortest orthogonal distance between a flight line and turbine hub. A flight line could never be further from a turbine than its closest endpoint (see also [13–15]).

Data were available every 10 min from every CM turbine on the motion status of blades (stationary or moving) and wind speed (via hub anemometers) between 1 December 2015 and 9 August 2019. Hence, once the closest distance of a flight line to a turbine hub had been calculated (see below), the time when it was recorded in this period (based on start and end fixes) was rounded to the nearest 10 min to match wind speed and blade motion (stationary/moving) records from the same turbine.

2.5. Distance to Turbines and Intrinsic Habitat Preference

Examination of the influence of turbines on flight behaviour may be confounded if birds' records are taken from distances where turbines could not possibly be influential [61]. Therefore, analysed data included flight line records within 1 km of a wind turbine location [13–15]. Flying birds can avoid wind turbines in 3D (e.g., [13–15,27,42]), and if only horizontal distances are used, a bird flying "across" but well above a turbine array could incorrectly be deemed to be close to a turbine location in 2D, falsely suggesting no avoidance. We used the closest 3D distance from a flight line to a turbine hub location as our measure of eagles' proximity to a turbine and the response variable.

The altitude of a bird at its closest 3D distance to a turbine is estimated using geometry and trigonometry. The closest point on a flight line to the nearest turbine is orthogonal to the line and can be found using the dist2d function in the lares R package [62]. Distances from the ends of the flight line to the turbine are found via Pythagoras's theorem, and the lines drawn from the endpoints to the turbine are the hypotenuses of two right-angled triangles. If the distance from the turbine to the line is known, Pythagoras's theorem or trigonometry can be used to find the distance along the flight line closest to the turbine. The altitude of the closest 3D position is found from the altitudes of the start and end locations weighted by the relative length of the line at its closest 2D location (see also [13,15]). Approximating the flight segment as a straight line does not allow for the micro-avoidance of turbines [20], so distances to turbines were likely to be conservatively low.

Turbine locations may be avoided not because of turbine presence but because the turbine is not in the habitat (including air space) preferred by golden eagles. Utilising the GET model [15,56], inherent habitat preference was an important influence in golden eagles' response to turbines for both non-territorial [13,14] and territorial birds [15]. This influence also extended to habitats away from the immediate vicinity of turbines [13–15].

We included GET estimates of habitat preference in analyses, replicating previous studies [13–15], to predict space use by eagles independent of the presence of turbines. GET provides a topographically based surrogate for the availability of orographic winds, which have repeatedly been found as influential in habitat selection studies of golden eagles and other large facultative/obligate soaring raptors [13–15,56]. "GET values" range from 1 to 10 and a GET 6 value is a switch point in preference, so GET 6+ indicates an increasingly preferred habitat.

A GET score for each turbine location, and hence the indicative eagle preference, was derived from the mode of the 50 m pixel containing the turbine tower and the four surrounding pixels. From tag records, the GET score was also calculated from the 50 m pixel underlying the closest 3D distance of a flight line to a turbine location, as described earlier.

2.6. Statistical Analyses

Analyses involved flight line data from a single territorial female and three non-territorial birds that had intruded into the focal territory [13,15]. Pegging tag data to an individual turbine contained repeated records from the same wind farm's turbines and birds' tags, and these were likely to violate the assumption of independent y-values [63,64]. Hence, we used bird identity (tag ID number) along with turbine identity as random factors in linear mixed models (GLMMs). To avoid potential singularity errors due to the small number of tagged individuals, we did not use age (territorial status) as an explanatory (fixed) factor because it was inextricably linked to a bird's identity (tag ID number).

Three fixed explanatory factors in GLMMs involved blade motion status (stationary or moving) and wind speed, recorded at each turbine's hub, and the habitat preference score at a turbine location relative to scores used by eagles in the surroundings (from estimates at flight line locations). For the latter factor, given previous results on the influence of

GET scores (robustly surrogating habitat preference; see above) at turbine and flight line locations [13,15], we resolved these two measures into a single explanatory factor: the GET score at the flight line minus the GET score at the turbine. Negative values in this metric are when a tag's flight line location has a higher GET score than the nearest turbine, and vice versa. With a single wind farm and data from relatively few birds, in order to make this resolution into a single factor, we followed advice when dealing with model selection to avoid overfitting models by overestimating model parameters according to available observations and keep the candidate model set low [65].

We used R version 4.2.3 [66] within RStudio ([67]; version 2023.06.01). Linear mixed effects analyses were undertaken with the lme4 package [68], and the R aictab library within the AICcmodavg package [65] assisted in selecting the best of the candidate models. In model selection procedures, we followed the use of the Akaike Information Criterion (AIC) [65,69,70] but with a small sample size, corrected AIC (AICc) values were used to rank models within the candidate model set [69].

3. Results

Records of flight lines from tagged eagles assigned to individual turbines were not evenly distributed across CM Wind Farm. About half (seventeen of thirty-five turbines) had less than ten assigned records and were excluded from further analyses, and 79% (1832/2316) of such pruned records were assigned to five turbines (Figure 1). Flight line records, as expected, were mainly assigned to the territorial female (96%, 2220/2316).

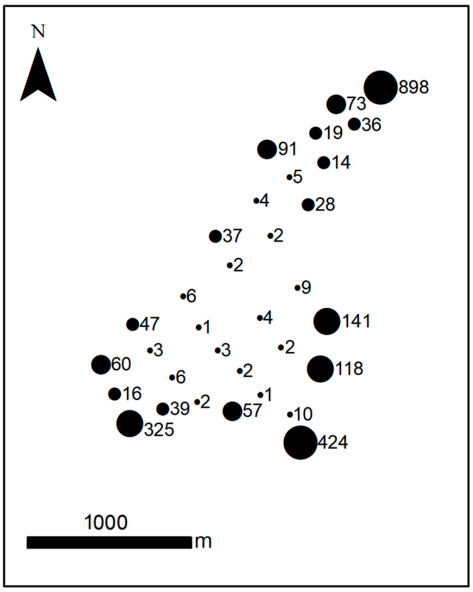

Figure 1. The number of golden eagle flight line records associated with each of the 35 turbines at CM Wind Farm.

GLMMs revealed through AICc that the best model to predict the proximity of eagle flight lines to wind turbines included all three fixed factors: blade motion status (Turn), wind speed at turbine hub (Wind), and the habitat preference score (GET) relative to flight line locations and turbine locations (Table 1). The second-best model, without Turn (Table 1), was also ranked highly (ΔAICc < 4) and deserved further consideration [65,69]. This model without Turn (blade motion status) with low ΔAICc, however, suggested that the influence of Turn was relatively weak within the best model, and its explanatory presence was not weighty. Akaike weights (AICcWt: Table 1) showed that no other models had support and hence did not warrant further consideration in model averaging procedures.

Further analysis of the top two models confirmed that there was little difference between the top model with all three fixed factors and the second-best (excluding Turn: blade motion status) (Table 2). This was even though Turn was significant in the best model ($p = 0.036$ using

α = 0.05 as a two-tailed threshold: Table 2). Hence, despite this significance, the influence of Turn (blade motion status) was weak, whereas reflecting the information-theoretic approach, the influences of habitat preference (relative GET scores at the turbine and birds' locations) and wind speed at the turbine hub were far stronger (Table 2).

Table 1. Results of initial model selection based on three fixed factors (predictors): Turn = blade motion status (stationary or moving turbine blades); Wind = wind speed at turbine hub (m/s); and GET = relative GET habitat preference score (GET score at flight line minus GET score at turbine). Random factors involved bird identity (tag ID number) and turbine identity. The distance of the eagle flight line record from the turbine hub was the dependent (response) variable. AICc gives Akaike model values corrected for small sample size, ΔAICc provides differences based on the best model, AICcWt shows the relative weight of each model in the candidate model set when sum = 1, and LL shows log-likelihood values for each model.

Model	df	AICc	ΔAICc	AICcWt	LL
Turn + Wind + GET	7	32,498.92	0.00	0.77	−16,242.44
Wind + GET	6	32,501.29	2.37	0.23	−16,244.63
Turn + GET	6	32,517.54	18.62	0.00	−16,252.75
Turn + Wind	6	32,523.72	24.79	0.00	−16,255.84
Wind	5	32,526.00	27.08	0.00	−16,257.99
GET	5	32,532.15	33.23	0.00	−16,261.06
Turn	5	32,544.15	45.23	0.00	−16,267.06
Null	4	32,559.22	60.30	0.00	−16,275.60

Table 2. Comparison of the two best models identified by GLMMs and AICc weighting (Table 1). Distance from the hub (for the eagle flight line record) was the response (dependent) variable in both models. Model 1 was the highest ranked and included all three fixed factors, whereas Model 2 was second-ranked and excluded Turn (blade motion status). Wind = wind speed at turbine hub, GET = relative GET habitat preference score (GET score at flight line minus GET score at turbine), and Turn = blade motion status (stationary or moving turbine blades). Significant *p*-values (with α = 0.05) are emboldened. The two models were also assessed against the null model of random effects (bird identity and turbine identity). σ^2 is the overall variance of the random effects. τ_{00} shows random intercept variances for each random factor and essentially illustrates how similar each tag or turbine was to each other (if the intercept variance is small, the tag or turbine intercepts are very similar). ICC is the intraclass correlation coefficient. ID and turbine subscripts refer to each of the two random effects' sample sizes. Note that around 30% of the variation in distance to the hub was explained but only around 3% by the fixed effects (e.g., respectively, Conditional R^2 against Marginal R^2). Note also how all the coefficients are similar between the two models and that the loss of explained variation by excluding Turn was very small.

	Model 2			Model 1		
	Distance from Hub			Distance from Hub		
Predictors (fixed factors)	Estimates	CI	*p*	Estimates	CI	*p*
(Intercept)	820.35	688.60–952.09	**<0.001**	834.06	701.94–966.19	**<0.001**
Wind	−15.58	−20.89–−10.27	**<0.001**	−13.29	−19.01–−7.56	**<0.001**
GET	−25.67	−35.36–−15.97	**<0.001**	−25.77	−35.48–−16.05	**<0.001**
Turn				−37.59	−72.68–−2.50	**0.036**
Random Effects						
σ^2		70,731.72			70,570.61	
τ_{00}		14,571.97 $_{\text{turbine}}$			15,491.51 $_{\text{turbine}}$	
		11,847.69 $_{\text{ID}}$			11,568.62 $_{\text{ID}}$	
ICC		0.27			0.28	
n		18 $_{\text{turbine}}$			18 $_{\text{turbine}}$	
		4 $_{\text{ID}}$			4 $_{\text{ID}}$	
Observations		2316			2316	
Marginal R^2/Conditional R^2		0.031/0.294			0.032/0.300	

Simple plots of the three fixed factors, from the best-fitted model (Table 1), against the response variable (distance of flight line from turbine hub) illustrated the relative weakness of the relationship between blade motion and the proximity of eagles' flight lines (Figure 2). Indeed, eagles showed marginally closer approach distances to turbines when their blades were turning, counter to an expectation that avoidance would be greater when blades were turning (Introduction).

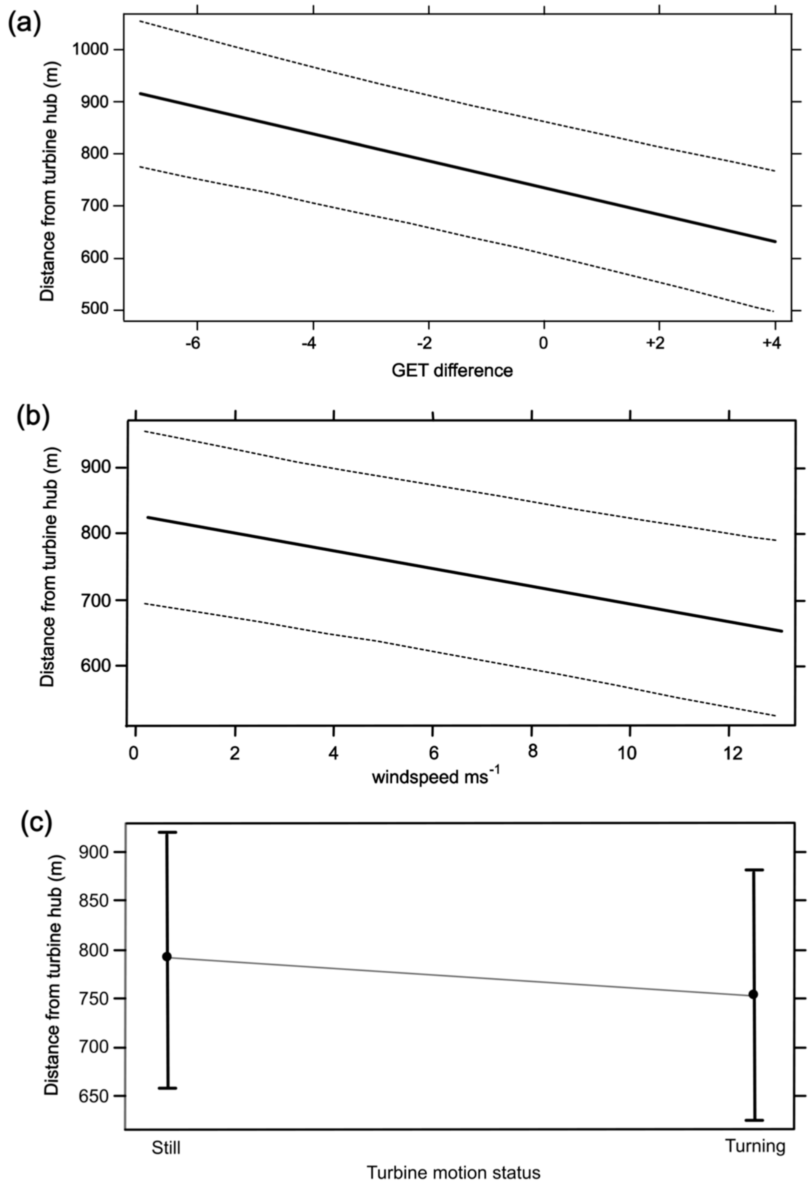

Figure 2. Plots of the three fixed factors fitted through the top model's results (Table 1) against the response (explanatory) variable and distance of flight record from a turbine hub. (**a**) Relative habitat preference difference according to GET score (GET score at flight line minus GET score at turbine). Negative values in this metric are when a tag's flight line location has a higher GET score than the nearest turbine, and vice versa. The plot shows that the influence of this factor was because eagles approached turbines closer when there was a higher GET habitat preference score underlying the turbine than underlying the flight line record further away. The solid line shows the fitted trend and dotted lines show 95% CIs. (**b**) Windspeed recorded at the turbine hub. Eagles were recorded closer to turbines at higher wind speeds. The solid line shows the fitted trend and dotted lines show 95% CIs. (**c**) Turbine motion status (still or turning). Eagles showed a slight tendency to approach turbines closer when their blades were turning. Vertical lines show 95% CI limits.

These plots additionally illustrate other modelled information-theoretic results because eagles went closer to turbines at higher wind speeds. Moreover, the influence of the habitat preference (GET) metric (Figure 2) showed that the distance to turbines was greatest when a tagged bird was over habitat that was better than at the nearest turbine. The distance was also closest when the GET score underlying the turbine was higher than at the nearest recorded location of an eagle.

Overall, the results showed that eagles rarely went close to turbines (Table 2, model intercept values; Figure 2, values and CI limits for the response variable).

4. Discussion

Our study included several caveats. It involved one wind farm and data from a few golden eagles, predominantly one territorial female. Such data limitations have not, however, prevented previous publications illuminating this research field [13,33,34,38,41] and others involving few satellite-tagged large raptors (e.g., [71–73]).

On our primary study objective (Introduction)—the effect of blade motion status—blade motion was often underpinned by shutdowns due to low wind speed (typically c. 3–5 m/s: [13]). The other cause of shutdowns were turbine maintenance or component failure with subsequent repair or refurbishment [13]. Hence, blade motion and wind speed were partially connected. Thorough separation of these two factors was not possible because of sample sizes (Methods).

There was no indication, however, across the range of wind speeds examined (Figure 2) that wind speed could override or be a contributor to the limited influence of blade motion status (see also [13]). There are few studies examining how large raptors with a strong inclination to avoid turbines respond to turbine blades' motion status. It would be advantageous, nevertheless, for a future study to examine such birds' responses in a before–during–after study with the focal period only due to shutdowns through maintenance/refurbishment/repair, thereby thoroughly excluding wind speed as a potential confounding influence on turbine shutdown effect.

Acknowledging these caveats, our findings were consistent with five previous results:

1. Golden eagles rarely approached wind turbines at distances that were close enough to present a risk of collision, consistent with wariness creating avoidance [13–15].
2. The potentially adverse effects of turbines were not homogeneous within a wind farm, and some turbines presented a greater risk of adversity, regardless of whether that erred more towards collision fatality at one extreme or functional habitat loss (through avoidance) at the other extreme [13].
3. The attractiveness of turbine locations, documented through GET habitat preference scores [15,56], was strongly influential on approach distances, as was the relative attractiveness of habitat surrounding the turbines [13–15].
4. Eagles were recorded at closer distances to turbines when wind speeds at turbines were higher [13].
5. The motion status of turbines was not a major factor influencing approach distances [13]. In the present study, there was a weak effect of blade motion. However, this was against what was reasonably expected on eagles' perception of a greater threat with moving blades because approach distances were marginally closer when blades were turning.

Discussing these findings in turn, when CM wind farm was part of wider previous Scottish studies [14,15], our result of substantial avoidance was expected. A previous result found that wind farm and tagged bird identities may create substantial variation [15]. Again, however, in the present study's focus at one wind farm and largely due to one territorial female, this finding of wariness was confirmed. Although the present study involved only four individuals (primarily one territorial female), the same finding was also documented for ten other territorial birds and twenty-four non-territorial birds at eleven wind farms [15], a detailed study at two wind farms involving seven non-territorial eagles [13], and a national study of eighty wind farms involving fifty-nine non-territorial eagles [14].

Our second finding confirmed that a wind farm is not a homogenous entity regarding birds' reactions to composite turbines because turbines differ in generating potentially adverse impacts. This is not new to our study system [13] or others (e.g., [31,32]). Indeed, the first demonstrations of such heterogeneity came from the earliest research on wind farms and raptors at Altamont, California, USA (e.g., [16]). Yet, despite such a long history of results on this established tenet, it has been claimed recently, apparently generically but unreasonably, that "it is unknown whether the risk to wildlife varies among turbines" [37]. Our study confirmed that individual turbines (through their locations) differ in their propensity to create adverse impacts (Table 2) and hence are an important consideration for wind farm design and assessment of wind farm proposals (e.g., [13,31]).

With such heterogeneity, we also found (Figure 1), following [13], that turbines in a wind farm array's interior were less often approached than outer turbines. This confirmation could, however, be partially through our process of assigning flight records to the nearest turbines, when most flight records were well away from turbine locations because, once more [13–15], avoidance of turbines was the substantial response (Table 2 and Figure 2). Eagles, again, rarely entered a turbine array or approached close to any turbine. As acknowledged previously [13], it is difficult to assign flight records to interior turbines, even using 3D records, when eagles rarely approach any turbines.

The present study, nevertheless, illustrated again that the primary attention in assessing the potential impacts of a wind farm's turbines should focus on proposed outer turbine locations and their underlying habitat preference (see below). It also suggests once more [13] that wind farm designs with simple rows (strings) may have a more adverse impact on Scottish golden eagles than more clustered configurations on a per-turbine basis, all else being equal. Turbine strings, in per-turbine impacts, have also been found to be more problematic elsewhere (e.g., [31]).

Our third finding, inequality in the underlying habitat preference of turbine locations affecting the proximity of birds' records, was also not novel or unexpected (e.g., [13–15,31,32]). On a large scale, this is an obvious feature of the potential effects of wind turbines on any bird species. Turbines located in offshore marine habitats will not affect resident terrestrial bird species, for example. On a smaller scale, terrestrial turbines in unsuitable habitats for a bird species will also have no effect on that species. (Several wind farms in Scotland, for example, are in lowland habitats not used by golden eagles; see [14,56].) Hence, at a finer scale, even when wind farms are in broadly suitable habitats for a study species, it should be expected that turbine locations will vary in attractiveness and have potential vulnerability to adverse effects [31,32,74].

While eagles in the present study substantially stayed well away from turbines, we found once more that eagles approached turbines closer when turbines were in a more preferred habitat, and the attractiveness of turbine locations also depended on the relative attractiveness of the surrounding habitat [13,15]. This finding reiterates that consequential adverse impacts from wind farm construction will be most evident at turbines that are in highly preferred habitats and have highly preferred habitats nearby.

In our study system, the demonstrable potential adverse impact is markedly towards functional habitat loss. In other study systems where eagles are apparently less wary of turbines, and hence where collision with turbine blades is more likely [8,18,21,25,34,36,37,75], the same considerations on the attractiveness of underlying turbine locations and their surroundings should also apply in generating a potentially adverse impact. Even if that impact may differ because of differences in birds' wariness of turbines and the more likely underlying effect [13–15].

As emphasised in previous studies [13,15], the sliding scale within the continuum between avoidance (creating functional habitat loss) and prospective collision (creating fatalities) can have similar underpinning processes towards the most likely adverse impacts, even if these differ. Proposed turbines that are in preferred habitats and surrounded by preferred habitats will be universally problematic when planning wind farms. Whether this goes more towards collision or functional habitat loss seems governed by the inherent wariness shown by birds to turbines. Nevertheless, the same principles underlying the attractiveness of turbine locations and surrounding areas apply.

Our fourth finding that eagles were recorded closer to turbines when wind speeds were higher was not novel [13]. This is probably because golden eagles depend facultatively on uplift winds for flight activity, which is frequently proxied by influential measures of topographic features that generate uplift wind energy [42,56,76–78] and when airspace is a critical habitat [79]. This is also apparent for other large raptors, which are facultative or obligate soaring species [31,80].

Wind turbines at higher elevations, where wind speeds and hence, efficacious energy capture can be greater (e.g., [6,7,47]) will necessarily potentially affect proximity to turbines for several soaring birds, such as golden eagles (e.g., [13,42,76,81]) and other large raptors (e.g., [80,82]). The propensity for closer proximity to turbines will often be greater at higher wind speeds through birds' need to gain elevation from underlying wind speed, recorded by speeds at turbine hubs in the present study and [13] and proxied by space use as a habitat [79] based on topographical metrics (see references above and [15,56]).

Our fifth finding involved the primary objective (Introduction). Eagles' approach distance to turbines was not strongly influenced by whether their blades were turning. The blade motion predictor was significant but weak and directionally counter to an expectation that approach distance should be greater when blades were turning.

This result confirmed that in our study system, blade motion status apparently made little or no difference in how close golden eagles approached turbines. The implication was that wariness was due to the wind turbine structure *per se* without perception of any danger posed by proximity towards potential collision risk or visionary realisation of the presence or possible consequence of moving blades [12]. As recorded by the present study and previously [13–15], Scottish golden eagles typically stay well away from wind turbines, by hundreds of metres, and their aversion seems due to turbine presence, not their moving parts. This is unless, in exceptional circumstances, a highly attractive habitat underlies turbine locations coincides with a highly attractive surrounding habitat. This unusual possibility in very low approach distances to turbines probably explains why collisions occur only rarely in Scotland [13]. Individual differences in birds' behaviours and wind farms' turbines also appear to be involved in approach distances (Table 2 in [15]), although avoidance is common to all, typically at hundreds of metres.

In conclusion, mitigation through turbine shutdown/curtailment [28,29,31,33,34,82,83] or increasing turning blades' visibility [12] can be effective for species, populations, individuals, or circumstances involving birds with no or limited wariness of turbines by reducing the primary impact of collision fatality. This effectiveness may not be universal, even in study systems where a collision is expected ([33,39,40], although see [35]). Regardless, however, as in our study system and others, such measures are not going to have much influence or provide mitigation for birds where the primary expected impact is functional habitat loss through avoidance (e.g., [27,61]).

Mitigation for functional habitat loss should focus more on compensatory creation of suitable habitat away from the wind farm, if possible. Functionally lost suitable vegetation habitats could include the conversion of unsuitable areas of vegetation within an affected occupied territory (e.g., dense conifer plantation; [49]) to suitable open vegetation away from the wind farm. At least in Scotland, however, this may prove to be difficult in practice because of the current government forestry policy such that any felling of woodland/forest must be replaced by comparable planting elsewhere [84]. In other situations, such as when the lost habitat is primarily through the avoidance of airspace occupied by turbines then mitigation may also be difficult because the airspace habitat [79] is largely created by topography and its assistance to efficient soaring flight [56]. Potential mitigation may, therefore, be even more challenging when such avoidance is at migration bottlenecks with, consequently, limited alternative routes [27,43].

A fundamental evaluation of birds' wariness of turbines in any study system [13] again appears critical and has important implications for wind farm designs and any proposed mitigation.

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