Assessing the cumulative impacts of wind farms on peatland birds: a case study of golden plover *Pluvialis apricaria* in Scotland

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SUMMARY

The distribution of golden plover across Scotland was modelled using land cover and management variables, and used to highlight the spatial association between golden plover abundance and current and proposed wind farm developments. Overlap was greatest in three biogeographical zones (the Western Isles, the Western Central Belt and the Borders Hills) and was estimated at *ca*. 5% of the biogeographical population in each case. New field data were used to predict the effects of wind farm development on golden plover populations, employing a conservative analytical approach to detect statistically significant wind farm related effects. The results provide evidence of significant avoidance of wind turbines by breeding golden plovers to a distance of at least 200 metres. Furthermore, wind farm sites appear to support lower densities of golden plover than predicted by the distribution model for sites without wind farms. Therefore, there is evidence for negative effects of wind farm developments on golden plover, and we suggest strategies to reduce any potential conflict between the need to promote wind energy and the need to maintain golden plover populations.

KEY WORDS: climate change, distribution modelling, displacement, renewable energy, uplands, waders.

INTRODUCTION

Wind energy currently accounts for *ca*. 0.5% of global energy production, but there is an urgent need to increase this contribution as part of the policy to limit global climate change (Sims *et al*. 2007). Within the UK, a target has been set for 50% of Scotland's electricity generation to come from renewable sources by 2020 (Scottish Government 2007), as this country's contribution to the 20% renewables target for all energy consumption by European Union member states (EU Renewable Energy Directive 2008). Onshore wind is currently one of the cheapest and most advanced sources of renewable energy, with considerable potential for expansion, leading to a rapid increase in the number of proposed wind farm developments. A high proportion of these are for locations in upland peatland areas, which generally offer high wind resources coupled with locations that are remote from major population centres.

Uplands in the UK support many habitats and species of high conservation importance (Thompson *et al*. 1995), and yet there is considerable uncertainty regarding the impacts of wind farms on biodiversity. Studies in other habitats and countries have highlighted the particular sensitivity of birds to wind farm development, through either increased mortality due to collision with the turbines or disturbance displacement manifest as individuals vacating suitable habitat close to the turbines (Langston & Pullan 2003, Drewitt & Langston 2006, Stewart *et al*. 2007). Effects vary between species and sites, but some poorly sited wind farms have caused many deaths (e.g. Everaert & Stienen 2006, Barrios & Rodriguez 2007, Smallwood & Thelander 2008). However, there has been little research within the UK to assess potential impacts of the increasing number of wind farms on upland birds, many of which are listed in Annex I of the EU Birds Directive 79/409/EEC (Thompson *et al*. 1995). Whilst some Annex I species are concentrated in Special Protection Areas (SPAs), most are dispersed more widely, and therefore may not be well protected by current planning regulations.

In this paper we investigate potential effects on golden plover *Pluvialis apricaria*, a widely distributed Annex I upland breeding wader (Charadrii), which Environmental Impact Assessment (EIA) documents often record as breeding within proposed wind farm areas. Golden plover are known to be associated with flat peatlands and montane ridges (Haworth & Thompson 1990, Brown & Stillman 1993, Stillman & Brown 1994, Pearce-Higgins & Grant 2006), and therefore are likely to occur in areas of wind farm development. We assess the likely impact of wind farms on this species in two ways. First, we use existing data to model the distribution of golden plover across Scotland, highlighting the anticipated overlap between areas of high golden plover density and wind farm development, in order to assess the potential severity of cumulative impacts of development on particular populations. Secondly, we use field data from eleven paired wind farm and control sites to quantify the impact of wind farm development on the distribution and density of golden plover.

METHODS

Modelling golden plover breeding densities

Existing data on golden plover breeding densities were taken from five surveys of peatland areas within Scotland (Tharme *et al*. 2001, Jackson *et al*. 2004, SNH 2004, Sim *et al*. 2005, Pearce-Higgins & Grant 2006). All of these surveys employed similar methods (Brown & Shepherd 1993) to assess breeding densities within 1 km squares, which were used to model distribution as a function of topographical, land cover and management variables. Topographical variables were derived from a 50 m resolution digital terrain model (DTM) of the UK, which was used to calculate mean altitude and the fraction of each 1 km square with surface slope less than 2º, 5º and 10º. Land cover was derived from the UK Land Cover Map LCM2000 (Fuller *et al*. 2003), reducing the number of predictor variables by grouping some ecologically similar categories to give seven land cover classes, namely: bog, open dwarf shrub, dense dwarf shrub, montane, woodland (broad-leaved and coniferous woodland combined), grassland (neutral, calcareous and acid grassland combined) and enclosed farmland (improved grassland and arable categories combined). Likely effects of grouse moor management (Tharme *et al*. 2001) were assessed following Whitfield *et al*. (2003), by deriving an index of grouse moor management as the fraction of each square covered by the 'strip muirburn' habitat class from the Scottish land cover map LCS88 (MLURI 1993). A measure of woodland fragmentation (Buchanan & Pearce-Higgins 2002) was derived as the cover of woodland within 1 km and 3 km buffers centred on each 1 km square, derived from a Scotland-wide map of woodland cover combining the National Inventory of Woodland and Trees (NIWT) with information about applications for woodland grant schemes (Smith & Gilbert 2000).

The data were divided into geographically distinct units based on SNH Natural Heritage Zones (NHZs) (SNH 2004) to allow for regional variation in associations between golden plovers and predictor variables (Bright *et al*. 2006, G. Buchanan *et al*. unpublished data). Because golden plover data were available for only some NHZs, adjacent NHZs were combined into four broad regions and a separate model was produced for each region (Figure 1). Models of the number of pairs in each square were constructed within a Generalised Linear Model (GLM) using PROC GENMOD in SAS v. 9.1 (SAS Institute 2003), specifying a Poisson error distribution and log-link function (Pearce-Higgins *et al*. 2006). To model density, the natural log of the area of suitable habitat within each square (the sum of bog, dwarf shrub, montane and grassland categories) was included as an offset. Parameter estimates were calculated using model averaging from GLM models comprising all possible combinations of predictor variables (Burnham & Anderson 2002, Whittingham *et al*. 2005, 2006). Because golden plover density can vary non-linearly with altitude, a quadratic measure for this term was also included. Three measures relating to woodland (cover within the 1 km square from LCM2000, and woodland cover within 1 km and 3 km) and three relating to slope (less than 2º, 5º and 10º) were derived, but to limit the number of predictor variables, only the most strongly correlated variable within each group was used (*cf*. Pearce-Higgins & Grant 2006).

Models were constructed using a random 90% of the data for each region, leaving 10% for testing the predictive ability of the models by regressing observed against predicted densities. Predicted values were first corrected to a 1:1 relationship with observed densities by regression against the model building data to ensure comparable model outputs between the four regions. These predictions were then combined to model golden plover densities across mainland Scotland and the Western Isles. Orkney and Shetland were excluded due to non-availability of survey data and because they were regarded as too distinct to be modelled using data from other NHZs.

The likely degree of overlap between golden plover distribution and wind farms was assessed, following Fielding *et al*. (2006), by overlaying maps of consented (approved and built) and proposed (scoping and application submitted stages) wind farm footprints from SNH's renewable energy database (February 2007 version, SNH unpublished)

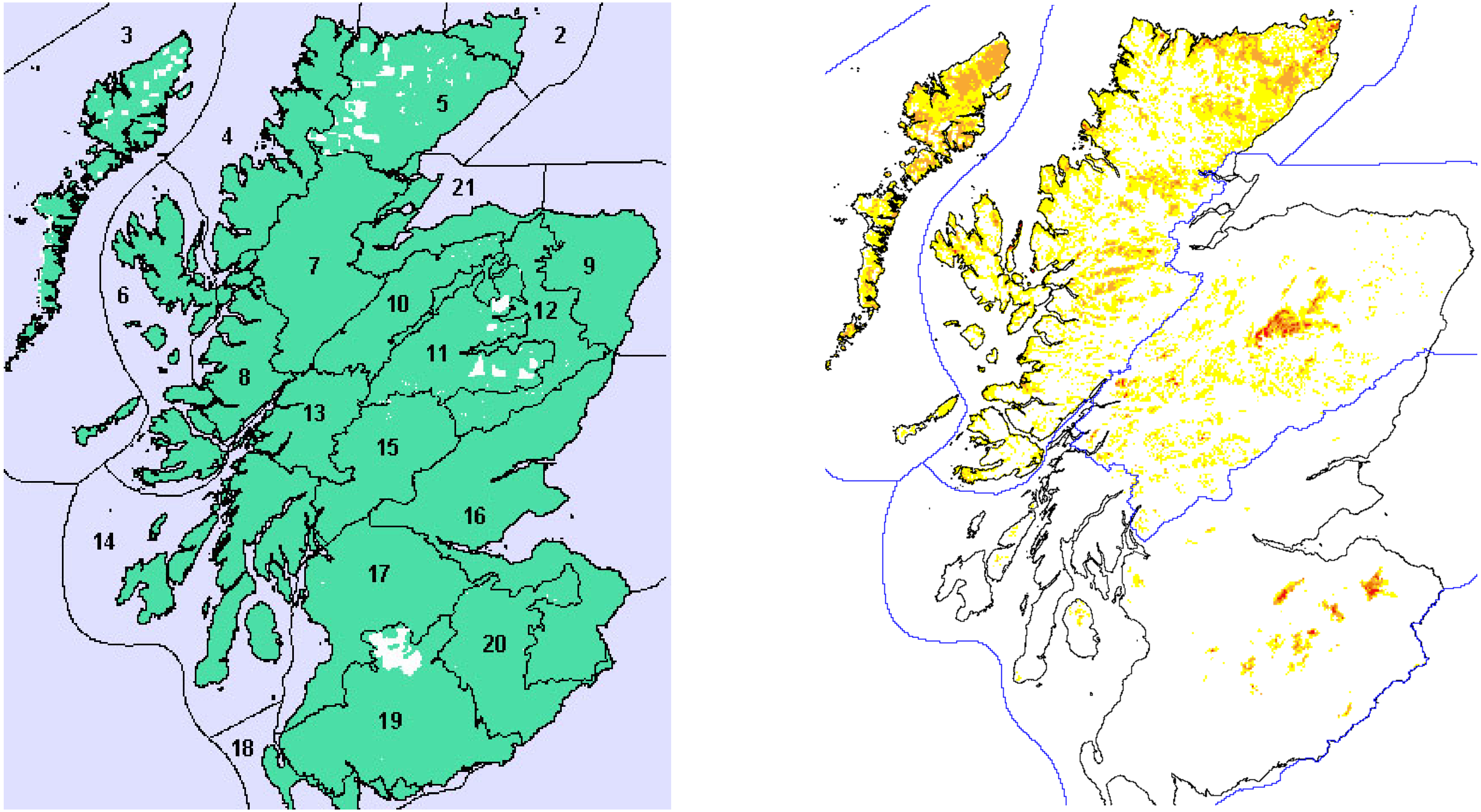

Figure 1. Maps of mainland Scotland and the Western Isles, showing (left) the locations of 1 km squares containing golden plover data used for model building (white) and the outlines of the different NHZs (black lines); and (right) predicted golden plover densities within each of the four regions (blue lines), based on the models in Table 2 (<0.2 pairs km^{-2}, white; 0.2–1 pairs km^{-2}, yellow; 1–2 pairs km^{-2}, light orange; 2–3 pairs km^{-2}, dark orange; 3–4 pairs km^{-2}, dark red; 4+ pairs km^{-2}, bright red).

onto the map of predicted golden plover densities. The proportion of golden plover pairs overlapping with wind farm footprints was estimated as a measure of the potential for significant cumulative impact on the population. This analysis was carried out separately for each NHZ because population level impacts of wind farms are currently assessed within biogeographical units (SNH 2006).

Modelling effects of wind farm development

Field methods

Eleven constructed wind farm sites located on unenclosed upland (moorland, rough grassland or blanket bog) habitats in Scotland were surveyed in 2006 (eight sites) and 2007 (three sites) (Table 1). The area surveyed at each site excluded enclosed grassland and forest or felled forest, and extended to a maximum of 1 km from the turbines. Each site was paired with a nearby 200 ha control site without turbines but with similar topography and habitat (based on digital terrain data and satellite images, Buchanan *et al*. 2005) to maximise comparability.

At eight of the wind farm sites, the abundance and distribution of breeding golden plovers was recorded on six occasions at approximately 12-day intervals between 17 April and 01 July. Access restrictions prevented the first visit to three of the sites surveyed in 2006. Control sites were surveyed on three visits only for logistical reasons. During each visit, surveyors walked transects 100 m apart, mapping all golden plover locations in conjunction with standard behaviour codes, on 1:12,500 maps. Sightings that were sufficiently accurate to indicate habitat use (i.e. birds were observed on the ground prior to disturbance) were separated by surveyors from less accurate sightings of flying birds or birds deemed to have moved prior to detection. Accurate sightings only were used for the analysis of habitat use, whereas all sightings in breeding habitat contributed to the estimates of breeding abundance.

Table 1. Summary characteristics of the eleven wind farm sites where field survey data were collected.

Site	Year of completion	Turbine height to hub (m)	Number of turbines	Site capacity (MW)	Survey area (km^2)
1	2002	60	24	31.2	4.64
2	1999	35	14	8.4	4.76
3	2005	70	42	97	6.48
4	2006	60	17	30	9.32
5	2004	60	21	48	7.12
6	2005	60	22	50.6	4.32
7	2000	40	26	17.2	6.24
8	1995	35	26	15.6	4.48
9	2000	40	20	13	8.20
10	2006	60	28	56	7.92
11	1996	30	36	21.6	4.72

The distribution and abundance of golden plover are influenced by the composition and structure of vegetation (Pearce-Higgins & Grant 2006). Therefore detailed field measurements of vegetation were made using a method adapted from Pearce-Higgins & Grant (2006) based on a 200 m x 200 m grid of squares across each site. Within each square, vegetation sampling points were located 20 m apart along two parallel transects 100 m apart, giving a total of ten points per square. At each point, maximum vegetation height was estimated to the nearest 5 cm using a bamboo cane with 1 cm wide white marks at 0, 10, 20, 30 and 40 cm from its base, held vertically. Species composition was assessed by recording the plant species touched by the tip of the cane as it was initially lowered onto the ground. Vegetation density was assessed from the visibility of the white marks when the cane was laid horizontally on the ground. The habitat within each grid square was characterised by summarising the data collected at all ten sampling points.

Golden plover are affected by a wide range of additional factors that need to be accounted for during the analysis (Tharme *et al*. 2001, Finney *et al*. 2005, Pearce-Higgins & Grant 2006). Mean altitude and slope were derived for each grid square from the UK DTM, and the proximity of each grid square to woodland was assessed from the NIWT map of woodland cover (see above). Public roads were digitised from published UK (Ordnance Survey) maps. The locations of turbines, above ground transmission lines and tracks were obtained from the appropriate energy companies or digitised from Ordnance Survey maps. Calculations of the distance of each grid square from the nearest woodland polygon, road, turbine, track and pylon were conducted in *Idrisi* v. 14.0 (Clark Laboratories 2003). These distances (d) were transformed (d_x) to eliminate the influence of particularly large values of d for sites where turbines, forests or pylons were absent, using the following equation:

$$d_x = \exp(0 - (d/250)) \quad [1]$$

Using 250 as the denominator ensured that d_x changed little beyond d = 1000 m, which was the maximum distance from the centre to the edge of the wind farm area, and reflected the likelihood that the magnitude of any avoidance would decline with distance (*cf*. Finney *et al*. 2005). A negative correlation of bird numbers with d_x indicates avoidance.

Analysis of variation in habitat use

Habitat use was calculated as the proportion of survey visits to each square during which golden plover were recorded, correcting for differences in survey effort between sites. Data from one site (11) where golden plover were not recorded were excluded from this analysis.

Before analysing the effects of wind farm variables it was important to attempt to eliminate any potentially confounding nuisance variables arising because the locations of turbines, tracks and transmission lines were non-random with respect to habitat and topography - for example due to preferential siting of infrastructure on flat, high altitude areas. A two stage modelling process was adopted to reduce the risk of such Type I errors, following Tharme *et al*. (2001) and Pearce-Higgins & Grant (2006). Models of habitat usage were constructed with a binomial error structure and logit link function, first using predictor variables that were unrelated to wind farm development (vegetation structure, composition, topography and distance to forest and public roads). The terms were selected as those predictor variables that were significant ($P < 0.05$) when correlated in a univariate manner with habitat usage. Both linear and quadratic terms were tested, and where the quadratic term was significant, both were included in the model. Where a number of different variables described the same feature in different ways (e.g. in the case of vegetation height and density), or where predictor variables were strongly correlated ($r > 0.5$), only the most significant term was included to reduce the likelihood of error associated with colinearity. To account for spatial autocorrelation, an autocovariate term was included throughout the modelling process (Finney *et al*. 2005, Pearce-Higgins *et al*. 2007). This is a measure of mean habitat usage within the surrounding grid cells, weighted by the reciprocal of distance to those squares (Augustin *et al*. 1996). Following the recommendation of Dormann (2007), the autocovariate term was calculated across the neighbouring two cells only, and the approach was extended further by also including the square of the autocovariate term to account for intra-specific interactions between individuals. A factor denoting wind farm identity accounted for different breeding densities between sites.

The Stage One model of habitat usage containing all the appropriate terms was then reduced to a minimum adequate model (MAM) using backward deletion of non-significant ($P > 0.05$) terms. Additional effects of wind farm variables (distance d_x to turbine, track and transmission line) were then incorporated and tested for significance separately. Due to the strong correlation between turbine distance and track distance ($r = 0.76$), no attempt was made to differentiate these two effects.

Given the dangers of Type I errors with respect to the variables of interest within a correlative study, the approach taken to detecting significant effects of wind farm variables was designed to be conservative. However, the fact that variables unrelated to wind farm development were taken into account before the significance and magnitude of wind farm variables were assessed precluded the application of model averaging techniques. Thus, rather than deriving the best model of plover distribution, the approach is regarded as pseudo-experimental, returning the probability of the hypothesis under test being rejected. To assess the likely severity of this limitation, the significance of wind farm related variables was tested against the full Stage One model, which was unaffected by the construction method for the Stage One MAM, prior to any variable reduction. Secondly, the inclusion of an autocovariate measure is a conservative approach to dealing with spatial autocorrelation that reduces the size and significance of the main effects (Dormann 2007).

Analysis of golden plover density

Finally, the model of golden plover breeding densities was used to predict the mean density of plovers on each of the eleven wind farm and control sites, using the data from the three survey dates when both wind farm and control sites were visited. After fitting predicted density, the significance of any differences in plover abundance between wind farm and control sites was assessed in order to test for evidence of reduced breeding densities associated with the wind farms. These analyses were conducted within a GLMM (generalised linear mixed model), with wind farm identity as a random effect. The maximum field count of golden plovers across the three visits was used to assess population size at each site (Pearce-Higgins & Yalden 2005), with the natural log of area used as an offset. The terms in the GLMM were the natural log of modelled density (Table 2) and a two-level factor denoting whether the site was a wind farm or control, along with the interaction between the two.

RESULTS

Modelling golden plover distribution

The models of golden plover distribution showed contrasting effects of some variables between regions (Table 2). There was a significant correlation between observed and predicted densities across the test data in all regions, although predictive power varied, being particularly poor in North region. Modelled densities were highest on the Western Isles, the peatlands of Caithness and Sutherland, the Cairngorms Massif and the Border Hills (NHZs 3, 5, 11 and 20; Figure 1). Population estimates based on these models were derived for all NHZs, although estimates for NHZs lacking survey squares should be treated with caution (Table 3).

The likely degree of overlap with consented and proposed wind farm footprints is used to highlight

Table 2. Models of golden plover density in each of the four regions (Figure 1). Superscripts for slope (< 2°, < 5° or < 10°) and woodland (cover within 1 km or 3 km buffer) indicate the predictor variable included in the model (see text) and [a] identifies variables omitted due to lack of variation in the data. The correlations between observed and expected values indicate model fit to the test data, the significance of which is indicated by the asterisks (*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$). For North and South regions, the values of r^2 in parentheses indicate the improvement in model performance following the deletion of one outlying point. N is the sample size for the model building data.

	North	East	West	South
Intercept	-2.97 ± 0.70	-10.14 ± 1.69	-4.97 ± 0.61	-6.72 ± 2.14
Bog	0.0082 ± 0.0052	-0.0097 ± 0.011	0.0027 ± 0.0041	0.014 ± 0.016
Dense dwarf shrub	0.016 ± 0.011	0.0003 ± 0.0093	-0.027 ± 0.012	0.012 ± 0.022
Open dwarf shrub	-0.0094 ± 0.0042	0.0092 ± 0.0063	0.0026 ± 0.0039	0.026 ± 0.013
Montane	[a]	-0.029 ± 0.0061	[a]	[a]
Grass	-0.019 ± 0.0074	0.011 ± 0.071	-0.0036 ± 0.0038	-0.022 ± 0.014
Enclosed	0.031 ± 0.013	0.086 ± 0.071	-0.053 ± 0.023	-0.0038 ± 0.034
Altitude	-0.013 ± 0.0039	0.011 ± 0.0038	0.018 ± 0.010	0.0087 ± 0.014
$(\text{Altitude})^2$	0.0019 ± 0.00066	-0.00004 ± 0.00070	-0.0079 ± 0.0057	-0.0043 ± 0.0021
Slope	0.0024 ± 0.00085[2]	0.014 ± 0.0032[2]	0.0024 ± 0.0018[10]	0.0020 ± 0.0028[5]
Woodland	-0.0049 ± 0.00022[3]	-0.0042 ± 0.0048[1]	-0.0035 ± 0.0016[3]	-0.0017 ± 0.0083[3]
Grouse moor index	[a]	0.50 ± 0.54	[a]	1.14 ± 0.74
Regression between observed (O) and predicted (P) density	O = 0.28 + 0.50P	O = 0.12 + 0.31P	O = -0.015 + 0.66P	O = 0.080 + 0.066P
Predictive ability (r^2)	0.06* (0.08)	0.31***	0.23***	0.08** (0.41)
N	410	329	324	351

Table 3. Estimated golden plover population within each NHZ (Figure 1) and the likely overlap with wind farm development. Bold type indicates NHZs containing golden plover survey squares, for which the modelled distributions are likely to be most accurate. Estimated population (pairs) is extracted from Figure 1. Overlap denotes the number / percentage of golden plovers within each NHZ which overlap with the footprints of consented, proposed and all wind farms. [1] indicates mainland fraction only

NHZ	Estimated population	Overlap with consented wind farms	Overlap with proposed wind farms	Overlap with all wind farms
2[1]	598	1 / 0.1	8 / 1.4	9 / 1.4
3	**2203**	**1 / 0.0**	**99 / 4.5**	**100 / 4.5**
4	1388	0 / 0.0	2 / 0.1	2 / 0.1
5	**2276**	**4 / 0.2**	**21 / 0.9**	**25 / 1.1**
6	1228	0 / 0.0	2 / 0.1	2 / 0.1
7	1582	4 / 0.3	3 / 0.2	7 / 0.4
8	712	0 / 0.0	0 / 0.0	0 / 0.0
9	97	0 / 0.3	1 / 0.9	1 / 1.2
10	**360**	**2 / 0.4**	**2 / 0.4**	**3 / 0.8**
11	**1432**	**0 / 0.0**	**1 / 0.1**	**1 / 0.1**
12	**156**	**0 / 0.0**	**1 / 0.5**	**1 / 0.5**
13	527	0 / 0.0	0 / 0.0	0 / 0.0
14	114	0 / 0.1	1 / 1.2	1 / 1.2
15	**399**	**0 / 0.0**	**2 / 0.5**	**2 / 0.5**
16	26	0 / 0.3	1 / 2.1	1 / 2.2
17	**59**	**0 / 0.8**	**4 / 6.7**	**4 / 7.0**
18	1	0 / 0.0	0 / 0.3	0 / 0.3
19	**114**	**0 / 0.2**	**1 / 0.7**	**1 / 0.7**
20	**734**	**1 / 0.1**	**41 / 5.6**	**42 / 5.8**
21	11	0 / 0.0	0 / 0.0	0 / 0.0
TOTAL	14017	12 / 0.1	189 / 1.3	201 / 1.4

NHZs where golden plover populations may be under the greatest pressure from wind farm development through cumulative impacts. Although the degree of overlap between currently consented wind farms and estimated golden plover distributions is relatively low (< 1% for each NHZ), when wind farms at scoping and application stages are included, an estimated 1.4% of the total population are within wind farm footprints, with the greatest degree of overlap in NHZs 17, 20 and 3 (Table 3). Thus there is considerable potential for wind farm sites within these NHZs to coincide with golden plover occurrence.

Variation in habitat use

Four environmental variables explained 16.1% of the variation in golden plover habitat use, which was positively related to altitude and the cover of open vegetation and negatively related to slope and proximity to forests (Table 4). There was a significant association between turbine proximity and modelled habitat suitability for golden plover ($\chi^2_1 = 35.35$, $P < 0.0001$), indicating that the natural habitat preferences of golden plover are for areas where wind turbines tend to be located. Nonetheless, after accounting for other habitat variables in the Stage One model, there was significant avoidance of turbines (Figure 2) (χ^2_1 = 4.79, P = 0.029, slope (d_x) = -1.22 ± 0.57) which remained significant when incorporated into the full Stage One model (χ^2_1 = 4.94, P = 0.026). There was additional evidence for avoidance of tracks (χ^2_1 = 4.11, P = 0.043, slope (d_x) = -1.05 ± 0.49), but not for avoidance of power lines (χ^2_1 = 0.07, P = 0. 79).

Effects on golden plover density

There was a strong correlation between observed golden plover densities on the wind farm and control sites and the expected densities mapped in Figure 1 (Figure 3; $F_{1,\ 19}$ = 11.21 P = 0.0034), providing further support for the accuracy of the map of modelled golden plover distribution. Actual relative to predicted densities on the control sites were significantly greater than on the wind farm sites ($F_{1,\ 19}$ = 14.39, P = 0.0012), and there was an almost significant interaction between the slopes of the two relationships ($F_{1,\ 18}$ = 3.68, P = 0.071). These results indicate a reduction in plover densities on the wind farm sites relative to the controls.

Table 4. Stage One minimum adequate model (MAM) of variation in golden plover habitat use.

Model	**Estimate**	**SE**	**Significance**	***P***
Intercept	-12.34	1.76		
Wind farm			χ^2_{10} = 25.30	0.0027
Autocovariate	5.05	1.54	χ^2_1 = 11.51	0.0007
(Autocovariate)^2	-3.83	1.75	χ^2_1 = 5.31	0.021
Forest	-7.37	2.35	χ^2_1 = 18.26	<0.0001
Altitude	0.10	0.0029	χ^2_1 = 11.66	0.0006
Slope	-0.24	0.058	χ^2_1 = 23.90	<0.0001
Cover open vegetation	0.025	0.0070	χ^2_1 = 13.92	0.0002

DISCUSSION

This is the first study to examine the likely impacts of wind farms on peatland birds such as golden plover, and we find considerable potential for negative effects. First, golden plover distribution shows close correspondence to the proposed locations of wind farms. Within wind farms, areas where turbines are located tend to be of high habitat suitability for golden plovers and, as a result, more than 1% of the estimated golden plover populations fell under the footprint of all potential wind farm developments in eight of the NHZs. Secondly, habitat use by golden plovers within wind farm areas was significantly reduced up to a minimum of 200 m from the turbines, and breeding density appeared to be lower than predicted at wind farm sites relative to control sites. Importantly, because they incorporate data from a range of wind farm sites, our results should have wide applicability.

Previous studies have highlighted turbine avoidance by wintering golden plover over distances of 50–850 m (median 135 m; reviewed by Hötker *et al.* 2006), whilst breeding golden plover have been shown to avoid heavily disturbed footpaths to a distance of 200 m (Finney *et al.* 2005), a similar figure to ours. This avoidance appears to contribute to a significant effect on breeding densities, despite the fact that the turbines are located in areas of high golden plover habitat suitability (being on areas of flat, open vegetation at high altitude). Although these differences are based on a relatively small sample of sites (10 of 11 wind farm/control pairs contained golden plovers), they are of sufficient magnitude to suggest that wind farm development can have a significant negative impact on local breeding golden plover densities, and reflect similar negative effects of wind farm development on wintering plover densities (Hötker *et al.* 2006). Whether the degree of displacement is of sufficient magnitude to have contributed to the decline in breeding density at the wind farm sites is debatable, and more research on the likely mechanism of decline would be of value. For example, could

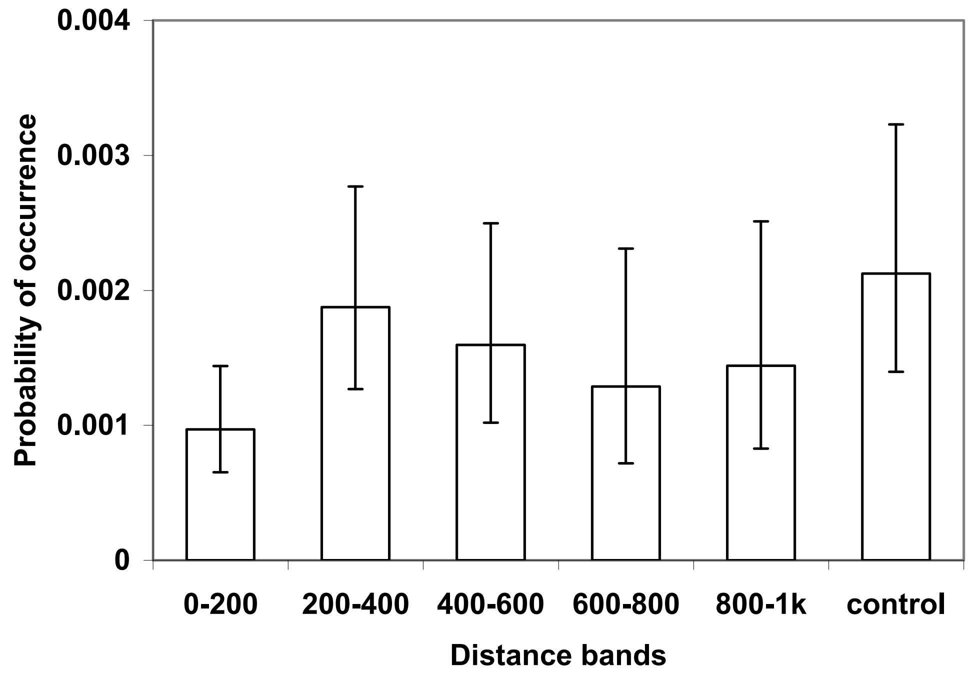

Figure 2. Golden plover habitat use (± SE) as a function of turbine distance. Bars present mean residual probabilities of golden plover occurrence per grid cell, per visit, after accounting for potentially confounding variables in the Stage One model (Table 4).

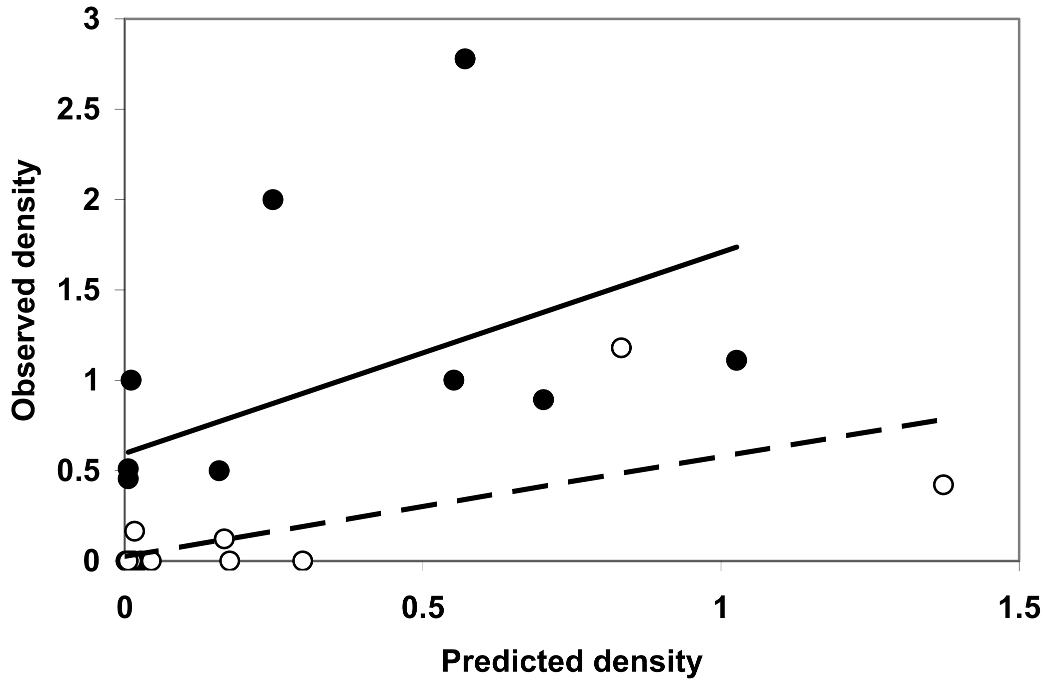

Figure 3. The correlation between observed and predicted golden plover densities (pairs km^{-2}) on the wind farm (open circles, dashed line) and control (closed circles, solid line) sites. Predicted densities were extracted from the map in Figure 1.

increased adult mortality also be occurring at these sites due to the collision of breeding birds with turbines? Golden plover may be at high risk of collision given their tendency to commute regularly from breeding habitats to enclosed farmland for foraging during both day and night (Pearce-Higgins & Yalden 2003), and their display flight behaviour.

It is worth noting that we have not, of course, monitored reductions in golden plover populations on wind farm sites with time, but simply compared densities between wind farm and control sites. We therefore interpret any differences between the two as resulting from the wind farm development, but such correlations may occur for other reasons such as the non-random placement of wind turbines in relation to golden plover densities. We regard this as unlikely, given that our analysis suggests that turbines tend to be located in areas of good golden plover habitat, but it would certainly be worth conducting an analysis of existing data from post-construction monitoring of golden plover populations at wind farms, to provide a temporal test of our conclusions.

Given the potential reduction in breeding populations associated with wind farm development, our assessment of the likely overlap between golden plovers and potential wind farm footprints usefully highlights biogeographical zones with the greatest potential for conflict. Specifically, the percentage overlap for three NHZs approaches or exceeds 5% of the modelled golden plover population. For the Western Isles (NHZ 3), this is due to the existence of a small number of large proposed developments on areas of peatland with high golden plover densities. Conversely, although only a few pairs are likely to be affected by development within the Western Central Belt (NHZ 17), any extensive wind farm development within the relevant upland areas is likely to have a significant impact because of the small NHZ population. Golden plovers appear to be similarly concentrated within the Borders Hills (NHZ 20), where there are again a number of extensive proposed developments. The likely cumulative impacts of new wind farm developments on golden plovers within these areas should therefore be given particularly careful consideration.

Our predicted golden plover distribution map has significant limitations, with fairly weak correlations between observed and expected densities at 1 km resolution (Table 2), although predicted densities were more strongly correlated with observed densities when assessed at a larger scale across the 22 sites (Figure 3). Our map of golden plover densities across Scotland is qualitatively similar to that produced at the 10 km square level in Gibbons *et al*. (1993), although the latter highlights greater densities in Sutherland, the Monadhliath mountains and Muirkirk uplands. It is also unclear how accurate our NHZ population estimates are likely to be. Our total estimate of 10,500 pairs for the Scottish mainland is considerably less than the 35,000 estimated by O'Brien (unpublished data) on the basis of corrected densities applied to the Gibbons *et al*. (1993) distribution. Our estimate of 2,200 pairs for the Caithness Peatlands (NHZ 5) is less than the 3,760 pairs of Whitfield (1996), although our estimate of 2,200 pairs for the Western Isles (NHZ 3) is similar to O'Brien's estimate of 2,600 pairs. These differences could be a result of golden plover declines across parts of the Scottish mainland between the times of previous estimates and our own (Sim *et al*. 2005), although the correlation between observed and predicted golden plover counts across the wind farm and control sites suggests that we may underestimate some populations. This probably results from the low predictive power of some models, which therefore fail to predict areas of high density. Our estimates should therefore be regarded as indicative and relative rather than absolute. However, with further refinement, for example by incorporating a wider spread of survey or remotely sensed data (Buchanan *et al*. 2005), our method could provide meaningful biogeographical golden plover populations against which to assess wind farm impacts.

To conclude, golden plovers appear to be sensitive to wind farm development by virtue of their occurrence on areas that are favoured for wind farm construction and the apparent reduction in breeding densities associated with wind farm development. Although it is likely that wind farm development on peatlands will have only a marginal effect on the golden plover population for Scotland, our results suggest that development in some areas could lead to potentially significant cumulative impact on regional populations. Climate change may also pose a significant threat to golden plover populations (Pearce-Higgins *et al*. 2005), and clearly it is important to promote the development of renewable energy sources in order to reduce greenhouse gas emissions (Sims *et al*. 2007). Populations that are under stress from wind farm development are likely to be more susceptible to additional pressures from climate change. To balance these two demands, we advocate the use of sensitivity maps to highlight geographical areas with the lowest potential for conflict between wind energy generation and species conservation.

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