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Greater impacts of wind farms on bird populations during construction than subsequent operation: results of a multi-site and multi-species analysis

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Summary

1. There has been a rapid increase in the development of renewable energy because of the need to combat climate change. One of the most widely used technologies has been onshore wind farms. These have the potential to affect birds through disturbance or collision, but the extent to which such developments cause general population declines, and therefore are of wider conservation concern, remains largely untested.

2. Monitoring data from wind farms located on unenclosed upland habitats in the UK were collated to test whether breeding densities of upland birds were reduced as a result of wind farm construction or during wind farm operation.

3. Data were available for ten species although none were raptors. Red grouse *Lagopus lagopus scoticus*, snipe *Gallinago gallinago* and curlew *Numenius arquata* densities all declined on wind farms during construction. Red grouse densities recovered after construction, but snipe and curlew densities did not. Post-construction curlew densities on wind farms were also significantly lower than reference sites. Conversely, densities of skylark *Alauda arvensis* and stonechat *Saxicola torquata* increased on wind farms during construction.

4. There was little evidence for consistent post-construction population declines in any species, suggesting for the first time that wind farm construction can have greater impacts upon birds than wind farm operation.

5. The impacts of wind farms were largely unaffected by technical specifications (turbine height, number or total generating power) and therefore are widely applicable.

6. *Synthesis and applications*. This study confirms that regulatory authorities and developers should particularly consider the likely impacts of wind farms on large waders. Greater weight should be given to the effects of construction on wildlife in impact assessments than at present. Mitigation measures during construction, including restricting construction activity to non-breeding periods, should be considered and tested as a means to reduce these negative effects.

Key-words: climate change, collision, displacement, disturbance, environmental impact assessment, mitigation, renewable energy, upland birds

Introduction

Concerns over security of energy supplies and global climate change mean that the renewable energy sector is expanding rapidly. Whilst wind energy currently comprises about 0·5% of global energy production, this is anticipated to increase to 5–29% by 2030 (IPCC 2007). The target within Europe is 20% of energy generation from renewable sources by 2020 (EU Renewable Energy Directive 2008); the UK target is 15% whilst Scotland has set an additional target for 100% of its electricity generation to come from renewable sources (Scottish Government 2011). Onshore wind is currently one of the cheapest and best-developed forms of renewable energy and has grown rapidly in the UK, with considerable potential for further expansion (Renewable UK 2010).

Some birds are particularly sensitive to wind farm developments, largely through collision with turbines or disturbance displacement (Drewitt & Langston 2006, 2008). Some poorly

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sited wind farms have resulted in sufficient deaths to have at least a local population-level effect on raptors (Barrios & Rodríguez 2004, 2007; Smallwood & Thelander 2008; Sterner, Orloff & Spiegel 2007; Thelander & Smallwood 2007) and seabirds (Everaert & Stienen 2007). The displacement of birds away from turbines can result in individuals abandoning otherwise suitable habitat, generally over distances of 100–200 m, although the effects vary considerably between sites, species and season/stage of the annual cycle (e.g. Leddy, Higgins & Naugle 1999; Larsen & Madsen 2000; Kowallik & Borbach-Jaene 2001; Hötker 2006; Hötker, Thomsen & Jeromin 2006; Devereux, Denny & Whittingham 2008; Pearce-Higgins *et al.* 2009b). Despite these studies from individual wind farms, there is little information on the generality of impacts upon particular species. The only existing formal meta-analysis of such effects suggested that the abundance of birds, particularly of wintering wildfowl and waders, tends to decline on wind farms (Stewart, Pullin & Coles 2007). However, the authors draw attention to the poor evidence base that exists with which to assess the wider applicability of observed wind farm impacts upon particular species.

The majority of onshore wind farm proposals in the UK have been in upland areas due to their high wind resource coupled with isolation from centres of human population (Renewable UK 2010). These areas support many breeding birds of high conservation importance (Pearce-Higgins *et al.* 2009a). A recent study suggested that wind farm developments may result in significant reductions in habitat usage from 100 to 800 m from the turbines after construction, depending on the species. This could result in reductions in the abundance of some breeding birds by up to 50% within 500 m of the turbines (Pearce-Higgins *et al.* 2009b). To test this suggestion, we collated the available data on temporal changes in bird populations across UK upland wind farms to examine whether there is evidence for declines in the abundance of breeding birds at wind farms. Not only does this add to the relatively limited evidence base globally for assessing the wider impacts of wind farms on birds (Stewart, Pullin & Coles 2007), but it also provides results that are directly applicable to current planning considerations in the UK uplands, and in other similar semi-natural habitats with a high wind resource, such as the peatlands of north-west Europe and southern South America, and the grasslands of central North America (Archer & Jacobson 2005).

Specifically, we tested three predictions: (i) Population densities will be reduced on wind farms during construction as a result of disturbance, relative to both the pre-construction period and reference sites; (ii) Population trends on wind farms post-construction will be different to trends on reference sites, as a result of either disturbance or collision mortality; and (iii) Any negative effects of wind farms will be greatest at sites with a high generating capacity that contain more or larger turbines.

Materials and methods

Using Royal Society for the Protection of Birds and Scottish Natural Heritage data bases, and the Renewable UK website (Renewable UK 2010), in autumn 2008 we identified suitable operational wind farms, selecting only those located on unenclosed upland habitats (blanket bog, moorland and rough grassland) with more than five turbines. Data up to and including the 2007 breeding season were included. From 30 potentially suitable wind farms, systematic post-construction bird monitoring data were available for 15 sites. The surveys of Pearce-Higgins *et al.* (2009b) provided additional post-construction data for three more sites that could be compared with pre-construction data, yielding a final sample of 18 sites (Table S1, in Supporting Information).

We obtained annual estimates of breeding bird abundance for these 18 operational wind farms and, where available, paired reference sites that lack turbines (12 sites, although data from the reference site extended to the pre-construction period for only eight sites). These are subsequently referred to as wind farms and reference sites, respectively, whilst we use the term site to denote the combination of a wind farm plus its paired reference site. Information was extracted from a combination of environmental statements (pre-construction data), monitoring reports (during construction and post-construction data) and earlier surveys of ten sites (Pearce-Higgins *et al.* 2009b). Breeding bird survey methods varied between sites but generally followed Brown & Shepherd (1993) or adaptations thereof (e.g. walking transects 200 m apart rather than a flexible route or three rather than two visits). To ensure data comparability within sites, where there was variation in the number of visits or the area surveyed between years, we subsampled the data from the more intensive surveys using the survey visits that most closely matched the dates of the surveys undertaken during the years with reduced survey intensity.

STATISTICAL ANALYSIS

Population densities were examined in two ways: against a three-level factor (PERIOD) separating pre-construction, construction and post-construction periods, and using years since wind farm construction (YEAR) as a covariate. The former tests for significant changes in abundance associated with wind farm construction, whilst the latter compares population trends following construction. To avoid PERIOD and YEAR being aliased, YEAR was coded as zero for pre-construction, construction and the first year post-construction, and subsequently increased incrementally with year. It was important to compare trends on wind farms with those on nearby reference sites (separated using a two-level factor – WINDFARM), to account for varying population trends in the wider countryside, tested by the significance of the PERIOD*WINDFARM and YEAR*WINDFARM interactions. Because of the nested nature of the data, unique identifiers for wind farm and reference sites, nested within site (wind farm and reference site combined), were included as random effects in a generalized linear mixed model. The numbers of breeding pairs were modelled using a Poisson error distribution and log link function, with the natural log of survey area as an offset to estimate density. As the overlap between the survey areas and the turbines were not standardized across wind farms, we calculated the proportion of the wind farm survey area that included a polygon drawn around the turbine array (OVERLAP), which averaged 0·27 (range 0·09–0·68). The closer this term was to one, the greater the likely impact of the wind farm upon breeding density. The OVERLAP*PERIOD*WINDFARM and OVERLAP*YEAR*WINDFARM interactions therefore test for the likelihood that the magnitude of any wind farm effects on bird populations will be positively correlated with the overlap of the survey area with the turbine array. The final model equation is listed below with the key variables of interest in bold.

$$\begin{aligned}\text{Density} = a &+ b_0\text{WINDFARM} + b_1\text{PERIOD} + b_2\text{YEAR}\\ &+ b_3\,\mathbf{WINDFARM * PERIOD}\\ &+ b_4\,\mathbf{OVERLAP * WINDFARM * PERIOD}\\ &+ b_5\,\mathbf{WINDFARM * YEAR}\\ &+ b_6\,\mathbf{OVERLAP * WINDFARM * YEAR} + \varepsilon\end{aligned}$$

Fewer than half of the wind farms were monitored for more than 3 years post-construction (Table S2); therefore, we also produced models that constrained the analysis to using only the data for the first 3 years following construction to check that the few wind farms with a long run of data did not unduly influence our results.

The results require careful interpretation because of the necessary use of interaction terms to account for the variable overlap between sites. If true, our first prediction would mean that species affected by wind farm construction would show specific differences in density at the wind farm, and also between the wind farm and reference sites. These were tested more precisely than possible using the general interaction terms outlined above, through examination of the pairwise differences in least-square means estimates of density estimated from the model of eqn 1 to account for variation in overlap between sites. Pairwise differences were used to identify significant contrasts between pre-construction, construction and post-construction factor levels, and between wind farms and reference sites, which can be related to our predictions. Specifically, we used the differences between bird densities on wind farms during construction, and both pre-construction and post-construction densities, to assess the effects of construction on bird densities at the wind farm. We used the differences between the wind farm and reference sites to check that the same patterns were not evident away from the wind farm. Our second prediction is easier to test and, if true, would result in significant WINDFARM*YEAR or OVERLAP*WINDFARM*YEAR interactions (eqn 1).

Previous studies have suggested that the response of bird populations to wind farms may vary according to turbine size and power (Hötker 2006; Stewart, Pullin & Coles 2007). Therefore, to test our third prediction, we examined the significance of additional three-way interactions between PERIOD*WINDFARM and YEAR*WINDFARM and the number, power and height of turbines at each wind farm, by separately inserting these terms into the full model (eqn 1). Turbine power and height were highly correlated (r = 0·92, n = 18, P < 0·001), although both power and number (r = −0·004, n = 18, P = 0·988), and number and height (r = −0·122, n = 18, P = 0·630) were not. All statistical analyses were conducted in SAS v. 9 (SAS Institute 2008).

Results

We analysed data for 10 species at five or more wind farms with reference sites (Table 1) and assumed that this is the minimum required for meaningful contrasts. There were insufficient data for the inclusion of any raptor species.

EFFECTS OF CONSTRUCTION PERIOD

We used the full models to account for potential effects of variation in the overlap between the survey areas and turbines. This term was statistically significant (P < 0·05) for 3/20 tests and close to significance (P < 0·10) for a further two. Therefore, it was more important than expected

Table 1. Significance of terms in models of bird density at wind farm and reference sites from eqn 1. Each cell gives the F value above the corresponding P value, with significant terms (P < 0·05) highlighted in bold. Because the significance of terms in models with higher-order interactions is difficult to interpret, the significance of the two-way interactions is given from a model excluding the three-way interactions, and the significance of the main effects is from a model with no interaction terms

Terms	Red grouse	Golden plover	Lapwing[†]	Dunlin	Snipe	Curlew	Meadow pipit	Skylark	Stonechat	Wheatear[†]
WINDFARM	$F_{1,8·9}$ = 0·68 0·43	$F_{1,8·6}$ = 2·65 0·14	$F_{1,11·7}$ < 0·01 0·98	$F_{1,4·0}$ = 0·53 0·51	$F_{1,8·6}$ = 0·48 0·51	$\mathbf{F_{1,6·8}}$ = **7·72** **0·03**	$F_{1,5·2}$ = 0·09 0·78	$F_{1,5·1}$ = 1·62 0·26	$F_{1,7·0}$ = 0·01 0·93	$F_{1,12·4}$ = 0·12 0·73
PERIOD	$\mathbf{F_{2,97}}$ = **6·24** **0·0028**	$F_{2,75}$ = 0·56 0·57	$F_{2,45}$ = 1·17 0·32	$F_{2,42}$ = 0·56 0·58	$\mathbf{F_{2,84}}$ = **7·23** **0·0013**	$F_{2,81}$ = 2·05 0·13	$\mathbf{F_{2,52}}$ = **21·39** **< 0·001**	$F_{2,68}$ = 0·83 0·44	$\mathbf{F_{2,57}}$ = **9.54** **0·0003**	$F_{2,54}$ = 0·56 0·58
YEAR	$\mathbf{F_{1,97}}$ = **14·08** **0·0003**	$F_{1,75}$ < 0·01 0·95	$F_{1,45}$ = 2·87 0·10	$F_{1,42}$ = 0·27 0·61	$F_{1,84}$ = 0·27 0·61	$F_{1,81}$ = 0·70 0·41	$\mathbf{F_{1,52}}$ = **92·51** **< 0·001**	$F_{1,68}$ < 0·01 0·99	$F_{1,57}$ = 0·65 0·42	$F_{1,54}$ = 0·02 0·89
WINDFARM* PERIOD	$F_{2,94}$ = 2·30 0·11	$F_{2,72}$ = 0·72 0·49	$F_{2,42}$ = 0·28 0·76	$F_{2,39}$ = 0·81 0·45	$F_{2,81}$ = 0·37 0·69	$F_{2,78}$ = 0·87 0·42	$F_{2,49}$ = 2·97 0·06	$F_{2,57}$ = 0·65 0·52	$F_{2,54}$ = 1·91 0·16	$F_{2,51}$ = 1·05 0·36
OVERLAP*WINDFARM* PERIOD	$F_{6,70·6}$ = 0·9 0·50	$F_{6,56·2}$ = 0·99 0·44	$F_{6,34}$ = 0·77 0·60	$F_{6,1}$ = 1·28 0·59	$F_{6,58·1}$ = 0·82 0·56	$F_{6,70}$ = 1·99 0·079	$\mathbf{F_{6,29}}$ = **9·29** **< 0·001**	$\mathbf{F_{6,41·7}}$ = **7·47** **< 0·0001**	$F_{6,38·1}$ = 1·19 0·33	$F_{6,32·0}$ = 0·31 0·93
WINDFARM*YEAR	$F_{1,94}$ = 0·52 0·47	$F_{1,72}$ < 0·01 0·92	$F_{1,42}$ = 0·02 0·89	$F_{1,39}$ = 1·93 0·17	$F_{1,81}$ = 0·05 0·83	$F_{1,78}$ = 0·06 0·81	$F_{1,49}$ = 1·30 0·26	$F_{1,65}$ = 0·42 0·52	$F_{1,54}$ = 3·23 0·078	$F_{1,43}$ = 0·35 0·56
OVERLAP*WINDFARM * YEAR	$F_{2,86}$ = 1·51 0·23	$F_{2,64}$ = 0·09 0·92	$F_{2,34}$ = 0·62 0·54	$F_{2,31}$ = 0·04 0·96	$F_{2,73}$ = 2·07 0·13	$F_{2,70}$ = 0·30 0·74	$\mathbf{F_{2,41}}$ = **8·84** **0·001**	$F_{2,57}$ = 1·45 0·24	$F_{2,46}$ = 2·65 0·082	$F_{2,51}$ = 0·03 0·86

[†]Wind farm identity covariance was non-estimable for lapwing and wheatear (< 0), and therefore results for these species do not fully account for the non-independence of data from individual wind farms. As neither contains any significant terms, this is unlikely to have affected our conclusions.

by chance. In each case, the direction of the effect was for fewer birds on wind farms at sites with a greater degree of overlap (Appendix S1).

Based on the full model, five of ten species showed a significant difference between pre-construction and construction densities on wind farms, whilst there were no such significant differences at the reference sites (Table 2). For four species, there were also significant differences between pre-construction and post-construction densities, whilst only one species showed such a difference on the reference sites. Statistically significant ($P < 0{\cdot}05$) changes in density in relation to wind farm construction were therefore much more prevalent on wind farm sites (11/30 tests) than on the reference sites (2/30 tests), and more prevalent than expected by chance, providing general evidence for construction activity affecting bird densities on wind farms. However, in only one case, curlew *Numenius arquata* (L.), did this also result in a significant difference between densities on wind farms and reference sites during or after construction.

Densities of red grouse *Lagopus lagopus scoticus* (Lath.), snipe *Gallinago gallinago* (L.) and curlew were significantly reduced at wind farms during construction (Fig. 1). Densities of red grouse had recovered by the first year post-construction, but no recovery was apparent for curlew or snipe. Importantly, curlew densities were also lower at the wind farm than at the reference site during construction ($P = 0{\cdot}053$) and post-construction (Table 2). Wind farm construction reduced curlew density on wind farm sites, leading to a contrast with both pre-construction densities, and densities on the reference sites (Fig. 1). These effects tended to be greater at wind farm sites with a high overlap between the turbine footprint and the surveyed area (Table 1, Appendix S1).

Conversely, skylark *Alauda arvensis* (L.) and stonechat *Saxicola torquata* (L.) densities tended to be greater at wind farms during and post-construction, as a result of an increase from low pre-construction densities at wind farms relative to reference sites. Meadow pipit *Anthus pratensis* (L.) densities at both wind farms and reference sites were reduced post-construction relative to pre-construction and construction periods.

EFFECTS OF YEAR

Post-construction population trends differed significantly between operational wind farms and reference sites for only one of the ten species, that is, there was a significant three-way interaction between OVERLAP*WINDFARM*YEAR for meadow pipit (Table 1). This indicated that trends were less positive on wind farms than reference sites (Fig. 2), particularly when overlap between the survey areas and turbines was high (Appendix S1).

The results from models using data for the first 3 years following construction were very similar to those based on all the data. There were no changes to the significance of terms listed in Table 1. The only changes to the differences in least-square means of bird densities (Table 2) were an increase in the significance of the reduction in stonechat densities from pre-construction and construction periods on reference sites ($t = 2{\cdot}34$, $P = 0{\cdot}024$), but a decrease in

Table 2. Summary of the results of contrasts in estimated densities of birds, estimated using least-square means from the full model presented in Table 1, in relation to the interaction between PERIOD (pr, pre-construction; co, construction; po, post-construction) and WINDFARM (WF, wind farm; RS, reference site)

Contrast	Interpretation	Red grouse	Golden plover	Lapwing	Dunlin	Snipe	Curlew	Meadow pipit	Skylark	Stonechat	Whinchat
WFpr:WFco	Change during	**3·56**	−1·46	0·36	−0·25	**2·22**	**2·14**	−1·22	**−4·38**	**−2·81**	0·35
	construction on WF	**0·0006**	0·15	0·72	0·80	**0·030**	**0·036**	0·23	**< 0·0001**	**0·0072**	0·73
WFco:WFpo	Change post-	**−3·77**	0·73	0·23	−0·27	0·14	0·04	**4·56**	1·20	−1·42	0·82
	construction on WF	**0·0003**	0·47	0·82	0·79	0·89	0·97	**< 0·0001**	0·23	0·16	0·42
WFpr:WFpo	Change pre- to post-	−0·26	−0·59	0·62	−0·47	**3·10**	**2·47**	1·64	**−3·45**	**−3·76**	1·18
	construction on WF	0·80	0·55	0·54	0·64	**0·0028**	**0·016**	0·11	**0·0011**	**0·0005**	0·25
RSpr:RSco	Change during	−0·07	0·72	0·02	0·78	0·41	−1·35	1·05	0·07	1·27	−1·31
	construction on RS	0·95	0·48	0·98	0·45	0·68	0·18	0·30	0·95	0·21	0·20
RSco:RSpo	Change post-	−1·18	−0·43	−0·07	−0·04	0·69	0·19	**2·62**	−0·49	−1·66	0·70
	construction on RS	0·24	0·67	0·95	0·97	0·49	0·85	**0·012**	0·63	0·10	0·49
RSpr:RSpo	Change pre- to post-	−1·14	0·43	−0·04	1·08	1·60	−1·32	**2·34**	0·87	0·20	−0·96
	construction on RS	0·26	0·67	0·97	0·29	0·11	0·19	**0·024**	0·42	0·85	0·34
WFpr:RSpr	Initial contrast	−1·45	1·94	−0·47	0·47	−0·03	−0·94	0·89	2·00	**2·01**	−0·78
	between WF and RS	0·17	0·06	0·64	0·65	0·98	0·35	0·39	0·080	**0·05**	0·44
WFco:RSco	Contrast in construction	−0·44	0·86	−0·42	−0·62	0·69	1·97	−0·47	0·58	−0·85	0·24
	density between WF and RS	0·67	0·40	0·68	0·54	0·49	0·053	0·65	0·59	0·40	0·81
WFpo:RSpo	Contrast in post-	−1·13	1·83	−0·46	−0·99	0·29	**2·18**	0·50	1·11	−0·50	0·32
	construction density between WF and RS	0·29	0·11	0·66	0·43	0·78	**0·033**	0·64	0·32	0·63	0·76

In each cell, the top value is t (a negative value indicates the first element of the contrast is lower than the second) and the bottom value is P. Significant ($P < 0{\cdot}05$) contrasts are highlighted in bold. The top three contrasts represent changes in the wind farm site. The second three contrasts are the equivalent changes on the reference site. The final three contrasts are between the wind farm and reference sites.

the significance of the previously reported differences in meadow pipit densities between construction and post-construction ($t = 1{\cdot}75$, $P = 0{\cdot}089$) and pre-construction and post-construction ($t = 1{\cdot}71$, $P = 0{\cdot}096$) periods on reference sites. The previously reported difference in curlew densities during construction on wind farms relative to reference sites, where densities were higher, increased in significance ($t = 2{\cdot}43$, $P = 0{\cdot}025$). Our conclusions are therefore not dependent on data from a small number of well-monitored wind farms.

EFFECTS OF WIND FARM CHARACTERISTICS

There were fewer significant additional interactions between variables describing turbine characteristics at different wind farms and WINDFARM*PERIOD and WINDFARM*YEAR interactions than would be expected by chance (Table 3). The few significant interactions detected were each for more negative effects of the wind farm upon population trends with increasing numbers of turbines. Red grouse population trends were more negative on wind farms with large numbers of turbines (e.g. slope of trend against turbine number for red grouse wind farms = $-0{\cdot}026 \pm 0{\cdot}0092$, red grouse reference sites = $-0{\cdot}0045 \pm 0{\cdot}015$), whilst both meadow pipit (slope of trend on wind farms = $0{\cdot}0014 \pm 0{\cdot}0044$, slope of trend on reference sites = $0{\cdot}013 \pm 0{\cdot}0046$) and skylark (slope on of trend wind farms = $0{\cdot}013 \pm 0{\cdot}0074$, slope of trend on reference sites = $0{\cdot}025 \pm 0{\cdot}010$) trends were more positive on the reference sites of large wind farms. Thus, in each case, there was a greater difference in trend between wind farms and reference sites at large wind farms.

Discussion

In common with other multi-species studies of wind farm impacts on birds (Barrios & Rodríguez 2004, 2007), we highlight considerable differences between species. Densities of red grouse, snipe and curlew were reduced on wind farms during construction, although red grouse densities appeared to recover by the first year of operation. The evidence for these effects being significant was strongest for curlew, as wind farm densities during and post-construction not only differed from the pre-construction densities on the wind farm, but also from the equivalent densities on reference sites. Our results suggest that curlew populations may decline by about 40% (Fig. 1) as a result of disturbance from construction work (based upon a mean survey area across all sites equivalent to a 620-m circular buffer around the turbines). This supports earlier work (Pearce-Higgins *et al.* 2009b) demonstrating a 30% lower density of birds within a 1-km buffer around turbines than expected from the habitat. Significant 53% declines in snipe densities on wind farms during construction, with no significant decline on reference sites, suggest that this species is also affected by construction, despite the lack of significant difference in snipe density between wind farms and reference sites (Fig. 1). Snipe were also shown by Pearce-Higgins *et al.* (2009b) to use areas of habitat within 400 m of turbines less than expected, leading to an expected 48% decline in abundance within 500 m of the turbines. Both the spatial study of Pearce-Higgins *et al.* (2009b) and the study of temporal variation in abundance presented here are therefore consistent, identifying these two waders as being particularly vulnerable to wind farms, and by a similar magnitude of effect.

We found little evidence for differences in population trends between operational wind farms and reference sites. This implies that any increase in mortality through collision with operating turbines, or other changes associated with wind farm operation, has little effect on local populations. Further, following any detrimental effects of disturbance during construction, populations may become habituated to operational wind farms. This potential null result is supported by the lack of decline in red grouse and golden plover *Pluvialis apricaria* (L.) abundance at an upland wind farm over a 3-year period of operation (Douglas, Bellamy & Pearce-Higgins 2011). However, these findings contrast with those of an earlier meta-analysis of Stewart, Pullin & Coles (2007) who found that greater declines in abundance occurred at wind farms that had been operating for longer. This difference may have resulted from the latter study primarily reviewing studies of wintering waterfowl populations, which may be more mobile than the breeding populations covered by our analysis.

Importantly, our results for breeding populations suggest that the main negative effects of wind farms may be through disturbance displacement during construction. High levels of activity and disturbance are likely to cause birds to vacate territories close to the turbines, particularly as many upland waders are known to be vulnerable to disturbance (Finney, Pearce-Higgins & Yalden 2005; Pearce-Higgins *et al.* 2007). Depending on their subsequent breeding success, they may not return to breed in subsequent years (Thompson & Hale 1989). The construction of a barrage has previously been shown to affect the distribution of wintering waders, including curlew (Burton, Rehfish & Clark 2002), and it is unsurprising that similar effects apply to breeding birds.

Our analysis found little evidence for consistent population declines in golden plover and wheatear *Oenanthe oenanthe* L. populations at wind farm sites (Figs 1 and 2), despite the fact that these species exhibited reduced habitat usage within 200 m of turbines (Pearce-Higgins *et al.* 2009b). A close to significant ($P = 0{\cdot}06$) difference in pre-construction golden plover densities between wind farm and reference sites (Fig. 1, Table 2) may suggest that some of the previous differences between wind farm and reference sites (Pearce-Higgins *et al.*2008) could have resulted from intrinsic initial differences in density. However, this could not account for displacement within wind farms (Pearce-Higgins *et al.* 2009b). Given that golden plover is listed on Annex I of the EU Birds Directive, more work is therefore required to understand the extent to which the observed displacement of this species translates into a significant population-level impact.

Our results suggest potential positive effects of wind farm construction on skylarks, meadow pipits and stonechats. Such effects may result from vegetation disturbance during construction creating greater openness in the sward structure,

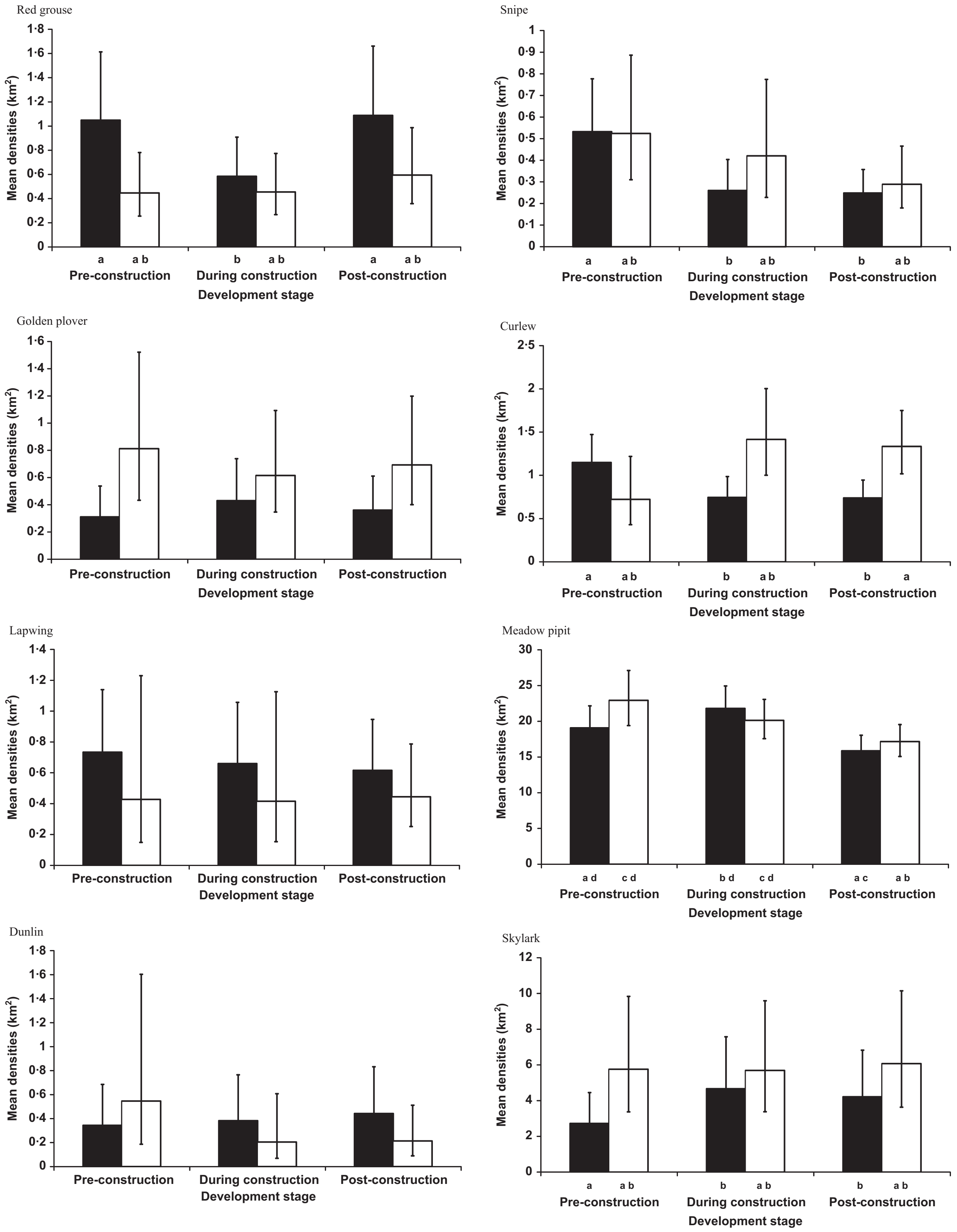

Fig. 1. Average densities (± SE) of upland birds on wind farms (black bars) and reference sites (white bars) in relation to different periods of wind farm development. Where present, individual letters link bars that do not differ significantly ($P > 0{\cdot}05$) using pairwise comparisons of density; differences between pairs of bars with all non-matching letters are therefore significant ($P < 0{\cdot}05$). Densities are derived from the models presented in Table 1 using least-square means, whilst the contrasts are summarized in Table 2.

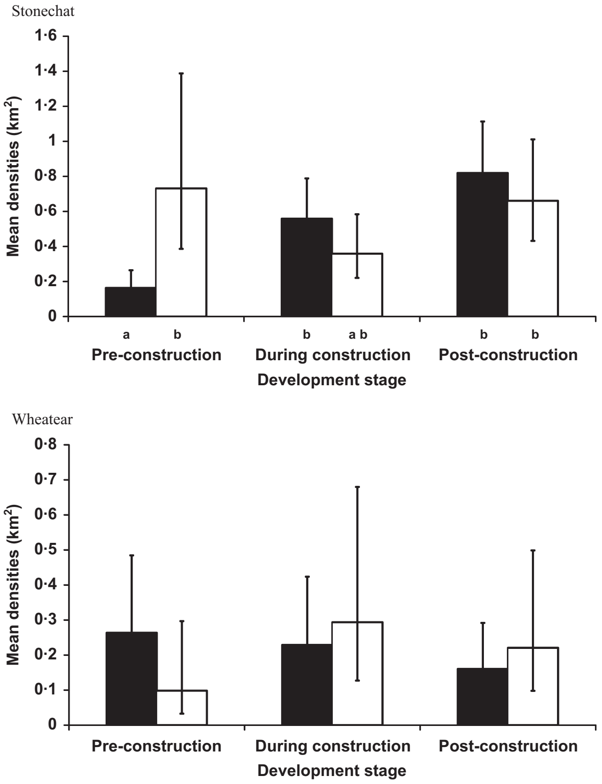

Fig. 1. (*Continued*).

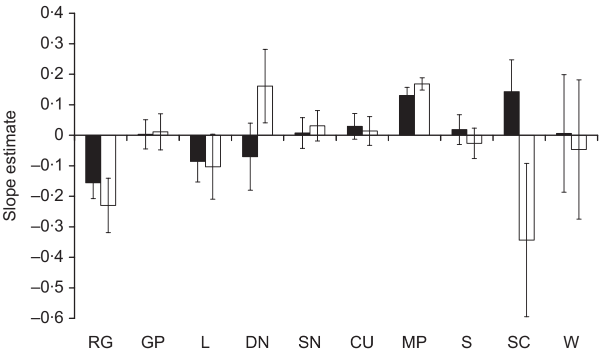

Fig. 2. Estimated post-construction population trends (±SE) on wind farm (black) and reference (white) sites derived from the models in Table 1, excluding the OVERLAP*WINDFARM*YEAR interaction to allow the term to be estimated for all sites. Letters refer to species (RG, red grouse; GP, golden plover; L, lapwing; DN, dunlin; SN, snipe; CU, curlew; MP, meadow pipit; S, skylark; SC, stonechat; W, wheatear).

known to benefit these species (Pearce-Higgins & Grant 2006). However, as these positive effects were most apparent at wind farms with a low overlap between the surveyed area and the turbine footprint (Appendix S1), they may be spurious, reflecting differences in the environmental characteristics of wind farm and reference areas, rather than beneficial effects of the wind farm itself. As it is also the waders most associated with short vegetation (such as golden plover, lapwing *Vanellus vanellus* L. and dunlin *Calidris alpina* L.; Pearce-Higgins & Grant 2006; Hancock, Grant & Wilson 2009), which appear least detrimentally affected by wind farms (Fig. 1), there is a need for more work on the inter-relationships between the habitat associations of species and their responses to wind farm development.

In common with both Hötker (2006) and Stewart, Pullin & Coles (2007), we failed to find any strong and consistent effects of either the generating capacity of the wind farm, or the size and number of turbines. The best available evidence suggests that the sensitivity of bird populations to wind farms is not *strongly* affected by the size or number of the turbines, although as the size of turbines and wind farms increases, this may change in the future. If true, this has two implications. First, it means that results from studies of wind farm impacts on birds are more likely to be generic to other wind farms with different specifications. Secondly, it means that the re-powering of the existing wind farms and the associated replacement of small turbines with larger devices may have little additional adverse impact on birds, aside, of course, from the potentially detrimental effects of turbine construction.

Our analysis has a number of limitations. First, our sample size was relatively low. Twelve of the 18 wind farms had some reference site data; however, as no species were ubiquitous, the true sample size was less than this for each analysis, particularly for some of the individual contrasts between wind farm stages. Secondly, there was a lack of standardized monitoring methods across the sites, although the impact of this was minimal as most surveys employ accepted methodologies (e.g. Brown & Shepherd 1993). These techniques are designed to allow rapid surveys of large areas and therefore can be associated with a significant degree of error at any one location (Pearce-Higgins & Yalden 2005). Thirdly, a number of wind farms have ongoing habitat management, such as tree felling, drain blocking or changes in grazing and burning regimes (see Pearce-Higgins *et al.* 2009a for a discussion of potential impacts of such management upon upland birds), as mitigation of potentially detrimental effects of the development. Fourthly, there is spatial heterogeneity in upland bird population trends (Sim *et al.* 2005). Combined, these factors are likely to have introduced additional variability to the observed population trends, which may have reduced our power to detect effects. Indeed, because of this variability, *post hoc* tests suggest that most of the non-significant tests that relate to our initial predictions were unlikely to become statistically significant with the addition of data from a few more sites. Therefore, we were likely to detect only the strongest and most consistent differences between wind farms and reference sites. The high degree of variance suggests that for most species, other factors will most strongly determine the population trajectories of species on wind farms, although this does not necessarily mean that a particular species will be unaffected by a specific wind farm development.

It is vital that good quality monitoring of bird populations at wind farms continues, to provide the potential to repeat this analysis in future when more data become available. Future analysis with a greater sample size should better examine the effects of site-specific factors such as mitigation management on population trends. Monitoring should employ standard

Table 3. The significance of three-way interactions between WINDFARM*PERIOD (top) and WINDFARM*TREND (bottom) and each of the wind farm characteristics, when inserted into the full models for each species (eqn 1)

	Turbine number	Turbine height	Turbine power
Red grouse	$F_{6,\ 65{\cdot}9} = 1{\cdot}04$, $P = 0{\cdot}41$	$F_{6,\ 52{\cdot}1} = 0{\cdot}19$, $P = 0{\cdot}98$	$F_{6,\ 52{\cdot}9} = 0{\cdot}21$, $P = 0{\cdot}97$
	$\mathbf{F_{2,\ 78} = 4{\cdot}06}$, $\mathbf{P = 0{\cdot}021}$	$F_{2,\ 78} = 2{\cdot}87$, $P = 0{\cdot}063$	$F_{2,\ 78} = 2{\cdot}99$, $P = 0{\cdot}056$
Golden plover	$F_{6,\ 52{\cdot}6} = 0{\cdot}51$, $P = 0{\cdot}80$	$F_{6,\ 40{\cdot}5} = 0{\cdot}17$, $P = 0{\cdot}98$	$F_{6,\ 38{\cdot}8} = 0{\cdot}15$, $P = 0{\cdot}99$
	$F_{2,\ 56} = 1{\cdot}42$, $P = 0{\cdot}25$	$F_{2,\ 56} = 0{\cdot}15$, $P = 0{\cdot}86$	$F_{2,\ 56} = 0{\cdot}26$, $P = 0{\cdot}77$
Lapwing	Did not converge	Did not converge	Did not converge
Dunlin	Did not converge	Did not converge	Did not converge
Snipe	$F_{6,\ 45{\cdot}6} = 0{\cdot}13$, $P = 0{\cdot}99$	$F_{6,\ 42{\cdot}1} = 0{\cdot}49$, $P = 0{\cdot}81$	$F_{6,\ 38{\cdot}1} = 0{\cdot}59$, $P = 0{\cdot}73$
	$F_{2,\ 65} = 0{\cdot}49$, $P = 0{\cdot}62$	$F_{2,\ 65} = 1{\cdot}57$, $P = 0{\cdot}22$	$F_{2,\ 65} = 2{\cdot}61$, $P = 0{\cdot}081$
Curlew	$F_{6,\ 62} = 0{\cdot}27$, $P = 0{\cdot}95$	$F_{6,\ 44{\cdot}1} = 0{\cdot}23$, $P = 0{\cdot}96$	$F_{6,\ 41{\cdot}5} = 0{\cdot}24$, $P = 0{\cdot}96$
	$F_{2,\ 62} = 0{\cdot}06$, $P = 0{\cdot}94$	$F_{2,\ 62} = 0{\cdot}47$, $P = 0{\cdot}62$	$F_{2,\ 62} = 0{\cdot}76$, $P = 0{\cdot}47$
Meadow pipit	$F_{6,\ 33} = 0{\cdot}47$, $P = 0{\cdot}82$	$F_{6,\ 19{\cdot}0} = 0{\cdot}29$, $P = 0{\cdot}94$	$F_{6,\ 19{\cdot}9} = 0{\cdot}37$, $P = 0{\cdot}89$
	$\mathbf{F_{2,\ 33} = 4{\cdot}28}$, $\mathbf{P = 0{\cdot}022}$	$F_{2,\ 33} = 1{\cdot}93$, $P = 0{\cdot}16$	$F_{2,\ 33} = 0{\cdot}98$, $P = 0{\cdot}38$
Skylark	$F_{6,\ 37{\cdot}4} = 2{\cdot}10$, $P = 0{\cdot}077$	$F_{6,\ 31{\cdot}1} = 1{\cdot}20$, $P = 0{\cdot}33$	$F_{6,\ 30{\cdot}5} = 2{\cdot}15$, $P = 0{\cdot}076$
	$\mathbf{F_{2,\ 49} = 4{\cdot}84}$, $\mathbf{P = 0{\cdot}012}$	$F_{2,\ 49} = 0{\cdot}60$, $P = 0{\cdot}55$	$F_{2,\ 49} = 0{\cdot}35$, $P = 0{\cdot}71$
Stonechat	$F_{5,\ 34{\cdot}6} = 1{\cdot}92$, $P = 0{\cdot}12$	$F_{5,\ 21{\cdot}8} = 1{\cdot}12$, $P = 0{\cdot}38$	$F_{5,\ 21{\cdot}1} = 0{\cdot}72$, $P = 0{\cdot}62$
	$F_{2,\ 39} = 1{\cdot}49$, $P = 0{\cdot}24$	$F_{2,\ 39} = 0{\cdot}52$, $P = 0{\cdot}60$	$F_{2,\ 39} = 1{\cdot}15$, $P = 0{\cdot}33$
Wheatear	Did not converge	Did not converge	Did not converge

Significant ($P < 0{\cdot}05$ highlighted) interactions are highlighted in bold. The threshold for significance of such multiple tests using the Bonferoni correction is $P = 0{\cdot}0004$.

approved methods, and data should be collected from both wind farm and paired reference sites before, during and after construction, to allow the full range of comparisons to be made. We were unable to collate sufficient data to examine raptor populations; species which have been subject to considerable risk of collision at certain sites (e.g. Barrios & Rodríguez 2004, 2007; Smallwood & Thelander 2008; Ferrer *et al.* 2012) and therefore call for continued and extended monitoring of this group. Further, generic monitoring data should be complemented by detailed mechanistic studies of the effects of wind farms on individual populations. This should use marked birds to compare demographic models of bird populations on wind farms and reference sites, to distinguish between source and sink populations that otherwise may be of similar density. We are uncertain how long any negative effects of construction may be manifest, and long-term monitoring at sites is required to examine whether negative effects persist or whether affected populations on wind farms recover over time. There also remains considerable uncertainty over whether displaced individuals are ultimately lost to the breeding population as a result of density dependence (cf. Yalden & Pearce-Higgins 1997), or breed successfully elsewhere. The non-significant increase in curlew numbers on reference sites during construction and post-construction is suggestive that such processes may occur, and this issue should be addressed as a high research priority, potentially by following changes in the distribution of marked individuals (e.g. Burton *et al.* 2006). This is of critical importance in determining whether any such displacement is of biological significance, but in the absence of such studies, we advocate the precautionary principle that displaced birds continue to be regarded as lost to the breeding population.

To conclude, despite limitations, our analysis has added to the relatively small evidence base for assessing the wider impacts of wind farms on birds, at a time of considerable pressure for further wind farm development (Bright *et al.* 2008). The results provide indications of negative impacts of wind farm development on populations of some upland species, with the most negative effects on those species previously found to exhibit the strongest avoidance of turbines: curlew and snipe (Pearce-Higgins *et al.* 2009b), supporting the conclusions of that study. Importantly, our analysis suggests effects appear to result from disturbance during wind farm construction, with additional declines in red grouse abundance during this period counteracted by increases in density in the year following construction. Further work should be conducted to understand the impacts of construction on large waders and the ways to mitigate such effects. These could include the construction of barriers or screens, as part of a rolling corridor of construction works to limit the extent of the disturbance zone, the implementation of no-go areas close to breeding territories, or the preclusion of construction activity during the breeding season to prevent detrimental effects of disturbance.

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Supporting Information

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

Appendix S1. The effects of overlap on the likely impacts of wind farm development on birds.

Table S1. Summary wind farm characteristics recorded across each of the 18 wind farms incorporated in the study.

Table S2. Summary of the survey data obtained for each wind farm.

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