Impacts of wind farms on swans and geese: a review

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Abstract

This review considers data published on the effects of offshore and onshore windfarms on swans and geese and finds that the information available is patchy. Of 72 swans or geese reported as collision victims at 46 wind farms, most (39 birds) were reported at 23 wind farms in Germany where such data are collated. Post-construction monitoring was undertaken for ≤ 1 year at 67% of 33 sites, making it difficult to test for cumulative effects or annual variation in collision rates. Site use by the birds was measured at only nine of 46 wind farms where collisions by swans and geese were monitored or recorded. Displacement distances of feeding birds at wintering sites ranged from 100–600 m, but preliminary evidence suggested that large-scale displacement also occurs, with fewer swans and geese returning to areas after wind farms were installed. Eight studies of flight behaviour all reported changes in flight-lines for swans or geese initially seen heading towards the turbines, at distances ranging from a few hundred metres to 5 km; 50–100% of individuals/groups avoided entering the area between turbines, but in some cases the sample sizes were small. Key knowledge gaps remain, including whether wind farm installation has a consistently negative effect on the number of birds returning to a wintering area; whether flight avoidance behaviour varies with weather conditions, wind farm size, habituation and the alignment of the turbines; provision of robust avoidance rate measures; and the extent to which serial wind farm development has a cumulative impact on specific swan and goose populations. It is therefore recommended that: 1) post-construction monitoring and dissemination of results be undertaken routinely, 2) the extent to which wind farms cause larger-scale displacement of birds from traditional wintering areas be assessed more rigorously, 3) further detailed studies of flight-lines in the vicinity of wind farms should be undertaken, both during migration and for birds commuting between feeding areas and the roost, to provide a more rigorous assessment of collision and avoidance rates for inclusion in collision risk models, and 4) the combination of collision mortality and habitat loss at all wind farms in the species' range be analysed in determining whether they have a significant effect on the population.

Key words: avoidance, collisions, displacement, offshore wind farms, terrestrial wind farms.

Wind farms have been installed increasingly across Europe during the late 20th and early 21st centuries, as governments seek to secure renewable energy supplies and reduce greenhouse gas emissions to combat climate change. The European Commission's Renewable Energy Roadmap (EU 2007) set a target of 20% of EU energy to be generated from renewable sources by 2020 (EU 2008). Wind energy accounted for 3.7% of EU electricity generation by early 2008, and the European Commission's goal of increasing that share to 12% by 2020 is regarded as achievable (European Wind Energy Association; EWEA 2008). Annual installations of wind power have increased steadily from 814 MW in 1995 to 93,957 MW installed across Europe in 2011, with the largest installed capacity in Germany, followed by Spain, Italy, France and the UK (EWEA 2012). Growth projections for wind-generated energy vary substantially depending on the analytical methods used and the scope for technological progress (EWEA 2009), but current capacity is expected to treble by 2020 (EWEA 2008). Within the UK, 348 wind farms (332 onshore, 16 offshore) were operational by July 2012, generating > 7,000 MW of wind power, with a further 64 under construction, 270 consented and 335 at the planning application stage (RenewableUK 2012). Planning applications for the large Round 3 offshore wind farms proposed for British coastal waters, and for further Scottish Territorial Water sites, will be forthcoming from late 2012 onwards, with the first Round 3 projects (if consented) operational after 2015.

The rapid development of renewable energy has been a challenge for environmental conservation organisations. Increasing evidence shows climate change having deleterious effects on wildlife (Parmesan & Yohe 2003; Root *et al.* 2003; Thomas *et al.* 2004) yet injudicious location of wind farms may have detrimental effects on some species, including birds (Langston & Pullan 2003; Barrios & Rodriguez 2004; Garthe & Hüppop 2004; Hötker *et al.* 2006; Sterner *et al.* 2007; Bright *et al.* 2008; EEA 2009). Adverse effects include direct collision mortality, habitat loss/degradation, displacement from feeding areas, barrier effects (birds flying around wind farms and thus potentially increasing energy expenditure), and disturbance (see reviews in Langston & Pullan 2003; Bright *et al.* 2006; Drewitt & Langston 2006; Fox *et al.* 2006; Inger *et al.* 2009). The risk of turbine collisions varies across species (perhaps dependent on visual acuity and depth perception at the time; Martin 2011), and wind farm location, with potential for there being population-level effects in some cases (Bright *et al.* 2008), and raptors being particularly at risk of colliding with the turbines (Sterner *et al.* 2007; Carrete *et al.* 2012).

Within the European Union, the planning application process for wind farm development requires wind farm companies to undertake environmental impact assessments (EIAs) under the terms of the EU's Environmental Impact Assessment Directive 85/335/EEC (as amended by Directive 97/11/EC) to determine whether the installation would have a significant effect on wildlife or other environmental features (Drewitt & Langston 2006). A

Strategic Environmental Assessment (SEA) is required for large scale developments or programmes under the SEA Directive 2001/42/EC, which integrates environmental considerations in the development of plans and programmes and builds on project-level EIAs by considering environmental issues earlier in the planning process (Drewitt & Langston 2006). Where proposals pose a threat to the integrity of protected areas, such as those designated by governments as Special Protection Areas (SPAs) for birds under the EU Birds Directive, the legislation requires that a Habitats Regulation Assessment (HRA) be undertaken. The HRA first assesses the impacts of the plan, against the objectives for conserving sites protected under European legislation, by considering whether there is a "Likely Significant Effect" (LSE) of the plan, either alone or in combination with other plans or projects. If there is considered likely to be a significant effect on the interests of the SPA, then the "Competent Authority" (*e.g.* the local council planning department for UK onshore sites; Marine Scotland/Scottish Government and the Marine Management Organisation (MMO) for offshore sites in Scottish territorial waters and in England) is required to undertake an "Appropriate Assessment" (AA) of a proposal, which should ascertain that there will be no adverse effects on the interests of the SPA before development can be consented. The question of how to assess the cumulative impacts on migratory bird populations of several wind farms being installed along the migration routes has been considered (de Lucas *et al.* 2007; Norman *et al.* 2007; Masden *et al.* 2010a) but has yet to be fully resolved. Information on the total number of wind farms along migration routes, and the cumulative effect of these on birds migrating to or from key sites for the population (*i.e.* SPAs and/or Ramsar sites), is still rarely (if ever) incorporated into AAs undertaken for new wind farm sites.

Although many wind farms are now operational or are currently under construction across Europe, and many more are proposed, available information on the effects of these developments is patchy. A review of bird abundance data analysed to assess wind farm impacts at 19 sites found that although wind farms may have significant biological impacts, particularly for Anseriformes (wildfowl) and Charadriiformes (waders), the evidence-base remains poor, largely because many studies are methodologically weak and of short duration (Stewart *et al.* 2007). Evidence is stronger for some avian species than for others; for instance, for wind turbines increasing raptor mortality (*e.g.* Thelander & Smallwood 2007; Dahl *et al.* 2012) and displacing upland birds (Pearce-Higgins *et al.* 2008, 2009), with greater displacement during construction than subsequent operation for a number of upland species (Pearce-Higgins *et al.* 2012). A spatially-explicit individual-based model of a population of Hen Harriers *Circus cyanea* on Orkney, which assessed the combined effects of collision rate, habitat loss and displacement from wind turbines, found that the larger spatial responses to turbines were from those located close to nest sites (Masden 2010). Removal of collision mortality from this model showed that the majority of population-level turbine impacts were associated with direct and indirect habitat loss in this particular circumstance, but few comparative studies of this kind exist to gain insight into the relative impacts of turbines on avian populations. At offshore wind farms, assessments have focussed mainly on their possible impacts on seabird populations (*e.g.* Garthe & Hüppop 2004; Langston & Boggio 2011; Cook *et al.* 2012; Furness & Wade 2012; Langston & Teuten 2012), which is appropriate given that these birds spend much of the year at sea, and tracking studies have recently been undertaken to provide detailed information on the potential for offshore wind farms to affect goose and swan populations at different stages of their migration (Griffin *et al.* 2010, 2011). But post-construction assessment of how wind farm development affects bird numbers and distribution is still generally lacking, despite post-construction monitoring being required at some sites, and such information being extremely useful for informing environmental impact assessments at new developments.

This paper aims to collate and assess published information on the observed effects of wind farms on swan and goose populations. As many of these populations breed at high latitudes, in areas currently not subject to wind farm development, the study focuses on observations made in the wintering range and during spring and autumn migration. The three main hazards that turbines pose to the birds (after Fox *et al.* 2006): 1) displacement/habitat loss (*e.g.* reduced use of prime feeding areas following construction of the turbines), 2) barrier effects (requiring a change in migration routes or local flight-lines to avoid wind farms, potentially increasing energy expenditure and disrupting links between sites), and 3) collision mortality (Desholm *et al.* 2006; Drewitt & Langston 2006) are all considered. Particular consideration is given to measures used to determine avoidance rates, which have been calculated as: 1) the number of birds changing their flight-lines to avoid a wind farm, and as 2) the number of collisions recorded for birds entering a wind farm (usually via carcass searches), as slight variations in avoidance rate measures result in significant variation in the bird mortality predictions made by wind turbine collision risk models (Chamberlain *et al.* 2006). Additionally the review aims to identify gaps in knowledge and to outline priorities for future assessment of the impacts of wind farm development on these species.

Methods

Detailed information on the responses of geese and swans to wind farms was obtained by checking original sources for swan and goose data in published reviews (including Bright *et al.* 2006, 2008; Drewitt & Langston 2006; Fernley *et al.* 2006; Hötker *et al.* 2006; Pendlebury 2006; de Lucas *et al.* 2007), and by internet searches for more recent scientific papers and grey literature reports. Of 16 constructed offshore wind farms in the UK, five are potentially on the flyways of migratory swans and geese (at Barrow, Lynn & Inner Dowsing, Robin Rigg, Scroby Sands and Walney Island); websites for these five sites were visited to check for information on swan and goose passage movements in post-construction monitoring reports. Bird casualties attributable to wind farm collisions in Germany have been collated by the State Office for Environment, Health and Consumer Protection of Brandenburg (LUGV) since 2002, and data recorded up to July 2012 were provided for this review (Staatlichen Vogelschutzwarte 2012 and T. Dürr pers. comm.). Observations reported in the literature of cases where the turbines did or did not affect swans and geese were grouped into the three main categories established as potentially influencing bird populations (*i.e.* displacement/habitat loss, barrier effects and collision mortality). Major studies of the effects of wind farms on waterbirds along the Baltic coast, such as Pettersson (2005) and Petersen *et al.* (2006) covered a range of species, particularly Common Eider *Somateria mollissima*; only observations made of swans and geese included in these studies are cited here.

For each of the wind farm studies, the number and alignment (linear/cluster) of turbines in the wind farm, its construction date, the swan/goose species potentially affected and the duration of post-construction monitoring was recorded. Methods were inspected to determine which studies rigorously assessed collision rates, as opposed to those where incidental collisions were recorded during observations of displacement and barrier effects. The former included ground surveys made for any turbine-related casualties (in the case of onshore wind farms), or where video cameras using infrared sensing, or further analysis of bird occurrences and flight trajectories were used to detect collisions (for the offshore sites). Thus cases where swans and geese were seen flying through a wind farm, but methods (*e.g.* aerial surveys or use of radar) did not permit, or analyses did not include, an assessment of collision frequency (*e.g.* Petersen *et al.* 2006; Plonczkier & Simms 2012), were omitted from the collision rate review (but included in the barrier effect review), as there was no evidence for collision rates being low or zero. For studies assessing barrier effects, the number of birds flying towards the wind farm, the number that changed their flight-path and the distance at which they did so was recorded. For those assessing displacement from feeding areas or roost sites, the distance to which the birds approached the wind farm footprint before and after construction was assessed, and whether the study recorded any changes in the total number of swans or geese staging or wintering in the vicinity (as a broader measure of displacement from the site) was also considered.

Collisions with turbines

The literature review and LUGV data found post-construction monitoring which reported or aimed to report on collision rates for swans and geese at 46 wind farm sites: three in Belgium, one in Bulgaria, 23 in Germany, six in the Netherlands, one in Norway, one in Poland, three in Spain, one in Sweden (Skåne being treated as a single site in the absence of information on individual wind farms in the county), two in the UK and five in the USA (Table 1, Appendix 1). Forty of these included carcass searches, and nine studies (at Sabinapolder, Waterkaaptocht and Energy Research Centre (ECN) in the Netherlands, at Hellrigg and Barrow Offshore in the UK, Saint Nikola in Bulgaria, Fehmarn in Germany and at Buffalo Ridge (Minnesota) and Stateline

Table 1. Summary of monitoring undertaken to determine swan and goose collisions with turbines (carcass searches and observed collisions) at wind farm sites, and the total number of collisions recorded, based on data presented in Appendix 1. Carcass searches were undertaken at all sites except for Barrow Offshore Wind, UK (where birds were observed entering and leaving the wind farm) and four sites in Germany where swans and geese were reported as accidental recoveries.

Country	No. wind farms with post-construction reports on collisions	No. where monitoring duration is known	No. with flight obs. (visual or radar)	No. with > 1 year monitoring	No. where monitoring linked to bird presence	Total no. swan or goose collisions recorded
Belgium	3	3	0	3	0	4
Bulgaria	1	1	1	1	1	0
Germany	23	14	1	1	1	39
Netherlands	6	6	3	2	4	13*
Norway	1	1	0	1	0	4
Poland	1	0	?	?	?	5
Spain	3	?	?	?	?	3
Sweden	1	1	0	0	0	1
UK	2	2	2	0	2	0
USA	5	5	2	3	1	3
TOTAL	**46**	**33**	**9**	**11**	**9**	**72**

*Two additional birds recovered near a wind farm are omitted, on the basis that they're not considered to be collision casualties.

(Washington/Oregon) in the USA) used radar or visual observations to record bird flights within the wind farm sites (Table 1). All were onshore sites except for Barrow Offshore Wind, UK, where observations were made of Pink-footed Geese *Anser brachyrhynchus* flying through the wind farm from an observation point 7–9.7 km from the site. Whilst this may seem too far for accurate collision rate assessment, it is included here as nine geese were seen both entering and leaving the wind farm at rotor height in autumn 2007 (Barrow Offshore Wind 2008). The Staatlichen

Vogelschutzwarte (2012) data reported 39 swan and goose casualties associated with 23 wind farms in Germany collated over a 12-year period (2002–July 2012) for an estimated 26 monitoring years (mostly ≤ 1 year of post-construction surveys per wind farm, including wind farms searched only once; see Appendix 1): 16 Mute Swans *Cygnus olor*, one Whooper Swan *Cygnus cygnus*, four swan sp., three goose sp., three Greylag Geese *Anser anser*, three White-fronted Geese *Anser albifrons*, three Bean Geese *Anser fabalis*, and six Barnacle Geese *Branta leucopsis*. Two more geese (either Bean Geese or White-fronted Geese) were seen colliding with a turbine at the Meyenburg wind farm, Germany, in October 2008 (in both cases the individuals were at the end of a flock of *c.* 100 geese passing through the site), but these were not included in the LNGV database because only feathers were found the following day (Honig pers. comm. in Langgemach & Dürr 2012). Overall, 34 swans and 37 geese (including two domestic geese) were recovered in the surveys across all countries. Two Bewick's Swans found near the Waterkaaptocht & ECN wind farms were not included in these totals because *post mortem* examination found no evidence for them being collision casualties (Fijn *et al.* 2012).

Of the 46 wind farms considered, 32 were known to have been in place for ≥ 5 years. Exceptions were Schlalach, Germany (built in 2010), Hellrigg , UK (2011), Saint Nikola, Bulgaria (2009) and 11 German wind farm sites where the construction date was not reported (T. Dürr pers. comm.). The duration of post-construction surveys for bird collisions was known for 33 sites, with 22 (67%) being undertaken for ≤ 1 year or winter to date, including four sites in Germany where collisions were reported following an accidental discovery rather than through frequent and systematic surveys of the turbines (Table 1). Of the eleven longer-term (≥ 2 year) surveys, swans or geese were recovered at seven sites (3 in Belgium, 2 in the Netherlands, 1 in Norway and 1 in the USA), but only the Buffalo Ridge (USA), St Nikola (Bulgaria), Urk (Netherlands) and Sabinapolder (Netherlands) wind farms provided information on the number of swans or geese in the study area. No swans or geese were found in carcass searches at St Nikola and Buffalo Ridge, but only a proportion of the turbines were checked in each case (Table 1) and variation in mortality for different turbines within the same wind farm was found to be more than double the variation among wind farms for raptors (Ferrer *et al.* 2012). Only nine of the studies which reported or aimed to record swan or goose collisions (by carcass searches and/or flight observations) assessed in any detail whether the wind farm was in an area used regularly by these species, either as a staging or wintering site (Saint Nikola, Fehmarn, Urk, Sabinapolder, Waterkaaptocht, ECN, Hellrigg and Buffalo Ridge) or on the birds' flight-path during migration (Barrow Offshore Wind, UK). Definite collisions (3 Mute Swans at Urk, 6 Greylags and 1 Canada Goose at Sabinapolder, and 6 Barnacle Geese at Fehmarn, Germany) were recorded at just three of these sites though the extent to which Buffalo Ridge coincided with goose habitat or flight-lines was unclear, and it would be difficult to determine collision frequency at Barrow using the methods reported there to date.

Bird monitoring data at the five sites in the USA reviewed by Fernley *et al.* (2006) and by Pendlebury (2006), led to Scottish Natural Heritage (SNH) advising that 99% avoidance rates be used in collision risk models developed to determine the impact of wind farms on goose species (SNH 2010). An accurate assessment of bird-use of these sites therefore is of particular importance, because collisions would need to be linked to the likelihood of birds flying through the array for determining the rate of collision with or avoidance of the turbines. At Buffalo Ridge, fortnightly bird counts and carcass searches were conducted for four years post-construction, during which there were 909 observations of Canada Geese *Branta canadensis*, 278 observations of Snow Geese *Anser caerulescens* and 92 observations of White-fronted Geese (the latter in 1997 only; Appendix 1) seen flying within the 354-turbine wind farm area – measured as being within 800 m of the array (Osborn *et al.* 2000; Johnson *et al.* 2000; Johnson *et al.* 2002a; Fernley *et al.* 2006). That no goose carcasses were found during the study is indicative of high avoidance by the birds using this site but, as noted by Fernley *et al.* (2006) corpse searches were not complete, with only 21–91 of the 354 Buffalo Ridge turbines searched each year (Johnson *et al.* 2000, 2002a). In such cases, it is important to ensure that the sample of searched turbines is not biased, particularly as some turbines within a wind farm pose a greater risk to the birds than others (Ferrer *et al.* 2012). Moreover, a test of search efficiency for goose carcasses placed under turbines in Scotland found that the proportion found during weekly searches ranged from 65% (assuming all missed geese had been removed by foxes) to 96%, with the most likely figure being 83% of geese present being found (Gill & Smith 2001).

There was little post-construction data on goose-use at the other wind farm sites considered in the USA. Pre-construction bird counts made at the Klondike wind farm (Oregon) found that the use of the study area by waterbirds was low; the only species observed was Canada Goose, with 43 flocks (4,845 individuals) seen flying over the study area in the year-long pre-construction survey in 2001 (Johnson *et al.* 2002b). Goose flights in the vicinity were not recorded post-construction when monitoring focussed on carcass searches, during which two Canada Goose carcasses were found (Johnson *et al.* 2003); Pendlebury (2006) mentions a 1-year post-construction bird survey at Klondike, but the results of this are not evident in the Johnson *et al.* (2003) report. At Nine Canyon (Washington), bird-use was likewise monitored only pre-construction; goose-use of the area at the time is unclear, use by waterbirds appeared to be lower than at Buffalo Ridge, Klondike and Stateline (Erickson *et al.* 2002), and post-construction carcass searches were again undertaken without any reference to the number of geese present in the area during the survey years (Erickson *et al.* 2003). At Top of Iowa, large numbers of Canada Geese were reported to occur on managed habitat 1–5 km from the wind farm in autumn, but except for carcass searches there were no detailed bird-use observations recorded at the wind farm

Table 2. Number of geese and swans of different species recorded as wind turbine casualties in different countries.

Species	Belgium	Germany	Netherlands	Norway	Poland	Spain	Sweden	USA	TOTAL
Mute Swan		16	3		5		1		25
Whooper Swan		1		1					2
Swan sp.		4							4
Bean Goose		3							3
Greylag Goose	1	3	8	3		3			18
White-fronted Goose		3							3
Canada Goose			1					3	4
Brent Goose			1						1
Barnacle Goose		6							6
Domestic Goose	3								3
Goose sp.		3							3
TOTAL	**4**	**39**	**13**	**4**	**5**	**3**	**1**	**3**	**72**

(Fernley *et al.* 2006), and goose flight in the collision-risk zone was said to be very rare (Jain 2005). Lastly, at Stateline, 11 groups of Canada Geese (363 birds) were recorded within the wind farm during bird counts, and one Canada Goose carcass was found in 6–7 searches made of the 454-turbine site post-construction in 2003 (Erickson *et al.* 2004). Fernley *et al.* (2006) and Pendlebury (2006) both noted the gaps in the data and Pendlebury (2006) went on to note that the studies could not be used to provide reliable estimates of avoidance rates (which were put at 96% for one site and > 99% for the other sites), but several years later this has not been re-evaluated with the benefit of new studies and 99% avoidance of wind farms by geese remains the recommended value for inclusion in collision risk models.

Despite there being only one wind farm in Germany where carcass searches are known to have continued for > 1 year, the number of swan and goose collisions with turbines in Germany (39 casualties) clearly outnumber those from all other countries considered (33 casualties; Tables 1, 2). The most commonly reported species was the Mute Swan, with 16 recovered in Germany, five in Poland, three in the Netherlands and one in Sweden (Winkelman 1989; Ahlén 2002; Hötker *et al.* 2006; Rodziewicz 2009; Staatlichen Vogelschutzwarte 2012), followed by the Greylag Goose (18 birds from different parts of Europe) and the Barnacle Goose (six recovered in Germany; Staatlichen Vogelschutzwarte 2012; Table 2), but in none of these cases was there any flight observation data, for determining frequency of bird-wind farm overlap, and thus avoidance rates for birds flying across the sites. Carcass searches were made for only 1–2 years at most sites (Table 1, Appendix 1), so these figures represent *c.* 1 season's additional mortality at best, rather than an assessment of mortality rate since each of the wind farms was constructed.

Observed barrier effects

The review by Hötker *et al.* (2006) found that seven of 127 wind farm studies (not all relating to swans or geese) assessed and found evidence for turbines having a barrier effect on goose movements during migration or whilst commuting more locally (*e.g.* between feeding and roosting sites), for: Bean Geese (1 study), White-fronted Geese (3), Greylag Geese (2) and Barnacle Geese (1). Single observations and extensive investigations were combined, and a barrier effect was assumed in quantitative studies if at least 5% of the individuals or flocks showed a measurable reaction by changing their flight direction to go around or over a wind farm (Hötker *et al.* 2006). These observations were made during daylight as there was insufficient information at the time (*e.g.* through radar studies) on the birds' flight-lines at night, when migration often occurs.

Eight published studies of swan or goose flight-lines in relation to wind farm location provided information on the birds' avoidance behaviour (Table 3). Of these, radar studies or a combination of radar and visual observations were undertaken for Bewick's Swans at Waterkaaptocht and at ECN, Netherlands (Fijn *et al.* 2007, 2012), Brent and Barnacle Geese at Olsäng, Sweden (Pettersson 2005), Barnacle Geese at Utgrunden, Sweden (Pettersson 2005), Pink-footed Geese at Lynn & Inner Dowsing, UK (Plonczkier & Simms 2012), and Greylag Geese at Horns Rev, Denmark (Petersen *et al.* 2006), with visual observations made of Pink-footed Geese at Barrow Offshore, UK (BOWind 2008) and at Hellrigg, UK (Ecology Consulting 2012) (Table 3). All reported some changes in flight-lines for swans or geese initially seen heading towards the turbines, with 50–100% of individuals or groups avoiding entering the wind farm site (Table 3). Avoidance distance varied from a few hundred metres (at Waterkaaptocht/ECN and at Hellrigg wintering sites, where the birds were commuting daily between feeding areas and the roost) up to 5 km for birds observed during migration (Table 3).

Desholm & Kahlert (2005) additionally found that the proportion of Common Eider and goose flocks entering the Nysted wind farm area decreased significantly from 40.4% (n = 1,406 flocks) during pre-construction (2000–2002) to 8.9% (n = 779) during the first year of operation (2003), but whether there was a difference in the proportion of geese compared with eiders entering the wind farm was not reported. Jain (2005) observed Canada Geese flying in between, around and above wind turbines at Top of Iowa, USA, but states that avian flight in the collision-risk zone was very rare across seasons. A study of Red-breasted Geese *Branta ruficollis*, White-fronted Geese and Greylag Geese at the Saint Nikola wind farm in Bulgaria reported on flight-lines and altitude of flight, and noted from radar data that 64% of the geese (n = 272,210 goose flights detected in winter 2010/11) were at rotor height (*c.* 50–150 m for this particular wind farm), with 1% of birds flying at below rotor height (0–49 m) and 36% above the turbines (Zehtindjiev & Whitfield 2011), but it was unclear whether the birds adjusted their flight-lines to pass around or over the wind farm, and thus exhibit avoidance behaviour.

Flight-lines might also shift at longer distances following wind farm construction; for instance, Petterssen (2005) noted that, once the turbines had been erected at Olsäng and Utgrunden, geese generally flew closer to the mainland (inside the line of the turbines), and Plonczkier & Simms (2012) likewise found that migrating Pink-footed Geese were more likely to fly inland of the Lynn & Inner Dowsing turbines in the third winter of their post-construction surveys. Earlier studies for other migratory waterbirds have demonstrated that even quite dramatic shifts in migration routes may have only small effects on total migration distance (Desholm 2003; Masden *et al.* 2009), but where birds show diurnal movements, such as between breeding colonies and food provisioning areas (Masden *et al.* 2010b) or night roosts and daytime feeding areas, the energetic consequences of avoidance could become significant.

The radar studies were unable to provide data on collision rates for birds flying within the wind farms because of the difficulty of following individuals within flocks (and thus identifying those that fail to leave the wind farm site) by radar. Visual observations of flight-lines made in conjunction with radar at Waterkaaptocht/ECN, Netherlands, and without radar at Barrow Offshore, UK and at Hellrigg, UK did not record any collisions,

Table 3. Records of swans and geese adjusting their flight-lines to avoid wind farms. Observation method: RAD = Radar; FL = flight observations. References: 1 = Fijn *et al.* 2007; 2 = Fijn *et al.* 2012; 3 = BOWind 2008; 4 = Ecology Consulting 2012; 5 = Plonczkier & Simms 2012; 6 = Christensen et al. 2004; 7 = Petersen et al. 2006; 8 = Pettersson 2005. Turbine alignment: * = linear alignment; ** = turbines in 2 lines; *** = cluster. Observation method: RAD = Radar; FL = flight observations.

Species	No. flight-lines directly towards wind farm	No. flights within wind farm	% avoidance	Wind farm name/ location	Built	No. turbines (hub height m)	Obs. method	Avoidance dimension (V = vertical; H = horizontal)	Avoidance distance	Duration of post-construction monitoring	Ref.
Bewick's Swan	364 birds	167 birds	54	Waterkaaptocht, Nths	2003	8* (78 m)	RAD & FL	H	Few hundred metres	3 days (winter 2006/07)	1, 2
Bewick's Swan	684 birds	308 birds	55	ECN test-park, Nths	2003–2006	9 ** (90 m)	RAD & FL	H	Few hundred metres	5 days (winter 2006/07)	1, 2
Pink-footed Goose	503 birds	9	98	Barrow Offshore, UK	2006	30*** (75 m)	FL[1]	V	2–3 km	21 days (2007)	3
Pink-footed Goose	1,022 birds within 200 m of turbines	4 groups	Unclear	Hellrigg, UK	2011	4*** (80 m)	FL	H	>200 m	38 h (22.12.11–09.03.12)	4
Whooper Swan	0 groups	0 groups	–	Hellrigg, UK	2011	4*** (80 m)	FL	H	>200 m		4

Pink-footed Goose	292 flocks	16 flocks[a]	94	Lynn & Inner Dowsing, UK	2006	54*** (70–100 m)	RAD	V[b] & H	Not reported	134 days (2008–2010)	6
Greylag Goose	8 flocks	3 flocks	63	Horns Rev, Denmark	2003	80*** (70 m)	RAD & FL	H & V	Not reported	69 days (244 h visual; 398 h radar; 2003–2005)	6, 7
Goose sp.	11 flocks	1 flock	91	Horns Rev, Denmark	2003	80*** (70 m)	RAD & FL	Not reported	Not reported		6, 7
Barnacle Goose	2 flocks	1 flock	50	Olsäng, Sweden	2001	5* (65 m)	RAD	Not reported	*c.* 5 km	52 days (2000–2002)	6. 7
Brent Goose	3 flocks (292 birds)	1 flock (17 birds)	94	Olsäng, Sweden	2001	5* (65 m)	FL	Not reported	*c.* 500 m		8
Barnacle Goose	2 flocks	0 flocks	100	Utgrunden, Sweden	2000	7* (65 m)	RAD	Not reported	*c.* 2 km	52 days (2000–2002)	8

[a]Numbers based on 167 of the 292 flocks (tracked by radar) heading towards the array actually crossing the array, and 84 (94.46%) of 93 flocks seen (from visual observations) crossing the footprint seen to gain height and fly above the turbines as they did so.
[b]Initial flight height not reported, so unclear whether geese gained height to clear (avoid) the turbines or continued on their same flight-lines when passing over the footprint.

but it seemed that the birds were flying in good weather conditions: either conditions were said to be good (Fijn *et al.* 2012), or good visibility was required for the observations to be made (Barrow Offshore Wind 2008), or conditions during vantage point (flight-line) observations were not recorded (Ecology Consulting 2012).

None of the studies reported adverse weather conditions during observations. The effects of strong winds, heavy precipitation or fog on the birds' ability to avoid the wind farm or to negotiate the turbines if flying within the wind farm therefore remains unclear, albeit that the low number of casualties reported from carcass searches to date indicates that adverse weather may not increase the risk to swans and geese substantially at terrestrial sites. The six Barnacle Geese recorded as wind turbine casualties in Germany were all found under a single turbine the day after fog and a storm, but it is not known whether the weather contributed to these collisions (T. Dürr, pers. comm.). Whether the size of the wind farm affects avoidance behaviour, with swans and geese being more likely to fly around smaller wind farms but to pass between the turbines for wind farms covering a larger area should also be considered, as this is relevant to the construction of larger wind farm sites over the next decade. The largest wind farm included in this review of observed barrier effects – the Horns Rev offshore wind farm in Denmark (80 turbines) – had a relatively high proportion (21%) of geese which were flying towards the wind farm continue through it (three of eight Greylag Goose flocks and one of 11 flocks of unidentified goose species; Table 3), but the sample sizes are relatively small and the number of individual birds involved were not recorded. Accumulated knowledge of how a range of individuals from different species react to turbines are however helpful for populating models of avoidance behaviour, which can be insightful for predicting how geese and swans may respond to different sizes of wind farms and specific turbine configurations (Masden *et al.* 2012).

Displacement from feeding areas and roost sites

Displacement of birds from feeding areas and roost sites is an important consideration because migratory swans and geese tend to congregate at favoured (but frequently undesignated) feeding sites in winter, many of which are associated with roost sites that have been classified as Special Protection Areas (SPAs) under Article 4 of the Birds Directive (EC Directive on the Conservation of Wild Birds, 79/409/EEC) because of their importance for the species (Bright *et al.* 2008). Habitat quality in the non-breeding season has been shown to influence the timing of bird migration (Marra *et al.* 1998; Gill *et al.* 2001; Stirnemann *et al.* 2012), body condition during spring migration (Bearhop *et al.* 2004) and breeding success (Ebbinge & Spaans 1995; Madsen 1995; Norris *et al.* 2004; Inger *et al.* 2010). Loss of feeding or roosting habitats through disturbance or displacement by the turbines therefore could affect the birds' use of protected areas or result in them moving to suboptimal sites, with consequences for future survival and productivity (Gill *et al.* 2001; Norris & Taylor 2006; Ratikainen *et al.* 2008).

Birds' avoidance responses to wind farms vary within and between species, but swans and geese are considered sensitive to these developments because they frequent open landscapes (Hötker *et al.* 2006). The review by Hötker *et al.* (2006) indicated that the minimal distances to wind farms reported was 150 m (s.d. = 139 m, n = 8 studies) for swans and 373 m (s.d. = 226 m, n = 13) for geese, with the minimal distances recorded for geese during the non-breeding season ranging from 50–850 m. Papers considered in the current review likewise recorded displacement distances of 200–560 m for swans and 30–600 m for geese at terrestrial wind farms, and 2 km for one offshore site (Table 4), the latter estimated from maps illustrating Mute Swan displacement (Figure 51 in Petersen *et al.* 2006). For Pink-footed Geese, displacement was greater at wind farms where the turbines were arranged in clusters (200 m) than at linear or single turbine sites (100 m) (Larsen & Madsen 2000). Long-term post-construction studies, and thus information on whether birds adapt to the change in landscape, are rare. An exception is that of Madsen & Boertmann (2008), who found not only that Pink-footed Geese grazed closer to wind turbines *c.* 20 years after construction than 10 years previously (Table 4), but that the extent to which they habituate to the turbines varied across sites. Observations made at two sites – the Klim Fjordholme and Velling onshore wind farms in Denmark – indicated that the geese remained at a greater distance from the larger turbines (Madsen & Boertmann 2008), but more studies of potential habituation to different types of turbine are required to support these findings.

In addition to assessing the extent to which birds approach turbines at a local level, whether the construction of wind farms influences the extent to which swans and geese winter in an area should be considered. In her pioneering study of bird use of fields around the Urk wind farm, which consisted of 25 turbines (hub height = 30 m) positioned along a dyke bordering Lake IJsselmeer on the Noordoostpolder, the Netherlands, Winkelman (1989) found that, at the local level, Bewick's, Whooper and Mute Swans were displaced to feeding areas 200–400 m from the wind farm site post-construction, with pooled data for Bean Geese, White-fronted Geese and Barnacle Geese similarly suggesting 200–400 m displacement, albeit that this was a subjective assessment as the data did not permit a meaningful comparison of pre- and post-construction distances for the geese. Raw data indicated that more geese were counted in the study area pre- than post-construction; for the three swan species (combined), mean numbers were rather similar in comparison with the range of counts recorded (Table 4), but a significant negative impact was found for Whooper Swans in 1988/89, two years post-construction (Winkelman 1989). Goose counts were presented in a different manner, but these too indicated that, whilst the number of Bean Geese in the area increased substantially post-construction (mean values = 5,615 and 11,842, n = 10 years and 2 years pre- and post-construction, respectively; 111% increase), there was also a drop in

Table 4. Displacement distances recorded for swans and geese, measured as an absence or reduction in the number or density of birds in habitat near the wind farm. Observation methods: AS = aerial survey; DD = dropping densities; BC = bird counts. References: 1 = Petersen et al. 2006; 2 = Larsen & Madsen 2000; 3 = Madsen & Boertmann 2008; 4 = Kruckenberg & Jaene 1999; 5 = Kowallik 2002; 6 = T. Dürr pers. comm.; 7 = Bioconsult & Arsu 2010; 8 = Handke *et al.* 2004; 9 = Möckel & Wiesner 2007; 10 = Fijn *et al.* 2012; 11 = Fijn *et al.* 2007; 12 = Winkelman 1989; 13 = Ecological Consulting 2012. * = linear alignment; ** = turbines in 2 lines; *** = cluster.

Species	Wind farm	No. turbines (hub height m)	No. birds in vicinity (pre-construction)	No. birds in vicinity (post-construction)	Obs. method	Displacement distance (m)	Refs
Mute Swan	Nysted, Denmark	72*** (69 m)	8,662–10,604	2,882–3,478	AS	*c.* 2,000[a]	1
Pink-foooted Geese	Klim Fjordholme, Denmark	1–35[b] (25–50 m)	Not reported	Not reported	DD[c]	100–200[d]	2, 3
Pink-footed Goose	Thorup, Denmark	5* (31 m)	Not reported	Not reported	DD[c]	50–125[d]	3
Pink-footed Goose	Velling Maersk, Denmark	66*** (21–31 m)	Not reported	Not reported	DD[c]	30–100[d]	3
White-fronted Goose	Holtgaste, Germany	10* (50 m)	Not reported	Not reported	BC	400–600	4
Barnacle Goose	In Germany	??	??	??	DD	350–600	5, 6
Greylag Goose	Fehmarn, Germany	Various	??	??	BC	> 200	6, 7
Goose sp.	Krummhörn, Germany	??	??	??	??	300–400	6, 8
Greylag Goose	In Brandenburg, Germany	Various	??	??	??	250	6, 9
Bean Goose & White-front Goose	In Brandenburg, Germany	Various	??	??	??	500	6, 9

Bewick's Swan	ECN test-park, Nths	9** (90 m)	1,099	530	BC	560	10, 11
Bean Geese	ECN test-park, Nths	9** (90 m)	5,840	1,885	BC	464	11
Bean Goose	Urk, Nths	25* (30 m)	5,615	11,842	BC	200–400[e]	12
White-fronted Goose	Urk, Nths	25* (30 m)	8,570	7,697	BC	200–400[e]	12
Barnacle Goose	Urk, Nths	25* (30 m)	887	197	BC	200–400[e]	12
Mute Swan	Urk, Nths	25* (30 m)	129.2 (± 54.5; 81–246)	123.2 (± 85.7; 16–292)	BC	200–400[f]	12
Whooper Swan	Urk, Nths	25* (30 m)	102.3 (± 123.8; 0–519)	93.3 (± 104.8; 0–395)	BC	200–400[f]	12
Bewick's Swan	Urk, Nths	25* (30 m)	677.2 (± 629.7; 0–2,312)	614.9 (± 716.9; 0–2,402)	BC	200–400[f]	12
Pink-footed Goose	Hellrigg, UK	4*** (80 m)	3,950 (270–7,100)	2,175 (max = 9,320)	BC & DD	>600[g]	13

[a]Displacement of Mute Swans on coastal waters near the offshore wind farm; all other displacement distances are for onshore sites.

[b]Total of 61 mostly medium-sized wind turbines within the study area in recent years; all wind farms ≤ 5 tubines (including single turbines) except for one cluster of 35 turbines.

[c]Avoidance distance = point at which dropping density reached 50% of the maximum density along a transect perpendicular to the object.

[d]Median displacement distances; upper value recorded in 1998–2000, upper value in 2008.

[e]Pooled data for goose species; estimated as it was not possible to make a meaningful comparison of pre- and post-construction distances (Winkelman 1989).

[f]Pooled data for swan species.

[g]Geese mostly 600–1,500 m from turbines, but one flock of 70 birds seen within the wind farm site during surveys made in the post-construction winter (2011/12).

numbers of White-fronted Geese (8,570 *vs.* 7,697; 10% decrease) and Barnacle Geese (887 *vs.* 197; 78% decrease) in the vicinity (from Table 18 in Winkelman 1989). There was an increase in the number of Bean Geese, stable numbers of White-fronted Geese and a decline in Barnacle Geese across the Noordoostpolder over the same years (mean annual totals =11,387 *vs.* 35,791 for Bean Geese; 34,162 *vs.* 31,580 for White-fronted Geese; 6,211 *vs.* 2,807 for Barnacle Geese; from Winkelman 1989), but the proportion of Noordoostpolder geese recorded in fields up to *c.* 3.5 km from wind farm was lower after than before construction for all three species (49% *vs.* 33% for Bean Geese, 25% *vs.* 24% for White-fronted Geese and 14% *vs.* 7% for Barnacle Geese, pre- and post-construction in each case).

Bird counts made at the Saint Nikola wind farm in Bulgaria found that numbers of geese were much lower in winter 2010/11 (two years post-construction) than in 2008/09 (pre-construction) and 2009/10 (Zehtindjiev & Whitfield 2011), but winter 2010/11 was relatively severe so longer-term monitoring is required to determine whether there is any large-scale displacement of geese from the area.

In the only study which specifically analysed the proportion of birds wintering in the vicinity of a wind farm site before and after construction, Fijn *et al.* (2012) likewise found a significant drop, post-construction, in the proportion of wintering Bewick's Swans using the area where wind turbines had been installed in Polder Wieringermeer. Like Madsen & Boertman (2008), they found evidence for habituation, with swans feeding closer to the turbines later in the study, but with fewer birds present in the study area (Fijn *et al.* 2012). Thus, although swans may be displaced by up to 600 m from field feeding areas, with larger-scale displacement (*c.* 2 km) in one case where swans were feeding in coastal waters (Table 4), whether the proportion of population using areas where wind farm development has occurred diminishes post-construction, and the extent to which this is attributable to displacement by the turbines still needs to be addressed. This is also important for determining whether any mitigation plans (*e.g.* habitat management) in conjunction with wind farm development are likely to be successful. The potential for cumulative displacement impacts attributable to the arrangement of wind farms in the landscape, through possible non-linear synergistic effects with other wind farms or other landscape elements, also needs to be explored (Larsen & Madsen 2000).

Gaps in knowledge

In addition to needing better linkage of avoidance rates to the birds' use of the site, and a robust assessment of whether wind farm installation results in fewer birds returning to a wintering area, outlined above, more specific information on how the positioning and structure of wind farms affect the birds would be useful to ensure that any impacts are kept to a minimum. For instance, turbines come in variable sizes, and may be installed singly, linearly or as a cluster, but there are few detailed studies of the effects of turbine height and alignment on swans and geese. Larsen & Clausen (2002) initially suggested, from pre-construction observations, that Whooper Swans might be more at risk from a park of medium-sized turbines than large turbines as typical flight heights (mostly at 5–35 m when flying between feeding areas and the roost) would put them in the collision risk zone more often. On the other hand, birds (including swans and geese) may be more likely to be displaced over longer distances by larger turbines: Hötker *et al.* (2006) estimated from six studies included in their review that there was a 6.22 m increase in minimal distance between birds and a wind farm for every 1 m increase in tower height, though this change was not statistically significant. The only studies which aimed to test the effects of turbine height on goose distribution similarly found that geese are less tolerant of larger turbines, and may also be less likely to habituate to them (Larsen & Madsen 2000; Madsen & Boertmann 2008), but it should be noted that alignment is also relevant (with geese displaced further by a cluster of turbines than single turbines or those in a line; Larsen & Madsen 2000) and the interactive effects of height and alignment has yet to be assessed. More recently, Krijgsveld *et al.* (2009) used radar and carcass searches to study the collision risk for birds with large modern turbines at three wind farms in the Netherlands (Waterkaaptocht, Groettocht and Jaap Rodenburg), and found that the risk was *c.* threefold lower than for the smaller turbines for the species (not including swan and geese) passing through the wind farm sites. They suggested that one possible reason for this was that the increased height of the turbine allowed more birds to fly under the rotors, and also proposed that the wider spacing allowed more birds to pass between the turbines. The relative costs and benefits of potentially lower collision rates but higher displacement distances for the larger wind farms therefore should be assessed more rigorously for onshore sites.

The cumulative impact on migratory bird populations of several wind farms being installed along the migration routes, or within a wintering area, is known to be an issue but has yet to be resolved. Written guidance has been produced to assist in the process of ornithological cumulative impact assessment (CIA) for offshore wind farms (since Norman *et al.* 2007), and Fox *et al.* (2006) emphasised the importance of undertaking full Strategic Environmental Assessments (SEAs) for offshore wind farm sites, not least to comply with European legislation. Masden *et al.* (2010a) went on to argue for the benefits of elevating CIA to a strategic level, as a component of spatially explicit planning. Yet although there is an increasing tendency for developers of the large offshore wind farms to take into account other wind farms nationally, collision risk assessments for all wind farms along international migration routes, and the cumulative effect of these on birds migrating to/from key sites for the population (*i.e.* Special Protection Areas and/or Ramsar sites), are still rarely (if ever) incorporated into Appropriate Assessments undertaken for new wind farm sites. For most European and North American goose and swan populations, there is sufficient information about the precise migration routes, other hazards encountered along these corridors and the demographics of these populations to be able to make preliminary assessments of cumulative effects. Ultimately, this knowledge should be used to support the construction of robust models of their population dynamics to establish the relative costs of collision, barrier effects and habitat loss from each new wind farm proposal, based on existing sources of mortality and given current population trajectories.

Moreover, there has been a general lack of post-construction monitoring work undertaken, both for the early offshore sites and for the numerous smaller terrestrial wind farms. For those studies that have been undertaken, the collision rate and displacement data are not collated centrally, nor are they readily available in accessible reports for assessing existing impacts. A Scottish Wind Farm Bird Steering Group (SWBSG) has recently been formed, with the aim of bringing together the onshore wind farm industry, government agencies and conservation organisations to collate and analyse post-construction monitoring data collected in Scotland, but this is not (yet) being extended across the UK. Even in Germany, where collision data has been collated since 2002, in most cases monitoring is undertaken and reported to LUGV for only one year post-construction. Developers are reluctant to undertake post-construction monitoring (particularly for > 1 year) because of the cost involved, and up to now it has not been an automatic requirement of the planning process, although longer-term monitoring is recommended by SNH (SNH 2009). Data therefore are lacking for assessing cumulative impacts of existing wind farms, making it currently impossible to determine the extent to which each new wind farm would serially reduce the attractiveness of a site for swans and geese.

One drawback of undertaking post-construction monitoring for only one year is that this reduces the scope for determining the effects of weather conditions and poor visibility on the birds' flight-lines and large-scale avoidance of wind farm sites. Because wind speeds and birds' airspeeds are often of a similar magnitude, wind strength and direction has a major influence on the orientation and energy expenditure of migrating birds, but the extent to which birds are susceptible to wind drift appears to vary (*e.g.* Thorup *et al.* 2003; Green *et al.* 2004). Satellite-tracking and radar studies of swans and geese on migration indicate that migration routes may shift between years (Pettersson 2005; Griffin *et al.* 2011; Plonczkier & Simms 2012), and the extent to which this varies with weather conditions (especially wind drift) has yet to be determined. Variation in wind conditions was one explanation given for a lack of correlation between raptor abundance and collision rates at wind farms in Spain (Ferrer *et al.* 2012). Radar studies have demonstrated that birds continue to fly over or around wind farms after dark (Desholm & Kahlert 2005; Fijn *et al.* 2012), but one study also noted that the proportion entering the wind farm is higher at night (Desholm & Kahlert 2005). Whether familiarity with the wind farms will result in an increasing tendency for birds to pass through rather than over or around a site, the extent to which this increases their susceptibility to collisions with the turbines, and the effects of poor visibility (including night-time flights and fog) on their ability to avoid the rotors on flying within a wind farm has yet to be determined. Poor weather conditions, such as fog or low cloud, can affect visibility and studies of bird collisions with other structures (*e.g.* power lines) found that birds are much more susceptible to flying accidents under such circumstances (Brown 1992; Drewitt & Langston 2008; Jenkins *et al.* 2010; Prinsen *et al.* 2011; Barrientos *et al.* 2012). Additionally, strong winds (especially tail- or cross-winds) blunt the fine motor control of flying birds and consequently raise their susceptibility to collision (Bevanger 1994 and Crowder & Rhodes 2001 in Jenkins *et al.* 2010). Although difficult to assess, the frequency with which swans and geese encounter adverse weather during migration, and the extent to which this puts them at risk of large-scale losses at wind farms (through reduced ability to avoid the turbines), therefore should be considered and included in collision risk models, perhaps as a stochastic event in the modelling process. Likewise, geese and swans migrate at high speeds and at night (Griffin *et al.* 2010, 2011), so the ability of geese to avoid turbines under these circumstances should be assessed at existing wind farm sites, for instance by developing techniques for detecting collisions and measuring micro-avoidance rates within wind farms (Desholm *et al.* 2006; Collier *et al.* 2011).

Overview

Development of renewable energy has substantial benefits, notably reducing carbon dioxide emissions and the provision of a secure local energy supply, with wind power becoming a major contributor to this field over the past two decades. It has long been recognised that collisions with and displacement by the turbines could have a significant negative effect on birds, but the rate of wind farm development is still not matched by publication of rigorous peer-reviewed reports or papers from studies observing, carefully analysing and accurately reporting these effects (Stewart *et al.* 2007; Natural England 2010; this study). Before-after-control-impact (BACI) studies of the effects of wind farm development are not undertaken and reported routinely at onshore sites in the UK, despite these being recommended by statutory nature conservation bodies (*e.g.* Natural England 2010), yet such information would be invaluable for informing future wind farm development, including the preparation of EIAs and advising on height, alignment, and the effectiveness of mitigation programmes such as (in the case of swans and geese) habitat management to provide the birds with alternative feeding areas for the life-time of the turbines. Where post-construction surveys have been undertaken to date, they have usually been of short duration (1 year, although SNH guidance is for longer periods; SNH 2009) and treated as confidential (therefore not readily available) by the developer who commissioned the study. Moreover, except for the collation of collision data by LUGV in Germany and the new initiative (establishment of the SWBSG) in Scotland, there is no central national repository to assess whether post-construction surveys are being undertaken and reported appropriately, and to provide an information source to determine whether any significant impacts on birds (at the population or local level) are being addressed. Yet centralised post-construction monitoring data is crucial for determining actual impacts (as well as for validation and improvement of modelled predictions) and is required for cumulative impact assessments both for wind farm development along migration routes, and where turbines are installed in proximity to internationally important sites. Post-construction monitoring is undertaken more routinely for offshore wind farms, but again tends to be of short duration and not readily accessible, and within the UK the surveys have focussed more on the potential displacement of seabirds from feeding areas (which of course is an important issue) than on collision rates and barrier effects for birds on migration.

A species-specific approach is required in assessing the potential impact of wind farms on birds because, as noted by Jenkins *et al.* (2010) susceptibility to collision varies with morphology, as ocular structure and acuity affect a bird's ability to see structures and thus take evasive action (Bevanger 1994; Drewitt & Langston 2008), while size, mass and wing structure influence the time required to make the necessary adjustments (Brown 1992; Bevanger 1994; Rubolini *et al.* 2005). Reaction time is also affected by flight speed, which tends to be higher in heavy-bodied species, and a higher wing loading also reduces manoeuvrability (Bevanger 1994; Janss 2000). The highly social nature of swans and geese (where parent-offspring bonds may persist for many years, *e.g.* Warren *et al.* 1993) are also significant, since recent studies show that social interactions have a significant, non-linear and potentially large effects on collision risk (Croft *et al.* 2012). Hence, theoretically, relatively large, heavy and socially interactive birds (*e.g.* swans and geese) are more susceptible to collision than small, light and relatively large-winged birds with acute vision (Jenkins *et al.* 2010), and birds such as raptors which use predominantly downward (lateral) vision are particularly susceptible to collisions with turbines (Thelander & Smallwood 2007; Martin 2011; Dahl *et al.* 2012). Given our relatively weak ability to predict post-construction actual collision mortality (*e.g.* Ferrer *et al.* 2012) existing empirical and mechanistic methods of predicting collision risk at turbines should perhaps be augmented (Tucker 1996; Sugimoto & Matsuda 2011). One approach would be to gather more information about the underlying visual and behavioural processes of collision risk in particular species, in order to populate individual-based or agent-based simulation models that may provide more powerful predictive tools to supplement current approaches (*e.g.* Croft *et al.* 2012; Eichhorn *et al.* 2012).

This review found that 72 swans or geese were reported as collision victims at 46 wind farms, but most (39 birds) were reported at 23 German wind farms where such data are collated, and even there only usually for *c.* 1 year post-construction. Moreover, there was a lack of linkage of collision rates with the birds' use of a site; whether or not swans or geese occurred in the immediate area of the wind farm, or flew across/within the site, was considered at only nine of 46 wind farms where collisions by swans and geese were monitored or recorded. Likewise, avoidance of turbines should be related to whether or not flights were initially in line with the wind farm, rather than in relation to all bird movements in the area, as including the latter artificially boosts sample sizes used for calculating avoidance rates. Sample sizes for birds or flocks actually seen to change their flight-lines to avoid wind farms were available for only eight studies (Table 3); these gave a wide range for the proportion of birds that ultimately passed through the wind farm (2– 46%, for sample sizes of <5 birds or flocks) rather than going over or around the site, with interactive effects of wind farm size and visibility (day *versus* night-time flights and weather conditions) on large-scale avoidance yet to be assessed for swans and geese. Yet such information is important for collision risk models (Band *et al.* 2007; Band 2012), as minor changes in avoidance rates can have a major influence on the outcome of (and confidence in) the models (Chamberlain *et al.* 2006). Swans and geese have good eyesight and the review indicates that high levels of avoidance do occur. But avoidance rates of 98% for Whooper Swans and 99% for geese currently advocated by Scottish Natural Heritage for use for collision risk models (SNH 2010) should be revisited and based on better observational data than those available from the reviews (Fernley *et al.* 2006; Pendlebury 2006) which set the avoidance levels in the mid 2000s. Plans are underway to measure levels of micro-avoidance and collision rates by installing systems (using a variety of cameras and radar) within wind farms (Collier *et al.* 2011, 2012). Use of such technology would provide a major advance for contributing to model development and validation, as well as for determining whether wind farms are likely to have significant effects on survival rates for swan and goose populations.

This review has highlighted the relatively little attention paid in other studies to the potential for large-scale displacement of swans and geese from non-breeding feeding sites. Thus, although birds returning to an area may approach on average to 100–600 m from the turbines, closer (40–100 m) where habituation occurs (Madsen & Boertmann 2008), and were reported between turbines in two studies (Madsen & Boertmann 2008; Ecology Consulting 2012), count data provided in other studies suggest that fewer birds returned to study areas post-construction. In the one study that analysed this (Fijn *et al.* 2012), reductions in numbers were significant. Swans and geese favour open landscapes, and topographical features such as trees and hedge lines are known to have an adverse effect on site use (*e.g.* Madsen 1985). The combined effects of landscape (power lines, wind breaks, roads and settlements) caused an effective loss of 68% of the field feeding areas (40 km^2) available for Pink-footed Geese at Klim Fjordholme (Denmark), with the presence of 61 turbines (one farm of 35 turbines; the remainder of ≤5 turbines including single turbines) resulting in the loss of 13% of the remaining area (Larsen & Madsen 2000). The potential for wind farm development to cause large-scale displacement of geese and swans from internationally important wintering sites through habitat fragmentation and displacement from preferred feeding areas therefore should be analysed more rigorously and addressed more carefully in the planning process. This should include an assessment of small wind turbines (SWT), which like larger turbines, vary in size and scale. The only study to date aiming to quantify the effects of SWTs on bats and birds grouped three types of SWT (10 m high building-mounted, 6.5 m high free-standing, and 18 m high free-standing; Minderman *et al*. 2012) and did not consider swans and geese.

Several recommendations emerge from the information gathered in this review. Firstly, although several authors have emphasised in recent years the need for systematic post-construction monitoring, and dissemination of the results of these studies (*e.g*. Fox *et al*. 2006; Drewitt & Langston 2006; Natural England 2010) this information still seems to be lacking. Such monitoring programmes should be undertaken routinely, collated centrally, and adapted to quantify collision, barrier and displacement effects. Secondly, better information is required about the extent of large-scale and local displacement of geese and swans from feeding/drinking/roosting sites, and the effects of turbine number, size and alignment on such effective habitat loss. Thirdly, further detailed studies of the birds' flight-lines in the vicinity of wind farms are required, both during migration and for birds commuting between feeding areas and the roost, to provide a more rigorous assessment of collision and avoidance rates, and to quantify additional energy costs of any avoidance behaviour during regular local flights. Finally, the combination of collision mortality and habitat loss attributable to wind farms across a species' range should be analysed to determine whether the current sites and new developments will have a significant effect on the population. The development of new technology to determine collision rates for birds entering large wind farms should help to provide much more accurate assessments of the consequences of wind farm development for swans, geese and other avian species.

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Photograph: Bewick's Swans at the ECN wind farm, the Netherlands, by Wim Tijsen.

Appendix 1. Records of swans and geese found to have collided with wind turbines. References: 1 = Everaert 2008; 2 = Zehtindjiev & Whitfield 2010; 3 = Zehtindjiev & Whitfield 2011; 4 = Staatlichen Vogelschutzwarte 2012; 5 = Bioconsult & Arsu 2010; 6 = Musters *et al.* 1996; 7 = Winkelman 1989; 8 = Fijn *et al.* 2007, 9 = Fijn *et al.* 2012; 10 = Krijgsveld & Beuker 2009; 11 = Veerbeek *et al.* 2012; 12 = Bevanger *et al.* 2009; 13 = Rodziewicz 2009; 14 = Hötker *et al.* 2006; 15 = Ahlén 2002; 16 = BOWind 2008; 17 = Ecology Consulting 2012; 18 = Osborn *et al.* 2000; 19 = Johnson *et al.* 2000; 20 = Johnson *et al.* 2002a; 21 = Johnson *et al.* 2002b; 22 = Johnson *et al.* 2003; 23 = Fernley *et al.* 2006; 24 = Pendlebury 2006; 25 = Erickson *et al.* 2003; 26 = Erickson *et al.* 2004; 27 = Jain 2005. Countries: B = Belgium; NL = Netherlands; N = Norway; POL = Poland; S = Sweden; UK = United Kingdom; USA = United States of America. Observation methods: ACC = accidental finding; CS = carcass search; RAD = radar; FL = flight observations through/across wind farm; BC = bird counts. * = linear alignment; ** = turbines in 2 lines; *** = cluster.

Species	No. collisions	No. flights within wind farm	Wind farm name/location	Built	No. turbines (hub height)	Years/winters of post-construction monitoring	Obs. method	Duration of post-construction monitoring	CS linked to bird presence	Refs
Domestic Goose	2	Not recorded	Boudewijnkanaal, Belgium	2000–2001	14 * (60 m)	5	CS	*c.* 26 days/year (fortnightly; 2002–2006)	NO	1
Domestic Goose	1	Not recorded	Kluizendok, Belgium	2005	11** (98 m)	3	CS	*c.* 26 days/year (fortnightly; 2005–2007)	NO	1
Greylag Goose	1	Not recorded	Oostdam, Belgium	<2001	23** (23–55 m)	7	CS	*c.* 26 days/year (fortnightly; 2001–2007)	NO	1
Goose sp.	0	296,420 bird-flights in 2009/10; 70,450 in 2010/11[a]	Saint Nikola, Bulgaria	2009	52*** (105 m)	2[a]	CS, RAD FL & BC	78 days/winter (435 turbines searched in *c.* 50 days in 2010/11)	YES	2, 3
Whooper Swan	1	Not recorded	Niebull-Fahrehoft, Germany	Not known	?	ACC	ACC		NO	4
Mute Swan	1	Not recorded	Kossdorf, Germany	2004	15 (125 m)	1	1 CS	Only 1 search	NO	4
Mute Swan	1	Not recorded	Nauen-I, Germany	1999	22 (85–100 m)	1	CS	6 days (6–12 visits per turbine, in 2006)	NO	4

Appendix 1 (*continued*)

Species	No. collisions	No. flights within wind farm	Wind farm name/location	Built	No. turbines (hub height)	Years/winters of post-construction monitoring	Obs. method	Duration of post-construction monitoring	CS linked to bird presence	Refs
Mute Swan	1	Not recorded	Schlalach, Germany	2010	16 (179 m)	1	CS	*c.* 22 days (fortnightly Feb–Dec, in 2011)	NO	4
Mute Swan	1	Not recorded	Seelow, Germany	1996	1 + 13 (85–145 m)	ACC	ACC		NO	4
Mute Swan	1	Not recorded	Wittmannsdorf, Germany	1994–1997	7 (63–85)	1	CS	*c.* 52 days (2003–2004)	NO	4
Mute Swan	1	Not recorded	Zitz-Warchau, Germany	2003	20 (112 m)	4	CS	61–150 days/year (Nov 2003–Mar 2007)	NO	4
White-fronted Goose	2	Not recorded	Zitz-Warchau, Germany	1997–2003	20 (112 m)	4	CS		NO	4
Swan sp.	1	Not recorded	Klein Mutz, Germany	2003	8 (118 m)	ACC	ACC		NO	4
White-fronted Goose	1	Not recorded	Heidehof-Jüterbog, Germany	2007	31 (149 m)	?	CS	*c.* 22 days/year (fortnightly Feb–Dec)	NO	4
Bean Goose	1	Not recorded	Göllnitz, Germany	2001	6 (93–94 m)	ACC	ACC		NO	4
Goose sp.	1	Not recorded	Etzin-II, Germany	2006	3 (149 m)	1	1 CS	Only 1 search	NO	4
Goose sp.	1	Not recorded	Zachow-II, Germany	1994–1998	3 (55–85 m)	?	CS	Only 1 single search/year	NO	4
Mute Swan	1	Not recorded	Stuthof, Germany	?	*c.* 10 (<150 m)	?	CS	Only 1 single search/year	NO	4
Mute Swan	4	Not recorded	Dollart, Germany	?	Large wind farm (<100m)	?	CS	?	NO	4
Mute Swan	2	Not recorded	Wybelsumer, Germany	?	Large wind farm (<100m)	?	CS	?	NO	4
Swan sp.	3	Not recorded	Wybelsumer, Germany	?	?	?	CS	?	NO	4
Greylag Goose	1	Not recorded	Wybelsumer, Germany	?	?	?	CS	?	NO	4
Mute Swan	1	Not recorded	? (in Niedersachsen, Germany)	?	<10 (<100)	1	CS	52 days (weekly, 2001)	NO	4
Greylag Goose	1	Not recorded	Riepster Hamrich, Germany	??	?	?	?	?	?	4
Greylag Goose	1	Not recorded	Oevenum-Föhr, Germany	?	?	?	?	?	?	4

Bean Goose	1	Not recorded	Belgern, Germany	?	1	1	CS	Oct 1999–Mar 2000	NO	4
Bean Goose	1	Not recorded	Aschekippe Trattendorf-Zerre, Germany	?	1	?	CS	?	NO	4
Mute Swan	1	Not recorded	Krevese, Germany	?	1? (<100 m)	1	CS	52 days (weekly, 2000)	NO	4
Goose sp.	1									
Mute Swan	1	Not recorded	Westfehmarn, Germany	?	? (<100 m)	?	CS	1 search per week	NO	4
Barnacle Goose	6	Not recorded	Fehmarn, Germany	1990	>75*** (several sites) (<100 m)	1	CS & RAD	Autumn 2009	YES	4, 5
Brent Goose	1	Not recorded	Kreerak, Nths	1990	5 (30 m)	1	CS	*c.* 180 days (28.04.90–29.04.91)	NO	6
Mute Swan	3	Not recorded	Urk, Netherlands	1987	25* (30 m)	2	CS	Daily in autumn; 1–2 times/week in winter and spring	YES	7
Bewick's Swan	0–2	1,664+ (101 groups)	Waterkaaptocht, Nths	2003	8* (78 m)	1	CS & RAD	31 search-days (winter 2006/07)	YES	8, 9
			ECN test-park, Nths	2003–2006	9** (90 m)	1				
Greylag Goose	2	Not recorded	Anna Vosdijk, Nths	2007	5* (80 m)	1	CS	1–2 times/week	?	10
Greylag Goose	6	Not recorded	Sabinapolder, Nths	1995	6* (48 m)	2	CS & RAD	138 search-days in 2-year study	YES	11
Canada Goose	1	Not recorded	Sabinapolder, Nths	1995	6* (48 m)	2	CS & RAD	138 search-days in 2-year study	YES	11
Whooper Swan	1	Not recorded	Smøla, Norway	2002	68*** (70 m)	7	CS	52 days/year (weekly; 2003–2009)	NO	12
Greylag Goose	3	Not recorded	Smøla, Norway	2002	68*** (70 m)	7	CS	52 days/year (weekly; 2003–2009)	NO	12
Mute Swan	5	Not recorded	Kisielice-Łodygowo, Poland	2007	27*** (85 m)	?	CS	?	?	4, 13
Greylag Goose	1	Not recorded	Elgea Alava, Spain	<2003	???	?	CS	?	?	4
Greylag Goose	1	Not recorded	Elgea-Urkilla, Spain	2003	40***	?	CS	?	?	4
Greylag Goose	1	Not recorded	Guipúzcoa-Álava, Spain	<2009	???	?	CS	?	?	4
Mute Swan	1	Not recorded	Skåne (*c.* 20 sites), Sweden	<2002	51 (varied)	1	CS	1 visit/site (Aug–Oct 2002)	NO	14, 15
Pink-footed Goose	0	9	Barrow Offshore, UK	2006	30 *** (75 m)	1	FL[b]	21 days (2007)	YES	16
Pink-footed Goose	0	4 groups	Hellrigg, UK	2011	4*** (80 m)	1	CS, BC & FL	12 search-days; 38 h flight observations (22.12.11–09.03.12)	YES	17

Appendix 1 (*continued*)

Species	No. collisions	No. flights within wind farm	Wind farm name/location	Built	No. turbines (hub height)	Years/winters of post-construction monitoring	Obs. method	Duration of post-construction monitoring	CS linked to bird presence	Refs
Canada Goose	0	909 observations	Buffalo Ridge, USA	1994–1999	354*** (36–50 m)	4	CS & BC	Fortnightly bird counts and searches (15 Mar–15 Nov); 21–91 turbines checked each year (1996–1999)	YES	18, 19, 20
Snow Goose	0	278 observations	Buffalo Ridge, USA	1994–1999	354*** (36–50 m)	4	CS & BC		YES	18, 19, 20
White-fronted Goose	0	92 observations (in 1997)	Buffalo Ridge, USA	1994–1999	354*** (36–50 m)	4	CS & BC		YES	18, 19, 20
Canada Goose	2	Not recorded	Klondike, USA	2002	16* (65 m)	1	CS & BC	BC mostly pre-construction; 13 searches (monthly, Mar 2002–Mar 2003	NO[c]	21, 22, 23, 24
Canada Goose	0	Not recorded (proximity not assessed)	Nine Canyon, USA	2002	300*** (60 m)	1	CS	19 searches (4–5 days each; Sep 2002–Aug 2003)	NO	25
Canada Goose	1	11 groups (363 birds)	Stateline, USA	2001–2002	454*** (50 m)	2	CS & BC	5–6 searches of 399 turbines in 2002; 6–7 searches of 454 turbines in 2003	UNCLEAR	26
Canada Goose	0	Not recorded	Top of Iowa, USA	2001	89*** (72 m)	2	CS	*c.* 150 searches/year (i.e. every 2–3 days) under 26 of 89 turbines in Apr–Dec 2003 and Mar–Dec 2004.	NO	23, 24, 27

[a]Carcass searches reported for one winter; flight-line data recorded in two winters. Number of flights said to be for flights within project area (*i.e.* not necessarily through the wind farm), though flights through/across the wind farm illustrated on maps in the report, and 64% of flights were at rotor height. Groups of turbines stopped in January to reduce collision risk (Zehtindjiev & Whitfield 2011).
[b]Observations made at a distance of 7–9 km.
[c]Use of Klondike study area by waterbirds said to be low; only species of waterfowl observed was Canada Geese, with 43 flocks (4,845 individuals) seen flying over the study area in the year-long pre-construction survey in 2001 (Johnson *et al.* 2002b).