

Habitat use, disturbance and collision risks for Bewick's Swans *Cygnus columbianus bewickii* wintering near a wind farm in the Netherlands

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Abstract

Each winter ~ 30% of the Northwest European Bewick's Swan *Cygnus columbianus bewickii* population feeds in Polder Wieringermeer, the Netherlands, on waste crops left after the harvest. The area has also become important for generating energy as a result of wind farm development. This study analyses pre- and post-construction data on Bewick's Swan distribution, movements and foraging behaviour in the vicinity of a nine-turbine wind farm site, in order to determine the effects of wind turbines on wintering swans. The swans' flight-lines between feeding areas and the roost were recorded visually and using radar over 10 evenings in good weather conditions. Food availability on different agricultural plots appeared to be an important factor explaining swan numbers and distribution in the area. In circumstances with even food availability early in the season, swans showed a preference for foraging in areas further away from the turbines, indicating some displacement caused by the turbines. Nevertheless, swans increasingly fed closer to the wind turbines during the course of the season in response to food availability. The likelihood that a single Bewick's Swan passing through the wind farm will collide with a turbine (collision risk) at the nine-turbine site, determined from swan movements through the wind farm (number of swan flights per unit length per unit time) and from regular searches for carcasses, was estimated at 0–0.04% in winter 2006/2007. Avoidance behaviour was observed, with birds navigating around and between the lines of turbines. The observed disturbance of foraging birds early in the season, the acquired knowledge of avoidance responses, and the calculated collision rates in this study can be used for future assessments during planning and construction of new wind farms in wintering areas of Bewick's Swans, especially in areas where important congregations of world or flyway populations occur.

Key words: barrier effects, Bewick's Swan, collision, disturbance, Wieringermeer, wind turbines.

Government plans to reduce carbon emissions to slow down global climate change, include increasing the capacity to generate energy from renewable sources such as wind and tide. A primary area for the production of wind energy in the Netherlands is Polder Wieringermeer, in the northwest part of the country. Traditionally this area was cultivated agricultural land, but nowadays it is also increasingly used for generation of renewable energy. By 2010, several wind farms had been built in the area, with a total of 54 large turbines (>1 MW, hub height above 70 m) installed, along with 36 smaller solitary turbines (0.85 MW, hub height ~ 50 m). These ninety turbines generate a total of 106 MW of electricity but new turbines planned for the future will increase the capacity to 400 MW.

The Northwest European population of Bewick's Swans *Cygnus columbianus bewickii* has decreased substantially in numbers since the mid 1990s. It was estimated at 21,500 individuals in January 2005, and national trend indices indicate a further decline since then (Rees & Beekman 2010). The swans breed in arctic Russia and a large proportion of the population winters in the UK and the Netherlands. Polder Wieringermeer is an internationally important wintering area for the species, with counts indicating that 25–33% of the population use the site each winter. The polder provides feeding grounds in close proximity to roosting places, and the birds are able to feed on crop remains (mainly sugar beet) left after the harvest, typically from November onwards (van Gils & Tijssen 2007).

Previous studies have discussed three main ways in which wind turbines can affect

bird populations: through the disturbance and displacement of foraging and resting birds, by flying birds colliding with the turbines, and by the turbines potentially acting as a barrier during flight (Langston & Pullan 2003; Dirksen *et al.* 2007; Percival 2007; Drewitt & Langston 2008). Wind farms are known to have negative effects on some species (*e.g.* Madders & Whitfield 2006; Thelander & Smallwood 2007), but more detailed understanding of species-specific responses to the turbines is required for an adequate assessment of the impact of the turbines on bird populations. Research into the disturbance and displacement of birds has mostly focussed on changes in numbers at turbine locations (*i.e.* calculated a species-specific 'disturbance distance', *e.g.* Winkelman 1989; Schreiber 1993; Kruckenberg & Jaene 1999), but disturbance of foraging and resting waterbirds can also result in changes in physiology, behaviour and habitat choice (*e.g.* Orloff & Flannery 1992; Kruckenberg & Jaene 1999). Swans are potentially at risk of collisions because Whooper Swans are known to fly at altitudes of 5–45 m during commuting flights to feeding areas (Larsen & Clausen 2002). The collision risk (*i.e.* the probability that a given bird flying through the wind farm will collide with a turbine) is a combination of the probability of collision and the movement of birds through the wind farm area (*cf.* Desholm *et al.* 2006; Band *et al.* 2007). In general, the number of birds that collide with a turbine in a specific wind farm per unit time (*i.e.* the collision rate) differs between studies. Across species and locations, previously found collision rates range from 3.7–58

birds per year per turbine (*e.g.* Winkelman 1989; Winkelman 1992; Everaert & Stienen 2007). This rate depends on a range of factors including the number of birds flying through the area, the location and lay-out of the wind farm, landscape features, and the behaviour and physiology of the species (Thelander *et al.* 2003; Dirksen *et al.* 2007; de Lucas *et al.* 2008; Drewitt & Langston 2008; Martin 2011). The mortality rate and collision risk for Bewick's Swans have been modelled previously for a wind farm at Cheyne Court in the UK. Here, collision risk was estimated at 0.145 % of bird passages, with a mortality rate of 0.06 swans over 180 days, but it should be noted that the study used an avoidance rate of 0.9962 from observations made mainly of gulls (Painter *et al.* 1999) which have different flight characteristics (Chamberlain *et al.* 2006).

To the best of our knowledge, the study presented here is the first before/after assessment of the possible impact of wind turbines on Bewick's Swans at a wintering site. We used pre- and post-construction data to study whether the installation of multiple new wind turbines coincided with a change in Bewick's Swan numbers, distribution and habitat choice in the area. Furthermore, collision risk was assessed for Bewick's Swans at the site from a calculated collision rate and from measures of flight intensity through the area covered by the wind farm.

Methods

Study area

Between February 2003 (start of first building activities) and July 2006 (opening

and first month of full operation), the Energy Research Centre of the Netherlands (ECN) built a wind farm in the spring and summer months in Polder Wieringermeer (52°49'54"N, 5°04'50"E) in one of the agricultural areas used by large numbers of wintering Bewick's Swans. This farm consists of two lines of different types of turbines positioned west-east with a northern row of five and a southern row of four turbines. All turbines were rated > 2.3 MW with an average hub height of 90 m and a rotor diameter of 100 m (*i.e.* a rotor sweep area of 40–140 m above ground level). Turbines in the northern row are on average 300 m apart whereas turbines in the southern row are ~ 400 m apart, and the two rows are 1,600 m apart. Small red lights shine during darkness on top of the hub.

The study area (~ 1,860 ha) around the ECN turbines was divided into two contiguous parts: the wind farm area (~ 770 ha) in which the new wind farm was built, and an adjacent unchanged area (~ 1,090 ha) with no new turbines, hereafter referred to as the 'control' area (see Fig. 4 for an outline of the study area). Some solitary wind turbines were present near farms (3 in the wind farm area; 6 in the unchanged area) in the study area. These were installed several years before the study commenced and were smaller (maximum height reached by the rotors = ~ 80 m) than the new wind farm turbines.

Displacement of swans from their feeding areas

Surveys of the study area were conducted at around midday on a near daily basis in the

winter, prior to construction (from 23 October 2000 until 7 March 2001), and again after construction (from 27 October 2006 until 25 January 2007), to determine whether the swans were displaced from some of their feeding areas. The number of wintering swans present was recorded on each occasion, together with their distribution across the site and foraging behaviour. Swan numbers and distribution were also recorded in winters 2003/04 to 2005/06 inclusive, but these surveys were part of the monthly waterbird counts undertaken in the Netherlands, so were less frequent than in winters 2000/2001 and 2006/2007. Nevertheless, they provide a good indication of the numbers of swans present for each winter between the two study seasons. The distance from each group of swans (taken from the centre of the group) to the nearest turbine was measured using ArcGIS for each of the count days.

The swans' favoured food in the Polder Wieringermeer (mainly waste sugar beet and, to a lesser extent, carrots and potatoes) was available only between harvest and ploughing, the length of this period being determined by the farmers (Dirksen *et al.* 1991; W. Tijssen unpubl. data). Food availability in the study area was recorded during 2006/2007 (but not in 2000/2001) by mapping the different crop types on a field-by-field basis, keeping track of the harvest and noting the ploughing dates. By doing so, the total number of hectares of sugar beet fields was recorded. From farming records the total number of hectares of sugar beet fields in the study area in 2000/2001 could be determined.

Quantification of Bewick's Swan flights

The movements of swans passing the wind farm area during flights to and from night-time roosts were recorded visually and with radar. The use of radar provided precise information on flight behaviour (flight-lines) through and around the wind farms, as well as quantifying the number of flights, particularly during hours of darkness when visual observations were not possible. The radar system used was an X-band marine surveillance radar with a peak power of 12 kW (Furuno FR1510 MARK-3, X-band pulse repeat frequency $9,410 \pm 30$ MHz, vertical beam width 20° , rotation speed 24 rpm, supplied by Radio Holland Rotterdam) mounted on a 2 m high tripod. Radar range was set to 2.8 km to cover the entire study area. Due to lower detection probability at the outer limit of the radar range, effectively a circle around the radar with a radius of 2.5 km (19.6 km^2) was sampled. The radar system was positioned 0.8–1.5 km from the turbines and the radar thus reached a minimum of ~ 1 km beyond the turbines.

Bewick's Swan movements in the study area were monitored using radar over five evenings and the following mornings in winter 2000/01 from four hours around sunset and four hours around sunrise (two hours before until two hours after, in each case), to provide the Environmental Impact Assessment (EIA) of the proposed wind farm with baseline data on the flight-paths taken by the birds. Fieldwork was also carried out on seven evenings in 2006/2007, in differing but albeit generally good weather conditions for the time of year

(temperature = 6°–15°C, wind direction = S–SW; wind speed = 3–7 Bft; cloud cover = 4/8 to 8/8; precipitation = dry, with only occasional showers), from approximately 2 h before to 2 h after sunset. The departure of different groups of Bewick's Swans from the fields to roosting areas on nearby Lake IJsselmeer was highly synchronised and occurred over a relatively short period of time. Observations continued until all swans, as determined by the swan survey earlier that day, had left the study area for the roost. In case of poor visibility (due to darkness), species identification was determined from the birds' flight calls and the characteristic behaviour (size and speed) of echoes on the radar screen. If a potential group of swans seen on the radar was out of audible range, one of the field observers was directed towards the flying group to confirm species identification. Swan movements were also recorded on three additional evenings in 2006/2007 at a second wind farm in Polder Wieringermeer ('Waterkaaptocht'; 52°51'46"N, 5°02'22"E; ~ 4 km from the study area), which has eight similar 2.3 MW turbines in one line (see Krijgsveld *et al.* 2009), to increase the number of flight records.

All bird tracks observed in the field were digitised and, if positively identified by field observers, flight-path specifications (*i.e.* date, time, species, number of birds and altitude of flight) were stored in an ArcGIS database. This database was used to produce maps of the swans' flight-lines within and around the boundaries of the wind farms. The detailed flight data made it possible to calculate the proportion of the swans present in the study area and in adjacent feeding areas that passed

through the wind farm during flights to the roost. About 30 min after sunset observers were not able to observe flying swans in the field; however, at close distances, structures such as wind turbines might still be visible to flying swans, especially when some background illumination is present. As the exact extent of this phenomenon is unknown, we decided in this study to set the boundary between dark and light at 30 min after sunset, in other words when observers encountered reduced visibility. A diversion from the intended flight-path was defined as occasions when a swan discontinued its flight direction, in either the horizontal or vertical plane. These avoidance records were used in calculating swan movement ('flux') through the wind farm, which in turn was used to determine collision risk as described below.

Collision risk

The collision risk for Bewick's Swans in the study area was calculated by dividing the collision rate by the flux (*i.e.* the number of Bewick's Swan per area [m²] within the wind farm per unit time). Collision rate was investigated by regular searches for corpses combined with corpse disappearance rate experiments. Between 27 November 2006 and 2 February 2007, the area below the turbines in the study area and also at the Waterkaaptocht wind farm was searched for collision victims at 2–3 day intervals. The additional wind farm was included to increase the probability of finding collision victims, as earlier research found that the frequency with which birds collided with turbines was low (*e.g.* Winkelman 1992; Krijgsveld *et al.* 2009). The area within a

radius of 100 m of each turbine was searched, on the basis that previous studies found that victims fall within a radius of up to 1.1 times the hub height of the turbine (Winkelman 1992; Grünkorn *et al.* 2009), *i.e.* up to 88 m in this study. Swans are expected to fall at even closer range due to their high body mass (Krijgsveld *et al.* 2009). The searched area (100 m radius) therefore was considered large enough to include all potential victims. We included only those turbines under which vegetation type and height did not obstruct visibility of potential victims. Nevertheless, the total searched area in the winter of 2006/2007 was 15,697,457 m² (98.6%) of a total area of 15,927,874 m² around the turbines in both wind farms. The area below a turbine was searched either with binoculars from the base of the turbine (ECN wind farm) or by walking in parallel lines 4–6 m apart (Waterkaaptocht, see Krijgsveld *et al.* 2009), depending on visibility of potential victims. Because swans are conspicuous, with their large size and white colour, a detection probability of 100% was assumed. All victims found during the searches were recorded, photographed and sent to the Dutch veterinary laboratory CIDC-Lelystad for *post mortem* examination (internally and externally) to determine the cause of death.

Scavenging predators, such as Common Buzzard *Buteo buteo* and Red Fox *Vulpes vulpes*, roam the study area and might remove swan corpses during the study period, resulting in underestimates of collision rates. To determine the disappearance rate, seven defrosted carcasses were laid out in the study area (1 Brent Goose *Branta bernicla*, 4 Bewick's

Swans and 2 Mute Swans *Cygnus olor*), placed semi-randomly in all directions at distances of 1–100 m from the turbines. Turbines used for the disappearance test were not used in victim searches, to avoid predators and scavengers being attracted to the former, which could lead to an increase in disappearance of collision victims. Presence and condition (eaten, moved, buried) of carcasses were registered for two weeks after carcasses had been laid out. The probability that a carcass remained at a location was calculated as the probability that a carcass present on day t was still present at day $t + 1$, day $t + 2$, *etc.* Calculations were similar to those undertaken by Winkelman (1992) to facilitate comparison with other studies.

The number of collision victims, corrected for observer efficiency and disappearance rate (N_c), was determined by correcting the number of victims found (N_f), for the probability that a victim remains at the location rather than disappearing through scavenging (P_d), the probability of finding a victim (P_f), the fraction of the total area (100 m radius) underneath the turbine that was searched (F_s), and for the fraction of days of the research period that victims were searched for (F_d). The corrected number of collision victims used to calculate the collision rate for swans within the whole wind farm was thus calculated as follows (following Winkelman 1992): $N_c = N_f / (P_d \times P_f \times F_s \times F_d)$.

Statistical analysis

Data were analysed using SPSS version 15.0. Changes in swan numbers wintering in the study area over the years were calculated as a

proportion of the total number recorded across Polder Wieringermeer (Fig. 1). The numbers of swans in the wind farm area and the adjacent unchanged ('control') area did not follow a normal or a Poisson distribution (Figs. 1 & 2); non-parametric statistics (Chi-square test and Spearman Rank correlation) therefore were used to analyse these data. Distance to the nearest turbine in relation to date (Fig. 3) was analysed using a logarithmic regression. Linear regressions on arcsine transformed proportionate data were used to model the carcass disappearance rate (Fig. 5). Mean values are given \pm s.d. unless otherwise stated.

Results

Swan numbers during the winter

Bewick's Swans were present in the study area from 23 October to 7 March in winter 2000/01 and from 1 November to 28 January in winter 2006/07. The maximum numbers counted in the study area (*i.e.* in both the 'control' and the wind farm areas) were significantly lower in 2006/07 than in 2000/01 ($\chi^2_1 = 36.9$, $P < 0.001$; Table 1). The shorter period that swans were present in the area, in combination with the lower peak counts, resulted in fewer swan-days being recorded in the year following construction than beforehand ($\chi^2_1 = 128.6$, $P < 0.001$). The wind farm area and the adjacent 'control' area showed a similar decrease in the total number of swan-days, but the seasonal maximum count decreased more substantially within the wind farm site (Table 1).

In contrast, the maximum number of birds present across the whole of Polder

Wieringermeer was higher after construction (Table 1). Pre-construction, in 2000/2001, up to 89% of the winter's maximum number of swans counted across Polder Wieringermeer was found in the wind farm area and 70% in the adjacent 'control' area. Post-construction, in 2006/2007, these percentages decreased to 24% and 29% respectively. The proportion of the total number of birds in Polder Wieringermeer that visited the study area decreased significantly in the years between 2000/2001 and 2006/2007 ($r_s = -0.90$, $n = 5$, $P < 0.05$; Fig. 1).

The proportion of the Northwest European Bewick's Swan population wintering in Polder Wieringermeer has increased during the study, from 5% of the total population in 2000/2001 to 11% in 2006/2007 (Rees & Beekman 2010; Table 1). In contrast, the study area within Polder Wieringermeer appears to have become less attractive with 5% of the Northwest European population present in 2000/2001 and 3% in 2006/2007.

Swan feeding distribution

There was a within-winter shift in the distribution of swans across the study area in relation to variation in the availability of sugar beet remains following the harvest in the 2006/2007 season. Numbers in the 'control' area correlated significantly with the number of hectares of fields with food remains in that area during habitat assessments ($r_s = 0.38$, $n = 85$, $P < 0.01$), but there was no significant association between the number of swans and the number of hectares with food remains in the wind farm area ($r_s = 0.24$, $n = 64$, n.s.). In 2000/2001

Table 1. Numbers of swan-days (sum of number of swans on each day of the field season, on days when counts were missing, gaps in data were calculated as the average of the two counts spanning the missing count) and seasonal maximum numbers in the 'control' and wind farm areas in the two study seasons 2000/2001 and 2006/2007. Also shown are the proportions of the total number of birds wintering in the Wieringermeer and of the total Northwest European population. Changes in abundance between the two study seasons are expressed as a percentage.

	2000/2001	2006/2007	Change
<i>Total number of swan-days</i>			
'Control' area	20,714	4,546	- 78%
Wind farm area	34,586	9,526	- 72%
<i>Seasonal maximum count</i>			
'Control' area	860	550	- 36%
Wind farm area	1,099	530	- 52%
Polder Wieringermeer	1,230	2,233	+ 82%
<i>Proportion of Wieringermeer birds</i>			
'Control' area	0.70	0.29	- 59%
Wind farm area	0.89	0.24	- 73%
<i>NW European population (Rees & Beekman 2010)</i>			
	23,000	21,500*	- 7%
<i>Proportion of NW European population</i>			
Polder Wieringermeer	0.05	0.11	+ 120%
Entire study area	0.05	0.03	- 40%

*Note that the Northwest European population figure for Bewick's Swans described in Rees & Beekman (2010) is based on the census of January 2005 and not 2007.

such a shift was not observed and Bewick's Swans were present in both 'control' and wind farm areas throughout the season.

The number of birds in the wind farm area increased when the number of hectares with available food decreased in the 'control' area ($r_s = -2.53$, $n = 85$, $P < 0.05$; Fig. 2).

These results imply that, when food was available on fields both with and without turbines, the swans generally foraged in the area without the newly-constructed turbines. Up to 530 birds (95% of the peak count for the study area in 2006/07) were recorded on fields within the area with new

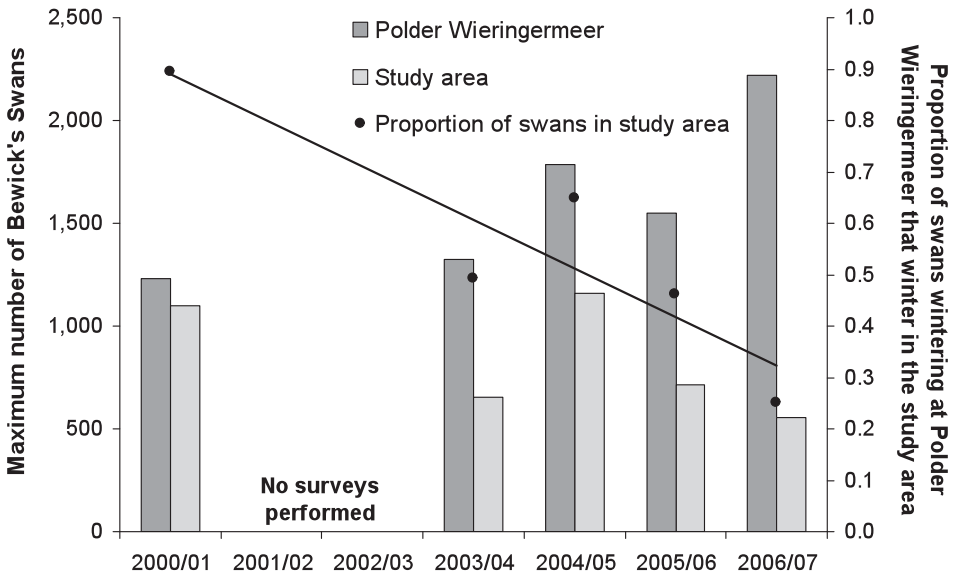


Figure 1. Maximum numbers of swans counted each winter in the study area and across the Polder Wieringermeer. The proportion of the Bewick's Swans wintering in Polder Wieringermeer recorded in the study area is also illustrated. The wind farm was built during the summer months between summer 2003 and summer 2006.

turbines on 12 individual days in November, but these were resting on grass and not foraging. At the beginning of the 2006/2007 season, when sugar beet remains were available in both areas, the swans foraged predominantly in the 'control' area. Later in the season when most of the fields in the 'control' area had been ploughed, the swans moved to the wind farm area and closer to the turbines to utilise the sugar beet remains that were still available there.

Bewick's Swans foraged significantly closer to the turbines as the season progressed (Fig. 3; logarithmic regression of distance of birds to the nearest turbine versus date: $F_{1,84} = 65.62$, $r^2 = 0.44$, $P < 0.001$). This effect was attributable mainly to a large number of birds feeding at

greater distances from the turbines at the start of the season. Excluding these birds from the analysis still resulted in a significant, albeit smaller, decrease in the distance of the swans from the turbines as the winter progressed ($F_{1,77} = 21.05$, $r^2 = 0.22$, $P < 0.001$). The decrease in distance was not due to the distribution of harvested fields as the distance of harvested fields to the turbines did not decrease significantly during the course of the season (linear regression of distance of fields to the nearest turbine versus date: $F_{1,32} = 0.39$, $r^2 = 0.01$, $P = \text{n.s.}$). The distance between foraging and resting Bewick's Swans and the turbines was on average 560 m (s.e. = 57.9, $n = 86$), whereas the minimum recorded distance was 125 m.

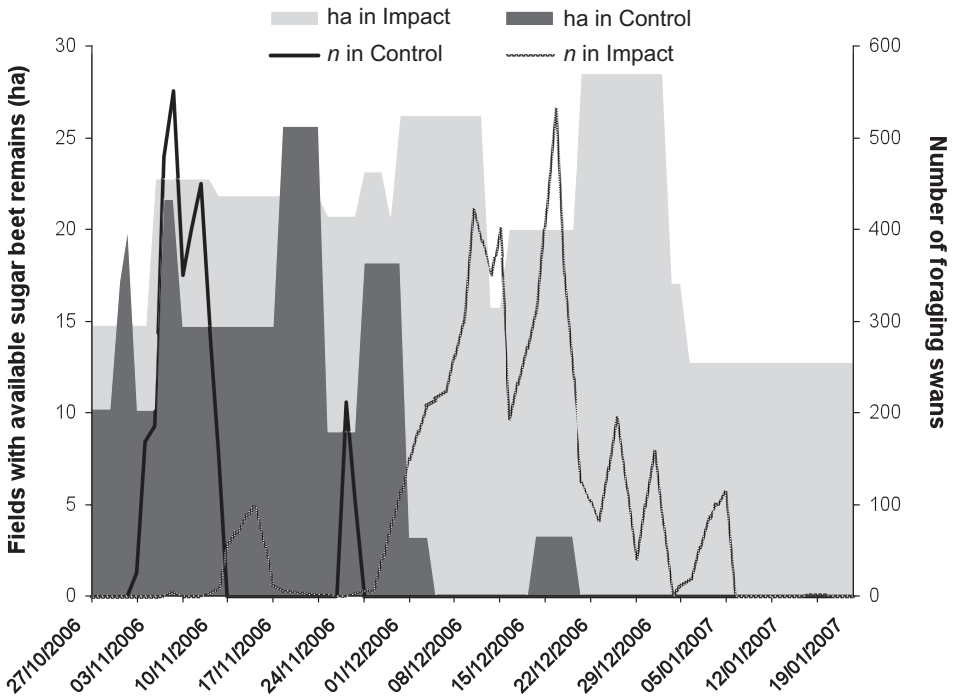


Figure 2. Numbers of swans in the 'Control' (no new large wind turbines) and wind farm 'Impact' (nine new large wind turbines) sections of the study area in relation to the availability of sugar beet remains. Early in the winter, when waste sugar beet was available in both areas, Bewick's Swans fed in areas away from the turbines.

Swan flights in the study area

Swans flew towards the roosting sites in the late evening and early night. At least 1,664 Bewick's Swan flight-paths for 101 groups flying to the roost were recorded in both wind farms during eight out of ten fieldwork evenings in 2006/2007 (flights were not recorded during two evenings as swans were absent from the study area and no swans flew past from adjacent areas). This is a minimum estimate of the total number of swan flights as 33 groups were recorded only as radar tracks in complete

darkness, > 30 minutes after sunset. The birds giving these tracks could be identified as Bewick's Swans on the basis of flight calls but group size could not be determined. A minimum group size was estimated on these occasions, based on the number of birds counted by the field observer earlier in the day. There was substantial variation in the timing of the evening flights to the roost. Of all groups of swans, $61 \pm 41\%$ (range: 0–100%, $n = 7$ nights, 101 groups) flew after dark (> 30 min after sunset) each night in 2006/2007. Group size was limited to 16 ± 41 (range 1–300) birds at maximum. Of all

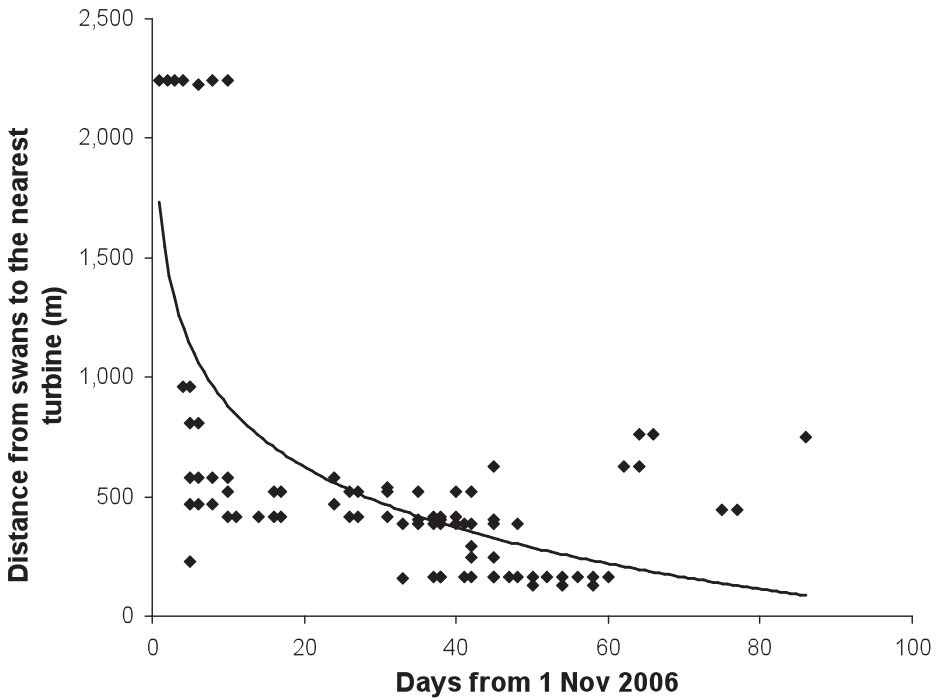


Figure 3. Distance of Bewick's Swan flocks in the study area to the nearest turbine during the course of winter 2006/07, from 1 November onwards (logarithmic regression with $r^2 = 0.44$).

individual swans flying towards the roosting sites, $75 \pm 35\%$ (range: 0–100%, $n = 7$ nights, 1,664 birds) flew after dark. Birds that flew past the outer edge of the wind farm adjusted their flight direction at a distance of a few hundred metres at maximum ($n = 562$ birds). Of all swans present in the area an average per day of $16 \pm 22.5\%$ (range: 0–65%) flew through the wind farm during commuting flights (Table 2).

In 2000/2001, Bewick's Swans generally flew in straight lines from fields where they had been feeding during the day towards the roost site (Lake IJsselmeer), although no fixed flight-paths through the landscape

were identified. Foraging areas were similar in 2006/2007 (albeit not identical to those recorded in 2000/01, due to crop rotation and a decrease in the area of sugar beet available) and birds were seen to fly in a similar direction to the roost. In 2006/2007 birds adjusted their flight-paths to the presence of the wind turbines during both light and darkness; however, neither large deflections around the entire wind farm nor panic reactions in the air were observed. Birds avoided turbines by navigating around individual turbines and between rows of turbines (as illustrated for the evening of 24 November 2006 in Fig. 4).

Table 2. Bewick's Swan flights in the study area (ECN) and in the nearby Waterkaaptocht wind farm (WK), recorded as visual and radar observations of the swans' flight-paths. The number of swans that were present in, or flying through the study area is shown; the percentage of these birds that flew close to or through the wind farm during commuting flights (% head towards wind farm), and thus potentially at risk of collision, was calculated (*i.e.* number flying towards wind farm/number swans*100). Of the birds that flew toward the wind farm, some avoided the wind farm entirely (% deflecting, *i.e.* number deflecting/number swans*100) and some flew through the wind farm (% through wind farm, *i.e.* number through wind farm/number swans*100).

Date	Location	No. swans	% head to wind farm	% deflecting	% through wind farm
21 Nov 2006	ECN	94	18	14	4
24 Nov 2006	ECN	294	100	98	2
01 Dec 2006	ECN	51	100	100	0
07 Dec 2006	ECN	459	66	1	65
16 Jan 2007	ECN	9	100	100	0
01 Dec 2006	WK	351	43	12	32
03 Jan 2007	WK	227	70	53	16
10 Jan 2007	WK	206	26	17	9
Mean \pm s.d.		211 \pm 155.1	65 \pm 33.6	49 \pm 44.0	16 \pm 22.5

Collision rate estimates

Two Bewick's Swans were found dead during > 2 months of searching for corpses in the study area (31 field days, average interval between searches = 2.3 days). Collision with the wind turbines could be ruled out as the cause of death in both cases for the following reasons: 1) there were no fractures or dislocations found during *post mortem* examinations, 2) the birds were found > 150 m from the turbines, and 3) the birds were

found upwind of the wind farm and the wind force was strong (4–5 Bft) on both days. Dissection did not reveal a clear cause of death and it was assumed that the swans had died of natural causes or been killed by a predator. That no swans were found to have collided with the turbines during the study period does not however, mean that the collision rate was zero. In order to consider the potential consequences of collision-related mortality, a collision rate was determined based on the assumption that

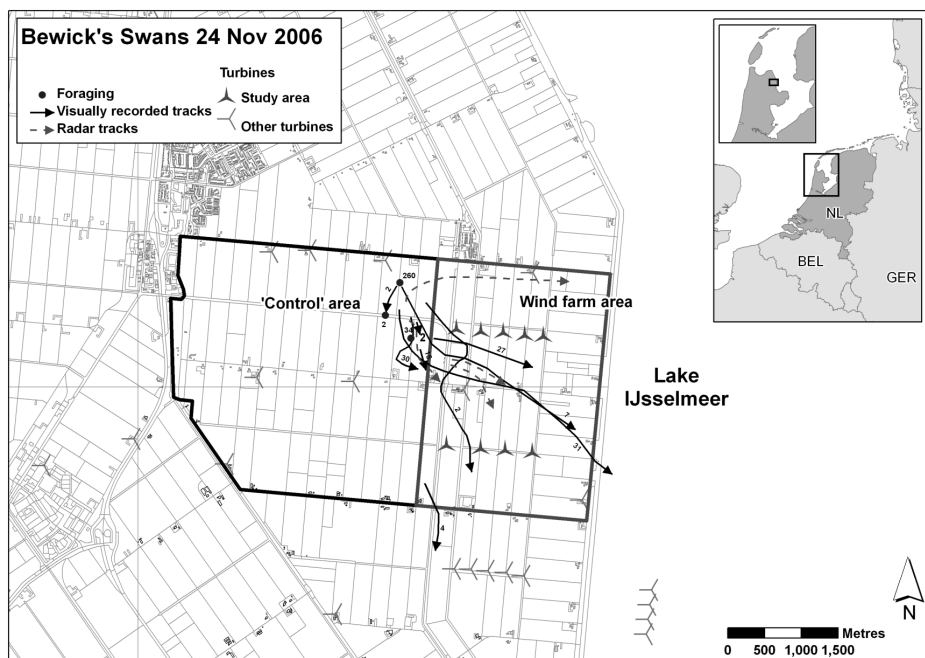


Figure 4. Map of the study area, showing the wind farm area (eastern part) and the adjacent 'control' area (western part), with Bewick's Swan flight-paths (arrows) from foraging fields to the Lake IJsselmeer roost on 24 November 2006. Numbers adjacent to the arrows indicate group size. Insert shows the location of the study area within the Netherlands.

one turbine victim was found in this study. This does not provide an absolute measure of collision rate, but does give a maximum estimate of collision rate for the studied season. This figure can subsequently be used to estimate maximum collision risk (see next section). The probability that a victim was found (P_f) was set to 1 (see Methods section).

The disappearance tests found that seven carcasses placed in the study area disappeared at a slow rate (Fig. 5). After four days, two were scavenged but all were still present and recognisable. Only one bird, a Mute Swan, totally disappeared during the 14-day trial; it was found to have been buried by a Red Fox at the foot of a turbine, six days

after being laid out. The remaining six carcasses were still present and recognisable after fourteen days. A scavenging animal moved two birds, by 1 m and 25 m respectively. The probability (P_d) that a bird was still present (after the average search interval in this study: 2.3 days) was 0.97 (linear regression: $P_d = -0.0255 \times \text{number of days since placement} + 1.026$, $r^2 = 0.71$, Fig. 5). The proportion of the total area underneath the turbine that was searched (F_s) was 0.986. The proportion of days over the search period that victims were searched for (F_d) was set to 1 as the mean interval between searches was smaller than the quickest disappearance of laid-out corpses.

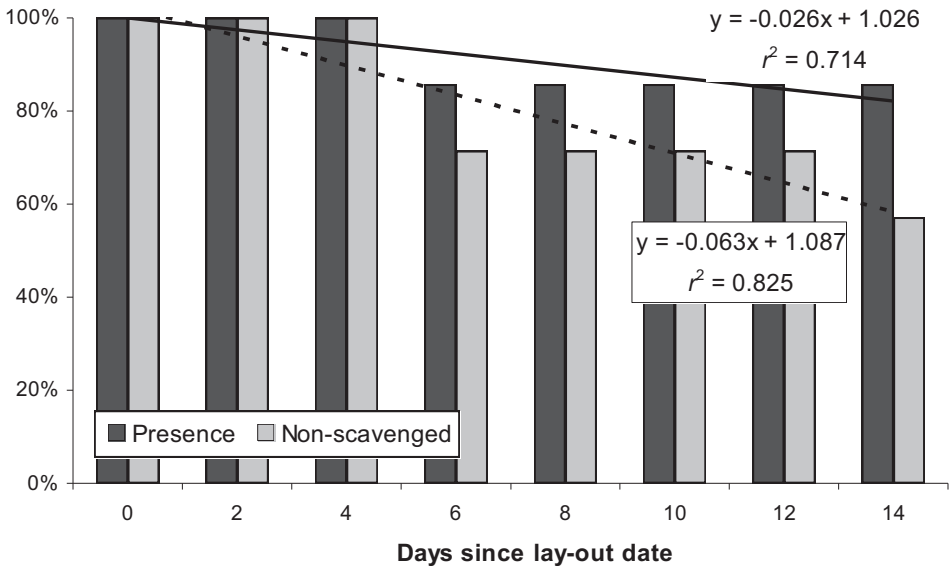


Figure 5. Status of seven carcasses for up to 14 days after being placed in the study area. Shown are the percentage of carcasses still present at the location after x days (black bars, closed line, linear regression $r^2 = 0.71$ and a slope of -0.026) and the percentage of carcasses remaining at the location without being scavenged by predators (grey bars, dotted line linear regression $r^2 = 0.83$ and a slope of -0.063).

Fitting the number of collision victims found (between zero and one) to the above parameters, gives an estimated collision rate of 0–1.05 swans colliding with the turbines each season for both wind farm sites. The study season consisted of 1,163 ‘turbine search days’ (number of turbines * number of search days) so the estimated collision rate is $1.05/1,163 = 0.0009$ per turbine per night. This collision rate implies a maximum of approximately 2–3 victims per winter (15 October – 15 March) in both wind farms considered in this study.

Collision risk

The near-daily swan counts gave an average of 132 Bewick's Swans present each evening during the 2006/2007 winter. Of these 132

birds, 16% flew through the wind farm area (see the swan flights section above). Assuming that the route to and from the roosting area is flown twice per day, and that dusk flights are as risky as dawn flights (noting that light levels are low in both cases), an average of 42 swan-flights pass the turbines every 24 h. With an estimated maximum collision rate of 0.0009 birds per turbine per night, the maximum collision risk can be calculated as: $(17 \text{ (turbines)} * 0.0009) / 42 = 0.0004$ (fraction), or 0.04% of all swans passing the two wind farms. Because no actual collision victims were found, this collision risk reflects the maximum risk; the actual risk estimate is of 0–0.04 % of Bewick's Swans passing these particular turbines colliding with them in each 24 h period.

Discussion

Disturbance of foraging swans

The proportion of the total number of Bewick's Swans wintering in Polder Wieringermeer that visited the study area was significantly lower after construction of the wind farm (2006/2007) than before it was built (2000/2001). This decrease was particularly evident in the wind farm area in comparison with the adjacent area, suggesting that the birds had been displaced by the newly-constructed turbines. Whilst the installation of the turbines seems to have made the wind farm area less attractive to the swans, the birds' use of the 'control' area (without newly-built turbines) also diminished, probably due to changes in food availability between the two study seasons. In particular, a smaller proportion of the study area was used for sugar beet cultivation in 2006/07 compared with 2000/2001 (100 ha *versus* 64 ha). On arrival in the Netherlands, Bewick's Swans start feeding on water plants in other parts of the country and only start feeding on crop remains in Polder Wieringermeer later in the season (Beekman *et al.* 1991; Dirksen *et al.* 1991). The timing of availability of harvest waste is thus important for wintering Bewick's Swans in the Netherlands and an absence or lower availability of crop remains might cause shifts to other foraging areas.

Our study found that displacement of Bewick's Swans from the wind farm area was most evident at the start of the season, when there appeared to be an abundant food supply for the birds. The swans were more likely to forage in areas without turbines while food was available in both the

'control' and wind farm areas. Only later in the season, when food sources were limited to just the wind farm area, swans increasingly fed in areas closer to the turbines. This decreasing distance between foraging swans and the turbines may be due to a lack of food further afield, to habituation to the wind farm, or a combination of these factors. Displacement by wind turbines has also been reported for Whooper Swan *Cygnus cygnus* and for several species of geese, with the displacement of birds evident up to 400 m of the turbines (Winkelman 1989; Kruckenberg & Jaene 1999). Habituation to wind turbines has also been found for the same species (Kruckenberg & Jaene 1999; Larsen & Madsen 2000; Madsen & Boertman 2008). Devereux *et al.* (2008) showed that wintering farmland birds (non-waterbirds) were not influenced by wind turbines; however, our results suggest that these results are not applicable across all species wintering in farmland areas.

Barrier effects

Although the swans appeared to be displaced from potential feeding areas, there was no evidence for the wind farm acting as a barrier during the evening flight; the birds navigated between and around the turbines during their flights to the roost. This ability to adjust their flight-paths is in line with studies made of other waterbird species (Dirksen *et al.* 1998; Tulp *et al.* 1999; Desholm & Kahlert 2005; Masden *et al.* 2009). The small size of the wind farm in this study (nine turbines in two rows) and the large spacing between turbines may have helped to ensure that these two lines did not

act as a barrier to flying birds. The use of modern large wind turbines may help both to make the structures more obvious to the birds (thus reducing collision risk) and also perhaps reduce the chance that birds perceive the turbines as barriers because the larger spacing between individual turbines makes it easier for the birds to pass between them (Krijgsveld *et al.* 2009). The same reasoning can be applied to increasing the numbers of turbines within a wind farm, as more turbines will enhance the perceived barrier effect. The orientation of the turbine rows will also have an effect, since turbines constructed in rows parallel onto the dominant flight direction of birds commuting between foraging and sleeping areas will present less of a barrier than when perpendicular to it. In the extreme, such a barrier effect could potentially render roosting or foraging sites inaccessible, especially where the energetic costs of avoidance make significant additional contributions to energy budgets. Due to crop rotation, flight-paths could potentially change between years. In this study, tracking of flight-paths was limited to only one pre- and one post-construction year; adequate assessment of barrier effects requires monitoring in multiple pre- and post-construction years.

Collision risk

Avian turbine collision risk varies widely between species and also between habitats; for instance, raptors are often found to collide with turbines in mountainous areas (de Lucas *et al.* 2008; Smallwood & Thelander 2008). Swans and geese are rarely reported as turbine victims, although swan

collisions with power-lines have been recorded frequently (*e.g.* Brown *et al.* 1992; Rees 2006). This study found no collision victims among Bewick's Swans during the research period, but the assumed one collision victim per season would equate to 0–0.04% of swans passing the wind farm turbines. These probabilities are very low but are similar to results from extensive research at two other turbine farms involving geese and swan in other parts of the Netherlands (Krijgsveld *et al.* 2009). The collision risk at this wind farm is lower than that calculated for Bewick's Swans in the UK (from Chamberlain *et al.* 2006) at a larger study site (26 *versus* 9 turbines), located near Romney Marsh, a proposed Ramsar site with nationally important numbers of Bewick's Swans for the UK. However, numbers of swans on Romney Marsh were much lower (mean maximum = 123 swans per winter during 2005–2009, Calbrade *et al.* 2010) than in the current study at the Polder Wieringermeer.

This study covered no evenings and mornings with fog or mist; on nights with poor visibility, collision risk for swans could be higher (Brown *et al.* 1992). However, evenings or mornings with poor visibility (< 300 m) were rare (five out of 114 dusks and dawns, Royal Netherlands Meteorological Institute, KNMI-station Berkhout, 21.11.2006–6.01.2007, downloaded from www.knmi.nl), so effects of fog or mist probably have negligible effects on the collision risks found in this study.

Given our various assumptions, we suggest a mortality rate of 0–3 swan victims per winter for the whole wind farm, of similar order of magnitude to 0.06 swans

per 180 days found for the UK (from Chamberlain *et al.* 2006). Collision risk can be estimated, but where low, actual collision rates can be difficult to determine. In other studies, casualties are most frequent in bird-rich areas and on mountain ridges (Hötker *et al.* 2006; Thelander & Smallwood 2007; de Lucas *et al.* 2008), but elsewhere, chances of collision are much lower. To date, no clear avian population effects from wind turbines have been demonstrated, although these effects will be greater for long-lived species with low reproductive rates, such as seabirds and raptors (Thelander *et al.* 2003; Horch & Keller 2005; Hötker *et al.* 2006; Stienen *et al.* 2007). In the case of the Bewick's Swans in Polder Wieringermeer the collision risk calculated in this study is so low that it is not expected to cause negative effects on the locally wintering swans. However, as Polder Wieringermeer now supports large numbers of individual wind farms, the combined effects of all these wind turbines, together with changes in cropping and land use, could combine to reduce overall wintering numbers of swans even in the absence of collision mortality.

Implications for conservation and future developments

In conclusion, this study shows that although the collision risk for swans with turbines was low at the site, wind farms can result in a diminished use of foraging habitat. Increasing demand for renewable energy could result in more and larger turbines which could reduce the attractiveness and carrying capacity of Polder Wieringermeer for wintering Bewick's Swans. Polder Wieringermeer is a

key wintering area for > 3% of the Northwest European Bewick's Swan population, whilst the adjacent Lake IJsselmeer roosts are of international importance under the EC Birds Directive and are designated as a Natura 2000 Specially Protected Area. This Birds' Directive Annex I species has declined in recent years (Wetlands International 2006; Rees & Beekman 2010) so changes to the potential carrying capacity of these important areas should be considered with caution. The increasing use of rural land in Polder Wieringermeer for the construction of wind turbines may have adverse impacts on the quality of the habitat for wintering waterbirds in the future.

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Photograph: Bewick's Swans on pasture in the Netherlands by Jelger Herder (www.digitalnature.org).