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OFFSHORE WIND FARM IMPACTS

Seabird avoidance and attraction at an offshore wind farm in the Belgian part of the North Sea

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Abstract Through before–after control-impact designed ship-based seabird surveys, seabird displacement occurring after the installation of an offshore wind farm at the Belgian Bligh Bank in 2010 was studied. Results demonstrate that northern gannet (*Morus bassanus*), common guillemot (*Uria aalge*) and razorbill (*Alca torda*) avoided the wind farm area, and decreased in abundance with 85, 71 and 64%, respectively. Lesser black-backed gull (*Larus fuscus*) and herring gull (*Larus argentatus*) were attracted to the wind farm, and their numbers increased by a factor 5.3 and 9.5. Other gull species too were found to frequent the turbine-built area, most notably common gull (*Larus canus*), black-legged kittiwake (*Rissa tridactyla*) and great black-backed gull (*Larus marinus*). The ecological incentives behind the observed attraction effects are still poorly understood, but on top of the increase in roosting possibilities it is plausible that offshore wind farms offer enhanced feeding opportunities. Importantly, attraction of seabirds to offshore wind farms implies an increased collision risk.

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Introduction

The large scale development of offshore wind farms (OWFs) in European waters raises concern on their impact on seabirds. Anticipated effects range from increased mortality caused by collision to habitat loss, habitat change and barrier-effects (Exo et al., 2003; Langston & Pullan, 2003; Fox et al., 2006; Drewitt & Langston, 2006; Stienen et al., 2007). Clearly, the installation of an OWF strongly changes the marine environment, not only because of the imposing physical appearance, but also due to the underwater changes following the introduction of turbine foundations in a mostly soft-bottom marine ecosystem. This paper focusses on displacement of seabirds following the construction of the Bligh Bank OWF at the Belgian part of the North Sea (BPNS).

Vanermen et al. (2013) estimated seasonal numbers occurring at the BPNS based on data collected from 2001 to 2007. About 46,000 seabirds appear to be present in Belgian waters during winter, of which more than 20,000 auks (*Uria aalge* and *Alca torda*). Offshore, the wintering community is dominated by common guillemot (*Uria aalge*), razorbill (*Alca torda*) and black-legged kittiwake (*Rissa tridactyla*), while the nearshore bird community mainly consists of great crested grebes (*Podiceps cristatus*), scoters (*Melanitta* sp.) and red-throated divers (*Gavia stellata*). In summer, fewer birds are present (on average 15,000), but terns (*Sterna* sp.) and gulls (*Larus* sp.) exploit the area in favour of their breeding colonies located in the port of Zeebrugge. For several species, numbers residing at the BPNS exceed the 1%-threshold of their biogeographic population (Mitchell et al., 2004; Wetlands International, 2013): great black-backed gull (*Larus marinus*) in winter and little gull (*Hydrocoloeus minutus*) during spring migration, while summer population thresholds are exceeded for both common tern (*Sterna hirundo*) and lesser black-backed gull (*Larus fuscus*) (Vanermen et al., 2013).

Birds have been found to avoid wind farm areas, resulting in loss of habitat. Land-based research shows that highest disturbance occurs outside the breeding season, and mainly in species of open habitats, with disturbance distances up to several hundreds of metres (Drewitt & Langston, 2006; Hötker et al., 2006). Offshore, pilot projects in Denmark and the Netherlands have shown a decrease in numbers of divers (*Gavia stellata/arctica*), great crested grebe, long-tailed duck (*Clangula hyemalis*), northern gannet (*Morus bassanus*), common scoter (*Melanitta nigra*), little gull, lesser black-backed gull, black-legged kittiwake, common/arctic terns (*Sterna hirundo/arctica*) and both auk species (Petersen et al., 2006, 2011; Leopold et al., 2013). On the other hand, OWFs have also been shown to attract seabirds and at the Dutch OWEZ & PAWP wind farms numbers of great cormorant (*Phalacrocorax carbo*) increased significantly after wind farm construction (Leopold et al., 2013). Comparing the results obtained at different locations demonstrates that displacement effects can be site-specific, and little gulls for example were found to avoid the Dutch PAWP wind farm, while there was a post-construction increase in numbers at the Danish Horns Rev wind farm. Leopold et al. (2013) further argue that the degree of displacement might be affected by wind farm configuration, with both northern gannet and common guillemot showing stronger avoidance to the PAWP than to the OWEZ OWF, with its lower density of turbines. In time seabirds may also habituate to the presence of wind turbines in their foraging areas, as already demonstrated for gulls, terns and great cormorants at several small coastal wind farms (Dierschke & Garthe, 2006).

To assess changes in seabird densities following the construction of the OWF at the Bligh Bank, a Before–After Control–Impact (BACI) monitoring program was designed. Stewart-Oaten and Bence (2001) review on several approaches for environmental impact assessment differing in goals and time series available, and with regard to a specific disturbed site, a BACI design is their suggested approach. In a BACI study, samples are taken before and after a possible impact, in both a disturbed (impact) and an undisturbed (control) location. This kind of monitoring set-up thus provides a control in both time and space, and allows evidence for an environmental impact to be based on changes in the impacted area that did not occur in the control area (Green, 1979). As seabird numbers are subject to high temporal variation (Maclean et al., 2013), replication in time is strongly advised, and ideally, samples in the control and impact area are taken simultaneously (Bernstein & Zalinski, 1983; Stewart-Oaten et al., 1986).

Monthly ship-based seabird surveys across delineated impact and control areas were started in 2008, almost 2 years before the first piling activities, and this paper reports on the results obtained after 3 years of post-construction monitoring.

Methods

Wind farm study area

The wind farm at the Bligh Bank is located 46 km off the Belgian coast. It has an area of 17 km^2 and ranges in water depth from 20 to 37 m. The farm consists of 5 rows of eleven 3 MW turbines (with 500–650 m distance in between) and a transformer platform, all of which were installed on steel monopile foundations. The first construction activities took place in September 2009, and the wind farm became fully operational by December 2010.

BACI monitoring set-up

In this study, the disturbed impact area is considered to be the zone where effects of turbine presence can be expected, and was delimited by surrounding the Bligh

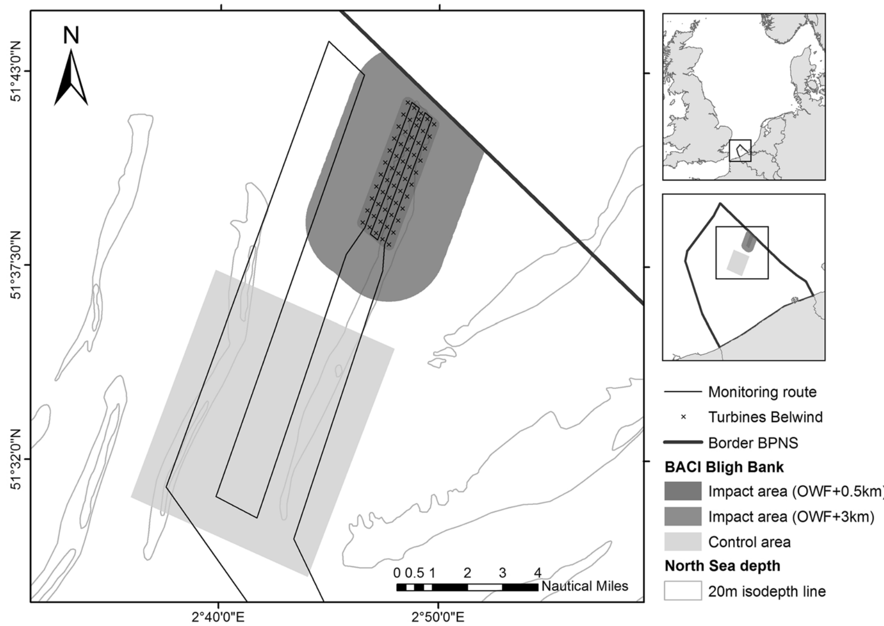

Fig. 1 Control and impact areas at the Bligh Bank study area

Bank wind farm by a buffer zone of 3 km (Fig. 1). This buffer distance is based on the avoidance distances as found for scoters and long-tailed ducks during the Danish research project at the Nysted OWF (Petersen et al., 2006). Next, a control area was delineated, harbouring comparable numbers of seabirds and showing a similar range in water depth and distance to the coast (Vanermen et al., 2006, 2010). The distance between control and impact area was chosen to be small enough to be able to count both areas on the same day by means of a research vessel, thus minimising variation resulting from short-term temporal changes in seabird abundance and observation conditions.

We analysed changes in seabird abundance in one control area and three different impact areas, being (1) the OWF in its phase I configuration of 55 turbines surrounded by a 500 m wide buffer zone, (2) the OWF surrounded by a 3 km wide buffer zone and (3) the buffer zone itself (the area within a distance of 0.5–3 km from the nearest turbine) (see Fig. 1).

Ever since 2008, the study area was surveyed monthly by counting seabirds along a fixed monitoring route, which can be completed in 1 day and covers the control as well as the impact area (Fig. 1). We also included historical survey results (collected before 2008), provided that both areas were visited at the same day. The reference period includes all available data prior to OWF construction in September 2009, totalling 63 surveys. Impact data could be collected from September 2010 on, and 39 post-impact surveys were performed until December 2013. With two area counts per survey, this makes up for a total database of 204 records (see Tables 1, 2).

To investigate seabird displacement effects, we used data on eleven seabird species occurring regularly in the Bligh Bank wind farm area, being northern fulmar (*Fulmarus glacialis*), northern gannet, great skua (*Stercorarius skua*), little gull, common gull (*Larus canus*), lesser black-backed gull, herring gull (*Larus argentatus*), great black-backed gull, black-legged kittiwake, common guillemot and razorbill.

Ship-based seabird counts

Ship-based seabird counts were conducted according to a standardised and internationally applied method, combining ‘transect counts’ for birds on the water and ‘snapshot counts’ for flying birds (Tasker et al., 1984), applying a transect width of 300 m. Seabird surveys were only executed during favourable conditions, defined by good visibility, a calm to moderate wind force (<6 Bft) and a significant wave height of less than 2 m.

Seabird counts are usually aggregated per 2–10 min tracks. To avoid auto-correlation between subsequent counts and to minimise overall variance however, we aggregated our count data per area (control/impact) and

Table 1 Number of surveys and number of km^2 monitored per month in the control and impact area (OWF + 3 km buffer), before and after wind farm construction

Month	Before (<2010)				After (2010–2013)			
	Control		Impact		Control		Impact	
	n	Σ (km^2)	*n*	Σ (km^2)	*n*	Σ (km^2)	*n*	Σ (km^2)
January	3	21.6	3	13.6	3	30.8	3	25.0
February	10	73.8	10	33.8	4	41.1	4	25.2
March	4	28.4	4	11.3	5	39.9	5	37.2
April	5	38.5	5	14.5	3	35.4	3	25.3
May	4	26.1	4	9.7	3	41.8	3	27.7
June	4	28.4	4	14.1	2	19.2	2	12.6
July	4	31.8	4	14.4	2	27.0	2	19.5
August	10	62.1	10	21.7	2	20.7	2	19.9
September	3	19.6	3	8.7	2	30.6	2	13.5
October	7	42.4	7	22.4	3	41.8	3	20.2
November	3	12.4	3	9.6	4	36.1	4	26.5
December	6	30.9	6	12.2	6	56.9	6	37.0
Total	63	416.0	63	185.9	39	421.3	39	289.6

Table 2 Number of surveys per year in the control area and impact area (OWF + 3 km buffer)

	Year	Control	Impact	Σ (km^2)
Reference period (before)	1993–2007	38	38	270.9
	2008	12	12	157.1
	2009	13	13	173.9
Impact period (after)	2010	4	4	55.4
	2011	12	12	236.1
	2012	14	14	218.1
	2013	9	9	201.3

per monitoring day, resulting in day totals for both zones. Taking into account the distance travelled, these day totals can be transformed to seabird densities.

Data modelling

When a counted subject is randomly dispersed, count results tend to be Poisson-distributed, in which the mean equals the variance (McCullagh & Nelder, 1989). Seabirds however often occur strongly aggregated in (multi-species) flocks, typically resulting in count data with a high proportion of zeros, relatively few but sometimes very large positive numbers and a high variance exceeding the mean. Such over-dispersed data can be analysed by a generalised linear model with a quasi-poisson (QP) or a negative binomial (NB) distribution (Ver Hoef & Boveng, 2007). Here we applied a NB distribution as this distribution is to be preferred over a QP in case of high over-dispersion (Zuur et al., 2009). In case data appeared to exhibit more zeros than can be predicted by a NB distribution, zero-inflated NB (ZINB) models were used (Potts & Elith, 2006; Zeileis et al., 2008). A ZINB model consists of two parts: (1) a 'count component' modelling the data according to a NB distribution and (2) a 'zero component' modelling the excess in zero counts.

The response variable (Y) equals the total number of birds observed (inside the transect and during snapshot counts) per survey in the control or impact area. To correct for varying monitoring effort, the number of km^2 counted was included in the model as an offset-variable. The explanatory factor variables used were area factor CI (control—impact), time factor BA (before–after) and turbine factor T (turbine presence–absence). Lastly, the continuous variable month (m) was used to model seasonal fluctuations by fitting a cyclic sine curve, described by a linear sum of sine and cosine terms (Stewart-Oaten & Bence, 2001; Onkelinx et al., 2008), as for example in:

$$\log(\mathrm{Y}) = \mathrm{Offset}(\log(\mathrm{km}^2)) + \mathrm{a}_1 + \mathrm{a}_2 \cdot \sin\left(2\Pi\frac{\mathrm{m}}{12}\right) + \mathrm{a}_3 \cdot \cos\left(2\Pi\frac{\mathrm{m}}{12}\right) \tag{1}$$

In Eq. 1, seasonality is modelled applying a single sine curve with a period of 12 months. For certain species however, the seasonal variation might be captured better by adding another sine curve with a period of 6 or 4 months, on top of the one with a period of 12 months, thus allowing to model more than one peak in density per year, as for example in Eq. 2:

$$\log(\mathrm{Y}) = \mathrm{Offset}(\log(\mathrm{km}^2)) + a_1 + a_2 \cdot \sin\left(2\Pi\frac{\mathrm{m}}{12}\right) + a_3 \cdot \cos\left(2\Pi\frac{\mathrm{m}}{12}\right) + a_4 \cdot \sin\left(2\Pi\frac{\mathrm{m}}{6}\right) + a_5 \cdot \cos\left(2\Pi\frac{\mathrm{m}}{6}\right) \tag{2}$$

This method performed much better compared to the inclusion of month as a factor variable, which actually splits the data in twelve subsets, resulting in highly unreliable coefficient estimates. We did not account for interaction between CI and seasonality since differences in seasonal patterns are not expected to occur at such a small spatial scale. When applying a ZI model, the zero-component was limited to an intercept, linked to the response by a logit-function. ZI models were only used when they returned a zero-inflation of at least 10% with more than 95% confidence.

First, the reference data were modelled to see whether the area factor CI should be retained because of a significant difference in numbers between impact and control area before wind farm construction. If so, the full dataset including impact data was modelled by adding the factor variable BA. The change in seabird numbers expected to be due to OWF presence is then estimated by the interaction between time and area BA:CI (Green, 1979). On the other hand, a non-significant area effect CI in the reference data allows to remove this factor (thus gaining a degree in freedom) and to model the full dataset adding factor variables BA and T, the latter estimating the effect of OWF presence on seabird numbers. Following are the two types of impact model that are in use (with seasonality being the best fitting sine wave):

$$\log(\mathrm{Y}) \sim \mathrm{seasonality} + \mathrm{BA} + \mathrm{CI} + \mathbf{BA{:}CI}, \tag{3}$$

$$\log(\mathrm{Y}) \sim \mathrm{seasonality} + \mathrm{BA} + \mathbf{T}. \tag{4}$$

All data handling and modelling were performed in R.3.0.1 (R Core Team, 2013a), making use of the following packages: lmtest (Zeileis & Hothorn, 2002), MASS (Venables & Ripley, 2002), reshape (Wickham, 2007), pscl (Zeileis et al., 2008; Jackman, 2011), foreign (R Core Team, 2013b) and RODBC (Ripley & Lapsley, 2013).

Results

By analysing the impact dataset according to the modelling protocol as set out above, several significant displacement effects were detected (Table 3). The model coefficients in Table 3 are estimates of the (multiplicative) change in seabird numbers in the Bligh Bank OWF area, and are displayed in the natural log scale. Figures 2 and 3 illustrate the modelled densities in the control and impact area before and after wind farm construction, for all five species for which we found significant displacement effects.

Three species avoided the wind farm area at the Bligh Bank, i.e. northern gannet, common guillemot and razorbill, and decreased in abundance with 85, 71 and 64%, respectively (Table 3; Fig. 2). In contrast to razorbill, northern gannet and common guillemot were also found to avoid the area from 0.5 km up to at least 3 km from the nearest turbines, yet to a lesser extent than the wind farm itself (respective decreases of 69 and 53%).

Results for little gull suggest avoidance of the wind farm area itself, opposed to a slight increase in numbers in the immediate surroundings, yet these changes were not significant. For northern fulmar and great skua, the coefficients are highly negative, suggesting avoidance. Indeed, neither one was observed in the impact area after wind farm construction, but this was mostly due to an overall decrease in numbers, indicated by a significant effect of the time factor BA.

On the other hand, monitoring results showed a significant attraction effect for lesser black-backed gull and herring gull, and weighed against the trend observed in the control area, their numbers increased by a factor 5.3 and 9.5, respectively (Table 3; Fig. 3). For lesser black-backed gull, the attraction effect was

Table 3 Model coefficients estimating OWF-related displacement and their respective *P* values (significant avoidance indicated in italics, significant attraction in bold face; $P < 0.05$*, $P < 0.01$**, $P < 0.001$***)

	Impact area (OWF + 0.5 km)		Impact area (OWF + 3 km)		Buffer area (0.5–3 km)	
	Coeff.	*P* value	Coeff.	*P* value	Coeff.	*P* value
Northern fulmar	−16.62	0.987	−17.20	0.986	−16.49	0.987
Northern gannet	*−1.92*	*0.000****	*−1.53*	*0.000****	*−1.16*	*0.003***
Great skua	−16.21	0.995	−16.95	0.994	−16.25	0.995
Little gull	−1.15	0.270	−0.13	0.891	0.31	0.730
Common gull	1.91	0.155	1.19	0.332	−0.27	0.805
Lesser black-backed gull	**1.66**	**0.012***	**2.71**	**0.000****	**2.71**	**0.000****
Herring gull	**2.25**	**0.001****	0.89	0.201	0.37	0.580
Great black-backed gull	0.38	0.419	0.42	0.310	0.48	0.293
Black-legged kittiwake	0.04	0.930	0.25	0.527	0.47	0.255
Common guillemot	*−1.23*	*0.000****	*−0.94*	*0.000****	*−0.75*	*0.007***
Razorbill	*−1.01*	*0.031**	−0.76	0.080	−0.39	0.378

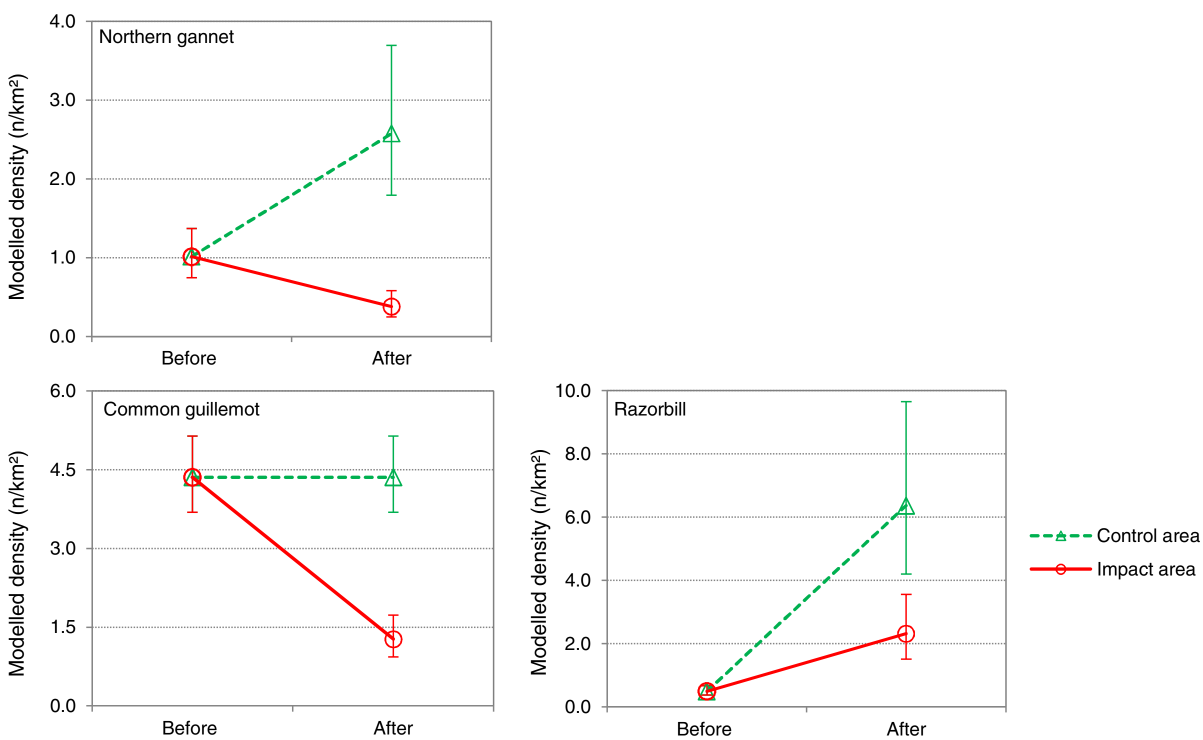

Fig. 2 Modelled densities (±std. errors) for the months with maximal numbers of northern gannet (November), common guillemot (January) and razorbill (February), three species found to avoid the OWF (+0.5 km) at the Bligh Bank

significant for up to at least 3 km away from the wind farm, which was not the case for herring gull. Positive model coefficients, indicating possible attraction, were also found for common gull and great black-backed gull, yet these effects were not statistically significant.

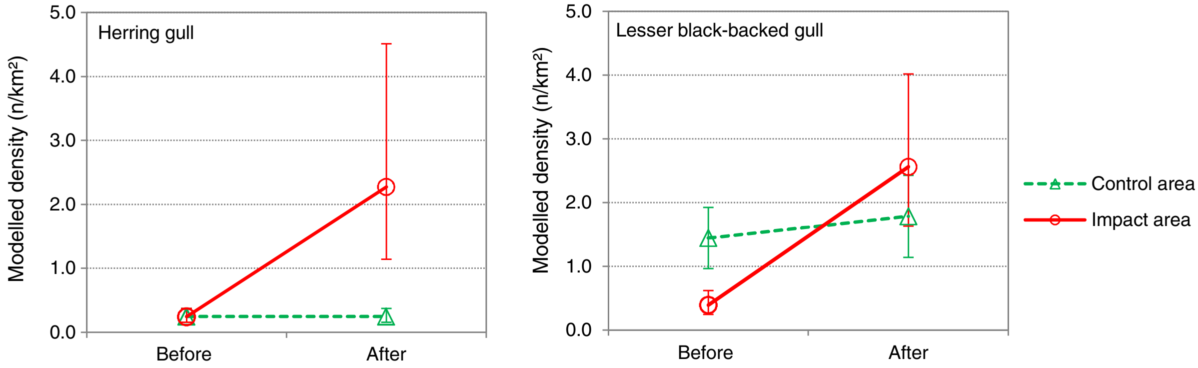

Fig. 3 Modelled densities (±std. errors) for the months with maximal numbers of herring gull (January) and lesser black-backed gull (April), two species found to be attracted to the OWF (+0.5 km) at the Bligh Bank

Discussion

This paper studied seabird displacement following the construction of an OWF at the Belgian Bligh Bank. To this end, a BACI monitoring design was implemented by delineating an impact and control area, and performing monthly ship-based seabird surveys across these areas from 2 years before till 3 years after construction.

While the importance of temporal replication in BACI assessments is widely recognised, there is disagreement on the role of spatial replication, i.e. the inclusion of several control locations (Bernstein & Zalinski, 1983; Stewart-Oaten et al., 1986; Underwood, 1994; Stewart-Oaten & Bence, 2001). In a 'seabirds at sea' context however, including more than one control area is almost unfeasible, considering the obvious logistic and financial limitations. Stewart-Oaten & Bence (2001) do stress that BACI is a model-based approach in which the control is chosen deliberately to be correlated with the impacted site, and used as a covariate to reduce unexplained temporal variation and correlation. Therefore, the authors argue that multiple controls are not needed, but can however be useful for insurance, model checking and causal assessment.

This study revealed significant attraction of lesser black-backed and herring gulls towards the Bligh Bank wind farm. Our impact analysis could not detect a significant effect on the numbers of common gull, great black-backed gull and black-legged kittiwake, but all three species showed increased abundance and were regularly observed between the turbines. The attraction of gulls to the Bligh Bank OWF was rather surprising since at-sea gull distribution is strongly determined by the presence of fishing trawlers (e.g. Camphuysen & Leopold, 1994; Garthe, 1997), and the main anticipated effect of the presence of OWFs on gulls was thus a decrease in densities resulting from the prohibition for trawlers to fish inside wind farm boundaries. During the first 2 years of post-construction monitoring, gulls occurring inside the Bligh Bank OWF were only observed resting on the water or at the above-water constructions, strongly supporting the idea that their presence was to be interpreted in the view of increased roosting possibilities. Since October 2012 however, flocks of black-legged kittiwakes were repeatedly observed foraging inside the wind farm boundaries. Strikingly, the percentage of kittiwakes displaying active foraging behaviour (pecking or diving for food) inside the wind farm (5.8%) was much higher than in the control area (0.7%) ($Chi^2 = 163.5$, df = 1, $P < 0.001$). At the OWF at the Thorntonbank, just south of the Bligh Bank and fully operational since the end of 2013, lesser black-backed gulls were encountered foraging on pelagic prey in between the turbines, as well as feeding on the intertidal fouling communities on the readily accessible jacket foundations.

The introduction of turbine foundations as hard substrate in a soft-bottom marine ecosystem has been shown to result in a cascade of environmental changes, and several studies have demonstrated the fast development of hard-bottom communities and attraction of associated fish, the so-called 'reef effect' (Leonhard & Pedersen, 2006; Leonhard et al., 2011; Reubens et al., 2013; De Mesel et al., 2013; Degraer et al., 2013). As the shallow Bligh Bank is subject to strong tidal currents (up to 1 m/s), water turbulence in the wake of the turbines may force potential prey to the surface, providing enhanced feeding opportunities to seabirds (Hunt et al., 1999). We also cannot ignore the possible long-term benefits of the exclusion of fishery activities, allowing the soft-bottom ecosystem in between the turbine foundations to recover from decennia of heavy beam trawling impact (Kaiser & Spencer, 1996; Duineveld et al., 2007; Depestele et al., 2012). Whether these underwater and hydrodynamic changes will actually result in enhanced feeding possibilities and subsequent attraction of seabirds is yet unknown and should be explored through oriented research in the coming years.

At the Bligh Bank wind farm, three species responded negatively to the presence of offshore turbines, i.e. northern gannet, common guillemot and razorbill. Accordingly, significant avoidance by gannets and both auks was observed in the Dutch OWEZ and PAWP wind farms (Leopold et al., 2013; Krijgsveld et al., 2011), and indications of avoidance by auks were also found by Petersen et al. (2006) at the Horns Rev wind farm in Denmark.

The most plausible reason for the avoidance effect found in these three offshore species is disturbance owing to the presence of rotating above-water constructions in their usually wide open marine habitat. Interestingly, our results show that for none of these species avoidance was complete. Since seabirds are known to readily exploit areas with high and predictable food availability, good or even improved foraging conditions might enhance the habituation of birds that are now still reluctant to enter the wind farms.

Power analyses on BACI monitoring data collected at the BPNS showed that for some seabird species, even a substantial change in density (e.g. a decrease of 75%) can be hard to detect statistically, and up to 10 years of monitoring may be needed to obtain sufficient power (Vanermen et al., 2014 in submission). Indeed, numbers of several seabird species have changed after wind farm construction at the Bligh Bank, without the differences reaching statistical significance. Owing to a larger sample size, more years of monitoring will allow to better distinguish between displacement, indifference and attraction of seabirds. Power can further be improved by explaining the variation in counted numbers as much as possible, and in this respect, the inclusion of tidal state into the models might prove particularly rewarding (Schwemmer et al., 2009; Embling et al., 2012; Cox et al., 2013; Scott et al., 2013).

Long-term monitoring at the various wind farm sites is further needed to anticipate the possible habituation of seabirds to the presence of wind turbines (temporal variation) or the fact that displacement effects may differ between sites (spatial variation). The present methodology is suited to detect a sustained increase or decrease in mean abundance after wind farm construction. In case of habituation however, one deals with a so-called 'pulse disturbance', reducing the mean abundance for a limited period of time which recovers thereafter. To detect this kind of effect, a different approach is needed, including one more time variable (e.g. year) into the model, and testing the interaction between the time after disturbance and the area factor (Underwood, 1994).

We will continue to monitor seabird presence in and around the Belgian OWFs, with increased attention to their behavioural- and foraging-related actions, and to how these relate to tidal state and associated currents. To better understand the link with local feeding possibilities, further monitoring could include a hydro-acoustic research on pelagic prey communities (Jurvelius & Sammalkorpi, 1995; Emmrich et al., 2010), or a diet study on the seabirds occurring inside OWFs, analysing for example faeces samples found on roosting sites. Further studies should also be done to investigate whether the benefits of improved foraging conditions would weigh up against the costs of additional mortality. Because with wind farms attracting seabirds, more birds face the risk of colliding with the turbine blades. Importantly, as seabirds are long-lived species with delayed maturity and small clutch sizes (Croxall & Rothery, 1991), even small changes in adult survival may have a substantial impact at a population level (Sæther & Bakke, 2000; Stienen et al., 2007), potentially turning a seemingly favourable feeding area into an ecological pitfall.

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References

Bernstein, B. B. & J. Zalinski, 1983. An optimum sampling design and power tests for environmental biologists. Journal of Environmental Management 16: 35–43.

Camphuysen, C. J. & M. F. Leopold, 1994. Atlas of seabirds in the Southern North Sea. IBN research report 94/6, NIOZ report 1994–1998, INB, NIOZ & NZG, Texel.

Croxall, J. P. & P. Rothery, 1991. Population regulation of seabirds: implications of their demography for conservation. In Perrins, C. M., J.-D. Lebreton & G. J. M. Hirons (eds), Bird Population Studies, Relevance to Conservation and Management. Oxford University, Oxford: 272–296.

Cox, S. L., B. E. Scott & C. J. Camphuysen, 2013. Combined spatial and tidal processes identify links between pelagic prey species and seabirds. Marine Ecology Progress Series 479: 203–221.

Degraer, S., R. Brabant & B. Rumes (eds), 2013. Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Learning From the Past to Optimise Future Monitoring Programs. Royal Belgian Institute of Natural Sciences, Brussels.

De Mesel, I., F. Kerckhof, B. Rumes, A. Norro, J.-S. Houziaux & S. Degraer, 2013. Fouling community on the foundations of wind turbines and the surrounding scour protection. In Degraer, S., R. Brabant & B. Rumes (eds), Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Learning From the Past to Optimise Future Monitoring Programs. Royal Belgian Institute of Natural Sciences, Brussels: 123–137.

Depestele, J., W. Courtens, S. Degraer, J. Haelters, K. Hostens, J. -S. Houziaux, B. Merckx, H. Polet, M. Rabaut, E. W. M. Stienen, S. Vandendriessche, E. Verfaillie & M. Vincx, 2012. An integrated impact assessment of trammel net and beam trawl fisheries "WAKO II". Final report D/2012/1191/2, Belgian Science Policy Office, Brussels.

Dierschke, V. & S. Garthe, 2006. Literature review of offshore wind farms with regard to seabirds. In Zucco, C., W. Wende, T. Merck, I. Köchling & J. Köppel (eds), Ecological Research on Offshore Wind Farms: International Exchange of Experiences – Part B: Literature Review of Ecological Impacts. Federal Agency for Nature Conservation, Bonn: 131–198.

Drewitt, A. L. & R. H. W. Langston, 2006. Assessing the impact of wind farms on birds. Ibis 148: 29–42.

Duineveld, G. C. A., M. J. N. Bergman & M. S. S. Lavaleye, 2007. Effects of an area closed to fisheries on the composition of the benthic fauna in the southern North Sea. ICES Journal of Marine Science 64: 899–908.

Embling, C. B., J. Illian, E. Armstrong, J. van der Kooij, J. Sharples, C. J. Camphuysen & B. E. Scott, 2012. Investigating fine-scale spatio-temporal predator–prey patterns in dynamic marine ecosystems: a functional data analysis approach. Journal of Applied Ecology 49: 481–492.

Emmrich, M., I. P. Helland, S. Busch, S. Schiller & T. Mehner, 2010. Hydroacoustic estimates of fish densities in comparison with stratified pelagic trawl sampling in two deep, coregonid-dominated lakes. Fisheries Research 105: 178–186.

Exo, K.-M., O. Hüppop & S. Garthe, 2003. Birds and offshore wind farms: a hot topic in marine ecology. Wader Study Group Bulletin 100: 50–53.

Fox, A. D., M. Desholm, J. Kahlert, T. K. Christensen & I. K. Petersen, 2006. Information needs to support environmental impact assessment of the effects of European marine offshore wind farms on birds. Ibis 148: 129–144.

Garthe, S., 1997. Influence of hydrography, fishing activity and colony location on summer seabird distribution in the south-eastern North Sea. ICES Journal of Marine Science 54: 566–577.

Green, R. H., 1979. Sampling Design and Statistical Methods for Environmental Biologists. Wiley Interscience, New York.

Hötker, H., K.-M. Thomsen & H. Jeromin, 2006. Impacts on biodiversity of exploitation of renewable energy sources: the example of birds and bats. Facts, gaps in knowledge, demands for further research and ornithological guidelines for the development of renewable energy exploitation. Michael Otto Institut im NABU, Bergenhusen.

Hunt, G. L., F. Mehlum, R. W. Russell, D. Irons, M. B. Decker & P. H. Becker, 1999. Physical processes, prey abundance, and the foraging ecology of seabirds. Proceedings of the International Ornithological Congress 22: 2040–2056.

Jackman, S., 2011. pscl: A Package of Classes and Methods for R Developed in the Political Science Computational Laboratory. Stanford University, Stanford.

Jurvelius, J. & I. Sammalkorpi, 1995. Hydroacoustic monitoring of the distribution, density and the mass-removal of pelagic fish in a eutrophic lake. Hydrobiologia 316: 33–41.

Kaiser, M. J. & B. E. Spencer, 1996. The effects of beam-trawl disturbance on infaunal communities in different habitats. Journal of Animal Ecology 65: 348–358.

Krijgsveld, K. L., R. C. Fijn, M. Japink, P. van Horssen, C. Heunks, M. Collier, M. Poot, D. Beuker & S. Dirksen, 2011. Effect studies offshore wind farm Egmond aan Zee: final report on fluxes, flight altitudes and behaviour of flying birds. Bureau Waardenburg report nr 10-219, Bureau Waardenburg, Culemborg.

Langston, R. H. W. & J. D. Pullan, 2003. Wind farms and birds: an analysis of the effects of wind farms on birds, and guidance on environmental assessment criteria and site selection issues. T-PVS/Inf (2003) 12, RSPB/Birdlife International, UK.

Leonhard, S. B. & J. Pedersen, 2006. Benthic communities at Horns Rev before, during and after construction of Horns Rev offshore wind farm. Final report, Bio/consult A/S, Denmark.

Leonhard, S. B., C. Stenberg & J. Støttrup (eds), 2011. Effect of the Horns Rev 1 offshore wind farm on fish communities: follow-up seven years after construction. Technical report, The Danish Energy Authority, Kopenhagen.

Leopold, M. F., R. S. A. van Bemmelen & A. Zuur, 2013. Responses of local birds to the offshore wind farms PAWP and OWEZ off the Dutch mainland coast. Report C151/12, Imares, Texel.

Maclean, I. M. D., M. M. Rehfisch, H. Skov & C. B. Thaxter, 2013. Evaluating the statistical power of detecting changes in the abundance of seabirds at sea. Ibis 155: 113–126.

McCullagh, P. & J. A. Nelder, 1989. Generalized Linear Models, 2nd ed. Chapman and Hall, London.

Mitchell, P. I., S. F. Newton, N. Ratcliffe & T. E. Dunn, 2004. Seabird Populations of Britain and Ireland: Results of the Seabird 2000 Census (1998–2002). T & A D Poyser, London.

Onkelinx, T., G. Van Ryckegem, D. Bauwens, P. Quataert & E. Van den Bergh, 2008. Potentie van ruimtelijke modellen als beleidsondersteunend instrument met betrekking tot het voorkomen van watervogels in de Zeeschelde. Report INBO.R.2008.34, Research Institute for Nature and Forest, Brussels.

Petersen, I. K., T. K. Christensen, J. Kahlert, M. Desholm & A. D. Fox, 2006. Final results of bird studies at the offshore wind farms at Nysted and Horns Rev, Denmark. NERI report, National Environmental Research Institute, Denmark.

Petersen, I. K., M. MacKenzie, E. Rexstad, M. S. Wisz & A. D. Fox, 2011. Comparing pre- and post-construction distributions of long-tailed ducks *Clangula hyemalis* in and around the Nysted offshore wind farm, Denmark : a quasi-designed experiment accounting for imperfect detection, local surface features and autocorrelation. CREEM Technical report 2011–1, Centre for Research into Ecological and Environmental Modelling, St Andrews.

Potts, J. M. & J. Elith, 2006. Comparing species abundance models. Ecological Modelling 199: 153–163.

Reubens, J., S. Degraer & M. Vincx, 2013. Offshore wind farms significantly alter fish community structure: aggregation of Atlantic cod and pouting. In Degraer, S., R. Brabant & B. Rumes (eds), Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Learning From the Past to Optimise Future Monitoring Programs. Royal Belgian Institute of Natural Sciences, Brussels: 115–121.

Ripley, B. & M. Lapsley, 2013. RODBC: ODBC database access. R package version 1.3-7 [available on internet at http://www.CRAN.R-project.org/package=RODBC].

R Core Team, 2013a. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna [available on internet at http://www.R-project.org].

R Core Team, 2013b. Foreign: read data stored by Minitab, S, SAS, SPSS, Stata, Systat, dBase, etc. R package version 0.8-55 [available on internet at http://www.CRAN.R-project.org/package=foreign].

Sæther, B.-E. & Ø. Bakke, 2000. Avian life history variation and contribution of demographic traits to the population growth rate. Ecology 81: 642–653.

Schwemmer, P., S. Adler, N. Guse, N. Markones & S. Garthe, 2009. Influence of water flow velocity, water depth and colony distance on distribution and foraging patterns of terns in the Wadden Sea. Fisheries Oceanography 18: 161–172.

Scott, B. E., A. Webb, M. R. Palmer, C. B. Embling & J. Sharples, 2013. Fine scale bio-physical oceanographic characteristics predict the foraging occurrence of contrasting seabird species; Gannet (*Morus bassanus*) and storm petrel (*Hydrobates pelagicus*). Progress in Oceanography 117: 118–129.

Stewart-Oaten, A. & J. R. Bence, 2001. Temporal and spatial variation in environmental impact assessment. Ecological Monographs 71: 305–339.

Stewart-Oaten, A., W. W. Murdoch & K. R. Parker, 1986. Environmental impact assessment: "pseudoreplication" in time? Ecology 67: 929–940.

Stienen, E. W. M., J. Van Waeyenberge, E. Kuijken & J. Seys, 2007. Trapped within the corridor of the Southern North Sea: the potential impact of offshore wind farms on seabirds. In de Lucas, M., G. F. E. Janss & M. Ferrer (eds), Birds and Wind Farms: Risk Assessment and Mitigation. Quercus, Madrid: 71–80.

Tasker, M. L., P. H. Jones, T. J. Dixon & B. F. Blake, 1984. Counting seabirds at sea from ships: a review of methods employed and a suggestion for a standardised approach. Auk 101: 567–577.

Underwood, A. J., 1994. On beyond BACI: sampling designs that might reliably detect environmental disturbances. Ecological Applications 4: 3–15.

Vanermen, N., E. W. M. Stienen, W. Courtens & M. Van de walle, 2006. Referentiestudie van de avifauna van de Thorntonbank. Report INBO.A.2006.22, Research Institute for Nature and Forest, Brussels.

Vanermen, N., E. W. M. Stienen, W. Courtens, T. Onkelinx, M. Van de walle & H. Verstraete, 2010. Monitoring seabird displacement: a modelling approach. Report INBO.R.2010.12, Research Institute for Nature and Forest, Brussels.

Vanermen, N., E. W. M. Stienen, W. Courtens, T. Onkelinx, M. Van de walle & H. Verstraete, 2013. Bird monitoring at offshore wind farms in the Belgian Part of the North Sea: assessing seabird displacement effects. Report INBO.R.2013.755887, Research Institute for Nature and Forest, Brussels.

Vanermen, N., T. Onkelinx, P. Verschelde, W. Courtens, M. Van de walle, H. Verstraete & E. W. M. Stienen, 2014. Assessing seabird displacement at offshore wind farms: power ranges of a monitoring and data handling protocol. Manuscript submitted for publication.

Venables, W. N. & B. D. Ripley, 2002. Modern Applied Statistics with S, 4th ed. Springer, New York.

Ver Hoef, J. M. & P. L. Boveng, 2007. Quasi-poisson vs. negative binomial regression: how should we model overdispersed count data? Ecology 88: 2766–2772.

Wetlands International, 2013. Waterbird population estimates [available on internet at http://www.wpe.wetlands.org/].

Wickham, H., 2007. Reshaping data with the reshape package. Journal of Statistical Software 21 (12) [available on internet at http://www.jstatsoft.org/].

Zeileis, A. & T. Hothorn, 2002. Diagnostic checking in regression relationships. R News 2 (3): 7–10 [available on internet at http://www.cran.r-project.org/doc/Rnews/].

Zeileis, A., C. Keibler & S. Jackman, 2008. Regression models for count data in R. Journal of Statistical Software 27 (8) [available on internet at http://www.jstatsoft.org/].

Zuur, A. F., E. N. Ieno, N. J. Walker, A. A. Saveliev & G. M. Smith, 2009. Mixed Effects Models and Extensions in Ecology with R. Springer, New York.