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OFFSHORE WIND FARM IMPACTS

Equivocal effects of offshore wind farms in Belgium on soft substrate epibenthos and fish assemblages

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Abstract With the construction of wind farms, new hard substrates are introduced in the marine environment. Between the turbine rows and around the wind farms, however, the soft sediments remain. The inhabiting fauna of these sandy sediments may be influenced by the presence of the turbines and the absence of fisheries in the wind farms. These effects were investigated for epibenthos, demersal fish, and benthopelagic fish in the Thorntonbank and Bligh Bank wind farms in the Belgian part of the North Sea. Inside the wind farms, several local and temporal effects were detected, including both temporary construction effects (e.g., decreased densities of dab, ophiuroids and dragonets) as refugium effects (e.g., the presence of relatively large plaice). At the wind farm edges, only few temporary effects were noted, but real edge effects due to changes in fisheries intensity or 'spillover' from the wind farms could not be shown. The observed effects were not consistent between both wind farms, which is not surprising, given the differences in epibenthos and fish communities, sandbank topography, fishing pressure, development stage of the wind farms, and the used foundation types. This inconsistency stresses the importance to replicate monitoring activities across wind farms and along the identified gradients.

Keywords Wind farm · Belgium · Epibenthos · Fish · BACI · Soft substrate

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Introduction

Offshore wind farms are often built in typical sandy, soft sediment habitats. Since the start of offshore wind farm construction in Europe, a number of studies have described the reef effects of the newly introduced hard substrates on the epibenthic fauna and demersal and benthopelagic fish in the direct vicinity of these wind farms (e.g., Wilhelmsson et al., 2006; Andersson et al., 2009; Reubens et al., 2011; Bergström et al., 2013; Reubens et al., 2013a, b). In between the turbines and their scour protection layers, however, the soft sandy sediments remain, and studies focusing on the fauna in the soft substrates between the turbines are scarce. The inhabiting fauna of those soft sediments can be influenced by the presence of the turbines in the wind farm and by the absence of fisheries (as fisheries are excluded in most European wind farms, wind farm areas have the potential to function as marine reserves). In this sense, the establishment of wind farms combines the effects of hard substrate addition and the effects of the delineation of marine reserves. At the border of the concessions, wind farm effects can give rise to "spillover" (export of biomass to surrounding habitats by recruitment or migration out of the reserve), and in turn, the observed or expected spillover can cause a concentration of fishing effort at the margins of a reserve (or even just within it) in the belief that this delivers better catches (Forcada et al., 2009). In the present study, we considered the combined effects of wind farm construction and fisheries exclusion (wind farm effects) and the effects of spillover and effort concentration (edge effects) in an integrated design.

Wind farm effects include (1) depletion of phytoplankton by high densities of filtrating organisms on and around the turbine, which can negatively affect the growth of filter feeders on the seabed; (2) input of organic material from organisms associated with the turbines as well as entrapment of organic material by the turbines, which enriches the seabed, and enhances the abundance of deposit-feeding organisms and their predators; (3) predation by fish and crabs associated with the turbines, negatively affecting prey species abundance; and (4) reef effects enhancing the abundance of pelagic fish species and the attraction of flatfish to the reef (Wilhelmsson et al., 2006; Andersson et al.,2009; Wilhelmsson, 2009). Additionally, underwater noise, vibrations, and electromagnetic fields can disturb the resident fauna (Wahlberg & Westerberg, 2005; Petersen & Malm, 2006).

Edge effects can occur due to spillover, due to a local reallocation of fishing effort, and due to fishery infringements in the no-take zone (Little et al., 2005; Berkenhagen et al., 2010). Spillover from marine protected areas (MPA) has been indicated by a number of studies (e.g., Russ et al., 2003; Forcada et al., 2009) and is mostly signaled by an increase in landings resulting from enhanced capture adjacent to the MPA, and by an aggregation of effort. However, the potential of a closed area such as a wind farm to produce spillover depends on a number of factors, including habitat continuity, the mobility and age distribution of fish, the size and continuity of the MPA, and the occurrence of infringements (Murawski et al., 2000; Little et al., 2005; Goni et al., 2008, Forcada et al., 2009).

Detailed studies on soft substrate epibenthos and/or fish in wind farms have been carried out in Denmark, the UK and the Netherlands, but at different time scales and with different designs and sampling techniques. In Denmark, gill nets were combined with dredges and hydro-acoustics between the turbines at distances up to 230 m from the wind farm (Leonhard et al., 2011). These results showed changes in fish abundances, fish communities, and species diversity. Seven years after construction, small scale effects of single turbines were obvious. For example, Van Deurs et al., (2012) found negative effects on juvenile sandeels, but impacts on the wind farm scale could not be discerned. In the Netherlands, short-term (2 years) monitoring results indicated no effects on the benthos in the sandy area between the OWEZ turbines, and only minor effects on the fish assemblages near the turbines (Lindeboom et al., 2011). At a distance of 200 m from the turbines, there was an increase of sole, whiting and striped red mullet, and a decrease of lesser weever in the wind farm compared to the reference areas. Based on trawl samples taken during the construction phase in the North Hoyle wind farm in the UK, no major changes in invertebrate and fish numbers and distributions were found (Anonymous, 2005). Although edge effects are important in assessing the effects of wind farms in a marine region, they received less attention compared to the wind farm effects in these studies.

In the present study, we investigated whether the changes in species diversity, density, species composition, size distribution, and biomass of the epibenthos, demersal fish, and benthopelagic fish living on the soft sandy substrates between the turbines (including their scour protections) and at the edges of two wind farms that are located in the same area but that differ in several aspects, can be related to the introduction of hard substrates (windmill foundations and scour protections) and the absence of fisheries in the farms (wind farm effects), or to overflow effects and potentially increased fishing effort at the edge of the wind farms (edge effects).

Materials and methods

The already constructed wind farms on the Thorntonbank and the Bligh Bank in Belgian waters constitute patches of hard substrate on a seafloor dominated by sandy sediments, although the configurations of both wind farms differ substantially. The C-Power wind farm consists of 54 turbines (6 gravity-based foundations (GBFs) and 48 jacket foundations (JF) with a total capacity of 325 MW), built on the sandy

Thorntonbank, which is located 27 km from the Belgian coast. Water depth in the concession area varies between 18 and 24 m. At the time of this study, the Belwind wind farm was only partly completed, with 56 turbines constructed on monopile foundations and with a capacity of 165 MW. This wind farm is situated on the Bligh Bank at about 40 km off the Belgian coast, in water depths between 15 and 40 m.

The studied wind farms are situated at the eastern border of the Belgian part of the North Sea, which is an important fishing ground for mainly Dutch beam trawlers targeting flatfish (Pecceu et al., 2014). Detailed and complete VMS data from the period preceding wind farm construction are not available at present, but post-construction (2010–2011) analyses indicate that, as more turbines are being installed, the trawler-free areas enlarge (Vandendriessche et al., 2013). In 2012, the areas closed for fisheries contained the concessions and safety buffers of 3 turbine clusters. There were two clusters on the Thorntonbank of 19 and 17 km^2, and one cluster on the Bligh Bank of 21 km^2; totaling 57 km^2. Still, intrusions in the wind farms and their safety buffers are regularly reported (Anonymous, 2011), and fisheries intensity around the wind farms remains very high (Pecceu et al., 2014), with a slight increase in intensity at different sections of the wind farm edges (Vandendriessche et al., 2013).

To study wind farm and fringe effects on the soft substrate fauna, beam trawl samples were taken within the wind farms between the turbine rows (at ca. 200 m from the nearest turbines), just outside the edges of the concessions (edge stations), and at reference stations away from the concessions with comparable soft sediments and depths (Fig. 1). Fish fauna and epibenthos were sampled with an 8-meter shrimp beam trawl (22-mm mesh in the cod end) featuring a ground rope fitted with bobbins. The net was towed for 30 min (first three monitoring years) or 15 min (since third monitoring year) at an average speed of 4 knots, keeping the depth variation per track to a minimum. Time, start and stop coordinates, trajectory and sampling depth were noted to standardize values per surface unit. The sampling activities were repeated every 6 months (February–March and September–October) from 2005 to 2012 at the Thorntonbank (construction periods: 2008–May 2009 for GBFs, Apr 2011–Sept 2013 for JF), and from 2008 to 2012 at the Bligh Bank (construction period: Sept 2009–Feb 2010). Each year, the sampling design and number of samples were slightly adapted when necessary, based on the previous monitoring results and on wind farm accessibility. The epifauna, demersal fish, and benthopelagic fish from each sample were analyzed in detail on board of RV Belgica or in the lab.

We tested wind farm and edge effects for three ecosystem components (epifauna, demersal fish, and benthopelagic fish), for two seasons (autumn and spring), two sandbanks (Thorntonbank and Bligh Bank), and two habitats (sandbanks and gullies), since other studies indicated that these factors have a significant influence on epibenthos and fish variation (De Backer et al., 2010; Derweduwen et al., 2010). For each combination of these factors, tests were first done on the univariate measures density (ind/1,000 m^2), biomass (g WW/1,000 m^2, only for epibenthos), and diversity (species number S). Afterward, the community structure per ecosystem component was explored, again for each combination of factors. Finally, densities and size frequencies of a selection of species were analyzed. Differences between treatment groups over the years were visualized using time-evolution graphs (except for community structure). Non-parallelism in the trend lines (control versus impact) was interpreted as a possible sign of environmental impact (Schwarz, 1998), and was further investigated using a PERMANOVA approach. All analyses were run in PERMANOVA+ for PRIMER (Anderson et al., 2007). All Pseudo-F and *P* values are given in tables. All time-evolution graphs have been drafted, but only a selection are represented to illustrate the results.

The statistical analyses are based on a “Before After Control Impact” (BACI) design (Smith et al., 1993), similar to the studies of van Deurs et al. (2012) and Leonhard et al., (2011). They were conducted using 2-way crossed PERMANOVA analyses based on the factors period (BA), with years nested within BA, and site (CI). Since the number of replicates per treatment varied throughout the monitoring period, type III sum of squares were used. All data were fourth root transformed prior to analysis. Monte Carlo tests (indicated as “MC”) were performed when the number of unique permutations was <100. In case of significant interaction effects for the main test, pairwise tests were done. Community differences were analyzed based on the Bray-Curtis similarity measure. In the case of significant differences, the contribution percentages of species to these differences were calculated using the SIMPER routine. Further univariate analyses on

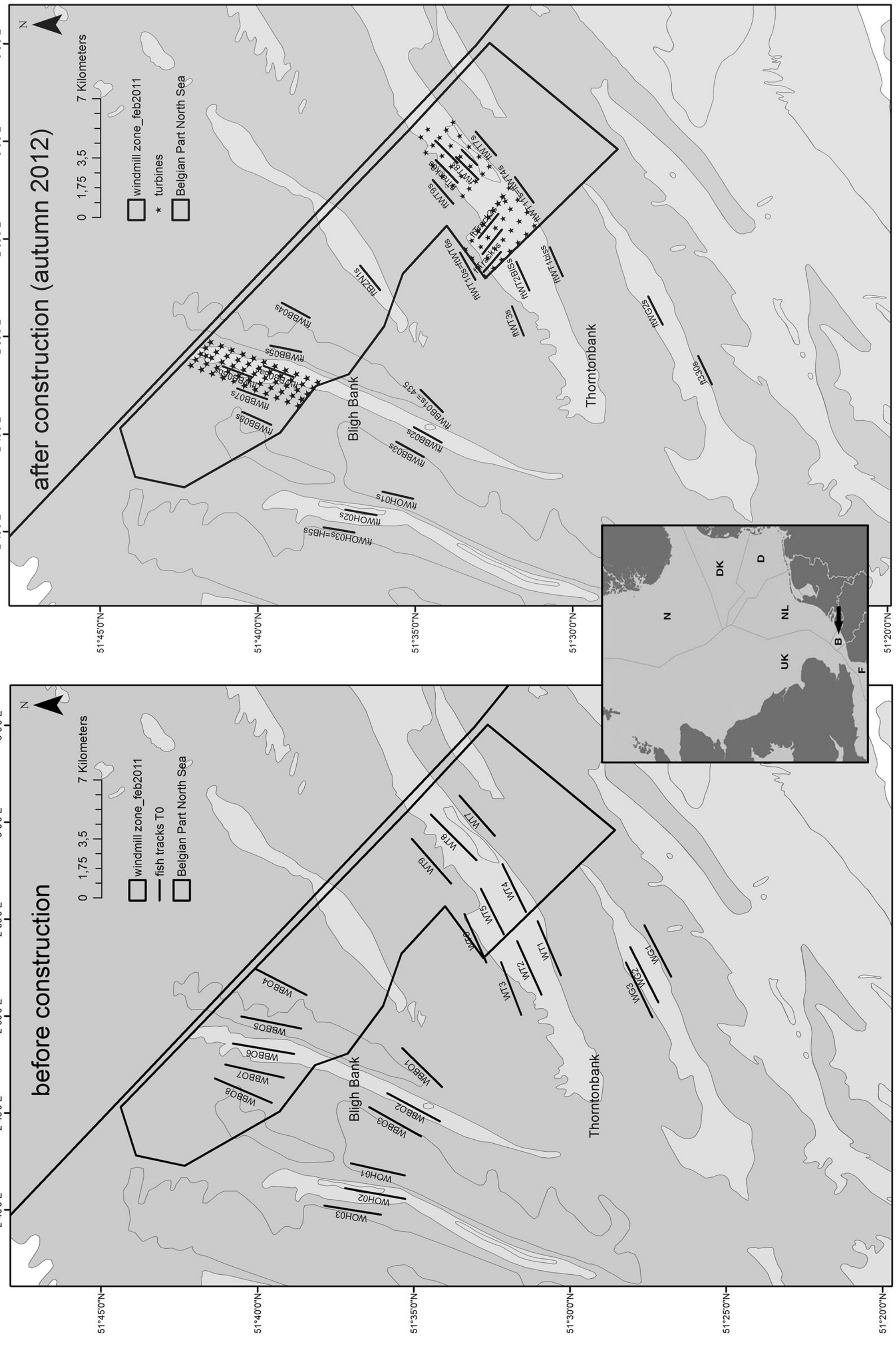

Fig. 1 BACI sampling design showing trawl locations before and after construction of both the Thorntonbank and Bligh Bank wind farms, and reference stations on adjoining sandbanks. Bathymetry is indicated as grayscale (*white* <5 m; *light gray* 5–20 m; *dark gray* >20 m). Inset indicates the position of the Belgian part of the North Sea relative to Belgium and its neighboring countries

Table 1 Number of trawl samples per BACI treatment

		BC	BI	AC	AI
Thorntonbank					
Spring					
Wind farm effect	Top	5	6	6	8
	Gully	6	2	10	2
Edge effect	Gully	6	4	10	8
Autumn					
Wind farm effect	Top	2	3	8	14
	Gully	3	1	13	2
Edge effect	Gully	3	2	13	10
Bligh bank					
Spring					
Wind farm effect	Top	2	2	6	2
	Gully	4	2	11	4
Edge effect	Gully	4	4	11	4
Autumn					
Wind farm effect	Top	2	1	8	5
	Gully	7	2	16	5
Edge effect	Gully	7	2	16	8

BC before-control, *BI* before-impact, *AC* after-control, *AI* after-impact

density, biomass, diversity, and length were based on Euclidean distance measures.

Since the number of years in the "after" group (i.e., years after construction) was limited for parts of the wind farms (the jacket foundations of the Thorntonbank wind farm were only constructed between 2011 and 2013) and as the BACI design does not easily pick up temporary effects, we also checked for differences between control and impact samples within particular years [indicated as CIY(BA)]. The number of trawl samples included in the BACI design tests is given in Table 1, and varied depending on the number of pre- and post-construction observations.

Results

Density, biomass, diversity, and species composition at ecosystem component level

We tested the edge effects and wind farm effects for all variables per ecosystem component, sandbank, habitat (sandbank top and gullies), and for the seasons autumn and spring. A significant overall effect on density was only seen for demersal fish at the Thorntonbank top in autumn when years were nested within the BA treatment (Table 2). The pairwise tests, however, did not reveal particular differences within a certain year. Biomass effects at the BACI level were seen at the Bligh Bank top in both autumn and spring, with increases in biomass after construction. Epibenthos biomass was higher at the Thorntonbank top stations in 2009 and 2012, but only the difference in 2009 turned out to be significant. The biomass effects at the Thorntonbank (autumn) and Bligh Bank (spring) are illustrated by the non-parallelisms in Fig. 2. We also observed a biomass effect at the Thorntonbank edge at the BACI level in spring, but the pairwise tests were not significant (Table 3). For species number, three overall tests for differences within particular years were significant. The pairwise tests only indicated a wind farm effect for demersal fish in the Thorntonbank in autumn 2008, but this was based on data from only three fish tracks. Differences in species composition due to the wind farm presence were only seen for demersal fish at the Bligh Bank gullies in autumn 2012 (Table 4). This difference was mainly due to different proportions of solenette *Buglossidium luteum*, sandeel *Ammodytes tobianus*, and dragonet *Callionymus lyra*, that showed higher abundances at the control stations (SIMPER contribution percentages in Table 5).

Density at species level

We tested the edge effects and wind farm effects for species that showed non-parallelisms in the time-evolution graphs between impact and control stations. Such non-parallelisms were seen at one or both of the wind farms, seasons, and habitats for *Ammodytes tobianus, Asterias rubens, Solea solea, Limanda limanda, Pagurus bernhardus, Psammechinus miliaris, Ophiura ophiura,* and *Callionymus reticulatus* (time-evolution graphs were drafted for 30 species). Significant edge effects were only seen for sole and dab at the Bligh Bank in spring 2012 (PERMANOVA results in Table 6, non-parallelisms in dab and sole illustrated in Fig. 3). In both cases, the non-parallelisms between edge and reference stations were striking and higher densities were observed in the edge stations. However, these differences did not result in a BACI effect, which means that they are either temporary or that they are the first signs of a persistent edge effect. Significant BACI wind farm effects were seen for sea stars and sole at the Bligh

Table 2 PERMANOVA results for BACI interactions (baci) and CI interactions within specific years (ciy(ba)) for density, biomass, species number, and species composition per ecosystem component

	Euclidean								Bray-curtis							
	Density				Biomass				Species number				Species composition			
	baci		ciy(ba)		baci		ciy(ba)		baci		ciy(ba)		baci		ciy(ba)	
	Pseudo-F	*P*	Pseudo-F	*P*	Pseudo-F	*P*	Pseudo-F	*P*	Pseudo-F	*P*	Pseudo-F	*P*	Pseudo-F	*P*	Pseudo-F	*P*
Benthopelagic fish																
BB aut																
Edge	0.99	0.40	0.64	0.58					1.37	0.32	0.18	0.91	2.53	0.15	0.50	0.83
Wind farm—top	5.60	0.14	0.25	0.75					6.11	0.12	0.42	0.60	0.43	0.71	1.48	0.33
Wind farm—gully	1.35	0.37	0.18	0.82					3.21	0.22	0.36	0.71	2.14	0.24	0.23	0.95
TB aut																
Edge	No test		2.55	0.09					No test		No test		0.46	0.67	1.20	0.33
Wind farm—top	0.76	0.42	0.77	0.58					3.81	0.12	0.31	0.89	0.91	0.46	0.76	0.73
Wind farm—gully	0.01	0.94	0.53	0.45						No test		No test	0.83	0.56	1.11	0.37
BB spring																
Edge	1.53	0.35	0.43	0.65					4.04	0.19	0.50	0.61	0.67	0.55	1.11	0.39
Wind farm—top	0.54	0.53	No test						0.50	0.53	No test		0.34	0.63	No test	
Wind farm—gully	2.50	0.38	0.69	0.42					0.02	0.91	7.91	**0.01**[4]	1.05	0.49	1.82	0.18
TB spring																
Edge	3.23	0.15	0.53	0.72					3.79	0.12	0.19	0.94	0.96	0.42	0.68	0.78
Wind farm—top	1.20	0.32	0.81	0.55					0.88	0.41	0.37	0.83	0.21	0.85	0.25	0.99
Wind farm—gully	7.99	0.10	0.30	0.75					0.63	0.55	0.05	0.95	0.55	0.66	1.45	0.24
Demersal fish																
BB aut																
Edge	0.93	0.42	0.47	0.70					0.76	0.44	1.94	0.16	0.68	0.53	1.29	0.21
Wind farm—top	0.01	0.94	0.50	0.63					6.20	0.16	0.05	0.95	0.74	0.56	1.55	0.19
Wind farm—gully	0.49	0.55	1.01	0.38					2.29	0.28	2.37	0.13	0.96	0.47	2.15	**0.03**[2]
TB aut																
Edge	0.48	0.56	1.66	0.21					0.45	0.56	1.08	0.39	1.64	0.25	0.89	0.56
Wind farm—top	1.49	0.33	21.44	**<0.01**[1]					0.67	0.45	0.78	0.57	1.31	0.41	0.59	0.64

Table 2 continued

	Euclidean								Bray-curtis							
	Density				Biomass				Species number				Species composition			
	baci		ciy(ba)		baci		ciy(ba)		baci		ciy(ba)		baci		ciy(ba)	
	Pseudo-F	*P*	Pseudo-F	*P*	Pseudo-F	*P*	Pseudo-F	*P*	Pseudo-F	*P*	Pseudo-F	*P*	Pseudo-F	*P*	Pseudo-F	*P*
Wind farm—gully	No test		No test						0.77	0.09	0.55	**0.03**[5]	1.01	0.42	1.34	0.16
BB spring																
Edge	0.29	0.66	1.85	0.20					0.37	0.62	2.88	0.09	0.37	0.73	1.02	0.43
Wind farm—top	2.49	0.19		No test					0.96	0.37	No test		1.11	0.40	No test	
Wind farm—gully	0.11	0.79	0.86	0.37					3.40	0.31	1.70	0.21	0.48	0.67	1.53	0.17
TB spring																
Edge	2.82	0.17	0.32	0.86					0.02	0.88	1.28	0.32	1.53	0.25	0.58	0.93
Wind farm—top	1.03	0.38	0.37	0.84					0.40	0.56	1.39	0.29	0.72	0.26	0.52	0.83
Wind farm—gully	0.96	0.46	0.06	0.94					1.08	0.42	0.60	0.56	1.55	0.56	0.70	0.82
Epibenthos																
BB aut																
Edge	8.88	0.08	0.27	0.84	12.35	0.06	0.07	0.97	1.97	0.25	0.24	0.87	0.57	0.65	0.73	0.85
Wind farm—top	6.12	0.14	0.99	0.43	29.56	**0.04**[8]	0.09	0.92	5.8674	0.16	0.07	0.93	1.83	0.25	0.67	0.74
Wind farm—gully	2.34	0.27	1.20	0.32	2.31	0.27	0.38	0.65	0.13	0.74	4.03	**0.03**[6]	0.96	0.42	0.97	0.50
TB aut																
Edge	0.77	0.45	0.18	0.91	0.20	0.69	0.07	0.98	0.10	0.78	1.28	0.32	1.05	0.43	0.64	0.83
Wind farm—top	2.83	0.18	2.15	0.11	2.64	0.19	5.53	**<0.01**[3]	0.76	0.42	0.40	0.83	0.86	0.51	1.26	0.19
Wind farm—gully	0.97	0.51	0.54	0.45	3.28	0.30	0.15	0.66	2.42	0.36	0.29	0.60	0.45	0.71	0.80	0.52
BB spring																
Edge	3.63	0.20	1.34	0.29	3.10	0.23	0.80	0.46	0.00	0.91	0.18	0.83	0.79	0.56	0.64	0.81
Wind farm—top	1.54	0.27	No test		9.58	**0.02**[9]	No test		0.34	0.59	No test		1.81	0.16	No test	
Wind farm—gully	3.90	0.28	0.77	0.40	12.98	0.16	0.14	0.72	2.04	0.40	0.82	0.38	2.86	0.27	0.49	0.81
TB spring																
Edge	1.46	0.31	0.75	0.55	14.03	**0.04**[7]	0.09	0.96	2.69	0.18	0.87	0.50	2.58	0.06	0.43	0.99
Wind farm—top	4.98	0.09	0.57	0.70	0.10	0.77	0.66	0.63	2.84	0.17	1.35	0.30	1.18	0.36	0.54	0.96
Wind farm—gully	2.08	0.28	0.50	0.60	2.14	0.24	0.83	0.46	1.51	0.34	0.10	0.89	0.80	0.57	0.43	0.93

For each test, the Pseudo-F and *P* values are given. Significant values are indicated in bold. Superscripts refer to pairwise tests presented in Tables 3 and 4

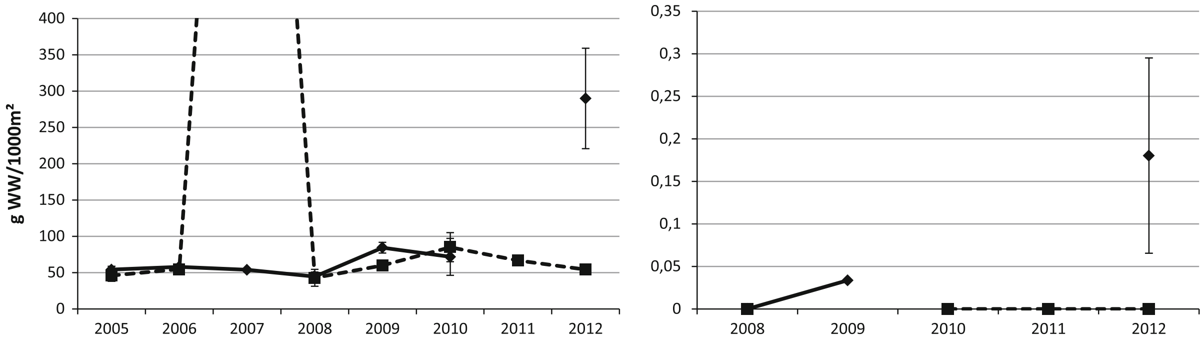

Fig. 2 Wind farm effects on epibenthos biomass (average gWW/1000 m^2 ± SE). *Full line* impact; *dotted line* reference. *Left* Thorntonbank in autumn between 2005 and 2012. The graph on epibenthos biomass was cut off at 400 g WW/1,000 m^2 due to an outlier of 1395 g WW/1,000 m^2 in 2007. *Right* Bligh Bank in spring between 2008 and 2012

Table 3 Pairwise test results for significant BACI interactions indicated in Table 2

	B(CI)		A (CI)	
	t	*P*	*t*	*P*
7	8.49	0.07	1.04	0.41
8	0.65	0.62	14.46	**<0.01**
9	0.33	0.80	7.76	**<0.01**

For each test, the Pseudo-F and *P* values are given. Significant values are indicated in bold

Bank top spring (PERMANOVA results in Table 6). Comparison of density data and biomass data for sea stars indicated that the increases were mainly due to a recruitment of small individuals. Significant effects within particular years were seen for sandeel in the Bligh Bank gullies in autumn 2012, for sea stars at the Bligh Bank top in autumn 2009 and 2011, for sole and dab at the Bligh Bank top in autumn 2011, and for ophiuroids and urchins at the Bligh Bank gullies in autumn 2009 (PERMANOVA results in Table 6, non-parallelisms in ophiuroids and urchins illustrated in Fig. 4).

Size distribution

PERMANOVA tests were done for species that showed non-parallelisms in the time-evolution graphs between impact and control stations concerning average length (or average carapax width in the case of crabs), or that showed differences in the length-frequency distribution graphs. Such differences were seen for *Limanda limanda, Pleuronectes platessa, Liocarcinus holsatus, Merlangius merlangus*, and *Ammodytes tobianus*. Significant BACI results on mean length differences were only found for whiting concerning edge effects at the Thorntonbank in spring (Table 7). The time series graphs and the length-frequency results (not shown) suggest that the differences were only minor. Effects within specific years

Table 4 Pairwise test results for significant cixy(ba) interactions indicated in Table 2. For each test, the Pseudo-F and p values are given

	2005		2008		2009		2010		2011		2012	
	t	p(MC)	*t*	p(MC)	*t*	p(MC)	*t*	p(MC)	*t*	p(MC)	*t*	p(MC)
1	0.38	0.74	0.66	0.55	0.19	0.86	2.66	0.08	No test		2.04	0.09
2	No test		0.70	0.71	2.09	0.09	No test		1.29	0.22	2.23	**0.04***
3	0.96	0.41	0.06	0.95	3.18	**0.05**	0.47	0.67	No test		2.00	0.09
4	No test		1.46	0.20	No test		No test		1.63	0.18	1.63	0.17
5	0.50	0.67	7.46	**0.02**	No test		1.00	0.42	No test		No test	
6	No test		2.12	0.10	4.13	0.06	No test		0.22	0.84	1.31	0.26

Significant values are indicated in bold. The asterisk refers to the SIMPER analysis for control and impact samples represented in this test, see Table 5

Table 5 SIMPER results for differences in the species composition of demersal fish at the Bligh Bank gullies in autumn 2012, as is indicated by the asterisk in Table 4 (line 2)

*Groups C & I						
Average dissimilarity = 32,57						
Species	Group C	Group I				
	Av.Abund	Av.Abund	Av.Diss	Diss/SD	Contrib %	Cum. %
Buglossidium luteum	1.14	0	5.08	6.7	15.59	15.59
Ammodytes tobianus	0.74	0	3.31	4.45	10.17	25.76
Callionymus lyra	0.73	0.51	2.48	1.13	7.6	33.36
Agonus cataphractus	0.49	0	2.12	1.56	6.51	39.87
Solea solea	0.59	0.34	1.9	1.11	5.84	45.71

were found for dab in autumn at the Thorntonbank top, where the mean length was about 4 cm lower at the impact stations compared to the reference stations in 2012. A similar decrease of length was also seen at the Bligh Bank gullies, but these were not significant. However, when taking a closer look at the length-frequency distributions (Fig. 5), we see that two size classes could be distinguished in dab for the reference stations throughout the years. In autumn 2011, the number of fish from the larger size class was strongly reduced in edge and impact stations. In autumn 2012, numbers were reduced in both size classes. It appears that dab is moving away from the edge and impact stations, initially only larger fish, but recently also the smallest fish seemed mostly gone.

Anecdotal observations

We made some observations that were not picked up by the statistical analyses but are worth mentioning in the context of wind farm effects. For plaice *Pleuronectes platessa*, for example, there was a general increase in density over the years (Fig. 6). In 2012, however, numbers had decreased in the impact gully stations, while numbers at other gully stations increased. No dramatic shifts in population structure were observed based on length-frequency analyses, but we did observe a small number of 'larger' animals (30–43 cm). The presence of large plaice was also noted during diving operations in the Bligh Bank wind farm (J. Reubens, pers. comm.). Similar observations were done for turbot *Psetta maxima*. Changes in sandeel size and density were not significant in the BACI design (except for impact gully stations in 2012, see above), but a few striking non-parallelisms were seen in the density and size evolution graphs of the sandbank top stations, with episodic increases of sandeel at both wind farms in both seasons at the sandbank top impact stations. Finally, lobsters *Homarus gammarus* have never been caught in the last decade during the many monitoring surveys of soft sediments that have been carried out by ILVO in the Belgian part of the North Sea. However, in autumn 2012, a lobster strayed from the wind farm hard substrates into the sandy area between the turbine rows of the Thorntonbank wind farm.

Discussion

Sampling design

A BACI design is most appropriate for impact studies like the present one (Smith, 2002). Still, some considerations need to be taken into account. A main point of concern with a BACI design is the risk of false positives in multiple testing. We tested two effects, three ecosystem components, two seasons, two sandbanks, and two habitats. Tests were performed on density, biomass, diversity, and community structure per ecosystem component, and on densities and size frequencies of a selection of species. As more attributes are compared, it becomes more likely that the impact and control groups will appear to differ on at least one attribute by random chance alone (e.g., Benjamini & Hochberg, 1995; Verhoeven et al., 2005). But even as such, the observed differences and trends were in most comparisons statistically not significant within the BACI framework, which can be related to several factors. First, there is the limited number of post-construction observations (1 year for the Thorntonbank wind farm phase II, i.e., the

Table 6 PERMANOVA results for BACI interactions (baci) and CI interactions within specific years (ciy(ba)) for density per species (selection)

			baci		cixy(ba)	
			Pseudo-F	p	Pseudo-F	p
Ammodytes tobianus	BB autumn	edge	1,51	0,30	2,82	0,07
		wind farm - gully	0,24	0,66	8,05	**<0,01**[1]
		wind farm -top	0,02	0,89	2,15	0,19
	BB spring	edge	0,05	0,83	0,20	0,82
		wind farm - gully	0,18	0,73	2,12	0,16
		wind farm -top	1,46	0,29	no test	
	TB autumn	edge	2,29	0,22	1,95	0,16
		wind farm - gully	1,74	0,40	0,18	0,67
		wind farm -top	0,00	0,99	2,10	0,11
	TB spring	edge	1,39	0,31	0,84	0,53
		wind farm - gully	0,83	0,46	0,10	0,88
		wind farm -top	0,35	0,59	1,65	0,22
Asterias rubens	BB autumn	edge	0,94	0,41	1,22	0,32
		wind farm - gully	10,94	0,09	0,60	0,57
		wind farm -top	1,48	0,35	7,49	**0,02**[2]
	BB spring	edge	0,07	0,81	0,58	0,55
		wind farm - gully	2,01	0,39 (MC)	2,08	0,17 (MC)
		wind farm -top	75,18	**<0,01**[10]	no test	
	TB autumn	edge	0,18	0,72	0,36	0,79
		wind farm - gully	0,65	0,58	0,25	0,59
		wind farm -top	1,83	0,24	2,23	0,10
	TB spring	edge	2,23	0,95	1,25	0,33
		wind farm - gully	0,06	0,83	0,20	0,78
		wind farm -top	1,08	0,40	1,06	0,41
Solea solea	BB autumn	edge	0,71	0,46	0,83	0,49
		wind farm - gully	1,14	0,39	0,91	0,43
		wind farm -top	0,01	0,96	6,94	**0,03**[3]
	BB spring	edge	0,23	0,68	3,95	**0,04**[4]
		wind farm - gully	3,08	0,33	0,76	0,40
		wind farm -top	28,90	**<0,01**[11]		no test
Limanda limanda	BB autumn	edge	0,28	0,59	1,83	0,18
		wind farm - gully	13,55	0,08	0,34	0,69
		wind farm -top	0,41	0,59	5,96	**0,03**[5]
	BB spring	edge	0,40	0,60	3,90	**0,04**[6]
		wind farm - gully	0,02	0,90	3,43	0,08
		wind farm -top	1,78	0,24	no test	
Ophiura ophiura	BB autumn	edge	0,41	0,57	0,24	0,86
		wind farm - gully	0,22	0,65	10,90	**<0,01**[7]
		wind farm -top	no test		1,32	0,32
	BB spring	edge	5,09	0,15	0,13	0,87
		wind farm - gully	0,09	0,83	2,19	0,16
		wind farm -top	0,25	0,64	no test	

			baci		cixy(ba)	
			Pseudo-F	p	Pseudo-F	p
Psammechinus miliaris	BB autumn	edge	0,10	0,77	0,47	0,71
		wind farm - gully	0,02	0,87	5,27	**0,01**[8]
		wind farm -top	0,01	0,92	2,40	0,15
	BB spring	edge	2,85	0,24	0,03	0,97
		wind farm - gully	52,05	0,09	0,08	0,78
		wind farm -top	0,67	0,45	no test	no test
Pagurus bernhardus	BB autumn	edge	0,02	0,91	0,59	0,64
		wind farm - gully	0,74	0,48	0,18	0,83
		wind farm -top	17,44	0,06	0,25	0,79
	BB spring	edge	7,69	0,12	0,09	0,91
		wind farm - gully	0,23	0,72	6,38	**0,02**[9]
		wind farm -top	1,63	0,26	no test	
Callionymus reticulatus	BB autumn	edge	0,94	0,40	0,58	0,64
		wind farm - gully	4,03	0,20	0,76	0,48
		wind farm -top	no test		no test	

	2008		2009		2011		2012	
	t	p (MC)	t	p(MC)	t	p(MC)	t	p(MC)
1	0,66	0,55	0,69	0,56	0,21	0,85	9,37	**<0,01**
2	0,63	0,65	19,68	**0,03**	8,15	**0,02**	3,70	0,06
3	no test		0,58	0,68	0,33	**<0,01**	1,00	0,42
4	0,67	0,54	3,83	0,16	0,37	0,73	351,67	**<0,01**
5	1,09	0,47	0,51	0,69	5,60	**0,03**	2,15	0,17
6	0,07	0,95	1,01	0,48	2,05	0,10	3,13	**0,04**
7	1,13	0,33	23,95	**<0,01**	0,02	0,99	1,08	0,34
8	0,62	0,56	4,47	**0,05**	2,57	0,06	0,97	0,39
9	0,37	0,72	no test		2,38	0,08	0,41	0,70

	B (CI)		A (CI)	
	t	p (MC)	t	p (MC)
10	279,54	**<0,01**	5,48	**<0,01**
11	1,00	0,42	11,40	**<0,01**

For each test, the Pseudo-F and *P* values are given. Significant values are indicated in bold. Superscripts refer to pairwise tests presented in the inset tables

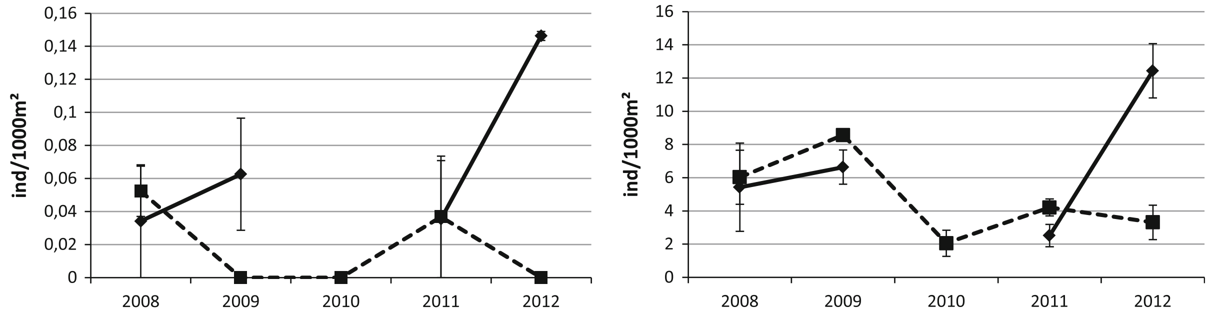

Fig. 3 Edge effects on species densities (average ind/1000 $m^2 \pm$ SE) at the Bligh Bank in spring. *Full line* edge; *dotted line* reference. *Left* sole *Solea solea*; *right:* dab *Limanda limanda*

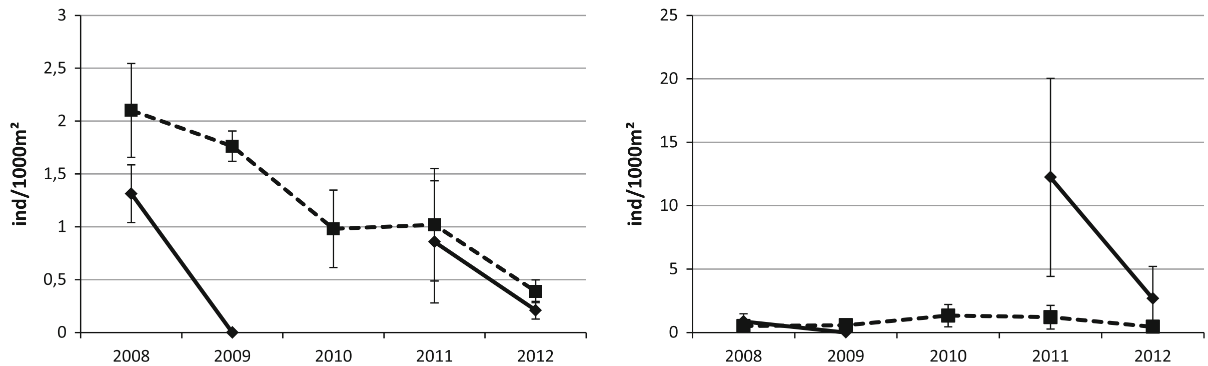

Fig. 4 Wind farm effects on species densities (average ind/1,000 $m^2 \pm$ SE) at the Bligh Bank gullies in autumn. *Full line* impact; *dotted line* reference. *Left* ophiuroids *Ophiura ophiura*; *right* urchins *Psammechinus miliaris*

placement of jacket foundations, 2 years for the Bligh Bank wind farm). This strongly limits the power of the analyses. The effects are likely to become more pronounced in the coming years, as it takes about three to five years to establish stable faunal communities after artificial hard structures are deployed (Jensen, 2002; Gray, 2006; Petersen & Malm, 2006), and it takes 5–15 years to detect species-specific effects of fishery closures (Babcock et al., 2010). Second, for safety reasons, the sampling distance relative to the turbines and their scour protections was still quite big (>180 m). The studies of Bergström et al., (2012, 2013) and Wilhemsson et al., (2006) indicated that dependent on the species, increased densities were limited to a radius of 20–160 m from the turbines in Swedish offshore wind farms. For the Belgian wind farms, this may mean that increases or changes in density, biomass, diversity, or community structure of the soft sediment communities between the turbines will remain limited or that it will take a long time before the reef effects expand into the sandy space between the turbine rows. Third, the trawler-free area was about 56 km^2 at the time of the study, which is still relatively small compared to existing MPAs. The Lyme MPA in the UK, for example, is 206 km^2 (Sheehan et al., 2013), while the Georges Bank closures were 17,000 km^2 (Murawski et al., 2000). Fourth, different effects were observed in spring and autumn, with most effects detected in autumn. This is probably due to the fact that epibenthos densities were generally higher in this season due to migration and the presence of adults rather than recruiting juveniles (Reiss & Kröncke, 2004). Similarly, the catchability of fish in trawl surveys is generally higher in summer and autumn than in spring and winter (Harley & Myers, 2001). This increases the number of observations of certain species within the autumn replicates and therefore enhances the power of the analyses. Finally, the BACI design does not easily pick up small or gradual changes, so temporary effects or effects with a time lag relative to the actual impact can only be traced by careful and detailed analyses of the available data,

Table 7 PERMANOVA results for BACI interactions (baci) and CI interactions within specific years (ciy(ba)) for average length per species (selection)

Species	Survey	Comparison	baci Pseudo-F	baci p	cixy(ba) Pseudo-F	cixy(ba) p
Merlangius merlangus	BB autumn	edge	0,11	0,76	1,81	0,19
		wind farm - gully	0,16	0,68	no test	
		wind farm - top	no test		no test	
	BB spring	edge	2,15	0,29	0,00	1,00
		wind farm - gully	5,51	0,26	0,06	0,81
		wind farm - top	no test		no test	
	TB autumn	edge	2,65	0,20	0,98	0,43
		wind farm - gully	0,50	0,60	2,30	0,17
		wind farm - top	0,11	0,77	0,09	0,98
	TB spring	edge	14,05	**0,02**[6]	0,04	1,00
		wind farm - gully	1,01	0,45	1,62	0,26
		wind farm - top	0,08	0,78	6,80	**<0,01**[1]
Pleuronectes platessa	BB autumn	edge	0,39	0,58	0,86	0,47
		wind farm - gully	0,59	0,53	1,63	0,22
		wind farm - top	0,31	0,65	2,07	0,19
	BB spring	edge	0,18	0,72	1,67	0,22
		wind farm - gully	1,86	0,39	0,03	0,86
		wind farm - top	0,29	0,62	no test	
	TB autumn	edge	1,17	0,36	0,75	0,54
		wind farm - gully	4,00	0,30	0,03	0,87
		wind farm - top	0,40	0,55	2,62	0,05
	TB spring	edge	0,01	0,94	1,04	0,42
		wind farm - gully	1,12	0,41	0,64	0,54
		wind farm - top	0,37	0,65	0,99	0,44
Liocarcinus holsatus	BB autumn	edge	2,75	0,22	0,06	0,97
		wind farm - gully	0,11	0,75	3,15	0,09
		wind farm - top	0,04	0,86	8,69	**0,02**[2]
	BB spring	edge	0,04	0,86	0,70	0,51
		wind farm - gully	2,13	0,39	0,38	0,54
		wind farm - top	no test		no test	
	TB autumn	edge	0,04	0,85	0,61	0,63
		wind farm - gully	1,90	0,40	0,01	0,89
		wind farm - top	0,05	0,84	0,39	0,82
	TB spring	edge	1,87	0,25	0,45	0,78
		wind farm - gully	1,24	0,39	2,41	0,20
		wind farm - top	0,64	0,48	0,36	0,79
Limanda limanda	BB autumn	edge	5,31	0,11	0,32	0,80
		wind farm - gully	0,64	0,49	3,51	**0,05**[3]
		wind farm - top	0,01	0,93	0,28	0,76
	BB spring	edge	2,47	0,27	0,36	0,69
		wind farm - gully	4,99	0,27	0,23	0,64
		wind farm - top	0,02	0,90	no test	
	TB autumn	edge	0,01	0,93	1,12	0,37
		wind farm - gully	0,67	0,57	0,38	0,55
		wind farm - top	0,04	0,86	3,93	**0,02**[4]
	TB spring	edge	0,38	0,57	2,11	0,13
		wind farm - gully	0,84	0,47	0,62	0,56
		wind farm - top	3,70	0,13	0,28	0,87
Ammodytes tobianus	BB autumn	edge	0,19	0,71	0,68	0,53
		wind farm - gully	0,38	0,64	1,35	0,27
		wind farm - top	5,32	0,16	0,09	0,92
	BB spring	edge	1,54	0,34	2,14	0,16
		wind farm - gully	0,29	0,72	0,51	0,49
		wind farm - top	2,09	0,21	no test	
	TB autumn	edge	0,60	0,54	1,07	0,38
		wind farm - gully	1,67	0,40	0,87	0,40
		wind farm - top	1,87	0,26	4,11	**0,02**[5]
	TB spring	edge	no test		2,67	0,11
		wind farm - gully	0,50	0,61	0,89	0,38
		wind farm - top	6,26	0,14	0,46	0,65

	2005		2008		2009		2010		2011		2012	
	t	p (MC)	t	p (MC)	t	p (MC)	t	p (MC)	t	p (MC)	t	p (MC)
1	0,06	0,96	1,93	0,19	1,58	0,36	no test		4,18	0,05	no test	
2	no test		2,51	0,24	1,54	0,36	no test		3,50	0,07	no test	
3	no test		1,97	0,12	0,51	0,67	no test		no test		2,46	0,06
4	no test		0,19	0,87	0,90	0,42	1,10	0,35	2,66	0,08	3,53	**0,01**
5	0,88	0,44	1,93	0,19	2,67	0,08	1,65	0,36	no test		no test	

	B (CI)		A (CI)	
	t	p	t	p
6	1,00	0,50	6,37	**<0,01**

For each test, the Pseudo-F and *p* values are given. Significant values are indicated in bold. Superscripts refer to pairwise tests presented in the inset tables

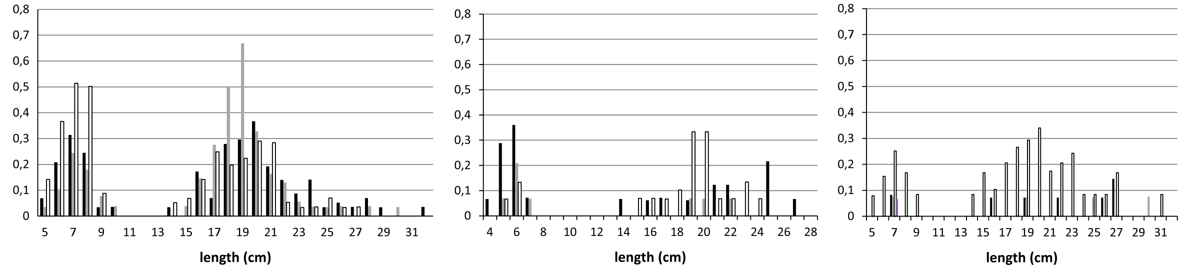

Fig. 5 Differences in length-frequency distributions of dab *Limanda limanda* at the Bligh Bank gully stations in autumn 2008 (*left*), 2011 (*middle*) and 2012 (*right*). *Black* impact edge; *gray* impact wind farm; *white* reference

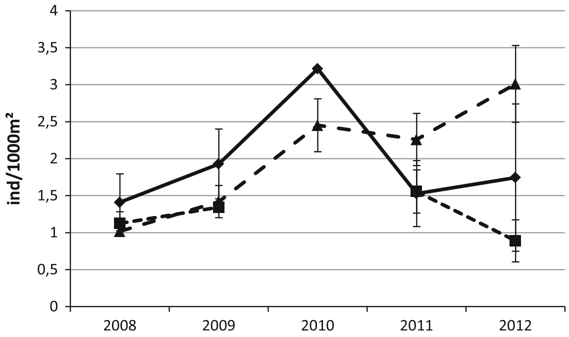

Fig. 6 Changes in plaice *Pleuronectes platessa* density (average ind/1,000 m^2 ± SE) at the Bligh Bank in autumn. *Full line* = impact edge; *striped line* impact wind farm; *dotted line* reference

taking into account the limitations of the design and methodology.

Wind farm effects

Some remarkable differences were observed between wind farm impact samples and reference samples for demersal fish, benthopelagic fish, and epibenthos, both at community and species level (summary in Table 8). Several wind farm effects were noted in autumn 2009 at the Bligh Bank, including a decrease in dab, dragonet, ophiuroids and squid, and an increase in sandeel. During this survey, the samples were taken only a few weeks after the piling activities started, so the observed changes were probably short term and temporary construction effects. Such temporary effects were also observed at the level of macrobenthos on the Thorntonbank, followed by a rapid recovery (Coates, 2014). As for post-construction effects, we noted changes in demersal fish composition, a decrease in number of demersal fish species, and an increase in epibenthos biomass. Whether these changes can be attributed to the presence of wind farms or the absence of fisheries are hard to prove based on the current monitoring design. Additional research on cause-effect relationships is needed to elucidate the contribution of each factor to the observed changes.

Importantly, the observed effects were not consistent between wind farms. This is not surprising, given the differences in communities (Derweduwen et al., 2010), in sandbank topography (Van den Eynde et al., 2010), in (historic) fishing pressure (Pecceu et al., 2014), differences in developmental stage of the wind farms, and used foundations types (Brabant et al., 2013). This inconsistency stresses the importance to replicate the monitoring activities across wind farms and along the identified gradients.

The changes in demersal fish can be related to the absence of fisheries in the wind farms and to local changes in sedimentology and infaunal prey species. For the commercially important flatfish in the Belgian part of the North Sea, we observed higher sole densities and changes in length-frequency distributions for dab and plaice. This may signal a refugium effect. However, bearing in mind that adult flatfish do not stay for long periods within a wind farm (Lindeboom et al., 2011), the refugium effect will be limited. On the other hand, dab seemed to move away from the soft sediments between the turbines. This can either mean that dab is really moving away from the wind farm, or that dab moves closer to the turbines (<180 m). Dab has rarely been observed close to the turbines during diving or angling (Reubens et al., 2013b), so the first hypothesis is probably the correct one.

Sandeels are an important food source for higher trophic levels. Lindeboom et al. (2011) found no indications of sandeels avoiding wind farms in the Netherlands. We noted changes in size distributions and densities of sandeel in both wind farms. This may be due to changes in the recruitment and pelagic activity of this fish species (Van Deurs et al., 2012). In Horns Rev I wind farm in Denmark, increased sandeel densities during and shortly after construction were attributed to changes in grain size and predator abundance (Leonhard et al., 2011; Van Deurs et al., 2012). If the hard substrate benthic community on the wind mill foundations further develops, more predators will be attracted to the area (Anonymous, 2006). This will surely affect the sandeel populations which normally reside in the soft sediments. Therefore, a focus on sandeels in the future Belgian monitoring program is advised, with a more suitable sampling strategy for quantitative estimations of sandeel densities.

The increase in epibenthos densities (e.g., sea stars, sea urchins, hermit crabs) is most probably related to the presence of hard substrates and their fouling communities and to the absence of fisheries in the wind farms. High numbers of young ophiuroids and starfish, and clusters of sea urchins have been observed on and near the turbines (De Mesel et al., 2013). Our

Table 8 Summary of the statistical results for the Thorntonbank and Bligh Bank

		spring			autumn		
		wind farm effect		edge effect	wind farm effect		edge effect
THORNTONBANK		top	gully	gully	top	gully	gully
community level	Density						
	Biomass			**epibenthos (BACI) ↑**	*epibenthos (2009) ↑*		
	Species number					*demersal fish (2008) ↓*	
	Species composition						
species level	density						
	mean length			**whiting (BACI) ↑**	*dab (2012) ↓*		
BLIGH BANK							
community level	Density						
	Biomass	**epibenthos (BACI) ↑**			**epibenthos (BACI) ↑**		
	Species number						
	Species composition					*demersal fish (2012)*	
species level	density	**sea star, sole (BACI) ↑**		*sole (2012) & dab (2012)↑*	*sole (2011) & dab (2011)↑, sea star* (2009) ↓, *sea star (2011)↑*	*sandeel (2012), ophiuroid (2009) & urchin (2009) ↓*	
	mean length						

Bold text indicates significant effects ($p < 0.05$) of the BACI interaction term. Text in italics indicates significant CI effects within specific years (but BACI effect not significant). Arrows indicate increase or decrease

observations in the surrounding sandy habitat are thus probably directly related to the presence of hard substrates. Especially for sea urchins, which predominantly feed on seaweed, hydroids, bryozoans, and barnacles, the presence of hard substrates is very important. The increased densities in the gullies may be the result of dislodgement from the turbines and the presence of coarse sediments (scour protection) around the wind turbines, which is the preferred habitat for green sea urchins. Additionally, sea urchins are prone to physical damage by trawling (Lokkeborg, 2005), so this species profits from the absence of commercial fish trawling within the wind farm. The occurrence of infringements, however, will substantially limit the beneficial effects (see further).

Mainly dominant scavenging species such as echinoderms and hermit crabs showed an increase in the wind farms. Signs of recovery of long living species vulnerable to trawling, as was seen for *Ostrea edulis* and *Sertularia cupressina* at Horns Rev (Anonymous, 2006), and *Sabellaria spinulosa* at the Thanet wind farm (Pearce et al., 2014) are only beginning to emerge. Coates (2014) found increases in tube-building polychaetes (Terebellidae) and the urchin *Echinocyamus pusillus* at the Bligh Bank concession, which is likely a result of the closure for fisheries. Lobsters have occasionally been observed by divers in a swedish wave farm (Langhamer et al., 2009) and at the scour protection layer of the gravity-based foundations at the Thorntonbank (De Mesel et al., 2013). The observation of a lobster on the soft sediments in our surveys suggests that the reef effect caused by the turbines is expanding into the sandy habitat in between the turbines. Lobsters perform extensive migrations in search of rocky habitats as shelter and food source (Krone et al., 2013). Artificial hard substrates like windmill foundations might act as stepping stones between the extensive soft sediment zones in the North Sea.

Edge effects

Local concentrations of fishing activity have been observed in the vicinity of closed areas (Stelzenmüller et al., 2008), potentially having effects on the resident fauna. As detailed VMS data (Vessel Monitoring System) from all vessels fishing in the vicinity of the wind farms in the periods before and after construction were not available for this study, it was difficult to prove that the fishing activity around the two already existing Belgian wind farms has changed significantly. However, based on Pecceu et al. (2014) and personal observations, we know that there is a high fishing intensity close to the wind farms. The ecological data presented in this study, however, did not reveal substantial edge effects, neither at the Thorntonbank nor at the Bligh Bank (Table 8). Effects of changed fisheries activities or overflow effects from the closed wind farms are possible but improbable at this time for a number of reasons. First, the trawler-free areas are still relatively small and fragmented (56 km^2), and intrusions are regularly reported (Anonymous, 2011). Little et al. (2005) showed that the establishment of a number of small reserves and the occurrence of regular infringements drastically reduce the beneficial effects of reserves. Second, the wind farms are still relatively "young" and the ecosystem in and around them is still developing (see section on wind farms effects). Consequently, edge effects will probably become more visible when the larger wind energy zone in the Belgian part of the North Sea is completely developed (with interconnected concessions and a single, uninterrupted edge) and when the infringements are reduced. In that scenario, biomass might increase even more than was observed now and overflow effects can attract fisheries to the edges, which will be detectable in local biomass and catch rate trends.

Conclusions

The results indicate that it is essential to further extend the time series within the same sampling design, and to replicate across wind farms along the identified gradients. This will increase the power of the statistical tests and shed a light on the maturation effect of the whole wind farm zone in the Belgian part of the North Sea. Wind farm effects were noted, both on a local and temporal scale, and at community and species level. However, only few effects were statistically significant, at least not within the BACI framework, and the effects were not consistent or even only anecdotal. On the long term, wind farm effects due to hard substrate addition are expected to extend into the soft substrates between the turbines in each wind farm and between the different concession zones. Additionally, the effects of fisheries exclusion will be enhanced as the size of the area increases and when the spatially separated trawler-free areas (as is the case now) are merged together to one uninterrupted zone. The analyses also indicated that wind farm effects concerning epibenthos, demersal, and benthopelagic fish should be followed-up very closely, mainly on species-specific length and density data, with an additional focus on sandeels. Up till now, substantial edge effects could not be shown. However, such effects will probably emerge in the following years as the wind farm area will be become a single entity and the effects of fisheries exclusion on target and non-target species will develop, and can then be traced by an integrated analysis of biological data (as in the present study) and detailed VMS data of Belgian and foreign vessels fishing in the Belgian part of the North Sea (Vandendriessche et al., 2011).

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