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Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community

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ABSTRACT: The rapid increase in offshore wind energy worldwide has raised concern about its potential risks to marine biodiversity due to habitat alteration, disturbance from noise and electromagnetic fields. This study presents results of surveillance studies performed at the Lillgrund wind farm in Sweden to investigate the integrated effects of these factors on the abundance and distribution patterns of benthic fish communities. The studies revealed no large-scale effects on fish diversity and abundance after establishment of the wind farm when compared to the development in 2 reference areas. Changes in some species and in community composition were observed over time but occurred in parallel in at least one reference area, indicating that fish communities in the wind farm area were mainly driven by the same environmental factors as those in surrounding areas. However, changes at smaller spatial scales were evident. Increased densities of all studied piscivores (cod, eel, shorthorn sculpin), as well as the reef-associated goldsinny wrasse, were observed close to the foundations in the first years of operation. The increase was probably attributed mainly to local changes in distribution rather than to immigration or increased local productivity. Simultaneously, weak or no aggregation of black goby, eelpout and shore crab, all potentially reef-associated but also prey species of the studied piscivores, was observed, which may indicate enhanced top-down control near the foundations.

KEY WORDS: Offshore wind farm · Wind turbine · Artificial reef · Fish · Distribution pattern · Predation · Environmental impact · Environmental monitoring

INTRODUCTION

The establishment of offshore wind farms (OWF) is increasing worldwide in efforts to increase the supply of renewable energy. However, OWF may be in conflict with marine biodiversity conservation. Currently available technology typically constrains the establishment of OWF in shallow marine habitats that have high ecological values, and reaching the goals of renewable energy production may require vast areas to be exploited (Gill 2005, Wilhelmsson et al. 2010). The potential effects of OWF on marine life have been repeatedly described as part of the planning process in environmental impact assessments, as required in most countries, but thorough empirical studies of the effects of large-scale OWF are still rare (Leonhard et al. 2011, Lindeboom et al. 2011). For fish, population- and community-level effects are poorly known, as available studies are typically short term or relate to individual fish species (e.g. Wahlberg & Westerberg 2005, Wilhelmsson et al. 2006a, Reubens et al. 2011, 2013, van Deurs et al. 2012).

Fish are expected to be affected by OWF in both positive and negative ways. A positive effect may occur due to the increased habitat complexity provided by the foundations and any additional scour protection structures. The introduced structures provide increased shelter and colonisation substrates for many marine organisms, which in turn may also attract foraging species (Wilhelmsson et al. 2006a, Wilhelmsson & Malm 2008, Maar et al. 2009, Reubens et al. 2013). This effect is also well known

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from other anthropogenic structures in the sea, such as oil platforms, piers, wrecks etc. (Claudet & Pelletier 2004, Wilhelmsson et al. 2006b, Seaman 2007, Langhamer & Wilhelmsson 2009, Langhamer et al. 2009). Although the most immediate effect is typically a redistribution of fish from nearby areas, the increased habitat complexity may also give rise to a local increase in productivity if growth rates are enhanced or mortality rates are reduced (Pickering & Whitmarsh 1997, Brickhill et al. 2005). However, the aggregation of fish may potentially have a negative population-level effect if it enhances the probability of the prey species being caught by fishing or by predation (Wilhelmsson 2012).

Concerns have also been raised that fish may be repelled from OWF areas because of noise disturbance or disturbance from electromagnetic fields created around cables on the seafloor (Nedwell et al. 2003, Nedwell & Howell 2004, Gill 2005, Wahlberg & Westerberg 2005, Öhman et al. 2007). These aspects may potentially decrease the value of the OWF as a habitat for fish, particularly for fish species with a well-developed hearing capacity or electroreception. Noise from the turbines may potentially increase stress levels in fish or harm internal communication by masking sound signals used by the fish (Andersson 2011, Popper & Hawkins 2012). Changes in electromagnetic fields may decrease foraging efficiency in species that use their electromagnetic sense for detecting prey, such as elasmobranchs (Kimber et al. 2011, Gill et al. 2012), or potentially disturb fish migration (Westerberg & Begout-Anras 2000, Westerberg & Lagenfelt 2008).

Because all these factors typically act simultaneously in an operational OWF, their relative importance for fish may be hard to disentangle and assess empirically. However, it may be anticipated that their integrated effect is reflected in the relative abundance and distribution of fish in the OWF area when compared to the situation before establishment and to reference areas.

In Sweden, the largest operational OWF today is the Lillgrund wind farm (Fig. 1). At its startup in late 2007, it was the world's third largest OWF. Permission for its establishment was granted in 2001 under the terms that a surveillance program would be conducted to monitor its effects on the surrounding environment. Here, we present the main results of those studies with respect to changes in the abundance and species composition of demersal fish, compared to 2 reference areas, and the results of additional studies of fish distribution patterns within the OWF area since its establishment.

MATERIALS AND METHODS

Study area

The Lillgrund wind farm is located in Öresund, which connects the brackish Baltic Sea with the Kattegat and the North Sea area. Salinity conditions are variable due to frequent changes in the direction of water currents in the strait. Yearly averages in salinity were 12.8 to 16.5 over the years of study, with no trends over time (SMHI 2012). Most of the fish species in Öresund (>95%) are of marine origin (HELCOM 2012). Fish monitoring studies (Andersson 2008) and commercial catches (ICES official catch statistics; www.ices.dk) show that the demersal fish community is dominated by cod *Gadus morhua*, flounder *Platichtys flesus*, plaice *Pleuronectes platessa* and eel *Anguilla Anguilla*, while the main spe-

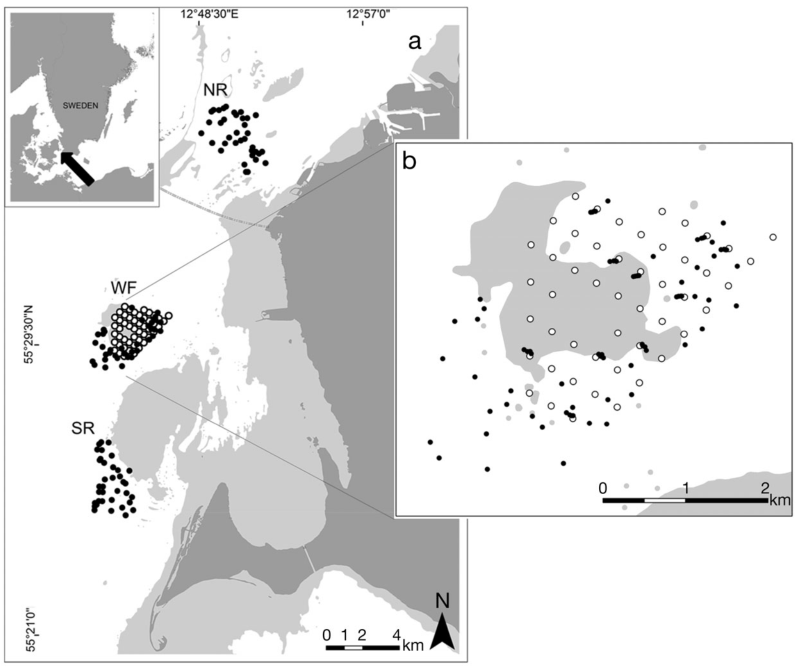

Fig. 1. (a) Location of the Lillgrund offshore wind farm (WF) and the 2 reference areas of study (NR = northern, SR = southern). (b) Stations included in the analyses of distribution patterns and additional stations sampled close to the turbines during the operational phase. Light grey areas = 0–6 m depth. ● = stations, ○ = turbines

cies in the pelagic zone are herring *Clupea harengus* and sprat *Sprattus sprattus*.

Trawl fishing has been banned in Öresund since 1932. Despite a fairly intense fishery using gillnets and hand-held gear, fishing mortality is substantially lower in Öresund than in surrounding seas (Svedäng 2010). Because of the relatively strong stocks in the area, no major changes in commercial fish populations were expected during the course of the study, even though fisheries using bottom-set gear were excluded from the wind farm area after its establishment. No information was available on the extent and changes in recreational fisheries in the area. The area is moderately affected by eutrophication, although nutrient loading has decreased in the past decade (Diekmann & Möllmann 2010). The strait is subject to heavy shipping traffic between the Baltic Sea and the North Sea.

The Lillgrund OWF is located in a shallow area (4 to 10 m depth) about 9 km from land. The wind farm consists of 48 turbines of 2.3 MW each (in total 110 MW), a grid of 36 kV alternating current cables, and a transformation station which is connected to land by a direct current cable (Unosson 2009). The turbines are placed in 8 rows 400 m apart on a gravitational concrete foundation on sandy substrate. The turbines are surrounded by a scour protection made of excavated rock (50 to 100 cm diameter; M. Andersson pers. comm.) extending approximately 20 m out from each foundation.

Field methods

Monitoring of fish communities within the wind farm area was conducted during the 4 yr before construction (2002 to 2005) and during 3 yr of operation (2008 to 2010). The same setup was also applied in 2 reference areas. No monitoring was conducted during construction (2006 to 2007).

The reference areas were located 8 km south (southern reference area, SR) and 13 km north (northern reference area, NR) of the wind farm. These areas were chosen to represent environmental conditions that were as similar as possible in terms of topography and distance from land (Fig. 1). Fish sampling took place in the same depth ranges in all areas (Table 1). Within each area, fishing stations were randomized at a minimum distance of 200 m from each other. The same stations were maintained throughout the study. In the first 3 yr, 24 stations were fished in each area. However, starting in 2005, the effort was increased to 36 stations to improve sampling precision at the area level, after evaluation of data from the first years of study. The stations within the wind farm area (WF) were located 130 to 1350 m from the nearest turbine.

Table 1. Water temperature, salinity and depth conditions in the studied areas. Temperature and salinity values are mean ± SD for the years of the baseline (2003 to 2005) and the operational phase (2008 to 2010). Data were obtained from daily measurements during the field sampling each year. Depth values are total range of studied depths. NR = northern reference area, SR = southern reference area, WF = wind farm area, WF_T = data from sampling close to the turbines

Area	Temperature (°C)	Salinity	Depth (m)
Baseline (2003 to 2005)			
WF	9.6 ± 1.0	10.9 ± 2.9	5.9–9.1
SR	9.4 ± 0.9	9.1 ± 1.6	5.8–8.7
NR	9.5 ± 1.3	15.4 ± 6.0	6.1–8.6
Operational phase (2008 to 2010)			
WF	10.7 ± 1.8	8.4 ± 2.4	5.9–9.1
SR	10.8 ± 1.8	8.3 ± 2.2	5.8–8.7
NR	10.6 ± 1.3	9.6 ± 3.8	6.1–8.6
WF_T	12.4 ± 1.6	8.1 ± 0.7	4.5–9.0

Additionally, during the operational phase, 40 stations were added at a closer distance to the turbine (WF_T) and sampled each year to study potential aggregation effects. These were positioned along transects from 10 of the turbines (4 stations per transect). The additional stations covered a 20 to 140 m distance from the nearest turbine, with the stations closest to the turbines positioned on the sandy bottom just outside the scour protection.

Monitoring was conducted in mid-May during 1 to 2 wk each year. This time period is representative of intermediate water temperatures for the area, with seasonal extremes occurring around August and February (SMHI 2012). As sampling throughout the year was not achievable within the limitations of the study, the chosen time period was conceived to optimize the number of species caught based on available knowledge of the physiological preferences of the expected species. The study mainly targeted non-migrating species, and no strong changes in fish abundance were expected among seasons. Water temperatures during sampling varied between the years of study but were similar in all areas each year. Salinity levels were highest in NR and lowest in SR (Table 1). The tidal amplitude in the area is marginal (Wulff et al. 2001).

Fishing was carried out using fyke nets according to national monitoring standards (Thoresson 1996).

Monitoring using fyke nets mainly targets benthic and demersal fish species, such as wrasses (mainly corkwing wrasse *Symphodus melops* and goldsinny wrasse *Ctenolabrus rupestris*), cod, eelpout *Zoarces viviparus*, sculpins (mainly shorthorn sculpin *Myoxocephalus scorpius*) and eel *Anguilla anguilla*. Based on compiled data from the Swedish national monitoring database of coastal fish species (www.slu.se/ KUL), these species together constitute up to 80% of the total catches in terms of numbers in shallow areas (<30 m) on the Swedish west coast. The fyke nets were 55 cm high with a semicircular opening, a 5 m arm and a mesh size of 10 mm. To attain a sufficient sample size, 3 pairs of fyke nets, connected arm to arm, were used at each station (Thoresson 1996). The connected fyke nets were put in place and lifted by hand from a small fishing vessel. The fyke nets were set in the afternoon and lifted in the morning. On each fishing day, an equal number of stations were fished in all areas (WF, SR, NR).

Catches were recorded directly on board by species and by 1 cm length groups, separately for each station. Biomass estimates of catches were obtained based on the length data using empirically determined length−weight relationships and were parameterized using data from several coastal fish monitoring programs on the Swedish west coast (Öresund-Kattegat-Skagerrak), applying a minimum number (n = 50) and minimum relationship strength (r^2 = 0.95) for each species (www.slu.se/KUL).

Analyses

Changes in the fish community with respect to biodiversity, species abundance and species composition, were analyzed by comparing the years of the baseline and the operational phase across areas (WF, SR, NR; Fig. 1a). The focus of these analyses was to assess the presence of changes in the fish community that could be attributed to effects of the wind farm at a larger scale (area level). Subsequently, the distribution pattern of fish within the wind farm was assessed based on data from WF during the operational phase (Fig. 1b).

Biodiversity

Changes in biodiversity were assessed using estimates of species richness and species diversity at the area level within each year. The estimates were based on rarefaction curves to enable comparisons among areas sampled with different numbers of stations and to minimize the influence of the number of individuals caught on the results (Gotelli & Colwell 2001). These were applied using the analytical procedure for sample-based and individual-based rarefactions available in EstimateS 8.2.0 (Colwell 2005). Species richness was estimated as the mean expected number of species in a pool of 100 individuals, where n = 100 was chosen to be able to include information from all areas and years with equal weight. The Shannon index, which combines information of richness and abundance (Huston 1994), was estimated as the mean expected value for 24 stations, which equals the number of stations per area sampled in the earliest years of the baseline. A few species that were observed in the sampling only occurred occasionally and were not considered representatively sampled by the gear. These were not included in the analyses. The species excluded were the pelagic species herring and sprat, and small-bodied and/or needle-shaped benthic species (butterfish *Pholis gunnellus*, fifteen-spined stickleback *Spinachia spinachia*, sand lances *Ammodytes* spp. and pipefishes *Sygnathus* spp.).

Differences between the years before and after establishment were assessed by a generalized linear model (GLM) with 2 nominal explanatory variables, 'Area' and 'Before/After' (B/A), and their interaction term. Differences in the development over time in the 3 studied areas were assessed based on the significance of the interaction term (Area × B/A). If a significant interaction was observed, univariate analyses were performed to assess differences in the temporal development in WF compared to the reference areas. Although an asymmetrical before-after-control-impact (BACI) approach (Underwood 1994) would ideally have been preferred to directly contrast the effect of the wind farm area to that of the reference areas, this approach was not feasible, as it would have required too many terms in relation to the available degrees of freedom (null df = 17 when biodiversity was estimated at the area level). To obtain a balanced comparison for the interaction term, i.e. to include an equal number of years before and after construction (2003 to 2005 vs. 2008 to 2010), data from 2002 were not included in the analyses. Also, samples collected close to the turbines during the operational phase were not included, as these were not represented by corresponding sampling during the baseline years. The analyses were performed assuming a Gaussian distribution.

Fish abundance

Changes in fish abundance were assessed for total fish and for the most commonly occurring species, namely cod, flounder, eel (yellow eel stage), eelpout, and shorthorn sculpin. The analyses were also performed for shore crab *Carcinus maenas*, which was common in the catches in all areas. Differences among areas over time were assessed by GLM using the same analytical setup as that described for biodiversity above. However, a Poisson distribution with a log-link function and correction of standard errors (quasi-Poisson) were applied. The analyses were performed on data aggregated to the area level so as not to violate assumptions of the method regarding distributions and homogeneity of variances. This was considered necessary because of a strong skewness caused by zero inflation when assessed at the station level, i.e. many stations had zero abundances of the species subject to analysis.

The analyses were performed in parallel on data based on biomass and abundance (mean number of individuals per station). However, as the results were similar, only data from the analyses based on biomasses are presented further.

Species composition

Changes in species composition were evaluated by multivariate analyses using PERMANOVA+ for PRIMER v6 (Anderson et al. 2008). First, a principal coordinates analyses (PCO) was performed to identify the direction of greatest total variation across the data set (Anderson et al. 2008). Subsequently, a canonical analysis of principal coordinates (CAP) was performed, which constrains the ordination to maximize differences among samples in relation to their predefined group identity (Anderson & Willis 2003). This analysis was applied to explore patterns in species composition that were likely to be associated with the presence of the wind farm. The analyses were performed using all available data. To be able to distinguish between differences relating to the presence of a wind farm and to general changes over time, 7 groups were identified, 1 group for each area during the baseline (B) years (2002 to 2005; SRB, NRB, WFB) and the operational (A) phase (2008 to 2010; SRA, NRA, WFA, WF_T). The distinctiveness of groups in terms of species composition was assessed by cross-validation using the leave-one-out allocation success option. The analyses were performed on data sets of mean calculated biomass per area and year, after square-root transformation. Similarity among samples was quantified by the Bray-Curtis index. Species with a frequency <5% in the data set were not included.

Spatial distribution

The distribution pattern of fish within the wind farm area was studied by assessing the relationship between fish abundance at each station and the distance of the station to the nearest turbine. The analyses were performed by GLM using all data from WF during the operational phase (Fig 1b). Thus, the total distance range investigated was 20 to 1350 m. The analyses were performed for the most common fish species in the area. For cod, separate analyses were also performed for size classes >37 cm and ≤37 cm, which corresponds to the catch size limit and approximately to size at maturity for cod in the area to provide separate estimates for juvenile and adult individuals. In an initial model, the explanatory variables 'Distance' (continuous, log-transformed) and 'Year' (of sampling, nominal) and their interaction were included. If a significant interaction was observed, continued analyses were performed separately for each year. If the interaction term was not significant, the model was run again, excluding the interaction term. Significance was evaluated assuming a Poisson distribution with a log-link function (Zuur et al. 2007) and correction of standard errors (quasi-Poisson).

All models were evaluated based on visual inspection of plots of the residuals in relation to the predicted values and the explanatory variables, and the presence of outliers was evaluated based on the Leverage values. The GLM analyses were conducted in R2.9 using Brodgar 2.6.6 (Highland Statistics).

RESULTS

Biodiversity

A total of 20 fish species were included in the analyses. A higher number of species was observed in all areas during the operational phase than during the baseline. In all, 5 more species were recorded in WF and SR during the operational phase, and 3 more were recorded in NR (Table 2). The increase could in part be explained by higher catches during the operational phase. When comparing estimates of species richness at similar abundance levels, based on rarefaction, these did not differ among areas or over time (Fig. 2, Table 3). The Shannon index differed

Table 2. Fish species observed in the wind farm (WF), southern reference (SR) and northern reference (NR) areas. B = observed only during baseline years, A = observed only during the operational phase, BA = observed during both, A(T) = observed only in the transects sampled close to the turbines, dash = not observed

Species	Common name	WF	SR	NR
Agonus cataphractus	Hooknose	A	A	A
Anguilla anguilla	Eel	BA	BA	BA
Centrolabrus exoletus	Rock cook	–	–	A
Ctenolabrus rupestris	Goldsinny wrasse	BA	A	BA
Cyclopterus lumpus	Lumpfish	BA	B	BA
Gadus morhua	Cod	BA	BA	BA
Gobius niger	Black goby	BA	BA	BA
Merlangius merlangus	Whiting	A(T)	–	–
Myoxocephalus scorpius	Shorthorn sculpin	BA	BA	BA
Platichtys flesus	Flounder	BA	BA	BA
Pleuronectes limanda	Dab	A	A	BA
Pleuronectes platessa	Plaice	BA	A	BA
Psetta maxima	Turbot	B	A	–
Raniceps raninus	Tadpole fish	A	–	–
Scopthalmus rhomus	Brill	–	A	–
Solea solea	Sole	A	–	A
Symphodus melops	Corkwing wrasse	A	–	BA
Taurulus bubalis	Longspined bullhead	BA	BA	BA
Zeugopterus punctatus	Topknot	BA	–	–
Zoarces viviparus	Eelpout	BA	BA	BA

among areas ($p < 0.001$) but not over time. The interaction term was not significant for any of the estimates (B/A × Area: $p = 0.5$ and 0.9, respectively, Table 3), indicating a similar development in all areas and no effect of the wind farm on biodiversity at this larger scale of study (Fig. 1a).

Fish abundance

Total fish biomass differed between areas and over time ($p < 0.01$ for Area and for B/A), but the changes over time were similar in all areas (B/A × Area; $p = 0.555$, Table 3). This was also true for most of the dominating fish species and for shore crab. One exception was eelpout (B/A × Area; $p < 0.05$), which showed a stronger increase in NR than in the other areas, although it occurred in low total biomass in this area (Fig. 3). When comparing the baseline and the operational phase, an increase in biomass was seen for shore crab, shorthorn sculpin and flounder, as well as for total biomass of fish, in all areas ($p < 0.05$).

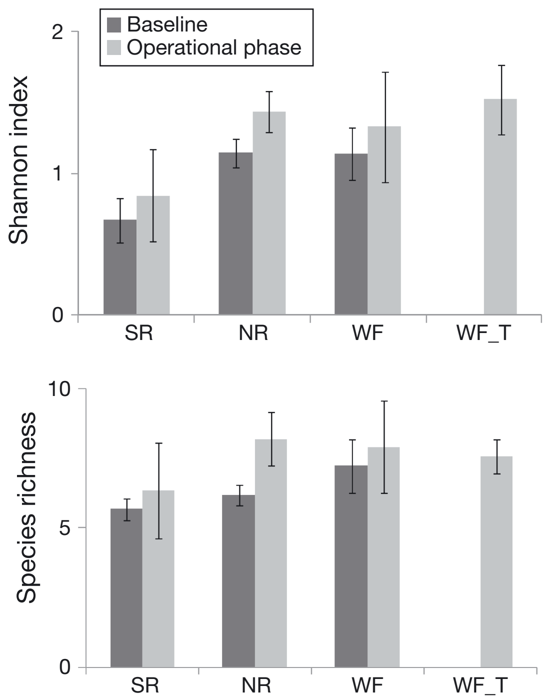

Fig. 2. Biodiversity in the studied fish assemblages, estimated by species richness and the Shannon index. Estimates are compared at n = 100 individuals for species richness and n = 24 stations for the Shannon index, based on rarefaction curves. Values are mean ± SD for the baseline years (2003 to 2005) and the operational phase (2008 to 2010). WF = wind farm, SR = southern reference area, NR = northern reference area. Corresponding information from sampling close to turbine foundations (WF_T) during the operational phase is shown for comparison

Species composition

The 3 areas showed distinctive differences in species composition that remained throughout the study. The first axis of the unconstrained ordination (PCO) mainly reflected differences among areas and encompassed a large proportion (58.4 %) of the total variation in the data set; Fig. 4a). Data points from NR (negative sample scores on PCO1) were mainly characterized by higher biomasses of cod and goldsinny wrasse, and data points from SR (positive sample scores on PCO1) were mainly characterized by higher biomasses of eelpout. The wind farm area showed similarities in species composition with both reference areas, as evident from the position of all WF data points in the centre of PCO1 (sample scores close to zero). PCO2 mainly represented differences over time and encompassed 18.7 % of the total variation. The patterns were mainly shaped by higher biomasses in the years after construction in all areas, as evident from the positive loading of most species vectors on the second axis. One exception was lumpfish *Cyclopterus lumpus*, which was most common in the

Table 3. Biodiversity, total fish biomass and biomass of dominating species in the wind farm and reference areas. Output of generalized linear model assessing differences between the years before and after the wind farm was established (B/A), among areas (Area) and their interaction term (B/A × Area). Expl D = proportion of null deviance explained

	Variable									Total
	B/A			Area			B/A × Area			Expl D
	Expl D	$F_{1,16}$	p	Expl D	$F_{1,14}$	p	Expl D	$F_{2,12}$	p	
Species richness	0.18	4.40	0.059	0.26	3.07	0.083	0.06	0.72	0.508	0.50
Shannon index	0.11	3.80	0.077	0.53	8.87	<0.001	0.01	0.70	0.900	0.64
Total fish biomass	0.30	11.70	<0.001	0.37	7.20	0.009	0.03	0.62	0.555	0.69
Black goby	0.19	4.56	0.054	0.07	0.84	0.457	0.00	0.06	0.944	0.26
Cod	0.02	0.97	0.334	0.67	16.60	<0.001	0.06	1.57	0.247	0.75
Eel	0.05	1.88	0.196	0.45	7.96	0.006	0.02	0.33	0.723	0.52
Eelpout	0.03	4.30	0.06	0.81	56.20	<0.001	0.07	4.88	0.028	0.91
Flounder	0.21	5.44	0.038	0.09	1.19	0.339	0.09	1.20	0.336	0.40
Goldsinny wrasse	0.00	0.15	0.708	0.81	40.80	<0.001	0.04	2.09	0.167	0.85
Shorthorn sculpin	0.21	6.93	0.022	0.22	3.66	0.057	0.18	3.01	0.087	0.62
Shore crab	0.16	5.6	0.035	0.43	7.42	0.008	0.03	0.58	0.578	0.63

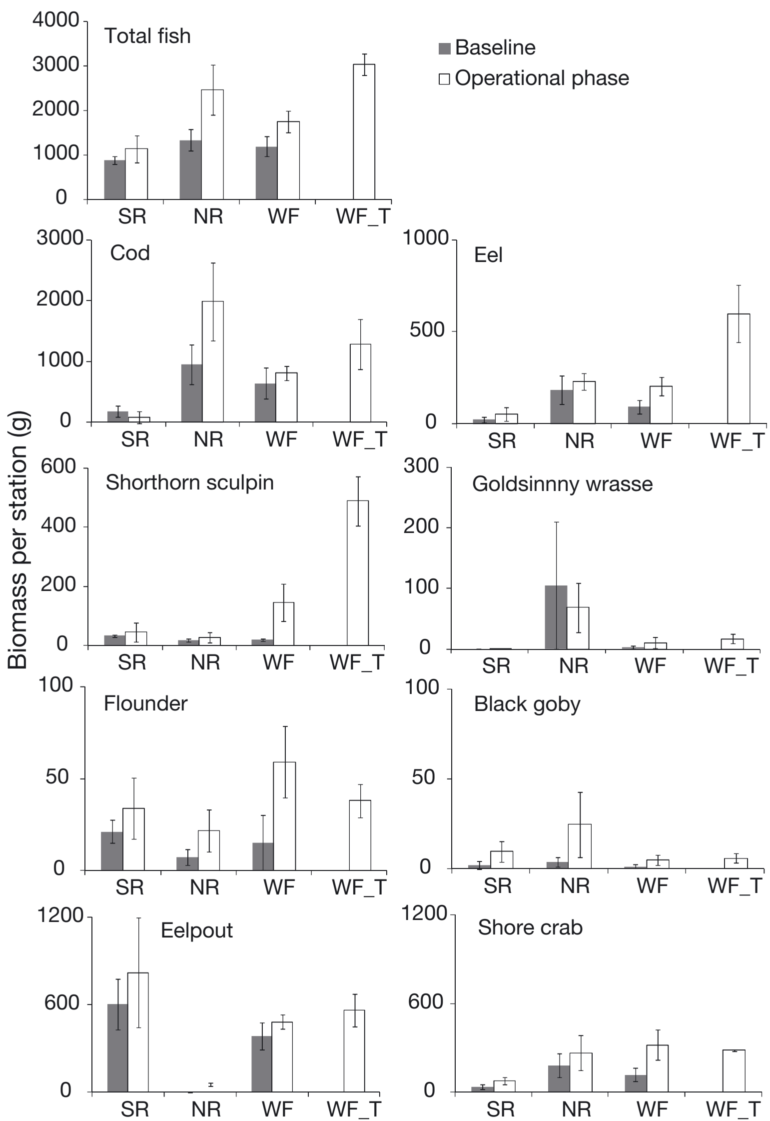

Fig. 3. Biomass of total fish, dominating species and shore crab. Bars show mean ± SD for the baseline years (2003 to 2005) and the operational phase (2008 to 2010). WF = wind farm, SR = southern reference area, NR = northern reference area. Corresponding information from sampling close to turbine foundations (WF_T) during the operational phase is shown for comparison

first years of the baseline. Within the wind farm area, WF_T during the operational phase showed high similarity in species composition to the stations sampled randomly over the whole wind farm area in the same years (WFA) but were characterized by higher biomasses of the dominating species.

The observed pattern remained in the constrained ordination (CAP) but was more pronounced (Fig. 4b). The CAP procedure retained 4 PCO axes, which together encompassed 91.0% of the total variation in the data set. The species mainly characterizing the wind farm area were eel and shorthorn sculpin. The predefined groups were clearly differentiated by the ordination ($p < 0.001$, based on the trace statistic), but the total misclassification rate according to the cross-validation was fairly high (33.3%). This was mainly due to data points representing the baseline years being classified to the operational phase within the same area and vice versa. This occurred both for reference areas and for the wind farm area, and 87.5% of the points were

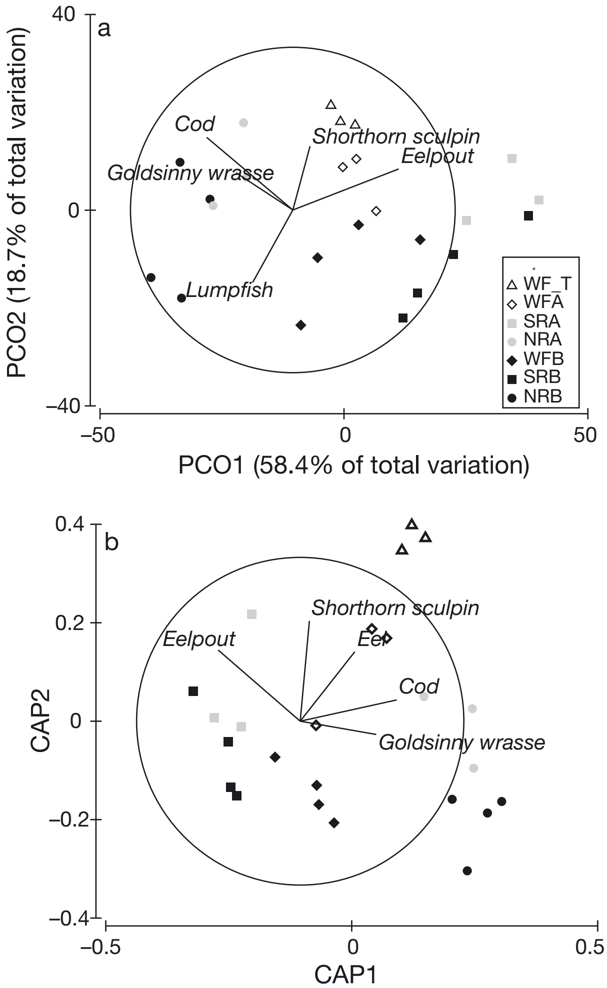

Fig. 4. Patterns in species composition represented by (a) unconstrained ordination (PCO) and (b) constrained ordination (CAP) showing similarities according to the Bray-Curtis index. The CAP was defined to maximize variability between samples with and without the wind farm and between samples from the baseline (B, 2002 to 2005) and the operational phase (A, 2008 to 2010; irrespective of wind farm presence). Vectors are shown for species contributing most to the observed pattern and point in the direction of relatively higher biomass. Only species with vector lengths >0.4 are shown (circle scales to vector length 1). WF = Lillgrund area, SR = southern reference area, NR = northern reference area, WF_T = additional sampling close to the turbine foundations during the operational phase

correctly classified with respect to area. Data points representing sampling close to the turbines were classified correctly in all 3 cases.

Spatial distribution

Increasing densities towards the turbine foundations was observed for 4 of the 7 species studied more closely, namely cod, eel, shorthorn sculpin and goldsinny wrasse (Table 4, Fig. 5). For cod, the response was somewhat stronger in the larger size class (Table 4). Roughly, the obtained models predicted a 2 times higher abundance of smaller-sized cod (≤37 cm) at a 30 m distance from the foundation than at a 300 m distance and a 3 times higher abundance of larger sized cod (>37 cm). For goldsinny wrasse, eel and shorthorn sculpin, the corresponding figures were 3, 5, and 12 times, respectively. No relationship to distance from the foundations was observed for eelpout, flounder or black goby. The interaction term was not significant for any of these species, indicating that the observed pattern was similar in all 3 yr of study (Year × Distance; $p > 0.5$ for flounder, eel and goldsinny wrasse, $p > 0.05$ for the other species). Thus, the interaction term was not included in the final models.

A significant interaction, however, was observed for the total number of fish and for shore crab, indicating a different pattern in different years (Year × Distance; $F_{2,222} = 4.06$, $p = 0.019$ for total fish, $F_{2,222} = 15.6$, $p < 0.001$ for shore crab). For the total number of fish, an increasing density towards the turbine foundations was observed in all years, but it was weaker in 2009 compared to the other 2 yr of study (overall effect of distance: $F_{1,226} = 64.8$, $p < 0.001$). For shore crab, the pattern was different in different years. An increased density towards the foundations was observed only in the last year of study, while in the first 2 yr, the opposite pattern was observed (Fig. 5).

DISCUSSION

The results of monitoring before and after establishment of the Lillgrund wind farm indicated no major effects on benthic fish diversity and abundance when comparing the wind farm area with the reference areas. Changes in the abundance of some species, as well as in community composition, were observed over time, but similar changes occurred in parallel in at least one of the reference areas. The results indicate that benthic fish communities in the wind farm area were mainly driven by the same environmental factors as those in surrounding areas.

However, at a smaller spatial scale, increased densities near the turbine foundations were observed in 4 of the most commonly occurring species, namely cod, eel, shorthorn sculpin and goldsinny wrasse. This pattern was observed in all 3 yr of the operational phase. Avoidance of the turbines, in terms of

Table 4. Fish densities within the wind farm area in relation to distance from the turbine foundations. Output of generalized linear model assessing the effects of distance to the nearest foundation (Distance) and year of sampling (Year) for the most commonly occurring fish species. Estimates indicate the magnitude and direction of effect for cases where the effect of distance was significant ($p < 0.05$). SE = standard error. Negative estimates for distance means that the density of fish decreased with increasing distance from the turbine ('an aggregation effect'). Estimates for Year 2009 and Year 2010 indicate the relative fish density in these years in relation to 2008. The interaction term was not significant in any of the models ($p > 0.05$). Expl D = proportion of null deviance explained by the model

Species	Distance		Year		Estimate (SE)				Expl D
	$F_{1,226}$	p	$F_{1,224}$	p	Intercept	Distance	Year 2009	Year 2010	
Shorthorn sculpin	94.8	<0.001	8.6	<0.001	5.8 (0.6)	−2.5 (0.3)	−0.4 (0.2)	−0.8(0.2)	0.37
Flounder	0.8	0.372	2.4	0.094	–	–	–	–	0.04
Goldsinny wrasse	5	0.026	24.2	<0.001	2.6 (0.8)	−0.9 (0.4)	−1.0 (0.3)	−3.0 (0.7)	0.28
Black goby	1.9	0.168	13.3	<0.001	–	–	–	–	0.15
Cod	41.6	<0.001	7	0.001	2.3 (0.3)	−0.8 (0.1)	0.5 (0.1)	0.4 (0.1)	0.19
Cod <37 cm	26.8	<0.001	5.4	0.005	1.8 (0.3)	−0.7 (0.1)	0.4 (0.1)	0.4(0.1)	0.15
Cod >37 cm	24.3	<0.001	2.9	0.058	1.7 (0.6)	−1.2 (0.3)	0.5 (0.3)	0.5 (0.3)	0.14
Eelpout	1.6	0.209	5.2	0.006	–	–	–	–	0.05
Eel	65.4	<0.001	30.6	<0.001	4.4 (0.4)	−1.7 (0.2)	−0.4 (0.1)	−1.1 (0.2)	0.33

lower densities close to the foundations, was not observed in any of the species. This indicates that any potentially negative effects from the wind farm during operation, such as noise disturbance and electromagnetic fields, did not override the attractive effect of the introduced structures for any of the species. The result confirms previous studies also indicating an aggregation of fish close to turbine foundations (Wilhelmsson et al. 2006a, Reubens et al. 2013) and is likely to be explained by increased shelter or food availability for fish in this area, as enhanced by the scour protection structures (cf. Reubens et al. 2013).

The study provided an interesting opportunity to monitor the effects of a large-scale OWF over several years and to include 2 reference areas. The results clearly show the importance of including more than one reference area to be able to evaluate the effect of the wind farm in relation to large-scale changes due to external factors. Although we did not explicitly explore reasons for the overall increase in biomass observed over time in this study, for both the wind farm and reference areas, it is likely to be at least partly related to slightly higher water temperatures during the operational phase (Table 1; Olsson et al. 2012).

The study also showed the importance of carefully addressing different spatial scales in the evaluation of impacts. In the studies of small-scale distribution patterns, increased densities closer to the foundations were observed for some fish species. This effect was not evident when using only data from the before-after monitoring, as few of these stations were situated close to the foundations. Based on the before-after monitoring, no increase in fish density was observed in the wind farm area at large compared to the reference areas. Combining these results, we conclude that the main effect of the wind farm on the studied fish communities was probably a change in the distribution of fish within the wind farm area rather than an effect on immigration rates or local productivity. Potentially, however, this distribution effect may be manifested as a general increase in fish abundance in the wind farm area at large over a longer time scale (Pickering & Whitmarsh 1997).

Interestingly, no aggregation pattern, in terms of higher densities closer to the turbine foundations, was observed for black goby or eelpout, and the effect was inconsistent between years for shore crab, although these species are known to prefer complex habitat types with holes and crevices. Potentially, the scale of study applied, with the closest stations being fished at some 20 m from the foundations, was not small enough to encompass the scale of aggregation of these species (Andersson & Öhman 2010), or some degree of noise disturbance from the turbines prevented aggregation. Another explanation, however, may be that a local density increase of these species close to the turbine foundations was counteracted by increased predation pressure from other fish species that aggregated around the foundations. Cod, eel and shorthorn sculpin are all known to be efficient predators on black goby, eelpout and shore crab (Costa et al. 1992, Salvanes & Nordeide 1993, Wennhage & Pihl 2002, Almqvist et al. 2010) and to potentially control their densities (Eriksson et al. 2011). This hypothesis is also supported by a slightly higher aggregation of adult cod compared to juveniles (Table 4).

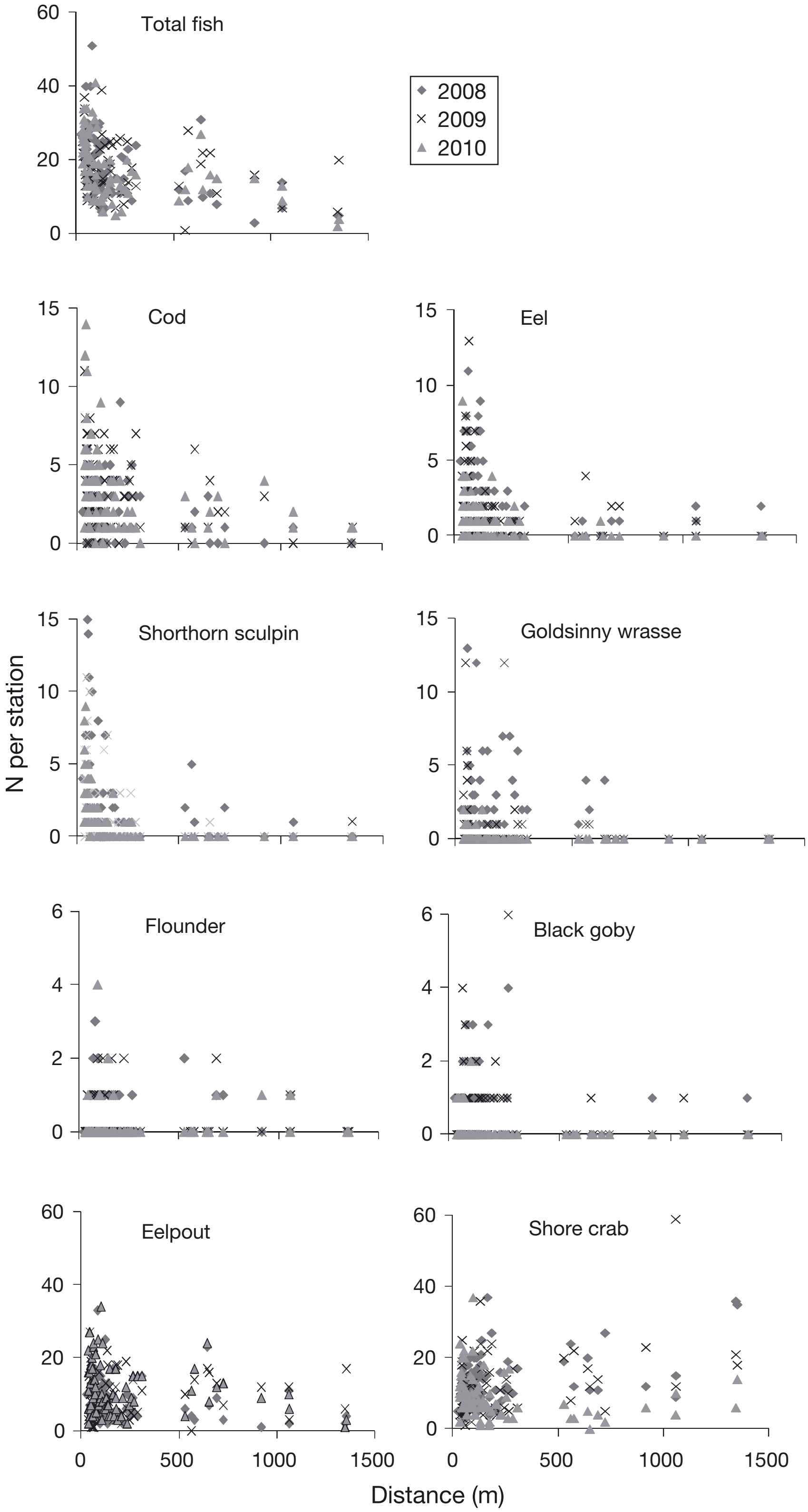

Fig. 5. Density of total fish, dominating species and shore crab in the wind farm area during the operational phase. Abundance per station plotted in relation to distance from the station to the nearest turbine foundation. For significance of the relationships, see Table 4

Top-down control, and an inverse relationship between predatory fish and their main prey, has recently been observed in areas near Öresund. In these studies, a decreasing abundance of cod due to overfishing was related to a predatory release on its main prey species (mesopredatory fish, i.e. small fish eating primarily invertebrates, and shore crab), followed by detrimental effects on different parts of the food web (Eriksson et al. 2011, Baden et al. 2012). However, a case study at some artificial reefs in Kattegat indicates that such a pattern can also be locally reversed. At the artificial reefs, a local increase in cod and European lobster *Homarus gammarus* was paralleled by a decreasing abundance of shore crab and other small decapods, probably as a combined result of introducing artificial reefs and a local fishing ban (County Administrative Board of Västra Götaland 2007, F. Sundqvist et al. unpubl.). Given the aggregation of some fish species observed at the Lillgrund wind farm, a similar development could potentially occur in this area over time. Future studies on the long-term development of fish communities in the wind farm area, including analyses of fish feeding behavior, may provide further insights into this field.

In summary, the current study from the Lillgrund OWF suggests that the large-scale development of the fish community in the wind farm area has not diverged from other parts of Öresund after establishment. Spatial patterns in the distribution of fish within the wind farm area do not indicate avoidance behavior at a smaller spatial scale. Instead, an increase in densities of piscivores around the foundations observed during the first years of operation, in combination with unchanged densities of smaller mesopredatory fish, gives some indication that OWF might provide long-term benefits by enhancing local ecosystem services.

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