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Theme Session O How does renewable energy production affect aquatic life?

Offshore wind farms and their impact on fish abundance and community structure

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Abstract

Deployment of offshore wind farms (OWF) is rapidly expanding these years. A Before-After-Control-Impact (BACI) approach was used to study the impact of one of the world's largest off shore wind farms (Horns Rev Offshore Wind Farm) on fish assemblages and species diversity. Fish were generally more abundant in the Control than the Impact area before the establishment of the OWF. Eight years later fish abundance was similar in both the Impact and Control area but the abundance of one of the most frequently occurring species, whiting, was much lower as compared to 2001. However, the changes in whiting reflected the general trend of the whiting population in the North Sea. The introduction of hard bottom resulted in higher species diversity close to each turbine with a clear spatial (horizontal) distribution. New reef fishes such as goldsinny wrasse, *Ctenolabrus rupestris*, viviparous eelpout, *Zoarces viviparous*, and lumpsucker, *Cyclopterus lumpus*, established themselves on the introduced reef area. In contrast very few gobies were caught near or at the OWF, presumably owing to the highly turbulent hydrographical conditions in the OWF. We suggest that the lack of this common prey fish is the main reason for the absence of larger predatory fish species

Keywords: spatial distribution, pisces, artificial reef effect, BACI

Introduction

Development of offshore renewable energy is rapidly expanding as part of a collective effort in Europe to increase its energy from renewable sources. Offshore wind farms (OWF) are a major component of this strategy. Until know only few studies have been published on the impact on the fish fauna of these large scaled installations. Deployment of an OWF alters the physical environment. Most OWF to date have been mono pile or gravity type – in the fist a pile is hammered deep into the seabed while in the latter a concrete foundation rest on the seabed. In the mono pile type a scour protection of boulders is placed around the base of each pile while in the gravity type the foundation is topped with boulders and additional boulders are placed for scour protection around the foundation. To facilitate construction and establishment costs most OWF are placed in relatively shallow waters (<20 m) and in areas with sandy seabed. Biologically, few studies have quantitatively documented how marine organisms are affected by introduction of OWF's structures. Benthic fauna (benthos and epifauna) communities was studied at Horn Rev OWF by Leonhard and Pedersen (2006) and at OWF Egmond aan Zee in Holland by Lindeboom *et al.* (2011). Both studies concluded that new fauna communities were introduced in close proximity to the single turbine and its scour protection while no difference was observed in the sandy areas between turbines. Filter feeders such as blue mussels (*Mytilus edulis*) also have shown to benefit from the OWF structures partly by adding new hard substrate for the mussels, partly by allowing mussels on the piles to feed higher in the water column where phytoplankton densities are higher (Maar et al. 2009). Fish attraction to underwater constructions at OWF has been reported for different gobiid species (Wilhelmsson et al. 2006, Andersson & Öhman 2010) and for gadoids such as cod (*Gadus morhua*) while flatfish such as sole (*Solea vulgaris*) show no affiliation to OWF structures or areas (Winter et al. 2010). For other types of underwater structures as wrecks, oilrigs, artificial reefs etc it is well documented that a number of fish species seeks these areas for refuge, shelter from currents or for foraging on the associated fauna (Page et al. 2007, Fernandez et al. 2008, Leitao et al. 2008).

Fish attraction to underwater structures could be due to genuine increase of a local population or represent a redistribution of the existing fish to a more confined area. Increased production implies an increase in the carrying capacity of the area (Bohnsack 1989). This includes increased feeding or shelter opportunities resulting in higher numbers recruiting to the adult populations. The rocky scouring around each wind turbine in an OWF increased hard bottom substrate for sessile organisms and plants and these together with rock crevices may provide refuge to fish of different sizes. Thus, structural diversity in an otherwise homogenous habitat feature has been shown to have positive effects on fish species diversity (Langhamer & Wilhelmsson 2009).

Horns Rev OWF was deployed in 2002, then the world’s largest OWF. It consists of 80 wind turbines, capable of providing 160 MW year^{-1}. The deployment of Horns Rev OWF introduced new habitats in terms of substrate type, complexity and vertical relief relative to the original habitat of a bare sandy bottom. It was thus expected that that local fish assemblages would be impacted, partly through attraction and partly through increased production through enhanced local carrying capacity. The water depth varies from 6-5 to 13.5 m within the farm area. The total OWF covers an area of 27.5 km^2, including a 200 m exclusion zone. Each wind turbine consists of a steel monopile 4 m in diameter rammed into the seabed (glacial and sea deposits of sand). The turbines are positioned 560 m apart. On the seabed around each foundation is a scour protection of up to 25 m in diameter consisting of boulders. A detailed description of the OWF is found in Leonhard and Petersen (2006).

The aim of this study was to analyse changes in fish abundance and species diversity within and outside the Horns Rev OWF. Since a baseline study was conducted in September 2001 and March 2002, directly before deployment of the farm it was possible to apply a Before-After-Control-Impact (BACI) experimental approach (Smith et al. 1993).

Methods

Field work

Surveys were conducted in September 2001 just before construction of the OWF, which was initiated in summer 2002 and again eight years later in September 2009 (After survey) (Table 1).

Fishing

Fishery was conducted with multi-mesh gillnets. Gillnets were deployed late in the afternoon and retrieved after approximately 6 hours. Each gillnet consists of 12 gillnet panels of different mesh size (6.5, 8.5, 11.0, 14.3, 18.6, 24.2, 31.4, 40.9, 53.1, 69.0, 89.8 and 116.7 mm) (Eigaard et al. 2000). The panels were randomly distributed and with a 1 m space between each panel to avoid the lead effect. The net was 1.5 m in height. In Before surveys all panels had a length of 6 m whereas in the After surveys’ panels were between 3 and 12 m. All reported catch numbers from all surveys was standardized to 6 m net panels.

Three turbines (turbines no. 55, 58 and 95) were selected in the Horn Rev OWF (the impact area) (Fig. 1). Turbine no. 55 (position N55 29.022 E7 50.737) is central positioned while turbine no. 58 (position N55 28.121, E7 50.958) and turbine no. 95 (position N55 29.038, E7 52.858) have peripheral locations in the park toward the South and East respectively (Fig. 1). At a given turbine gillnets were set at three increasing distances from the wind turbine foundation, near (0-100 m), middle (120-220 m) and far (230-330 m). Each gillnet setting was made with two replicates, typically in the North and South direction of the turbine. A control area with the same characteristics (depth and sediment type) as the impact area was chosen 6 km NW of the OWF. Gillnets in the control were set at a fixed station (N55 31.755, E7 43.221) in the same manner as in the Impact area with three settings with increasing distance and two replicates.

Fish catch was indentified to lowest possible taxonomic level except for sandeels which only determined to family level (Ammodytidae). All fish were measured to nearest cm (total length).

Data analysis

Analysis for changes in fish abundances, distribution and community structure followed the BACI design (Before After Control Impact) (Smith et al. 1993). Variation in abundance was analysed by general linear mixed models (GLMM) and variation of variance (ANOVA).

Catch numbers were assumed to follow a negative binomial distribution and were analysed by a mixed model for discrete data in the R software package glmmADMB (Anonymous 2007):

$$C = BA + CI + BA \times CI + RandErr$$

where *C* is catch in number, *BA* is the Before/After establishment of the OWF , *CI* is Control/Impact, and *RandErr* an added random effect for day and station.

Effect of distance to the nearest turbine in the impact area in 2009 was analysed by calculating the exact distance of the midpoint of each gillnet panel using the start position of the setting and the length of the gillnet panels. The effect was analysed in the negative binomial distribution model

$$C = distance + RandErr$$

The most abundant fish species were analysed on a species level while species that only occurred in smaller quantities were categorized into four groups based on their biological characteristics and habitat preference: demersal (DEM), pelagic (PEL), and reef habitat (ROC) fish.

Species diversity was calculated with the Shannon-Wiener index (*H'*):

$$H' = -\sum_{i=1}^{s} (p_i \, ln \, p_i)$$

where S is the total number of species and p_i is the frequency of the *i* th species calculated as the proportion of individuals of a given species to the total number of individuals caught at each of the stations at the three distances near (0-100 m), middle (120-220 m) and far (230-330 m).

Results

The most abundant species in the surveys were whiting *Merlangius merlangus*, dab *Limanda limanda*, and sandeels (Ammodytidae spp.). These species contributed with 77-84% of the catches in the Before and After survey in both Control and Impact areas (Fig. 2).

Fish sizes were in both periods and areas dominated by relatively small fish below 30 cm length. Size distributions for the whiting, dab and sandeel had modal lengths of respectively 12-14, 20-22, and 12-14 cm (Fig. 3). There was no significant difference in size distribution between Before-After or Control-Impact (ANOVA, p>0.09).

Abundance

Whiting abundance in significantly affected by both Before-After and Control-Impact and interactions effects (Table 2). Largest effects were seen in the Before After situation with a significant decline in numbers After (Fig. 4a). Significant Control-Impact effects were observed in the Before survey with higher densities in Control (GLM, $p<0.0001$) while there was no difference between Control-Impact in the after survey (GLM, $p>0.75$).

Dab occurred at similar densities in the surveys Before-After (Fig. 4b) (GLM, $p>0.8$). In both surveys there was a significant effect of Control-Impact with higher densities in Control (GLM, $p<0.014$). In the spring surveys the largest effect was Before-After with significant lower numbers After (GLM, $p<0.0001$) but also Control-Impact was significant also with higher densities in Control (GLM, $p<0.0001$) (Table 2).

Sandeels showed no significant difference in autumn between Before-After or Control-Impact Fig. 4c) (GLM, p>0. 12).

The remaining fish species, which all occurred in lower numbers, were categorised into the three groups DEM, PEL and ROC as described above. DEM fish showed the same tendencies as seen above for whiting with significant difference between in autumn Before-After (Fig. 5a)(GLM, $p<0.001$), and a change in Control-Impact with higher occurrence of DEM fishes in Control at Before (GLM, $P<0.001$) and no difference between Control-Impact After (GLM, $p>0.47$). PEL and ROC fish differentiated themselves from the previously treated species and groups in that they increased in abundance in the After survey (Fig. 5b). The increases were from almost none to moderate numbers which hampered direct statistical analysis of BACI effects. However, it was evident that ROC fish After occurred in Impact (up to 12 specimen per gillnet) and was totally absent in Control (Fig. 5c).

Distance to turbine.

The analysis of distribution patterns in relation to distance to the specific turbines in the Impact area in 2009 showed that only whiting (GLM, $p<0.02$) and the group ROC (GLM, $p<0.016$) the effect of distance was significant (Fig. 6). However, for whiting the analysis was biased by a single large catch of 23 whiting in a single gill net panel. When excluding this catch no significant effect of distance was seen for whiting (GLM, $p>0.17$). For the group ROC the number of specimen increased significant with decreasing distance to the examined turbine (Fig. 6).

Species diversity

The Shannon-Wiener species diversity index increased overall from Before to After (ANOVA, $p<0.008$), but there were no overall significant difference between Control and Impact or for any interactions effects (Table 3). However, when analysing the diversity index at the three distances near, mid and far from the location species diversity increased significant with decreasing distance to the wind turbines (linear regression, $r^2=0.22$, $p<0.05$) (Fig. 7).

Discussion

The introduction of hard substrate with Horns Rev OWF to the sand banks characteristic of the southern North Sea resulted in changes in the fish abundances and community and species diversity. Fish redistributed from being generally more abundant in the Control area before the establishment of the OWF while eight years later fish abundances was similar in Impact and Control area. This change in distribution pattern may be attributed to the deployment of the OWF increasing the suitability of this area as a more diverse fish habitat. Consistent with stock fluctuations of whiting in the North Sea, the abundance of this species decreased in both Control and Impact area (ICES 2010). The present study is the first BACI-analysis to include long-term effects (7 years after construction) on fish fauna. A newly published study by Lindeboom and et al. (2011) reports of the short terms (two years) effect of a Dutch OWF.

According to Jensen (2002), it takes around five years before stable communities are established. Since the Impact study was conducted eight years after the deployment of the OWF, it was assumed that a stable community had been established. The study on short term effects in the OWF off the Dutch coast showed only minor and non-significant effects upon fish assemblages and abundances before-after the OWF was deployed (Hille Ris Lambers & ter Hofstede 2009) (Lindeboom et al. 2011). The fish community still appeared to be highly dynamic both in time and space and thus in line with Jensen (2002) conclusion.

The increase in number of observed species and species diversity index in the autumn survey from Before to After and no significant difference between Impact and Control area can be attributed to a general regional (e.g. North Sea or part of the North Sea) trend in the fish fauna from 2001/02 to 2009/10, or to local effects of the Horn Rev OWF farm that extends beyond the wind farm to the Control area. However, the significant positive effect with proximity to turbines strongly suggest that besides any large scale trends in time or space, there is also a small scale effect of the single turbines. This increase in species diversity very close to the turbines implies that the turbines in the OWF have an effect. The small spatial scale effects of wind turbines have also been reported from studies (Wilhelmsson et al. 2006, Couperus et al. 2010, Winter et al. 2010).

The importance of changes in available prey for fish distribution patterns has been pointed out by several studies (Buckley & Hueckel 1985, Jansson et al. 1985). Infauna habitats were replaced with epibenthic communities with the introduction of hard bottom substrate after the deployment of the Horns Rev OWF (Leonhard & Pedersen 2006). The most dominant species observed was the tube-dwelling amphipod *Jassa marmorata* with densities exceeding one million ind. m^2 on the monopiles in the sublittoral zone to the scour protection. Stomach contents of pouting (T*risopterus luscus)* caught around wind turbines in the Belgian part of the southern North Sea showed that pouting was feeding on OWF-associated sessile epifauna, such as the amphipod *Jassa herdmani* (Reubens et al. 2011). However, while Reubens *et al.* were able to demonstrate an aggregative response of pouting to enhanced food provision, pouting was already present in the Horns Reef area before the deployment of Horns Rev OWF. This was also the case of rock gunnel(*Pholis gunnellus)*, and sculpins (*Myzocephalus* spp.) Within a few years of the OWF deployment, the blue mussels (*Mytilus edulis)* were well established in the sublittoral zone (Leonhard & Pedersen 2006), further diversifying food availability for fish. Blue mussels and snails together constituted between 95-98% of the gut content of goldsinny wrasses (*Ctenolabrus rupestris)* at a natural reef in the Kattegat (Dahl et al. 2009). This reef fish together with viviparous eelpout (*Zoarces viviparous)* and lumpsucker (*Cyclopterus lumpus)*, established themselves after the deployment of the OWF, significantly increasing the diversity of reef species in the impacted areas relative to the control area. Hence, the significant increase in fish diversity closer to the wind turbines may reflect a diversification of feeding opportunity caused by the newly established epibiota.

In contrast to other studies (e.g. Løkkeborg *et al.*, 2002), no clear spatial pattern was observed for pelagic or other demersal species in this study. This could be due to these fish being concentrated very close to the turbine and either not being fished or not registered adequately in our study since the catches were integrated from 0-100 m from the wind turbines. This view is supported by divers who have reported high fish densities immediately around structures at the Horn Rev OWF (pers. comm. Søren Larsen and Ulrik Westphal). At other OWF's enhanced fish abundance have been observed close to on the turbines - in the Baltic Wilhelmsson *et al.* (2006) reported higher concentrations of gobies within 5 m distance; and from the southern North Sea off Holland Winter et al. (2010) found that tagged cod had higher residence time near the turbines and Couperus et al. (2010) presented qualitative results that showed that fish concentrations around the turbines are much higher in the first 15 – 20 meters.

Gobies are a treasured food source for several large piscivore fish (cod; Magnhagen 1998, turbot; Sparrevohn & Støttrup 2008). Hence, the near absence of gobies in this study may partly explain why no increase in abundance of larger pelagic or demersal species was observed in the OWF area. Gobies have been shown to occur in higher densities in areas where blue mussels abound (Jansson et al. 1985), on natural reefs (Dahl et al. 2009) and in the vicinity of wind turbine foundations (Wilhelmsson et al. 2006, Andersson & Öhman 2010). The successful establishment of blue mussels in the sublittoral zone on the turbines of Horns Rev OWF (Leonhard & Pedersen 2006) was therefore expected to aggregate high numbers of gobies, and therefore indirectly also larger predatory fish. However, in contrast to the expected, gobies remained a rare encounter throughout all surveys. The near absence of gobies in this study was not due to sampling inefficiency. The gillnets used have been employed on natural reefs in the Kattegat with high catch rates of gobies (Dahl et al. 2009). Instead we expect that prevailing hydrographical conditions in the study area may have impacted their habitat suitability. Studies of stomach content of juvenile turbot suggested that gobies were abundant in bays protected from the dominant westerly wind, whereas they were rare on wave exposed open coastlines (Sparrevohn & Støttrup 2008). Horns Reef situated off the Danish west coast partly fringing the North Sea, Horns Rev OWF is exposed to the prevailing westerly winds being situated in the Danish west coast and exposed to average wave heights of between 1-1.5 m, current speeds of 0.7 to 1.5 ms-1 and sand transport of a magnitude of 500,000 m^3 (Leonhard & Pedersen 2006). This is further supported by findings, within Horns Rev OWF, of organisms typical for sand scoured habitats (Leonhard & Pedersen 2006). The absence of an important fish prey may thus explain why no significant increase in fish abundance of pelagic and demersal species relative to the control area was found, and why the catches were so highly variable.

Conclusions

In conclusion, introduction of hard substrate and higher complexity relative to the homogenous sand banks, characteristic of the southern North Sea, resulted in changes in the fish abundances, fish community and species diversity. Most pronounced was the aggregation and introduction of reef fishes, which increased biodiversity close to each wind turbine. We suggest that the increased diversity of fishes was a result of increased opportunity for feeding on epifauna established on the foundation of the turbines. The near absence of gobies due to the Horns Rev OWF being situated in a highly energetic environment is suggested as an explanation to why no significant increase in fish abundance of larger demersal and pelagic fish was observed in the impact area. On the other hand, the increased feeding opportunity provided by the benthic epifauna developed on the introduced hard substrate is suggested to have redistributed fish assemblages more evenly in the area.

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Tables

Table 1
Successful gillnets stations in areas and by survey. At each station gillnets were set at 3 different distances (near=0-120 m, mid=120-220 m and far=230-330 m) to the wind turbine and with a replicate of two settings (north and south of the turbine).

Area	**Location**	**Coordinates**		**Survey** **24 Sep -7 Oct 2001**	**11-18 Sept 2009**
Impact	55	N55 29.022	E7 50.737	24	24
	58	N55 28.121	E7 50.958	24	23
	95	N55 29.038	E7 52.858	18	24
Control	1	N55 31.755	E7 43.221	18	25
Sum				84	96

Table 2.
Test statistics on negative binomial GLM model on effects of BA-CI design in autumn surveys. #NA indicated where statistical failed due to significant trends in residuals or where model could not converge.

Season	Species	Fixed effects	Estimate	Std. Error	z	value	Pr(>|z|)
Autumn	Whiting	(Intercept)	2.504	0.417	6	2.00E-09	***
		CI	-1.342	0.475	-2.83	0.0047	**
		BA	-2.576	0.568	-4.54	5.80E-06	***
		BAxCI	1.559	0.654	2.38	0.0171	*
	Dab	(Intercept)	7.79E-01	0.3943	1.97	0.048	*
		CI	-1.1376	0.4611	-2.47	0.014	*
		BA	0.0883	0.5024	0.18	0.86	
		BAxCI	0.2523	0.5966	0.42	0.672	
	Sandeel	(Intercept)	-1.37E+00	0.8596	-1.6	0.11	
		CI	-8.41E-02	0.9798	-0.09	0.93	
		BA	-3.26E-01	1.135	-0.29	0.77	
		BAxCI	2.02E+00	1.2825	1.57	0.12	
	DEM	(Intercept)	0.921	0.288	3.2	0.0014	**
		CI	-0.836	0.336	-2.49	0.0128	*
		BA	-1.403	0.439	-3.2	0.0014	**
		BAxCI	1.093	0.501	2.18	0.0292	*
	PEL	(Intercept)				#NA	
		CI				#NA	
		BA				#NA	
		BAxCI				#NA	
	ROC	(Intercept)				#NA	
		CI				#NA	
		BA				#NA	
		BAxCI				#NA	

Table 3.
Test statistics on Shannon-Wiener index (H')on effects of Before (B), After (A), Control (C), Impact (I) design with estimated H'^ on significant effects.

Source	DF	Type III SS Mean Square	F Value	Pr > F	H'^
BA	1	0.71727	7.58	0.0085	B=1.07; A=1.35
CI	1	0.08632	0.91	0.3446	
BAxCI	1	0.02077	0.22	0.6416	

Figures

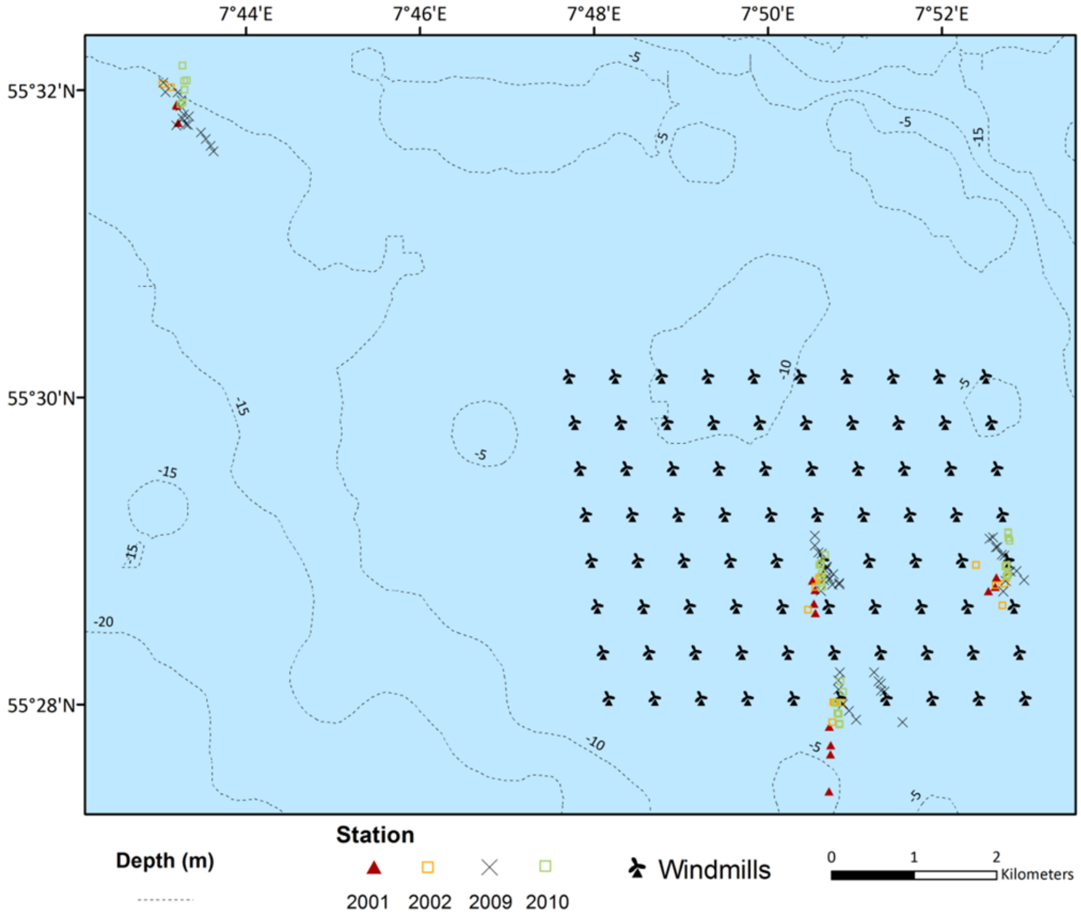

Figure 1.
Map of sampling locations in the Horns Rev OWF area. Different survey years shown by symbols. Present paper only present data from the 2009 survey. Stations in Control area located NW of impact area.

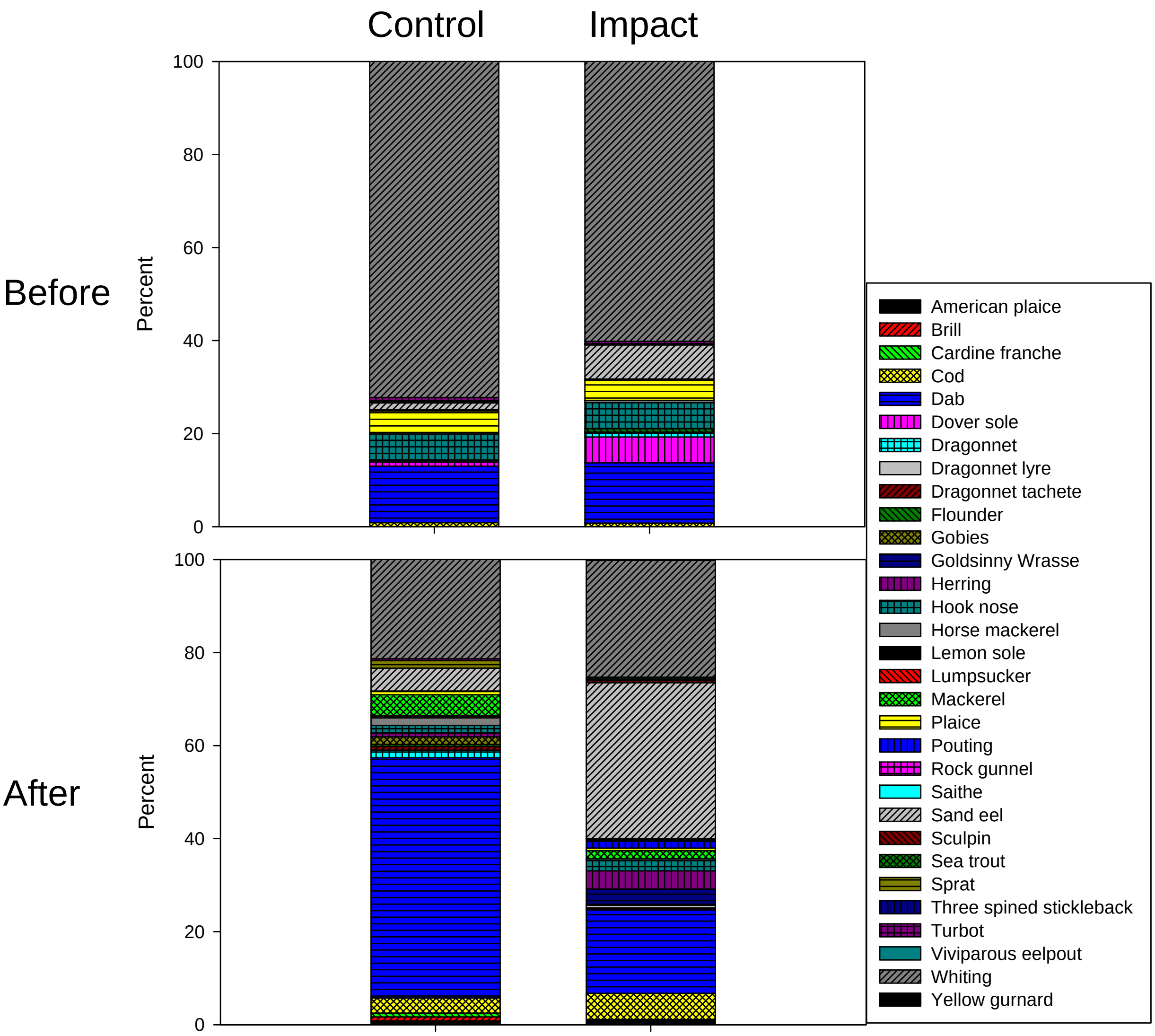

Figure. 2.
Relative distribution of fish species in surveys before and after in control and impact.

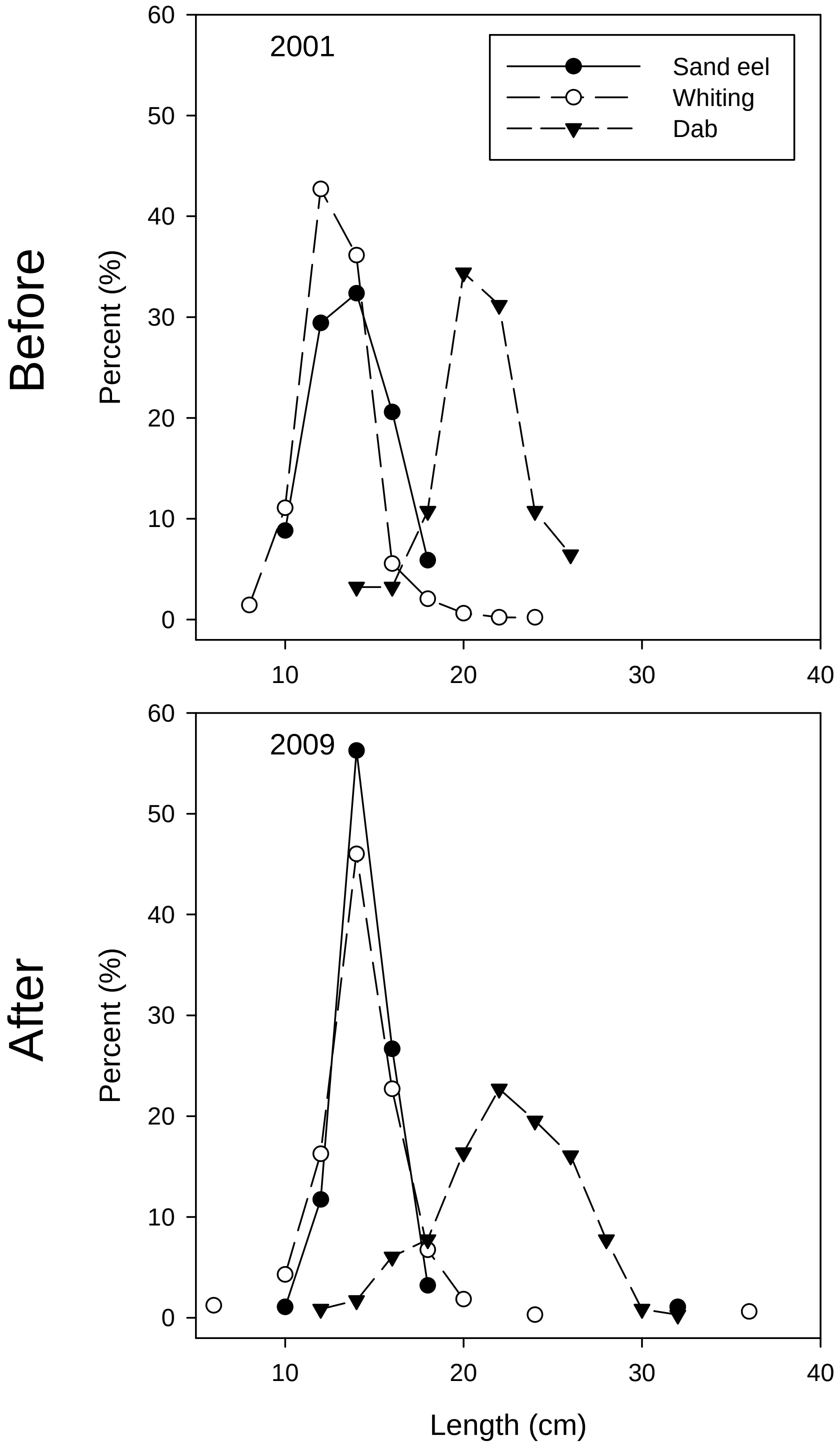

Figure 3.
Size distribution in 2-cm intervals for the most common fish species on the surveys: Before (top panel) and After (low panel) before (2001) and after (2009).

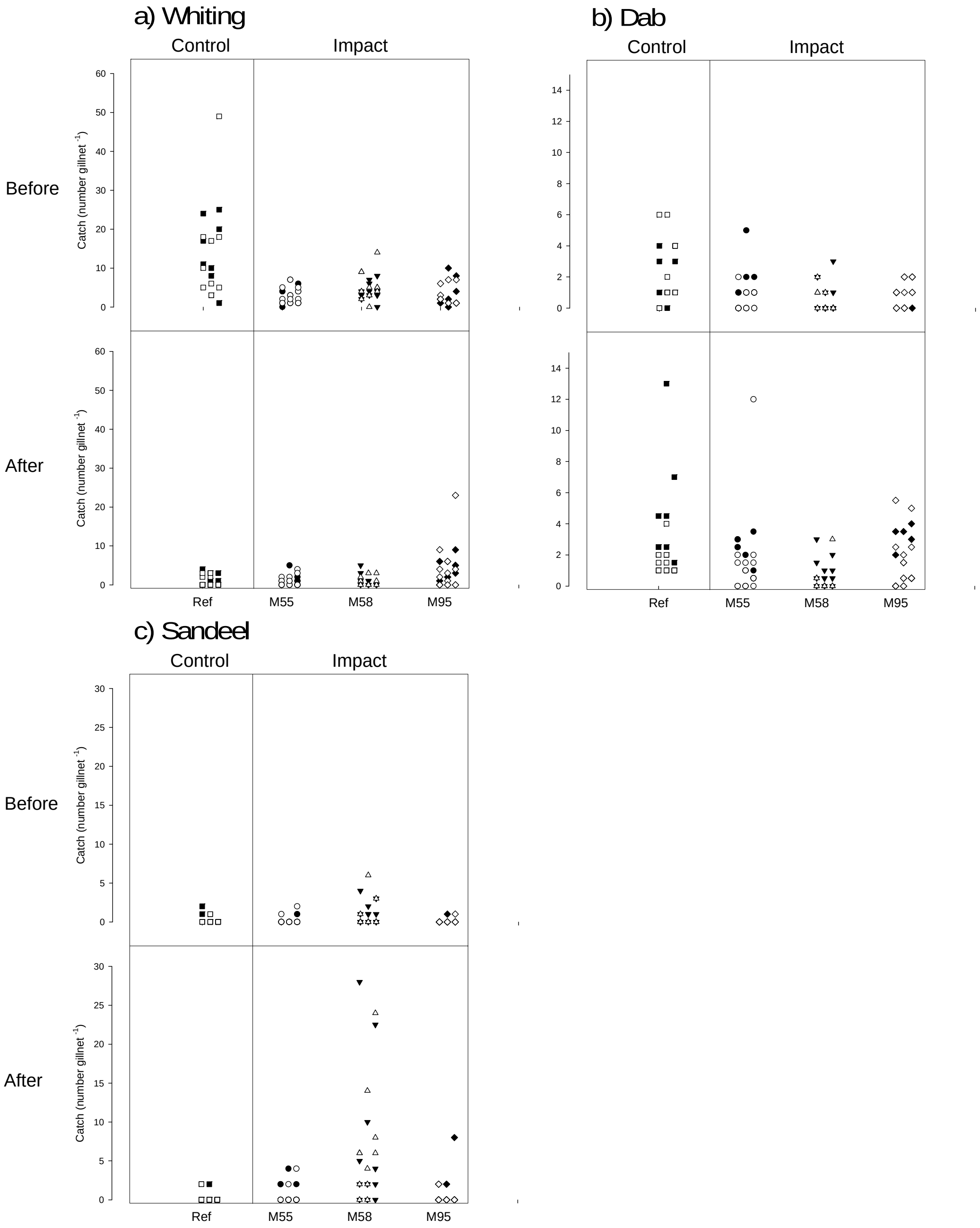

Figure 4.
Catch in numbers for the most abundant species whiting (a), dab (b) and sand eel (c) per gillnet setting before and after in control (Ref) and impact area (locations M55, M58 and M95). Black and white fill symbols indicate gillnet set respectively north and south of the station. The gillnet set at the 3 distances (near, middle and far) from the station is illustrated from left (near) to right (far)

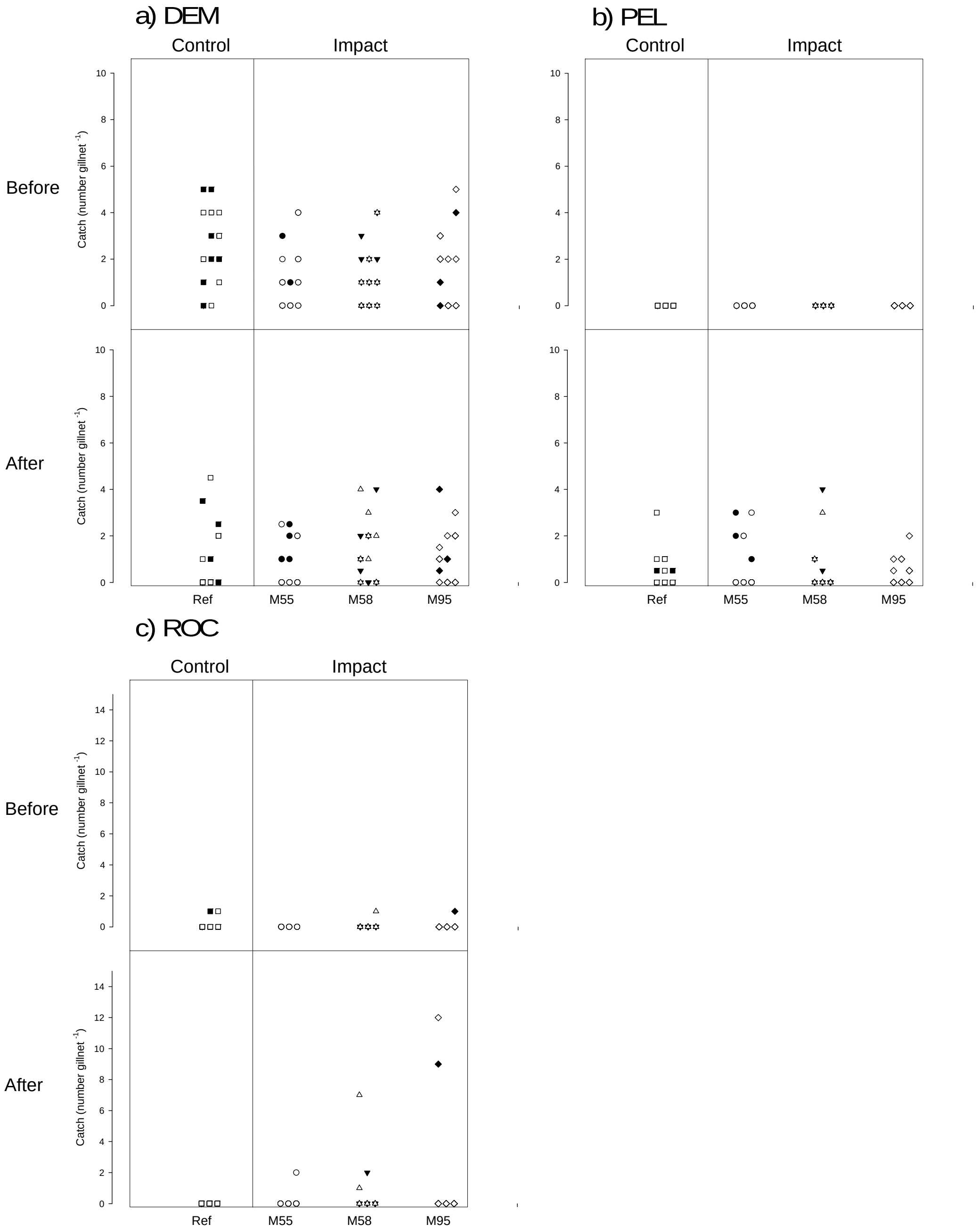

Figure 5.
Catch in numbers for demersal fish (DEM) **(a)**, pelagic fish (PEL) **(b)** and rock area habitat fish (ROC) **(c)** per gillnet setting. Captions otherwise similar to Fig. 4.

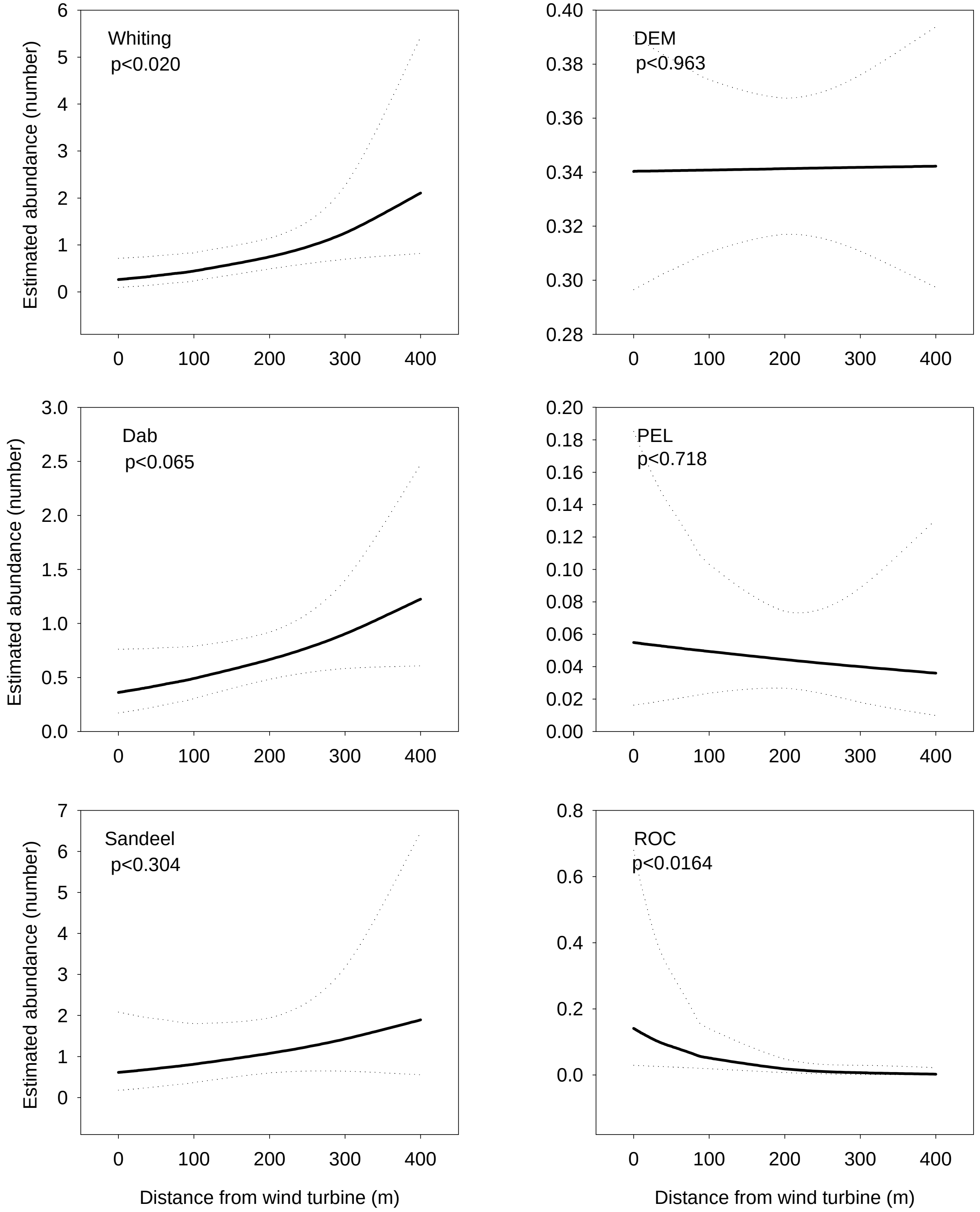

Figure 6
Estimated numbers of fish (solid line) +/- 95% confidence intervals (dotted line) for most common species and groups from negative binomial regression model on effect of distance to turbine. Probability of effect of distance to turbine shown by p.

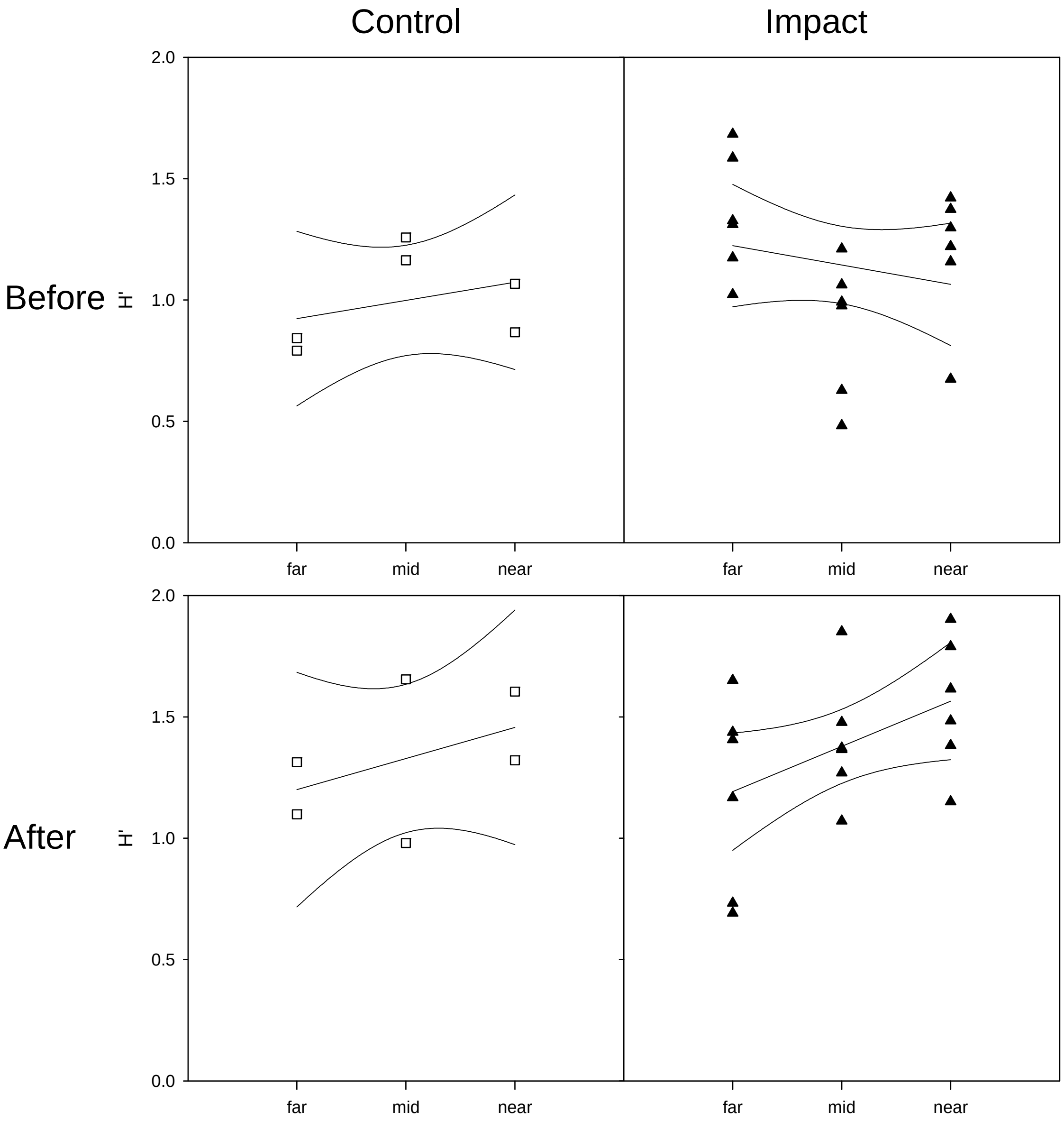

Figure 7.
Shannon-Wiener index for species diversity before-after- and control-impact areas. Solid lines show linear regression with 95 % confidential intervals.