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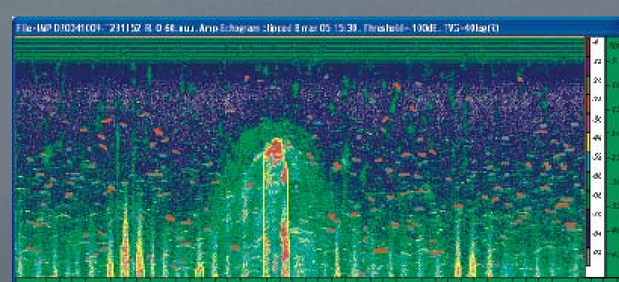
May 2006

Hydroacoustic Monitoring of Fish Communities at Offshore Wind Farms

Horns Rev Offshore Wind Farm Annual Report - 2005



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Summary

Several European studies have demonstrated that fish are attracted to artificially created hard substrates. Most attempts to quantify fish stocks near hard structures as well as natural reefs have used visual techniques. In order to improve results, the use of hydroacoustics has been used to quantify fish stocks around oil fields and in lakes. This methodological approach has been applied to assess impact on fish communities from introduced hard structures such as wind turbine foundations at Horns Rev Offshore Wind Farm. This study is a continuation of studies carried out from 2004 on behalf of the Environmental Group.

The aim of the present study was:

- To investigate the regional effects from the wind farm by studying differences in distribution patterns in local pelagic and semi pelagic fish communities between areas inside and outside the wind farm area.

- To investigate local effects from turbines on fish distribution patterns to demonstrate attraction or avoidance behaviour.

Dynamic, horizontal hydroacoustic survey were carried out along transects inside and outside the wind farm in autumn, 2005. Hydroacoustic data was collected using a split beam transducer mounted on a pan & tilt unit mounted to the side of a survey vessel. In order to describe the species composition and calibrate the acoustic signals, supplementary fishing was performed simultaneously with the acoustic surveys. The supplementary fishing was carried out with the use of survey gill nets and a small specially designed pelagic trawl. Post processing and analysis of hydroacoustic data was performed using Sonar5-Pro data application software.

General findings

During the supplementary fishing, a total of 21 different species were registered. Nine species were categorised as semi pelagic or varying between pelagic/semi pelagic and semi pelagic/benthic. The remaining 11 species were categorized as inhabiting benthic habitats. Sandeels and gobies were the most numerous with sand gobies dominating the smallest length group.

According to the analysis of the hydroacoustic data, a total of 12,099 fish were registered along the six surveyed transects. Most of the fish, 7,892 individuals, were classified as fish with a swim bladder (other fish) and the remaining 4,207 individuals were classified as sandeels.

Regional effects

No general and unambiguous regional effects were demonstrated by the presence of the wind farm during the hydroacoustic surveys at Horns Rev Offshore Wind Farm. No distinct, significant, temporal or geographic patterns in densities, biomass or length distribution could be found in sampling periods, diurnal variations, or transects inside and outside of the wind farm area. Different species composition might be responsible for the variances found in the fish communities. Abiotic factors, like the area with coarse

sand south of the wind farm, aggregated fish to a much higher extent than the presence of the wind farm itself.

Local effects

Fish density was expected to be higher inside the wind farm and especially higher in the vicinity of the turbine foundations because of a potential attraction effect on reef fish. However, no statistical evidence was found confirming that densities of pelagic and semipelagic fish near the vicinity of the turbines were different from between the turbines.

In conclusion, it is very difficult or impossible to achieve statistically useful representative replicates and geographical representative reference areas due to the high variability in the spatial and temporal distribution of both pelagic and semi pelagic fish populations. No statistically significant results were obtained for a regional or local impact on fish communities from the wind farm or the turbine foundations due to pronounced variability in biotic and abiotic factors influencing the fish communities.

Summary (in Danish)

I flere europæiske undersøgelser har man konstateret, at fisk tiltrækkes af kunstigt udlagte hårde substrater. Visuelle teknikker har været anvendt ved de fleste forsøg på at kvantificere fiskebestanden nær sådanne hårde strukturer såvel som på naturlige rev. Anvendelsen af hydroakustiske metoder har vist sig anvendelige til kvantificeringen af fiskebestande ved oliefelter og ved kvantificeringen af fiskebestande i søer. Ved Horns Rev Havmøllepark er hydroakustiske metoder blevet anvendt ved vurderingerne af påvirkningen på fiskesamfundet i forbindelse med introduktion af hårdbundssubstrater som møllefundamenter. Undersøgelserne i 2005 er en fortsættelse af de studier, der på vegne af Miljøgruppen, blev udført i 2004.

Formålet med undersøgelsen var:

- At undersøge den regionale effekt af vindmølleparken ved undersøgelse af mulige forskelle i fordelingsmønstrer af lokale pelagiske og semipelagiske fiskesamfund i områder henholdsvis indenfor og udenfor mølleparken.

- At undersøge lokale effekter af havmøller på fiskenes fordelingsmønster for at demonstrere en tiltrækkende eller undvigende adfærd.

I efteråret 2005 blev der foretaget dynamiske horisontale hydroakustiske undersøgelser langs transekter indenfor og udenfor mølleparken. De hydroakustiske data blev indsamlet ved hjælp at en split beam transducer monteret på en pan og tilt enhed på siden af et undersøgelsesfartøj. Til at beskrive artssammensætningen blev der parallelt med den hydroakustiske undersøgelse foretaget et supplerende fiskeri med oversigtsgarn og et mindre specialdesignet trawl. Efterfølgende databehandling og dataanalyser blev foretaget med dataanalyseprogrammet Sonar5-Pro.

Generelle resultater

Ved det supplerende fiskeri blev der registreret i alt 21 fiskearter, hvoraf 9 kunne kategoriseres som semipelagiske eller semipelagisk/bentiske arter. De resterende 11 arter var arter med udpræget bentisk levevis. Fangsten var domineret af tobiser og kutlinger med sandkutling som den mest dominerende i de små længdegrupper af fisk.

Ifølge analysen af de hydroakustiske data blev der i alt registreret 12.099 fisk på de 6 undersøgte transekter. Størstedelen af de registrerede fisk, 7.892 individer, blev klassificeret som fisk med svømmeblære (andre fisk), mens de resterende 4.207 individer blev klassificeret som tobiser.

Regionale effekter

Den hydroakustiske undersøgelse kunne ikke påvise entydige regionale effekter forårsaget af eksistensen af Horns Rev Havmøllepark. Der var ikke nogen entydige tidsmæssige eller geografiske sammenhængende mønstrer i densitet, biomasse eller længdefordeling mellem replikater, nat og dag eller transekter indenfor og udenfor mølleparken. En årsag til den betydelige variation i fiskesamfundene inden for og uden for mølleparken kan meget vel skyldes forskelle i artssammensætninger. Endvidere viste undersøgelsen, at abiotiske faktorer, som eksempelvis et område med groft sand og grus

syd for mølleparken tiltrak pelagiske og semipelagiske fisk i langt højere grad end selve mølleparken.

Lokale effekter

Det var forventet at finde en højere tæthed af fisk inden for mølleparken og specielt i umiddelbar nærhed af møllefundamenterne som følge af, at de hårde strukturer har en potentiel tiltrækning på fiskearter med tilknytning til rev. Det kunne ikke påvises, at tætheden af fisk ved fundamenterne var signifikant forskellig fra tætheden af fisk mellem møllerne.

Konkluderende er det meget svært eller umuligt at opnå anvendelige, repræsentative replikater og geografiske repræsentative referencer på grund af den store variation i den rumlige og tidsmæssige udbredelse af både pelagiske og semipelagiske fiskepopulationer. Der ikke opnået statistisk signifikante resultater for en regional eller lokal påvirkning på fiskesamfundet fra vindmølleparken eller fra møllefundamenterne antageligt som følge af, at fiskesamfundene i høj grad er under stærk indflydelse af udtalte variationer i såvel abiotiske som biotiske faktorer.

1. Introduction and objective

The creation of artificial substrates such as wind turbine foundations result in the establishment of new habitats in most areas where offshore wind farms are constructed. Turbine foundations might attract fish naturally or as artificial reefs contributing to an increased fish stock around these constructions. Leonhard and Pedersen (2005) have demonstrated fish attraction behaviour at Horns Rev Offshore Wind Farm while colonisation of artificial reef structures have been described and discussed in several other studies (Abelson & Shlesinger, 2002; Herrera et al., 2002, Relini et al., 2002; Pears & Williams, 2005). A study by Støttrup and Stockholm (1997) also showed an increase in fish catch per unit effort at or near natural or artificial reefs. These findings are significant because artificial reefs were created for fisheries enhancements in most European countries (Jensen et al., 2000a).

Most attempts to quantify fish stocks near natural or artificial reefs have used visual techniques although hydroacoustic techniques have also been used (Soldal et al., 2002). Hydroacoustic quantification of fish stocks has been performed around oil rigs (Soldal et al., 2002; Stanley and Wilson, 1996) and oil fields in the North Sea (Brünner et. al., 2003; 2004). Horizontal hydroacoustic methods have been used in lakes (Kubecka and Wittingerova, 1998; Knudsen and Sægov, 2002) and demonstrate the application of this method in fish stock assessment. Further, acoustic methods have also been used in the description of school structure and behaviour of pelagic fish (Soria et al., 2002).

In 2004, on behalf of the Environmental Group, studies were carried out using hydroacoustic techniques to describe fish behaviour and distribution of fish communities in relation to power generating activities at Nysted and Horns Rev offshore wind farms (Hvidt et al., 2004; 2005a; 2005b). The studies in 2004 showed good results concerning fish response in relation to turbine activity. The study showed that the hydroacoustic method with certain methodological improvements was an applicable methodological approach in the description of fish distribution around wind farm areas.

The aim of the present study was:

- To investigate the regional effects from the wind farm by studying differences in distribution patterns in local pelagic and semi pelagic fish communities between areas inside and outside the wind farm area.

- To investigate local effects from turbines on fish distribution patterns to demonstrate attraction or avoidance behaviour.

2. Site description

Horns Rev is an extension of Blåvands Huk extending more than 40 km to the west into the North Sea. Horns Rev is considered to be a stable landform that has not changed position since it was formed (Danish Hydraulic Institute, 1999). The width of the reef varies between 1 km and 5 km.

Blåvands Huk, which is Denmark's most western point, forms the northern extremity of the European Wadden Sea area, which covers the area within the Wadden Sea islands from Den Helder in Holland to Blåvands Huk.

2.1. Horns Rev Offshore Wind Farm

Horns Rev Offshore Wind Farm is located 14–20 km west of Blåvands Huk at water depths from 6.5 m to 13.5 m.

Figure 2.1. The offshore wind farm at Horns Rev and the cable trace to land at Hvidbjerg Strand. T marks the transformer platform.

The offshore wind farm is comprised of 80 wind turbines (Vestas V80- 2MW) erected in a grid pattern as shown in Figure 2.1. Thus, the total installed energy generating capacity is 160 MW. The distance between the individual wind turbines and rows is 560 m and the wind farm covers an area of 27.5 km^2 including a 200 m buffer zone around the wind farm.

The wind turbines are interconnected via a 36 kV cable grid, which is then connected to a transformer platform in the northeastern corner of the wind farm. The transformer platform is connected to land at Hvidbjerg Strand by a 150 kV cable. The cable is embedded into the seabed by water-jetting. The cable trace passes through an internationally protection area and is 19.5 km long.

The erection of the wind turbines started in March 2002 and the last turbine was in place on August 21st, 2002.

2.2. Turbine description

The wind turbine (WTG) foundations are constructed using the “monopile” concept. The monopile foundation consists of two main components; the pile, which is a steel pipe that is rammed into the seabed, and a transition piece, which is also a steel pipe but with a slightly larger diameter than the pile. The pile and transition piece are joined together over a stretch of 6 m. For the Horns Rev project, the monopile diameter is 4 m. The pile is driven to a depth of up to approximately 25 m. The joint between turbine and foundation is placed 9 m above mean sea level (MSL). At this level, a platform is placed and the wind turbine tower mounted. The main geometry of the wind turbines is shown in Figure 2.2.

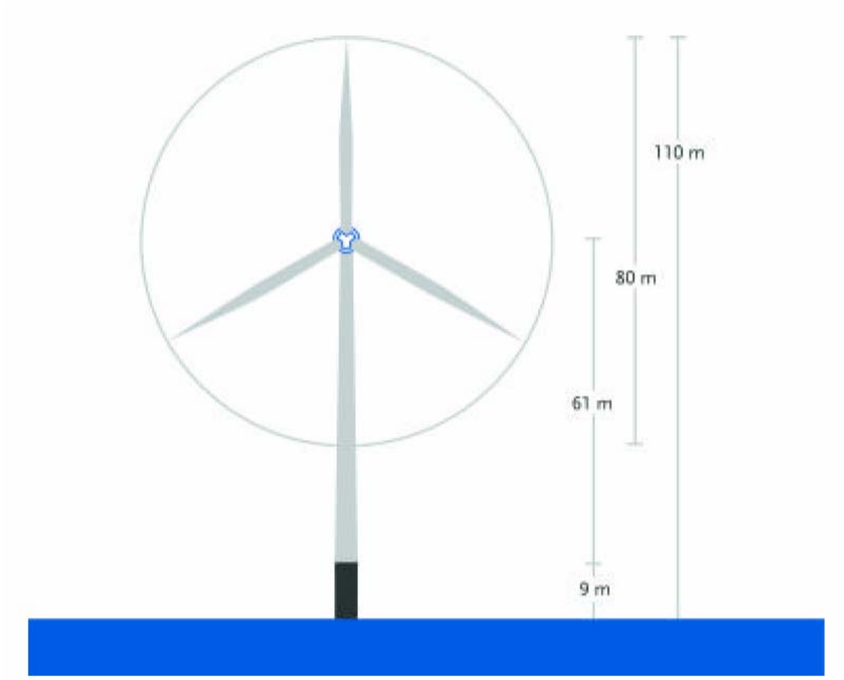


Figure 2.2 Wind turbine dimensions.

At the Horns Rev seabed, scour protection was necessary around the foundations to minimise erosion due to strong tidal and ocean currents at the site, Figure 2.3. The scour protection has a diameter of approximately 25 m in total and varies between sites. The scour protection is approximately 1.3 m in height above the original seabed and consists of a protective stone mattress, 0.8 m in thickness, of large stones up to 55 cm in diameter at distances of 0–10 m from the towers with a subjacent layer, 0.5 m in thickness, of smaller stones 3-20 cm in diameter. At the edge of the area with large protective stones, an area up to 4 m in width consisting of the smaller stones can be found at the turbine sites. Great variability exists in the band size of the large stones between and at turbine sites with large stones being found up 12-14 m from the monopiles.

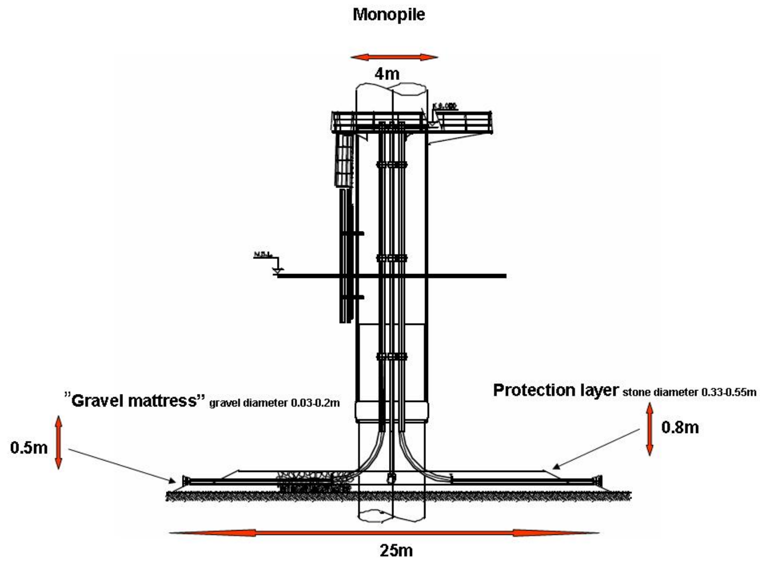


Figure 2.3. Wind turbine foundation and scour protection.

The turbine foundations including the scour protection cover approximately 39,300 m^2 of the seabed, which equals 0.14% of the total area of the wind farm.

2.2.1. Underwater noise emission from wind turbines

During operation, noise may arise from a variety of sources, including aerodynamic blade noise, gearbox meshing noise and noise from other machinery (Nedwell et al., 2003; Wizelius et al., 2005) with noise emission frequencies below 1000 Hz (Lindell and Rudolphi, 2003).

The generators used in offshore turbines are specially designed so that in low winds, the small generator windings are used for power production at 2/3 nominal rotor speed (11 revolutions per minute (rpm)). In higher wind speeds, approximately at 5 m/s, the generators switch to the main windings, operating at nominal rotor speed (17 rpm). When the generators shift from the small windings to the main windings, frequency change, noise and vibrations are generated. After the shift between the windings, the frequency is stabilized again.

The noise levels generated from the turbine are higher at low wind speeds compared to higher wind speeds where background noise from wind and wave action increases (Nedwell et al., 2003).

Structural borne vibrations originating from mechanical vibrations generated in the nacelle are thought to contribute the most to underwater wind turbine noise (Nedwell & Howell, 2004). Possible wind turbine underwater noise transmission paths are shown in Figure 2.4.

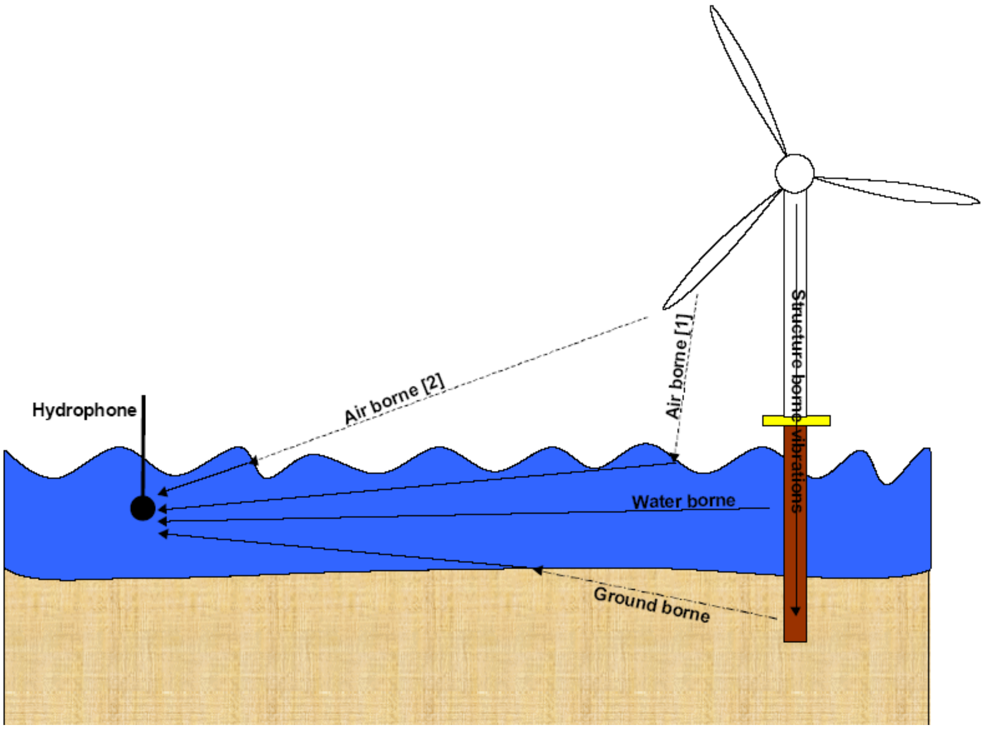


Figure 2.4. Wind turbine underwater noise transmission paths (After Nedwell & Howell, 2004).

Noise emission from the turbines might affect fish at the turbine foundations or near the turbines especially when shifting occurs between the windings (Hvidt et al., 2005b). But fish are adapted for living in noisy underwater environments having hearing thresholds (sensitivities of hearing) 10^5 times higher than humans (Nedwell et al., 2003).

Noise emission measurements at the turbines in operation have not been made at Horns Rev Offshore Wind Farm. Published results show that although the absolute level of the turbine noise increases with wind speed, its level above background noise, which is also wind dependent, remains relatively constant (Nedwell and Howell, 2004).

2.3. Biological changes

2.3.1. Geology and geomorphology

In geomorphological terms, Horns Rev is a terminal moraine. Its formation is probably due to glacio-fluvial sediment that was deposited in front of the ice shelf during the Saale glaciation, being pushed up at some point when the ice advanced. The constituents of the reef are therefore not the typical mixed sediment of a moraine but rather well sorted sediments in the form of gravel, grit and sand. Huge accumulations of Holocene marine sand deposits, up to 20 m in depth, formed the Horns Rev area that is known today with continuous accumulations (Larsen, 2003). Horns Rev can be characterised as a ridge blocking part of the sand volume transported along the Jutland coast. The yearly transport of sand is in a magnitude of 500,000 m^3 (Danish Hydraulic Institute, 1999).

Horns Rev is constantly adjusting to variations in hydrography and sea level changes but it is considered a quasi-stable formation that will continue to adjust to minor changes in the local conditions.

In the wind farm area, medium to coarse sediment with mean median particle sizes of approximately 345 µm were found in the baseline surveys (Leonhard, 2002). The sediment consists of almost pure sand with no or very low organic content (<1%) (Leonhard, 2000). Bed forms of small sand riffles are seen all over the area caused by the wave impact on the seabed. Tidal currents create dunes and riffles, showing evidence of sand transport directions both to the north and to the south. All structures in the area, apart from those in the tidal channels, indicate a prevailing transport direction towards south and southeast. Great variability exists in the sediment grain size distribution, Figure 2.4. The effects of strong currents are found towards slopes facing greater depths where coarse sand can be found with median particle sizes of 641-961 µm (Leonhard, 2000).

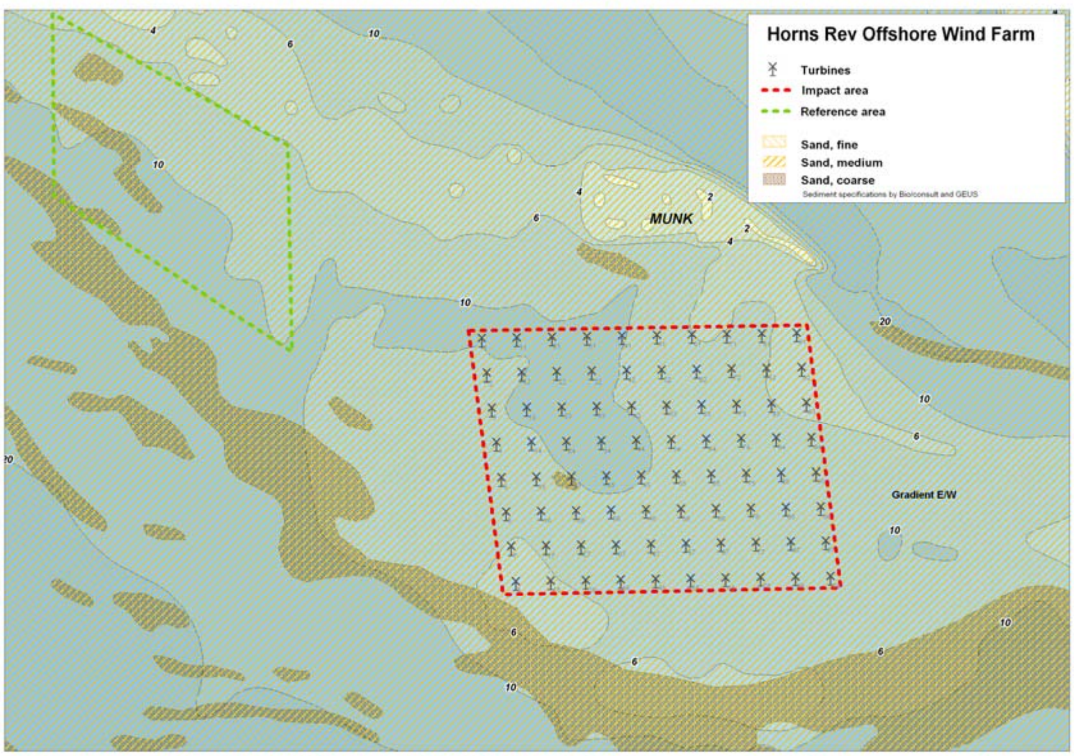


Figure 2.5. Type of surface sediment at Horns Rev besides areas of interest in the hydroacoustic investigation.

Along the cable trace, the sediment towards the shore and in the deeper areas down to 25 m consists of finer particles of silty sand and clay-silt (Leonhard, 2000).

2.3.2. Hydrography

Horns Rev is an area of relatively shallow water and is influenced by the ocean tide and dominated by waves. The North Sea is a complex resonant tidal system caused by the rectangular form of the basin. The mean tidal range in the wind farm area is about 1.2 m

(Danish Hydraulic Institute, 1999). Within the wind farm area, the water depth varies from 6.5 m to 13.5 m. The depth conditions in the area result in the waves breaking in the wind farm area. The average wave-height is about 1-1.5 m.

The hydrographical conditions in the Horns Rev area are mainly a result from the intrusion of Atlantic water into the southern part of the North Sea. The water moves erratically towards the Skagerak. The flow continues north as the Jutland coastal current and follows the Danish west coast towards the Skagerak under the effect of prevailing winds. The tidal current is mainly in a north-south direction with a prevailing NNE current and a mean current speed of 0.5-0.7 m/s. Current speeds above 0.7 m/s up to 1.5 m/s are not unusual at Horns Rev (Leonhard & Pedersen, 2004 and 2005). Stratified flows do not develop along the North Sea coast that cause the changing tidal currents and the rough wave environments that favours homogeneous conditions in shallower parts along the coastline. A strong thermocline is present in the centre of the North Sea. Although Horns Rev is situated in the transitional zone between the stratified zone and the well-mixed zone, this does not influence the hydrography at Horns Rev as stratified conditions will not develop at water depths less than 30 m (Danish Hydraulic Institute, 1999). Due to the mixing of the water in the coastal zone by the turbulent dynamics, oxygen depletion is not likely to occur at Horns Rev.

The salinity in the area ranges between 30-34 psu and is determined by the inflow of freshwater from the German rivers to the German Bight and the inflow of relatively high-saline water from the North Sea. Small differences in salinity of 1–1.5 psu have infrequently been recorded between the surface and bottom layers, especially after long periods of strong southeasterly winds.

Low clarity due to high amounts of re-suspended material in the water column is characteristic for the Horns Rev area. High temporal variability is found in the water clarity and is influenced by tidal current, wind induced current, current speed and seasonal plankton dynamics. In general, the water clarity is low in spring, 1.8-6.0 m in adjusted Secchi depth, and higher during autumn, 2.5-8.8 m. Pronounced daily variability in water clarity is found within a few hours and is associated with changes in the prevailing current directions from SSW to NNE (Leonhard & Pedersen, 2004 and 2005).

2.4. Fish behaviour reactions

Knowledge is very limited about fish response behaviour in relation to the introduction of hard bottom substrate as wind turbine foundations and wind turbine power production. Considerable literature on fish behaviour and fish attraction to deployed artificial hard substrates in Europe has been published in recent years (e.g. Jensen et al. (Eds.), 2000a). The fish community and fish species response to introduced hard substrates, such as turbine foundations, could be comparable to other studies on deployed hard substrates that generate forms of artificial reefs. However, it is important to note, that the introduced hard substrates at Horns Rev Offshore Wind Farm only covers an area less than 40,000 m^2 (0.14% of the total wind farm area). Thereby, it is logical to assume that the hard substrates can only cause a local and limited effect from a global point of view.

In addition, the introduction of offshore wind farms, besides the change in habitat, might introduce several other factors affecting fish and fish life such as artificial noise and vibrations from power generation, unusual light, reflections and electromagnetic fields (Lockwood, 2005).

2.4.1. Noise and vibrations

Fish are generally known to react to noise, vibrations, shadow changes and reflections (Anthony & Hawkins, 1983; Northmore et al., 1978; Mitson and Knudsen, 2003; Nedwell et al., 2004; Appelberg et al., 2005). Behavioural studies have shown that different fish species show different levels of sound sensitivity. Fish are classified as being highly sensitive, medium sensitive or low sensitive. Highly sensitive fish include herring-like fish while medium sensitive fish include cod-like fish with swim bladders (cod) and low sensitive fish include flat fish without swim bladders (Nedwell et. al, 2004). Most fish species can only detect sound from 1 kHz to 3 kHz while several species of the clupeids (e.g. herring-like fish) can detect sounds up to 180 kHz (or even higher) (Popper, 2000).

Baltic herring and sprat are strictly pelagic fish and have specialised hearing with low auditory threshold levels and a broad hearing bandwidth (50-75 dB at 200-3000 Hz) (Popper and Fay, 1993; Engell-Sørensen and Skytt, 2001). Semi-pelagic fish, such as Atlantic cod and whiting have a rather restricted frequency range and can hear frequencies up to approximately 300-500 Hz, (Popper and Fay, 1993; Engell-Sørensen and Skytt, 2001; Nedwell et al., 2004). At frequencies below 300-500 Hz., the lowest auditory thresholds are approximately 75-100 dB.

It is estimated that fish are consistently scared away from turbines only at ranges shorter than 4 m (wind speed higher than 13 m/s), but acoustic impact from offshore turbines on fish is restricted to masking communication and orientation signals rather than causing physiological damage or consistent avoiding reaction (Wahlberg & Westerberg 2005). Further, it was assumed that the detection distance to offshore wind farms for different fish species representing various hearing capabilities varies between 0.4 km and 25 km in the range of wind speeds from 8-13 m/s, e.g. the detection distance of cod would be 1.5 km to 2 km.

2.4.2. Light and reflections

Light is an influential parameter for fish behaviour in relation to foraging, avoidance, etc.. The importance of light for the diel variability of school structure of pelagic fish and for the foraging activity of predatory species is well known (Freon et al., 1996; Appelberg et al., 2005). Artificial light during the night coming from the aviation warning light on the nacelle and reflections from the rotor blades in daytime might have an impact on fish behaviour or migration patterns like artificial light from other constructions (Appelberg et al., 2005).

2.4.3. Electromagnetic fields

Sub-marine power cables interconnecting the turbines to the power station and transmitting the power to the distribution net onshore might affect fish (Lockwood, 2005). Some fish, like the common eel, are known to detect electric fields via passive reception of low-frequency voltage gradients (Gill and Taylor, 2001; Rodmell and

Johnson, 2005). Attraction behaviour for dogfish (*Cyliorhinus caniculus*) has been observed at a low electric field source of 0.1 µVcm $^{-1}$ at 10 cm. Some avoidance responses were observed with a field of 10 µVcm^{-1}, which is the maximum electric field expected to be emitted from 3 core sub-marine 150Kv/600A power cables (Rodmell and Johnson, 2005). Other literature shows that the sensitivity threshold of electro-receptive fish could be much lower than the electromagnetic field close to sub-marine power cables (Voitovich and Kadomskaya, 1997). As the electromagnetic field of a power cable is predicted to decrease with increased voltage, medium voltage power cables, which are commonly used in offshore wind farms, are likely to have the most acute effects on fish. Please refer to section 2.1 for a description of the interconnecting power cables at Horns Rev Offshore Wind Farm.

3. Methods

Acquirement of maximum data quality by the horizontal hydroacoustic survey method requires a calm water surface because the echoes of the transmitted signals received by the echo sounder are easily influenced by waves and unintended rocking movements of the boat caused by wave action. Wave action and rocking movements will reduce the size of the hydroacoustic space to be analysed by adding noise from the water surface as well as from the seabed. Therefore, a pre-requisite for this kind of survey is unusually calm weather.

3.1. Hydroacoustic system

The hydroacoustic system equipment consisted of a SIMRAD EK60 echo sounder unit with a horizontally aligned Simrad ES 120-4x10 split-beam transducer mounted on a pan & tilt unit, a transceiver and a laptop computer extended with a GPS-receiver.

Photo 1-2. The 4x10, 120KHz transducer and pan & tilt unit was mounted by a specially designed device on the port side of the vessel "MS Juli-Ane".

Figure 3.1. Illustration showing the spatial distribution of horizontal hydroacoustic beam

The transducer was mounted on a specially designed implementation unit on board the survey vessel M/S Juli-Ane in the sampling period September 4th to 6th, 2005. The implementation unit prevents transmissions of vibrations from water movements and vessel speed to the technical equipment. The transducer was placed horizontally on the starboard side of the vessel approximately 2 m below water level, Figure *3.1*. The transducer was connected to a transceiver that was placed onboard the bridge together with the PC laptop. The GPS-receiver was mounted with special attention to satellite signal interference. The position of the transducer in relation to the GPS-receiver was adjusted according to the offset.

To prevent reverberation, drifting, etc and to achieve optimal detection from the transducer beam, the horizontally aligned transducer could be tilted relative to the water surface and seabed by the remotely controllable pan & tilt unit. Thereby, it was possible to adjust and fine-tune the real-time vertical and horizontal (pan, role and heading) alignment of the transducer and acoustic beam relative to the water surface and seabed.

Multipath is the single largest cause of differential GPS position errors. In order to minimize the high risk of multpathing mitigation operating in offshore wind farms (Hvidt et al. 2005), the DG16 Sensor from Thales Navigation was used. The Strobe Correlator technology is a digital signal processing technique, implemented in the hardware and software of the DG16, which almost entirely removes multipath errors for reflected signals.

Navigation according to the planned survey transects was performed by GPS signals and the software “Navipac” from Eiva extended with sea-maps from C-Map.

The operating frequency of the transducer was 120 kHz and the pulse duration was set to 256 µS with a ping rate of 0.1 s^{-1}. The range of the horizontally positioned transducer was fixed at 0-100 m thereby giving the acoustic beam a maximum horizontal width of 15.7 m and a maximum vertical height of 7.7 m. For further details, please refer to Table 3.1

Table 3.1. Horizontal and vertical distribution and area of coverage of the acoustic beam-width from the 120 kHz split-beam transducer at different distances.

Transducer		**Distance m**									
120 kHz 10X4	½ angle	10.00	20.00	30.00	40.00	50.00	60.00	70.00	80.00	90.00	100.00
Horizontal	4.5	1.57	3.15	4.72	6.30	7.87	9.44	11.02	12.59	14.17	15.74
Vertical	2.2	0.77	1.54	2.30	3.07	3.84	4.61	5.38	6.15	6.91	7.68
Area m²		0.95	3.80	8.54	15.19	23.73	34.18	46.52	60.76	76.90	94.94

Prior to the survey, the echo sounder equipment was calibrated to the marine environment (temperature and salinity) found at Horns Rev Offshore Wind Farm. Calibration followed the guidelines given by the SIMRAD operator manual for the EK60 (SIMRAD, 2003). The internal clock of the laptop computer was set to Greenwich Mean Time (GMT).

Transects were surveyed at a speed over ground (SOG) of 0.5-2 knots depending on the current and wave conditions.

3.1.1. Field survey

The field study was carried out during September 4th -6th, 2005, which is during the same period that the highest observed autumn fish densities have been recorded (Leonhard and Pedersen, 2006). The hydroacoustic surveys were carried out along four transects covering the impacted and reference areas (Figure 3.2). The impacted area was defined as inside the Horns Rev Offshore Wind Farm while the reference areas were placed 3–7 km Northwest of the Horns Rev Offshore Wind Farm. The survey transects in the impact area and the corresponding survey transects in the reference area were determined by comparable depth and substrate regimes. Description of the substrate was achieved from GEUS.

Each of the transects were approximately 2 km long and were in parallel pairs placed to eliminate influence from the current direction.

Because the hydroacoustic signal from fish is dependent on the relative position of the fish according to the acoustic beam, transects were surveyed only when the current was northerly or southerly.

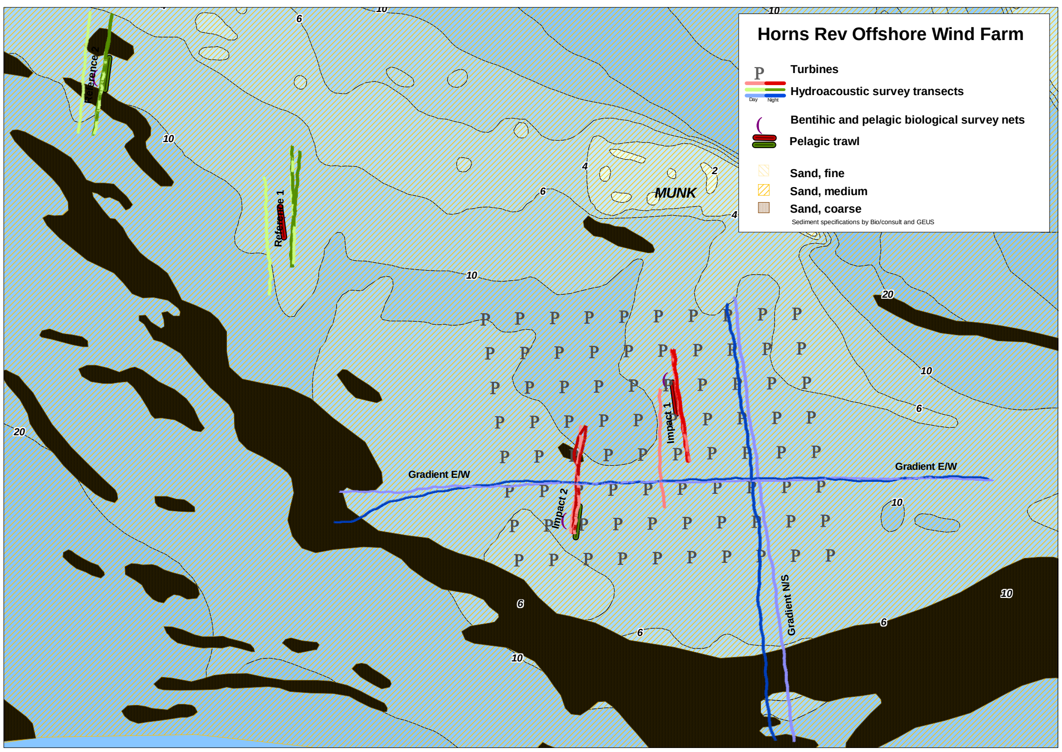


Figure 3.2. Map of Horns Rev Offshore Wind Farm showing surveyed transects in the impact and reference areas besides transects of gradient analysis.

Hydroacoustic surveys were conducted along two gradient transects extending outside the wind farm to analyse a possible gradient of fish abundance caused by the presence of the wind farm. The gradient transects were approximately 7 km and 10.5 km in length and extended 2.5–3 km outside the wind farm in a north to south (gradient transect N/S) and east to west (gradient transect E/W) direction, respectively (Figure 3.2).

Placements of the transects were chosen to achieve impact and reference transect pairs as identical as possible and gradient transects as homogenous as possible with respect to environment and topography correspondence. Furthermore, gradient transects were placed parallel to the turbine rows and at a distance of approximately 50 m to ensure that the acoustic beam covered the foundations.

A total of four surveys were performed at each impact and reference transect. To strengthen the statistical statement and to assess the diurnal variation, two identical surveys were executed during daylight (04:40 AM – 6:10 PM, GMT) and during darkness (6:10 PM – 04:40 AM, GMT). A survey during daylight (day) and a survey during darkness (night) were performed at each gradient transect.

3.2. Hydrographical conditions

Forecast of current direction and velocity was obtained from "MitVejr2" prior to the execution of the survey. The forecast clearly demonstrated a current direction alternating between north and south every 6th hour giving 5 hours of continuous survey. The forecast and visual observations made in the field were used to determined when to execute the hydroacoustic survey at each transect.

Furthermore, Elsam Engineering AS recorded hydrographical data at Horns Rev OFFSHORE WIND FARM. This data was implemented in the post-processing to correct for the aspect ratio of the fish in relation to the acoustic axis with the assumption that the fish were orientated towards the current direction.

3.3. Supplementary fishing

The available hydroacoustic methods used can detect fish abundance as well as size, distribution and biomass if the species composition is known. Because hydroacoustics are not yet capable of identifying individual fish species, traditional fishing techniques must be used on a small scale to identify the relative species composition in the area for use in the inter-calibration of size frequencies of the individual fish species. The result of the supplementary fishing is integrated in the post-processing calculations and in the statistical analysis of the size groups, size frequencies and biomass of the fish population.

In order to investigate the fish fauna and the validation of the observed fish species, traditional fishing methods using pelagic and benthic gill nets and a small pelagic trawl were carried out at each of the transects in the reference and impact areas, Figure 3.1.

The gill nets used were biological survey gill nets that measured 42 m in length and 1.5 m in height. The gill nets were composed of 14 equal sized sections each 3 m in length with different mesh sizes ranging from 6.25 mm to 75 mm. The monofile of the nets varied with the mesh size.

Parallel to the hydroacoustic data sampling, a pair of benthic and pelagic biological gill nets were set at dusk and tendered at dawn the following morning. To assess the diurnal variation, a new pair of nets immediately replaced the tendered nets and fishing was continued during the daytime. The biological survey gill nets were set from 6:00-7:30 AM and again from 18:00 until 19:30 PM. The gill net fishing was repeated simultaneously with the hydroacoustic data sampling.

Photo 3-4. Trawl and gill net fishing was handled from a large RIB. The catch was immediately processed on board and the samples frozen.

The small pelagic trawl was a specially designed trawl with mesh sizes ranging from 200 mm to 5 mm in the cod end. The opening of the trawl was approximately 6 m wide and 2.5 m high resulting in an opening area of approximately 15 m^2. The pelagic trawl was operated from a Ridge Inflatable Boat (RIB) driven by an outboard motor. The trawl distances were at least 500 m with the trawling samples being taken at the same time and in the same transect line as the hydroacoustic survey.

3.4. Post processing and data analysis

The raw EK60 hydroacoustic data files were converted to echogram files suitable for the post processing application, Sonar5-Pro (Balk and Lindem, 2005). Sonar5-Pro was used in order to optimise processing speed and connect the echogram data with additional information like current velocity, current direction, navigation, survey notes, environmental descriptions, pictures, etc. Sonar5-Pro was specifically designed to quantify fish densities, sizes and biomasses as well as track fish in the acoustic beam.

The Sonar5-Pro software makes it possible to filter out reverberations from the surface and the bottom as well as perform cross filter detection. The cross filter detection is relevant in cases like this study where the ratio between noise and fish signal is low. A low ratio is especially pronounced in echograms with signals of small fish and/or excessive background noise.

The converted echogram files were to some extent post-processed using the following main utilities:

- “Bottom detection” to avoid echoes from bottom material and constructions,
- “Cross filtering” to remove excessive background noise like reflections from the surface, down welled air bubbles etc.
- “Fillgap” to avoid multiple single echo detections etc.

In order to identify echoes from single fish (SED), the “tracking” process in Sonar5-Pro was used on the filtered echograms either as an automatic process or manually. These processes combine successive echoes from different targets into separate fish tracks. Echoes to be tracked can be single echo detections or clusters of samples rising above the background reverberation level. When a set of echoes has been combined, these echoes form a track. The track and calculated features were studied graphically in 2- and 3-dimensions and numerically to evaluate the validity of the fish tracks.

The measured target strength (TS) of fish varies according to species, size and relative position of the fish according to the acoustic beam. In traditional vertical hydroacoustic surveys, the aspect ratio does not have significant effects on the TS as the echo signal from the fish is reflected from the dorsal side. However, in horizontal mobile surveys variations in the positioning of the fish according to the acoustic beam (side aspect ratio) can add notable errors to the calculations of fish length.

To reduce the effect of varying aspect ratios, it has been assumed that fish mainly orientate themselves towards the current direction, which in turn is assumed to equal the side aspect ratio according to the acoustic beam. A TS-equation converting the TS dependant aspect ratio to length has among others been introduced by Lilja et al. (2000) by the equation:

$$Length(cm) = 10^{\frac{TS - B - C \cdot \cos^3(2a)}{A}}$$

where *A*, *B* and *C* are species-specific constants obtained by inter-calibration and *a* is the side aspect ratio.

Unfortunately, no hydrographical data concerning current for the period of survey was available to verify the current direction and velocity for transects surveyed. Therefore, the constant *C* was set to 0, assuming that all fish have the lateral side at a right angle to the acoustic axis.

During the tracking procedure, tracked fish where split into two groups of fish baskets. Guidelines where set up to distinguish tracks of fish from other objects capable of returning a hydroacoustic signal:

1. Tracks of target strength (TS) or observed echoes greater than a threshold of -54 dB were accepted in order to avoid tracks or echoes from objects of low TS values like jellyfish, small crustaceans, drifting algae etc. This group contains all observed species of fish with a swim bladder. In this group, the constants *A* and *B* where set to 20 dB and -68.9 dB, respectively. The threshold value of -54 dB at an aspect ratio of 90^0 (full lateral side) results in fish sizes smaller than 5.6 cm (total length) being excluded. This will result in the exclusion of small species like gobies (two-spotted goby and sand goby) and species without swim bladders like sandeels.

2. Tracks of target strength (TS) or observed echoes between –75 dB and –63 dB where accepted as fish without swim bladders, mainly sandeels. Sandeels have a target strength of -68.9 dB for a fish with a mean length of 12.44 cm (Mackinson et al., 2004a). For the TS-equation in question, this returns values of 20 dB and -68.9 dB for the constants *A* and *B*, respectively. The interval of threshold values for sandeel were extracted from the results of the supplementary fishing and the threshold values returned a sandeel length interval between 6.2–24.5 cm.

It is important to emphasize that all echogram files presented in this study were undertaken in identical transformation and analysis, which makes them mutually comparable. Also, it is important to emphasize that the TS to length conversion does not necessarily reflect the exact length of the fish monitored. However, the equation and the values of the constants used have justification because they are based on comparison and averages from several hydroacoustic studies.

The weight of a single detected fish was obtained by the length-weight equation:

$$Weight(g) = P \cdot Length^{Q}$$

where *P* and *Q* are the average of weighted species-specific constants. The values of *P* and *Q* from the length-weight (total length) relations were obtained for the two groups of fish baskets by consulting www.fishbase.org[1] and extracting species-specific distribution data from the supplementary fishing.

The two groups of fish baskets where added into a group after the TS-equation and the length-weight equation was executed for each target detected.

All hydroacoustic data was geographically orientated and structured in GIS (Geographical Information Systems), in which selections of specific data sets were also made. The geographical orientation was either an option in Sonar5-Pro or performed by the use of the software application “AcousticFishPositioning” (Haugaard, 2006) on SED-data.

In order to compare fish abundance and biomass of different parts of a transect and between transects, Catch Per Unit Effort (CPUE-density) was defined as the number of fish per 1,000 m^3 (CPUE-biomass) as gram fish weight per hectare[2].

The surveyed transects were divided into replicate lengths of 100 m of the distance sailed in order to evaluate regional variation. A fraction of the gradient transects including 6 turbines from the gradient transect N/S and 8 turbines from the gradient transect E/W where divided into replicate 25 m lengths in order to evaluate local variations in CPUE of fish density.

[1] www.fishbase.org is a webpage used by fish biologists covering more than 29,300 species, 21,6800 common names, 41300 pictures, 37,900 references and 1,340 collaborators. 20 million hits/month

[2] The definitions used for density and biomass is standard for hydroacoustic monitoring.

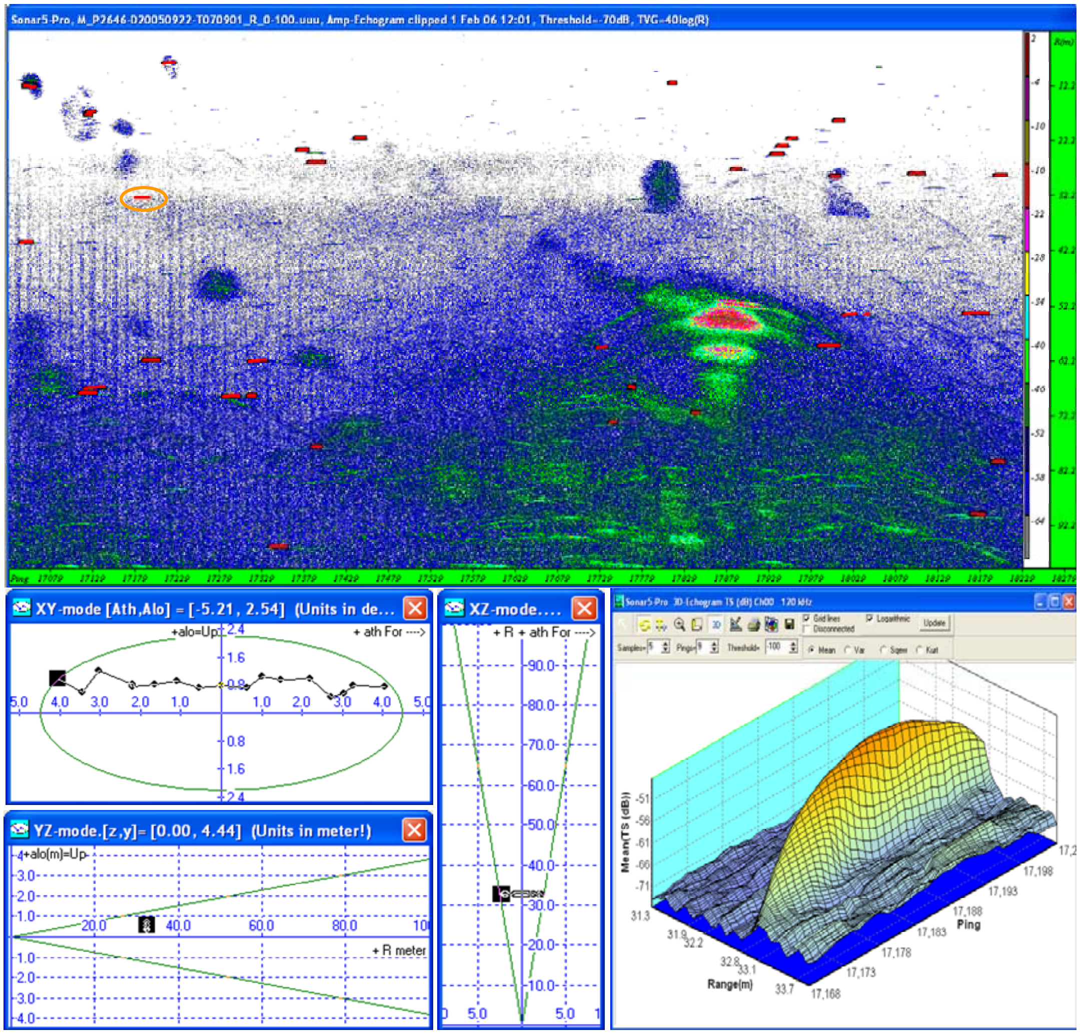


Figure 3.3. Example of a Sonar5-Pro processed echogram with detected fish (red markers). A turbine foundation is spotted around ping no 17,879 at a range of 50 – 60 m. Below the echogram are different modes visualising a registered fish track in the acoustic beam in xyz diagrams as well as a three dimensional plot of the fish track.

3.5. Statistical analysis

The hydroacoustic data from Sonar5-Pro was aggregated prior to statistical analysis to represent 100 m sailed distance. These aggregates are then considered to be replicates for the data analysis.

The data for analysis are two different kinds:

1. Single Echo Detections (SED) representing individual fish, Figure 3.4. The raw data consists of geographical position, length and biomass. The datasets were pre-processed by an aggregation to calculate the density and mean fish length per 100 m.

2. Estimates on volume based Catch per Unit Effort (CPUE) from Sonar5-Pro were aggregated to represent 100 m and 25 m sailed distance. CPUEs were calculated as both density (ind./1000^3) and biomass (kg/ha), Figure 3.3.

A statistical GLM (General Linear Model) was used to test differences in the survey at a 95% significance level. A normal distribution and homogeneity of variance in the dataset is a prerequisite for the analysis. To fulfil the requirements, both density and biomass data were transformed using LN(x+1), LN being the natural logarithm.

A series of GLM models were used with decreasing degree of complexity depending on the outcome of the more complex one.

3.5.1. Regional effects

For the SED data, a mixed, nested Analysis of Variance was used to analyse for differences in fish length. The starting model, which is the most complex, consists of:

- Fixed factors: Area (Impact/Reference), Sample and Diurnal Period (Day/Night)
- Variance components: Transect within Area, 100 metre interval within Transect
- Non-parametric methods, Mann-Whitney and Kolmogorov, were used to compare the length distribution between factors.

For the CPUE data, a similar mixed Analysis of Variance was used, consisting of:

- Fixed factors: Area (Impact/Reference), Sample and Diurnal Period (Day/Night)
- Variance component: Transect within Area

3.5.2. Local effects

To test for differences between turbine areas and non-turbine areas, data sets consisting of two to three CPUEs (25 m sailed distance) closest to the turbines were isolated and classified as "Turbine present". The new model with the fixed factor "Turbine present (yes/no)" added, was statistically tested as above, Figure 3.4..

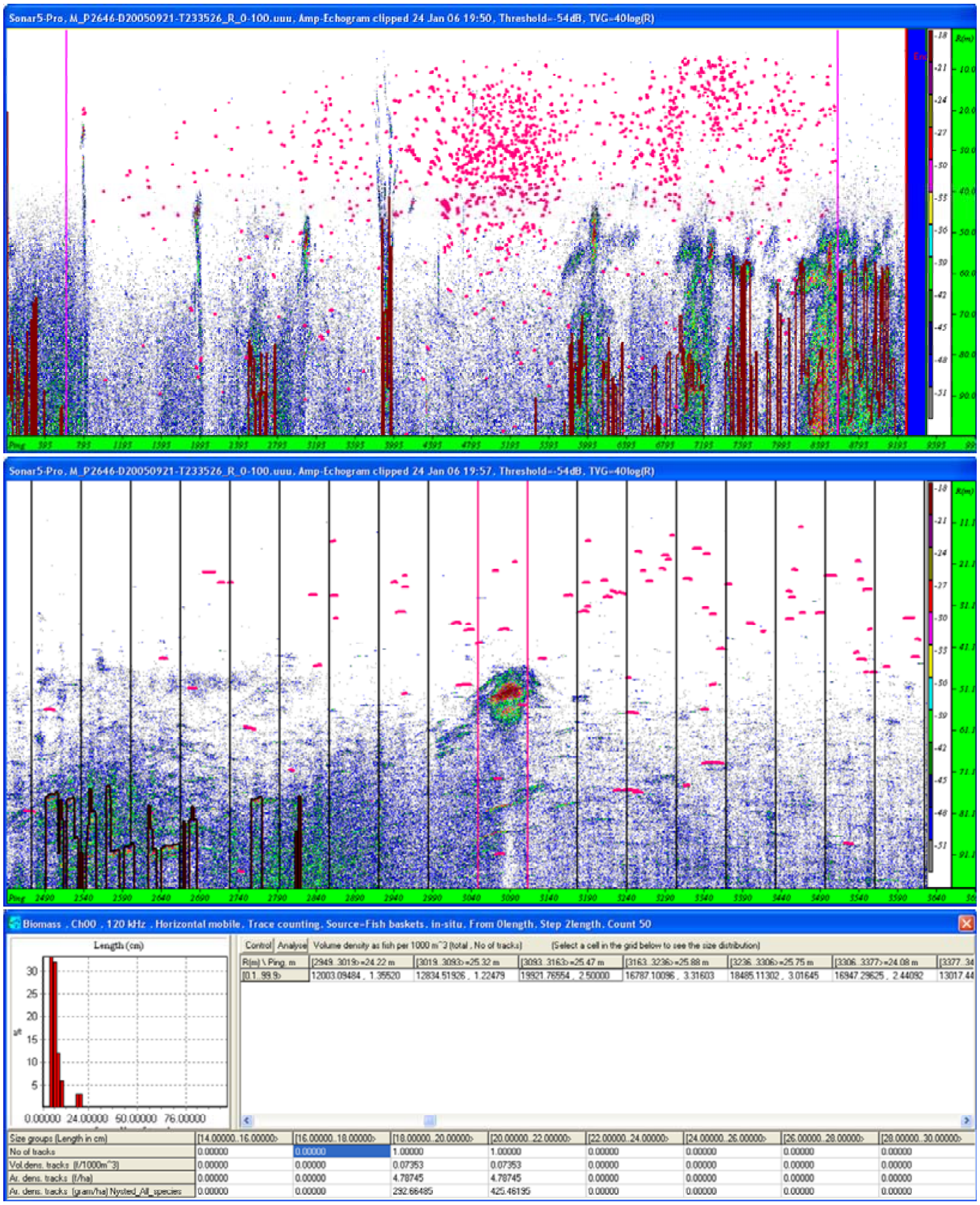


Figure 3.4. Sonar5-Pro processed echograms of a hydroacoustic survey along an impact transect. Uppermost; echogram of the transect bounded by pink lines showing bottom detection (brown line) and fish detections (red markers). Middle and lower; extraction of the transect showing intervals of 25 m for calculations of CPUE values of fish density for evaluation of local variation. The intervals were classified as "Turbine present yes/no" (Interval represented by red lines is classified as "Turbine present yes".

All data was geographically orientated and structured in GIS where selections of intervals in question were extracted. All the tests were executed in SPSS, a statistical software package.

The data flow and linking through the entire project, from data acquisition in the field to final statistical analysis, is illustrated in Figure 3.5.

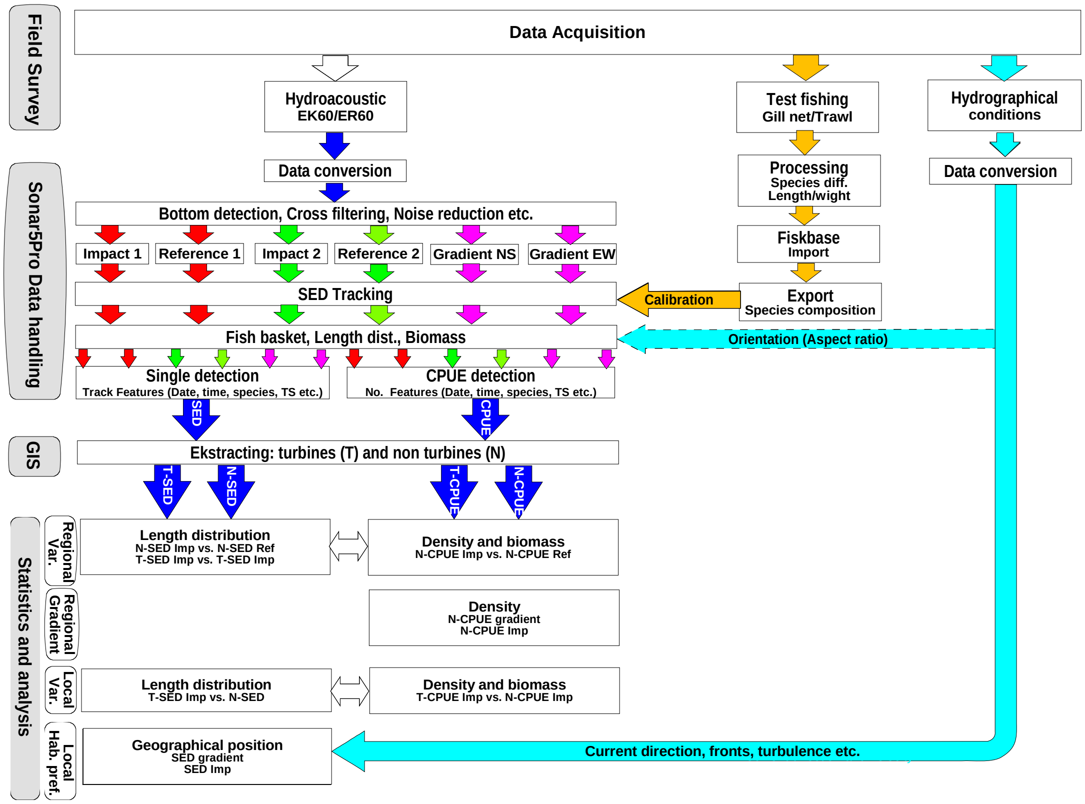


Figure 3.5. Schematic illustration showing flow, linking and handling of data through the entire hydroacoustic project at Horns Rev Offshore Wind Farm.

4. Results

4.1. Fish community distribution

During the supplementary fishing, a total of 21 different species were registered, Table 4.1. Of the registered fish species, only Atlantic horse mackerel was categorised as strictly inhabiting pelagic habitats. Nine species were categorised as semi pelagic or varying between pelagic/semi pelagic and semi pelagic/benthic. The remaining 11 species were categorized as demersal fish inhabiting benthic habitats. Five of the registered species were flatfish (brill, scaldfish, dab, European plaice and solenette). Of the 21 registered fish species, 10 species in three groups (sandeels, dragonet and flatfish) do not have a swim bladder in their adult stage, Table 4.2.

Table 4.1. The total number and weight of registered fish species that were caught during the supplementary fishing in each of the reference and impact transects. Fish species are categorised according to pelagic, semi pelagic and benthic behaviour.

Species	Category	Reference 1		Reference 2		Impact 1		Impact 2	
	Pel./Semipel./Benthic	Number	Weight (g)	Number	Weight (g)	Number	Weight (g)	Number	Weight (g)
Snake pipefish *Entelurus aequoreus*	- / - / +	-	-	-	-	-	-	1	4.5
Lesser pipefish *Syngnathus rostellatus*	- / - / +	-	-	1	1.2	-	-	-	-
Saithe *Pollachius virens*	+ / + / +	-	-	-	-	-	-	1	128.1
Whiting *Merlangius merlangus*	+ / + / -	-	-	-	-	1	39.6	-	-
Atlantic cod *Gadus morhua*	- / + / +	-	-	-	-	7	408.6	3	777.2
Atlantic horse mackerel *Trachurus trachurus*	+ / - / -	6	4.8	4	16.5	9	16.3	-	-
Striped mullet *Mullet surmuletus*	- / - / +	-	-	1	2.9	6	14.9	-	-
Goldsinny wrasse *Ctenolabrus rupestris*	- / - / +	-	-	-	-	-	-	2	101
Corkwing wrasse *Symphodus melops*	- / - / +	-	-	-	-	-	-	1	265.3
Lesser sand-eel *Ammodytes marinus*	+ / + / +	1	12.8	110	1236.7	5	57.9	1	15.3
Small sandeel Ammodytes tobianus	+ / + / +	-	-	11	143.6	-	-	-	-
Great sandeel *Hyperoplus lanceolatus*	+ / + / +	6	97.2	2	42.2	5	114.1	-	-
Sand goby *Pomatoschistus minutus*	- / + / +	20	42.1	37	91.3	293	446.6	2	3.9
Dragonet *Callionymus lyra*	- / - / +	2	88.1	2	4.3	1	8.2	1	50.5
Tub gurnard *Trigla lucerna*	- / - / +	-	-	-	-	1	16.2	-	-
Short-spined sea scorpion *Myoxocephalus scorpius*	- / - / +	-	-	-	-	-	-	1	160
Brill *Scopthalmus rhombus*	- / - / +	-	-	-	-	1	249.3	-	-
Scaldfish *Arnoglossus laterna*	- / - / +	7	58.5	5	47.5	5	56.9	1	10.4
Dab *Limanda limanda*	- / + / +	3	192.5	8	197.5	22	201.9	2	155.2
European plaice *Pleuronectes platessa*	- / + / +	6	209.1	2	20.3	55	743.3	1	16.5
Solenette *Buglossidium luteum*	- / - / +	-	-	-	-	1	7.2	-	-
Total		51	705.1	183	1804	412	2381	17	1687.9

Table 4.2. Percent distribution of the number of fish species into weighted size groups and the constants a(P) and b(Q) of the species-specific length – weight relationship. The constants are obtained from www.fishbase.org. The sensitivity to hydroacoustics is denoted by + or - for fish with or without a swim bladder.

	Length groups (percent)					LW Relationship		Acoustic sensetivity
Species	**3-5 cm**	**5-13 cm**	**13-19 cm**	**19-24 cm**	**>26 cm**	***a(P)***	***b(Q)***	**Svim bladder**
Snake pipefish *Entelurus aequoreus*	-	-	-	-	50.0	0.0002	3.000	+
Lesser pipefish *Syngnathus rostellatus*	-	0.3	-	-	-	0.0002	3.000	+
Saithe *Pollachius virens*	-	-	-	7.1	-	0.0104	2.972	+
Whiting *Merlangius merlangus*	-	-	0.9	-	-	0.0062	3.103	+
Atlantic cod *Gadus morhua*	-	0.3	6.3	7.1	50.0	0.0081	3.030	+
Atlantic horse mackerel *Trachurus trachurus*	6.2	1.4	-	-	-	0.0034	3.273	+
Striped mullet *Mullet surmuletus*	0.9	1.4	-	-	-	0.0047	3.309	+
Goldsinny wrasse *Ctenolabrus rupestris*	-	0.3	0.9	-	-	0.1230	3.000	+
Corkwing wrasse *Symphodus melops*	-	-	-	7.1	-	0.0065	3.150	+
Lesser sand-eel *Ammodytes marinus*	-	12.5	66.7	-	-	0.0031	3.000	-
Small sandeel Ammodytes tobianus	-	-	9.9	-	-	0.0015	3.169	-
Great sandeel *Hyperoplus lanceolatus*	-	-	7.2	35.7	-	0.0034	2.928	-
Sand goby *Pomatoschistus minutus*	86.2	55.7	-	-	-	0.0142	3.000	+
Dragonet *Callionymus lyra*	-	0.9	2.7	-	-	0.0262	2.442	-
Tub gurnard *Trigla lucerna*	-	0.3	-	-	-	0.0060	3.166	+
Short-spined sea scorpion *Myoxocephalus scorpius*	-	-	-	7.1	-	0.0126	3.124	-
Brill *Scopthalmus rhombus*	-	-	-	7.1	-	0.0055	3.305	-*
Scaldfish *Arnoglossus laterna*	-	5.2	-	-	-	0.0025	3.450	-*
Dab *Limanda limanda*	6.2	4.1	3.6	21.4	-	0.0058	3.217	-*
European plaice *Pleuronectes platessa*	0.4	17.4	1.8	7.1	-	0.0089	3.000	-*
Solenette *Buglossidium luteum*	-	0.3	-	-	-	0.0055	3.267	-*

* Swimbladder as larvae

Sandeels and gobies were the most numerous with sand gobies dominating the smallest length group. Sandeels dominated the three length groups from 5 cm to 24 cm, Table 4.2. The group of larger fish only represented two individuals, one of each species of snake pipefish and Atlantic cod.

4.2. General hydroacoustic results

According to the post processing of the recorded raw echograms, a total of 12,099 fish were registered in the hydroacoustic survey along the six surveyed transects, Table 4.3. Most of the fish, 7,892 individuals, were classified as fish possessing a swim bladder (other fish) and the remaining 4,207 individuals were classified as sandeels. The two classifications were summarised into one single group for statistical analysis.

Table 4.3. The number of fish registered during the hydroacoustic survey at Horns Rev from September 4th -6th, 2005. The number of fish is split into the subgroups "Other fish" including fish with target strength greater than -54 dB and "Sandeels" including fish with target strength in between -75 dB and -63 dB. Time was logged as GMT time.

Transect	Diurnal	Sample	Date (mm/dd)	Time (hh:mm)	Other fish	Sandeel	Total
Impact 1	Day	1	9.04	14:11	12	29	41
	Day	2	9.05	15:33	219	169	388
	Night	1	9.05	00:07	91	103	194
	Night	2	9.05	22:01	69	58	127
Impact 2	Day	1	9.04	15:32	80	23	103
	Day	2	9.05	14:40	392	103	495
	Night	1	9.05	01:16	20	54	74
	Night	2	9.05	23:16	44	61	105
Reference 1	Day	1	9.04	13:36	176	24	200
	Day	2	9.05	10:09	95	95	190
	Night	1	9.05	03:11	113	35	148
	Night	2	9.06	03:34	295	38	333
Reference 2	Day	1	9.04	12:08	46	16	62
	Day	2	9.05	08:36	1	33	34
	Night	1	9.05	04:21	57	38	95
	Night	2	9.06	03:45	105	45	150
Gradient EW	Day	1	9.06	07:13	104	341	445
	Night	1	9.04	20:23	1606	1567	3173
Gradient NS	Day	1	9.05	16:12	2557	689	3246
	Night	1	9.04	17:32	1810	686	2496

4.2.1. Regional variations – effects from the wind farm

The possible effects from the wind farm are demonstrated in the data analysis from the gradient transect surveys through the wind farm. In Figure 4.1 to Figure 4.4, acoustic registrations along gradient transects from night and day surveys are displayed as individuals (SED) and in CPUE units as density and biomass in GIS oriented maps.

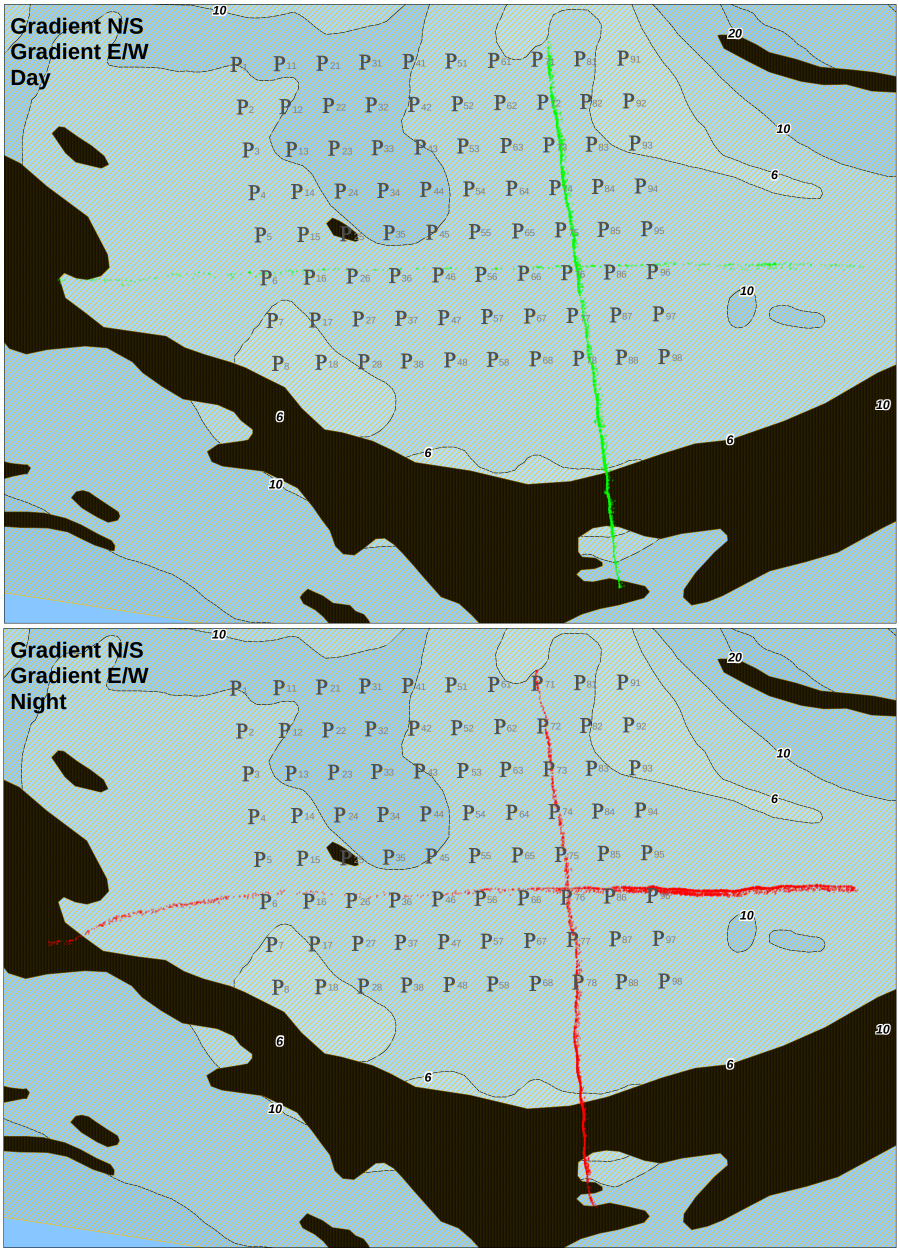


Figure 4.1. Distributions of Single Echo Detections of fish (SED) registered along gradient transects. The distributions are categorized in diurnal variations (day surveys in the upper map and night surveys in the lower map) from September 4th -6th, 2005.

Fish were detected along the gradient transects during both daylight and darkness with no obvious differences in distribution between the two surveys. Slightly more echoes from fish were detected during darkness, Figure 4.1.

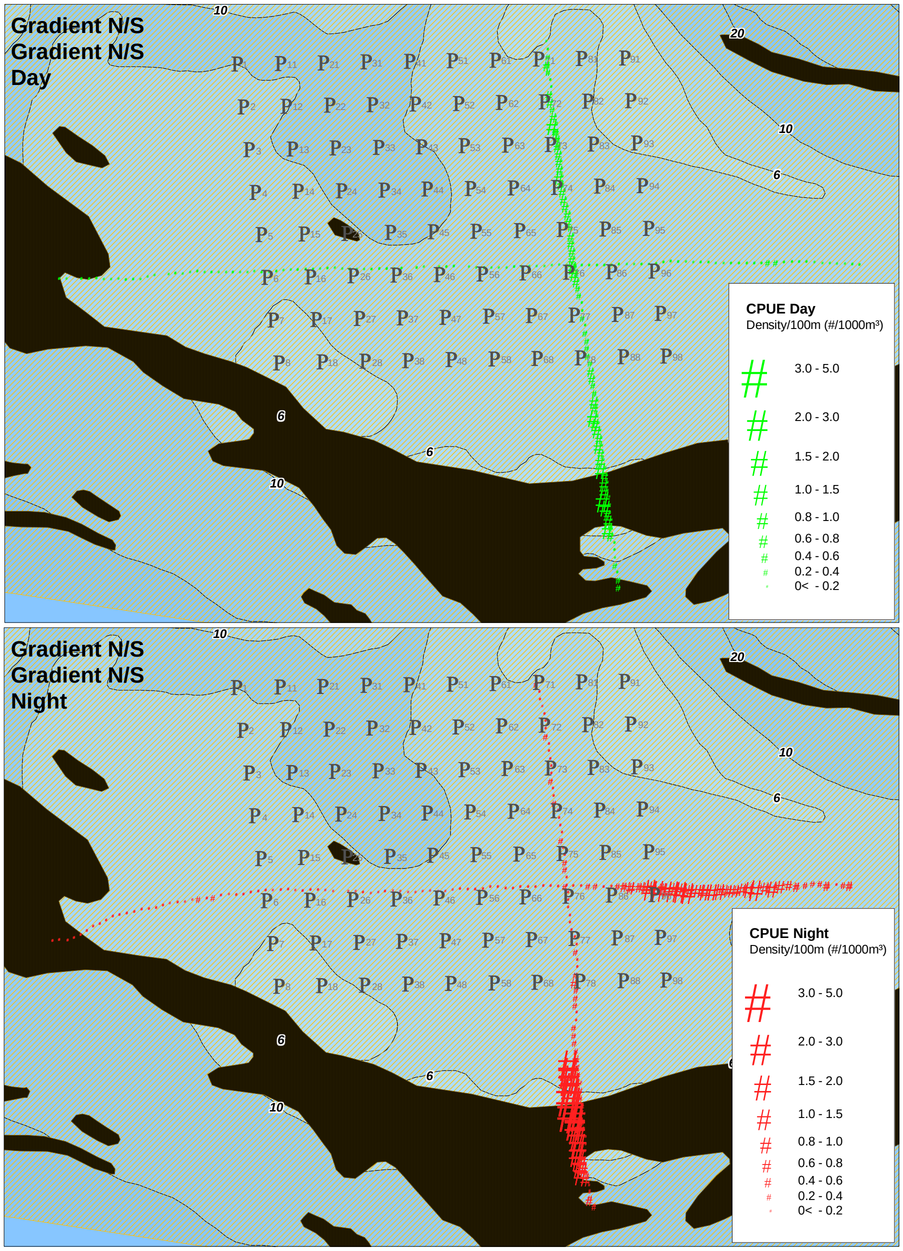


Figure 4.2. Fish density in CPUE (ind./1,000m^3) along the gradient transects. The densities are categorized in diurnal variations (day surveys in the upper map and night surveys in the lower map) from September 4th -6th, 2005. The sizes of the circles are proportional to the fish density.

However, based on the CPUE values, obvious differences were found along the transects surveyed with generally higher densities during darkness south and east of the wind farm as well as in the most eastern part of the wind farm, Figure 4.2 and Figure 4.3. Only low densities of fish were found west of the wind farm and in the western part of the wind farm during darkness as well as during daylight.

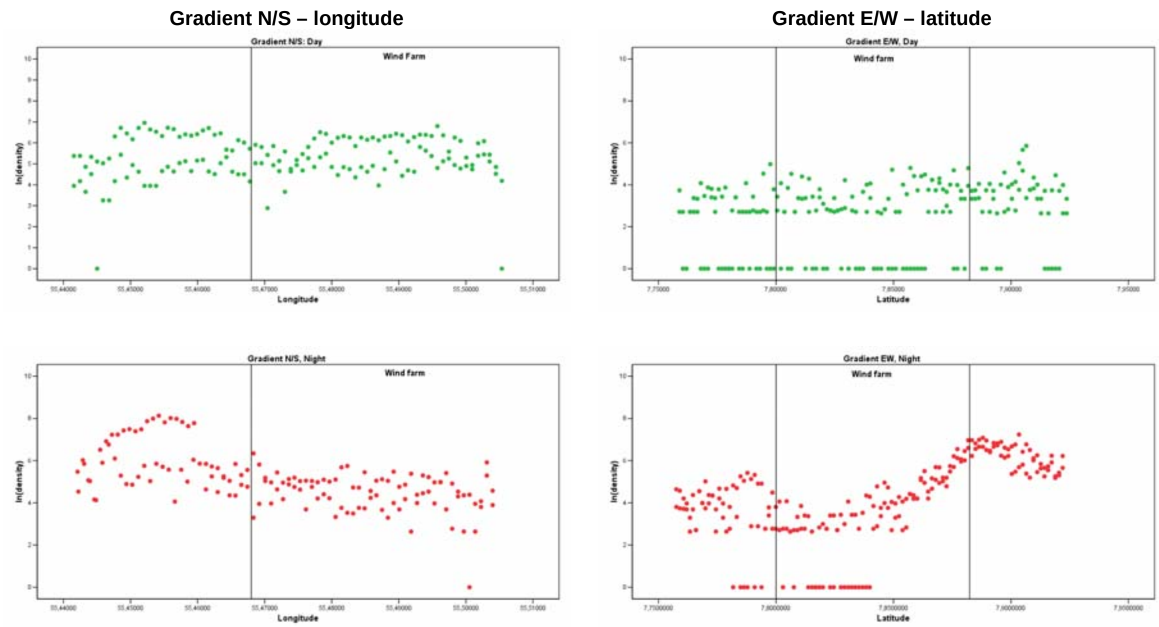


Figure 4.3. Distribution of the number of fish (ln(CPUE per 100 m sailed distance)) along the gradient transects inside and outside the wind farm. The distributions are categorized in diurnal variations (day-green colour and night-red colour) from September 4th -6th, 2005.

The distribution pattern of fish biomass was characterised by generally low values except during darkness in the very eastern part of the wind farm and east of the wind farm, where relatively high values were found, Figure 4.4

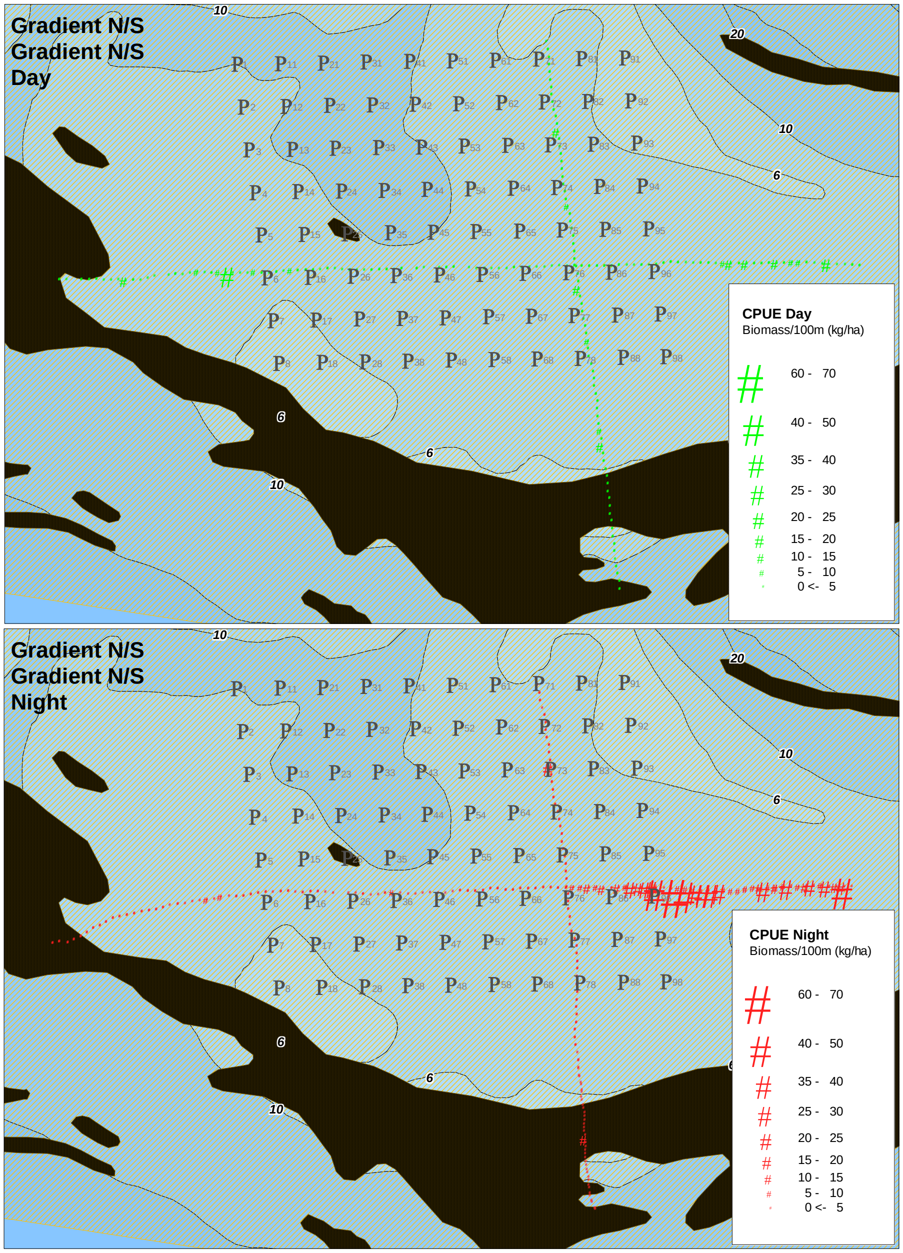
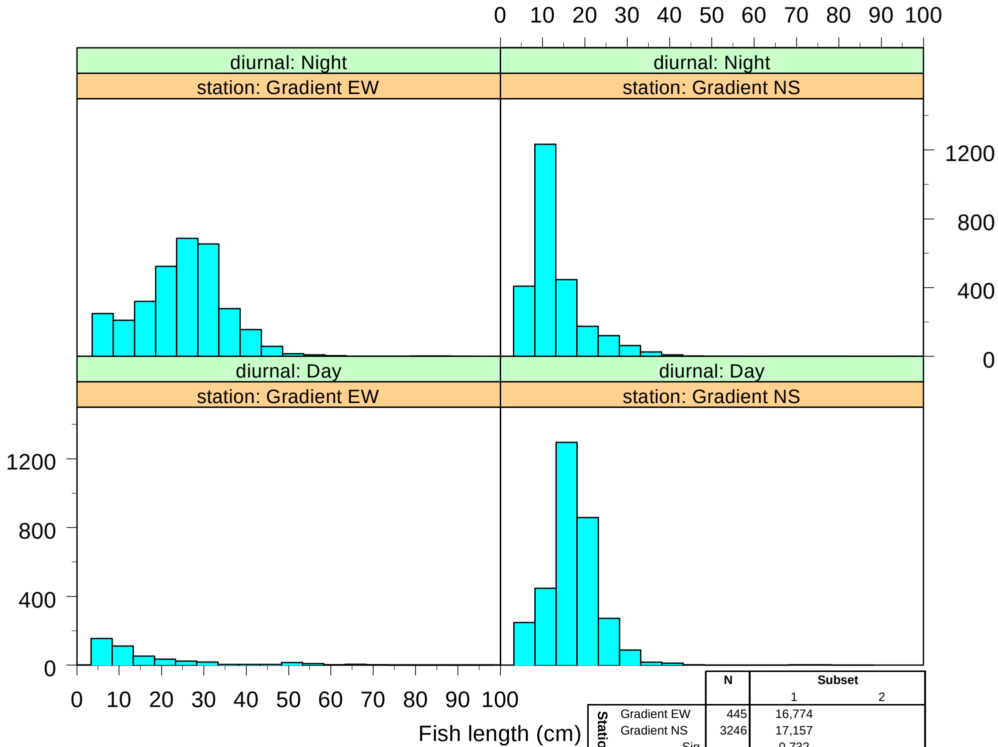


Figure 4.4. Fish biomass (CPUE kg/ha) along the gradient transects. The biomasses are categorized in diurnal variations (day-upper map and night-lower map) from September 4th -6th, 2005. The sizes of the circles are proportional to the fish biomass.

No significant differences were found in the population structure concerning the length distribution between the E/W and N/S gradient transects during daylight surveys, Figure 4.5. However, a shift in population structure was found along the E/W gradient transect from daylight to darkness towards a fish population of larger mean fish length. The larger mean fish length found during darkness along the E/W transect gradient was due to a positive gradient of fish mean length from West towards East, Figure 4.6.



		N	Subset 1	Subset 2
Station	Gradient EW	445	16,774	
	Gradient NS	3246	17,157	
	Sig.		0,732	
Diurnal	Gradient EW	3173		25,127
	Gradient NS	2496	13,224	
	Sig.		1	1

Figure 4.5. Length distribution of fish along the East-West and North-South gradient transects during the day and night surveys. Statistics: Means of fish length for groups in homogeneous subsets are displayed in table form, ANOVA (Student-Newman-Keuls).

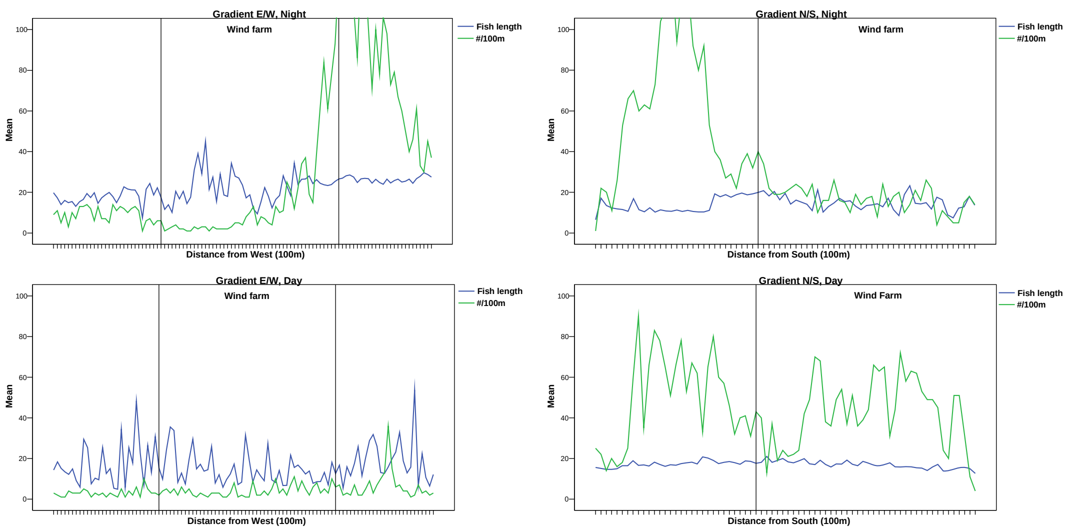


Figure 4.6. Distribution patterns of mean fish length and number pr. 100 m along the gradient transects during the night and day surveys based on SED data.

A pattern in the distribution of mean fish lengths along the E/W transect gradient during daylight could not be explained because of a pronounced large variation. This variation was more of an expression of the relatively low density of fish compared to other parts of the gradient transects, where density was higher giving more uniform mean values. Along the N/S transect gradient during both daylight and darkness, there was a tendency of slightly larger fish found in the southerly transition area from inside the wind farm to the open sea. However, the mean fish length was decreasing southward, which is in accordance with the high density but low biomass found south of the wind farm, Figure 4.2 and Figure 4.4.

The regional variation was also evaluated by comparing transects in the impact area with corresponding transects in the reference area. To achieve a statistical foundation, two transects in the impact and reference areas were surveyed by two samples during both daylight and darkness, Table 4.1. An acoustic registration along each of the impact and reference area transects from day and night surveys are displayed in Figure 4.7 and Figure 4.8 as individuals (SED) and in CPUE units as density and biomass in GIS oriented maps.

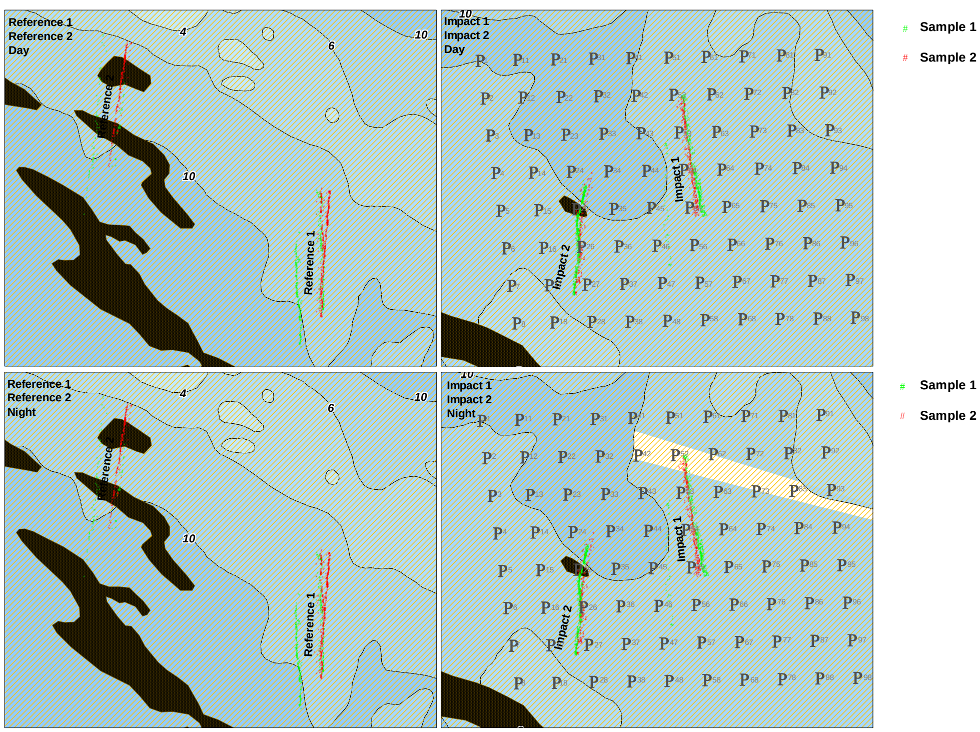


Figure 4.7. Distributions of Single Echo Detections of fish (SED) registered in the impact and reference area. The distributions are categorized in diurnal variations (day-upper maps and night-lower maps) and variations according to samples from September 4th -6th, 2005.

A trend towards higher fish densities in the wind farm area during daylight is evident especially along the impact 2 transect at sample 2, Figure 4.8. However, the exact opposite finding was found during darkness with the highest densities being found along the reference 1 transect. In general, fish densities were higher from the second sample. Relatively large biomass values were found along the reference 2 transect during the second day sample resulting in fish with higher mean fish lengths, Figure 4.9.

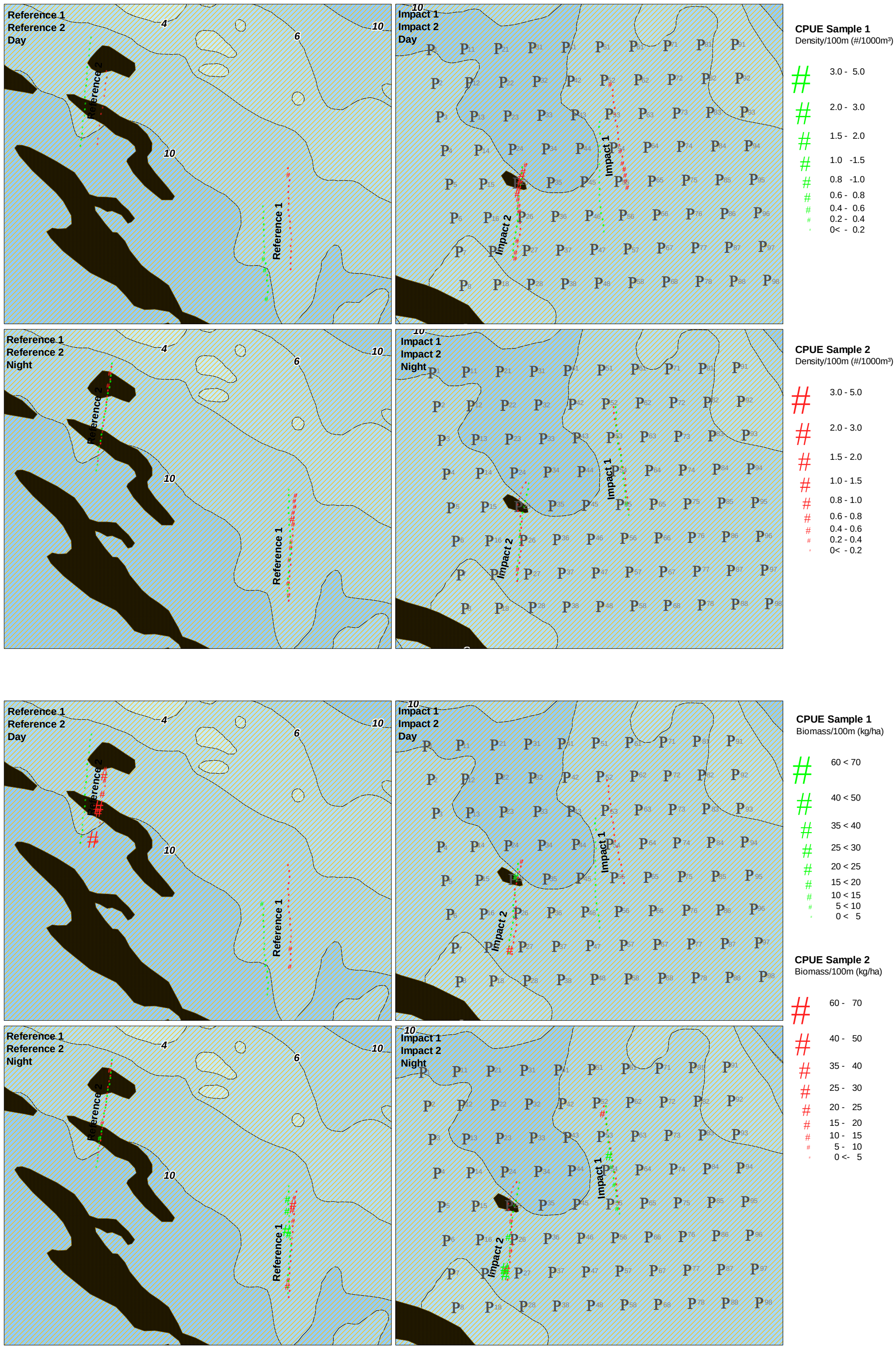
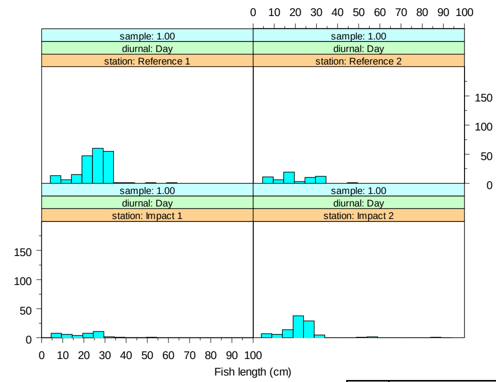
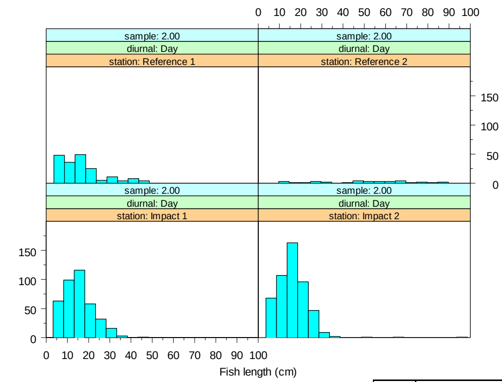


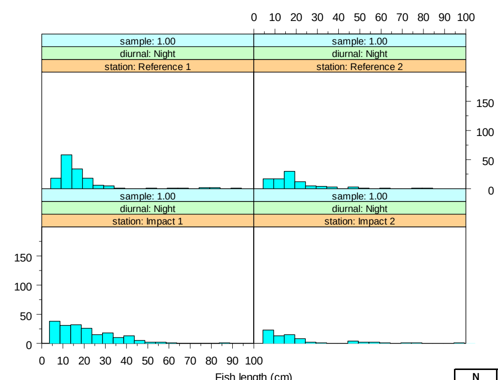
Figure 4.8. Fish density (CPUE ind./1,000^3) and biomass (CPUE kg/ha) (CPUE per 100 m sailed distance) in the impact and reference areas. The densities are categorized in diurnal variations and variations according to samples from September 4th -6th, 2005. The sizes of the circles are proportional to the fish density.



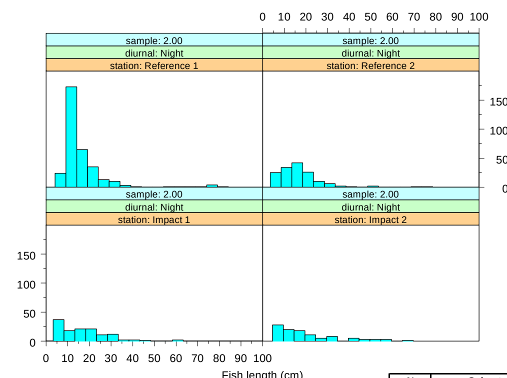
	N	Subset		
Station		1	2	3
Impact 1	41	19,92		
Reference 2	62	20,88	20,88	
Impact 2	103		22,65	22,65
Reference 1	200			24,52
Sig.		0,388	0,114	0,094



	N	Subset	
Station		1	2
Impact 1	388	15,27	
Impact 2	495	16,24	
Reference 1	190	16,51	
Reference 2	34		50,20
Sig.		0,565	1



	N	Subset
Station		1
Reference 1	148	18,30
Reference 2	95	19,93
Impact 2	74	20,52
Impact 1	194	21,06
Sig.		0,052



	N	Subset	
Station		1	2
Reference 1	333	16,22	
Reference 2	150	16,70	
Impact 1	127	16,87	
Impact 2	105		20,30
Sig.		0,875	1

Figure 4.9. Fish length distribution along the impact transects inside the wind farm and the corresponding reference transects outside the wind farm in diurnal and sample conditions. Statistics: Means of fish length for groups in homogeneous subsets are displayed in table form, ANOVA (Student-Newman-Keuls).

Length distribution patterns were analysed to evaluate the fish population structures between transects in the impact and reference areas, Figure 4.9 At one occasion, a significant similar population structure was found from sample 1 during the night survey along all transects. There was a significant cross effect dividing the transects into three subgroups along the daylight survey from sample 1. The population structures were similar at three of the transects from sample 2 while the mean fish length was distinctly larger along the reference 1 transect. The same observation was made during the night survey from sample 2, although the impact 2 transect was isolated. In general, none of the tests showed a significant pattern in population structure between impact and reference areas.

A transect specific comparison in the analysis of differences between the reference and impact areas is of importance because of the significant differences between transects. The outcome of the statistical analysis in the fish density variation (CPUE density) between the transects in the impact and reference areas is summarised in Table 4.4 and Figure 4.10. A clear statistical difference between reference and impact areas could not be explained because of pronounced cross effects. The analysis of biomasses (CPUE biomass) did not reveal any differences between impact and reference transects. The biomass of fish along the different transects showed less divergence than the density except for reference 2 and impact 1 transects, which have the lowest and highest values comparing both diurnal variance and variance between samples.

Table 4.4 Results of statistical analysis on logarithmic transformed CPUE of density and biomass from each transect surveyed in the impact area (reddish colours) and reference area (greenish colours). Homogeneous (non-significantly different) transects are grouped in subsets. Statistics: Means of fish density for groups in homogeneous subsets are displayed in table form, ANOVA (Student-Newman-Keuls).

LN(CPUE density)			N	Subset					
Transect	Diurnal	Sample		1	2	3	4	5	6
Reference 2	Day	2	14	2,689					
Impact 1	Day	1	19	2,986	2,986				
Reference 2	Day	1	19	3,220	3,220	3,220			
Impact 2	Day	1	17		3,860	3,860	3,860		
Reference 2	Night	2	19		3,869	3,869	3,869		
Impact 2	Night	1	17		3,904	3,904	3,904		
Reference 2	Night	1	19		3,942	3,942	3,942		
Impact 2	Night	2	18			4,303	4,303	4,303	
Reference 1	Day	1	19			4,326	4,326	4,326	
Impact 1	Night	2	19			4,342	4,342	4,342	
Reference 1	Night	1	19				4,496	4,496	
Impact 1	Night	1	19				4,869	4,869	4,869
Reference 1	Day	2	18				4,932	4,932	4,932
Impact 1	Day	2	19					5,150	5,150
Reference 1	Night	2	19					5,411	5,411
Impact 2	Day	2	17						5,850
		Sig.		0,329	0,107	0,055	0,115	0,062	0,066

LN(CPUE biomass)			N	Subset		
Transect	Diurnal	Sample		1	2	3
Reference 2	Day	1	19	0,251		
Impact 1	Day	1	19	0,284		
Reference 2	Night	1	19	0,448	0,448	
Reference 2	Night	2	19	0,503	0,503	
Impact 1	Night	2	19	0,550	0,550	
Impact 2	Day	1	17	0,678	0,678	
Impact 1	Day	2	19	0,690	0,690	
Impact 2	Night	2	18	0,753	0,753	
Reference 1	Day	2	18	0,811	0,811	
Reference 1	Day	1	19	0,827	0,827	
Reference 1	Night	1	19	0,868	0,868	
Impact 2	Night	1	17	0,903	0,903	
Impact 2	Day	2	17	1,019	1,019	1,019
Reference 1	Night	2	19	1,070	1,070	1,070
Impact 1	Night	1	19		1,197	1,197
Reference 2	Day	2	14			1,633
		Sig.		0,083	0,152	0,079

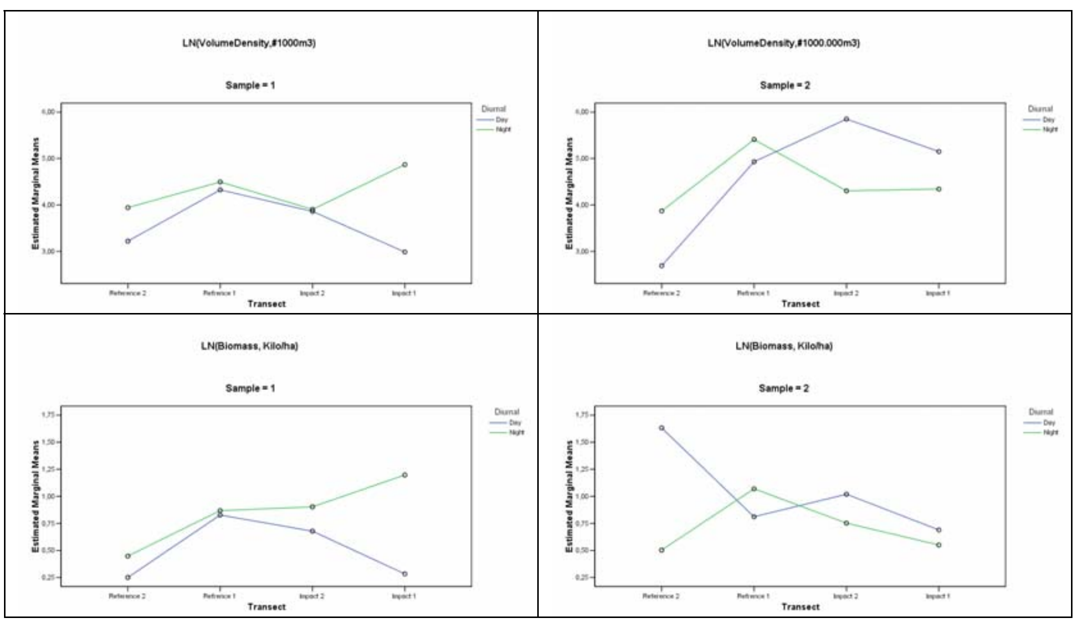


Figure 4.10. Day (blue) and night (green) average fish density and average fish biomass distribution based on CPUE at surveyed transects in impact and reference areas.

4.2.2. Local variations – effects from the turbine foundations

Local variations in the fish density were shown in the spatial distribution pattern at the turbine foundations along two sections of the E/W and N/S transect, Figure 4.11. This result was more or less consistent with the results shown for the regional variation. Very few fish were detected along the E/W gradient during both the day and night. The fish distribution pattern did not indicate a habitat preference for near the foundations. Fish density was found to be much higher along the N/S gradient transect survey, especially during daylight and at some turbine foundations.

However, no statistical evidence was found confirming that fish densities near the vicinity of the turbines were different from in-between the turbines. On the contrary, there was a tendency, but not significant, of lower fish densities at the foundations than in-between the foundations except for the E/W transect gradient during darkness, Figure 4.12.

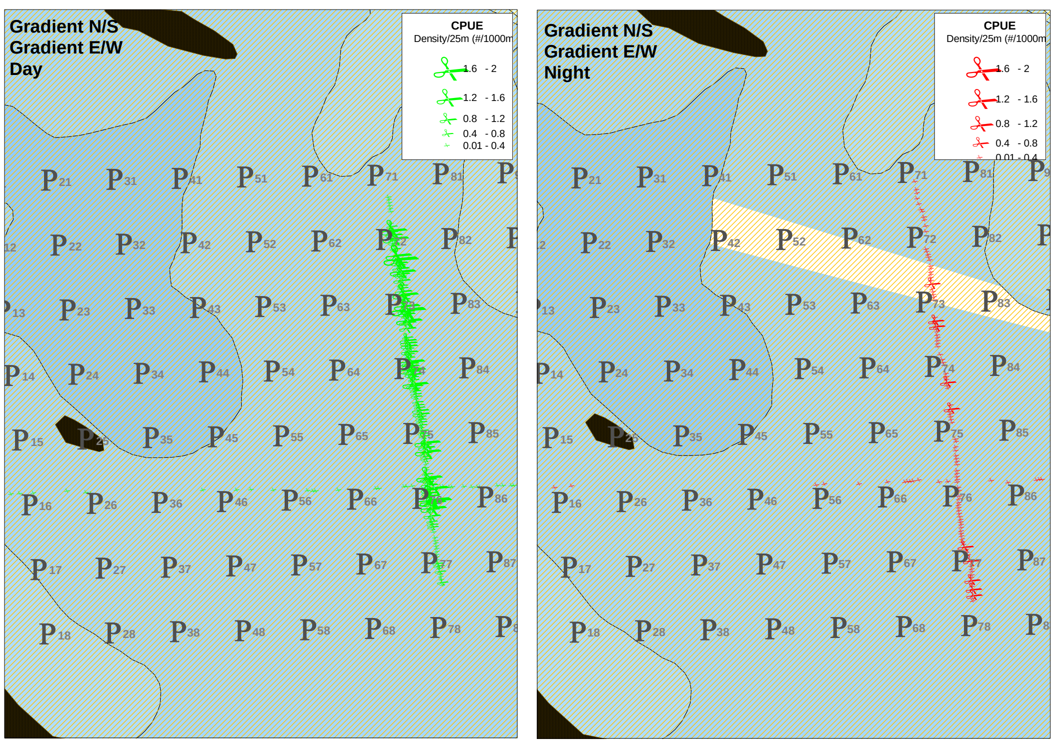


Figure 4.11. Fish density (CPUE ind./1,000^3) during daylight and darkness for selected sections of the gradient transects inside the wind farm (CPUE per 25 m sailed distance) from September 4th -6th, 2005. The sizes of the circles are proportional to the fish density.

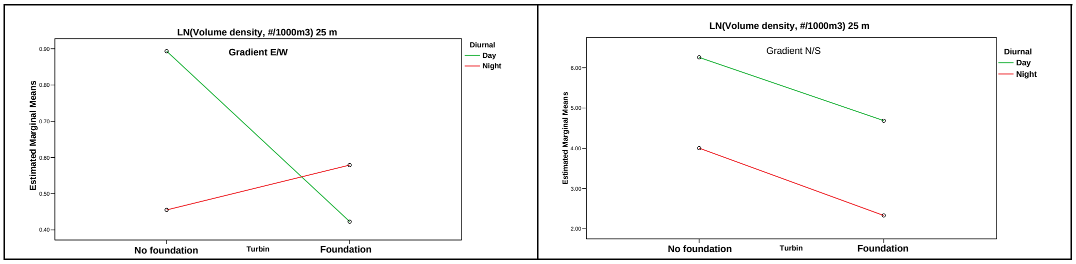


Figure 4.12. Day (green) and night (red) average density distribution based on CPUE per 25 m sailed distance along sections of surveyed transects in the wind farm covering areas in-between and areas around turbine foundations.

Photo 5-6 Samples from supplementary fishing. Left: Sub-sample from trawl including brown shrimp, harbour crabs and hermit crabs from a small trawl haul. Right: a bundle of juvenile scaldfish extracted from a trawl sample.

5. Discussion

Ten additional species, besides the 21 fish species registered in this study, have been registered during the hard bottom substrate surveys in the offshore wind farm at Horns Rev since the erection of the wind turbines in 2002 (Leonhard and Petersen, 2006). This gives a total of more than 31 species considered as elements of the natural fish community around Horns Rev Offshore Wind Farm. From a hydroacoustics point of view, European sprat (*Sprattus sprattus*) is the most interesting of the 10 additional species observed by Leonhard and Petersen (2006) because it has a swim bladder and has pelagic behaviour. However, it is uncertain if sprat contributes to the hydroacoustic detections in this study because sprat was not registered by the supplementary fishing. The majority of fish and fish species were observed during the autumn study rather than the spring study. In addition to studying the fish species, spatial and temporal variations in the fish fauna have also been observed (Leonhard and Petersen, 2006).

From the 31 species considered as elements of the natural fish community at Horns Rev Offshore Wind Farm, the 12 species of fish with swim bladders (horse mackerel and Atlantic cod being most numerous) were directly accessible for the hydroacoustic method used in this study. Furthermore, with the knowledge of sandeels being numerous and of commercial interest in the area around Horns Rev, the hydroacoustic system was set-up to monitor the weak acoustic signals of the three species of sandeels found.

5.1. Natural patterns in distribution and numbers

Most pelagic and semi pelagic fish species display a natural diel pattern in behaviour and distribution (Axenrot et al., 2004). Diel variation in the fish community at Horns Rev was expected, however, no unambiguous diel variation pattern could be revealed from the hydroacoustic data. There was a trend, though not significant, of a higher density during darkness except during one occasion inside the wind farm area where the occurrence of pelagic and semi pelagic fish were higher during daylight. The opposite diel variation was found during a similar hydroacoustic investigation at Nysted Offshore Wind Farm (Leonhard et. al., 2006).

Diurnal variations in pelagic and semi pelagic species are well known. Diurnal variability of school structure has also been found for pelagic fish using hydroacoustic methods (Fréon et al., 1996). Pelagic fish generally disperse at dusk and aggregate in schools at dawn (Fréon et al., 1996). No obvious aggregations in schools were found during the hydroacoustic survey at Horns Rev Offshore Wind Farm. Although, along the gradient transects, a diurnal pattern of forming more dense aggregations of fish during darkness was found especially south and east of the wind farm with more loose aggregations during daylight.

Numerous sand gobies were observed forming schools in the Horns Rev Offshore Wind Farm area during daylight (Leonhard and Petersen, 2006). Different species composition between the reference areas and the wind farm areas might also reflect the differences in the hydroacoustic distribution pattern and vertical migration pattern (Hunter et al., 2004). The different species composition was shown for sand gobies (Svensson, et al., 2000; Thetmayer, 1997) with a high variability in the schooling behaviour of the pelagic and semi pelagic species. Although, there was a high number of sand gobies registered during the supplementary fishing in the wind farm at impact 1, there was no clear evidence of a corresponding registration by the hydroacoustic equipment because only the larger individuals of the sand gobies were accessible to the acoustic set-up due to the minimum threshold value set.

Despite the dermersal behaviour of benthic species, some of them leave the sediment surface momentarily to forage or migrate to the pelagic zone. The off-bottom activity is most often seen during dusk, dawn and darkness. The pelagic activity of the flatfish during dusk and dawn can be seen as a synergistic effect of both high food availability and low predation risk during this period, whereas the ascendance during darkness typically is for migration. The ascendance takes place higher in the water column and uses the tidal water current for passive transport (De Veen, 1978). The benthic species are only expected to minimally contribute to the specimens observed with the hydroacoustic gear, not only because of their behaviour, but also because most of these species have a small swim bladder or none at all.

Dissolution of schools during darkness is also well documented by the diel rhythm in sandeels (Muus, et al., 1998; Jensen, 2003; Freeman et al., 2004). The sandeels are buried in the seabed sediments during darkness and emerge into the pelagic zone to feed as light intensities increase above approximately 10 lux (Muus, et al., 1998; Freeman et al., 2004). Besides light intensity, other physical and biological parameters have also been found to influence the distribution of sandeels. Water temperature and food availability is especially found to be of great importance, but a correlation between bottom current velocity and sandeel densities has also been found, e.g. a strong tidal current regime usually resulting in high densities of sandeels (Freeman et al., 2004). The three species of sandeels caught during the supplementary fishing contribute to the natural diurnal variations in the area.

The Atlantic cod, like the sandeel, exhibits a diel vertical variation in distribution (Michalsen et al., 1996). The diel variation in cod is further intensified by other physical parameters as well, such as current velocity (Michalsen et al., 1996). The cod is mainly found close to the bottom during daylight and in the pelagic zone during darkness. This diurnal vertical distribution is caused by the feeding behaviour of the cod. Cod forage by odour on sessile invertebrates during darkness and forage on mobile species by vision during daylight (Løkkeborg, 1998). This diurnal pattern of the Atlantic cod could also contribute to the observed hydroacoustic distribution pattern, although very small individuals were found during darkness in the wind farm area, which were unlikely to be cod. On the other hand, a fish community with relatively large fish size was found at reference transect 2 during daylight (high biomass but relative low density), that probably reflects larger cod entering the area. During the same time, there were almost no small fish found in the same location.

5.2. Effects from the wind farm

5.2.1. Regional variations

No general or unambiguous regional effects were demonstrated by the presence of the wind farm during the hydroacoustic surveys at Horns Rev Offshore Wind Farm. Although, fish attraction behaviour and rapid fish recruitment has generally been demonstrated by the presence and introduction of artificial hard substrate and reef structures (Jensen et al., 2000b; Leewis and Hallie, 2000; Leewis et al., 2000;

Lockwood, 2005; Öhman & Wilhelmsson, 2005). Schools of whiting and Atlantic cod associated with the turbine foundations were also observed at Horns Rev Offshore Wind Farm (Leonhard and Petersen, 2004) and North Hoyle Offshore Wind Farm (Lockwood, 2005).

The hydroacoustic survey demonstrated that none of the surveyed transects in the reference or impact areas could be regarded as replicates with respect to the temporal differences in the surveyed periods. Due to these temporal differences, statistical significant cross effects were found between the factors analysed. No distinct temporal or geographic patterns in densities, biomass or length distribution could be found in sampling periods, diurnal variations, or transects inside and outside of the wind farm area. The great variability in temporal, diurnal and spatial distribution of pelagic fish as well as variations in schooling dynamics demonstrates that traditional statistical designs of impact assessments with predefined geographical impact and reference areas are difficult to manage with respect to dynamic and fluctuating pelagic fish communities. Hydroacoustic surveys at offshore installations have also shown difficulties in obtaining statistically significant results although spatial diurnal differences in the pelagic and semi pelagic fish populations have been demonstrated (Soldal et al., 2002).

Different species composition might be responsible for the differences found in the fish communities inside and outside of the wind farm area. For example, Atlantic cod, which displays nocturnal dispersion behaviour, might be more abundant inside the wind farm area than outside. Sandeels have demonstrated a strong preference for sediments with coarse sand (particle size between 0.25-1.2 mm) (Wright et. al. 2000), which has especially been found in an area south of the wind farm. According to the results achieved from the gradient transects, the area with coarse sand south of the wind farm aggregates fish, probably sandeels and their predators, to a much higher extent than the presence of the wind farm itself. Hvidt et. al. (2005a) demonstrated a similar phenomenon of aggregation of fish in connection to the same areas of sediment with coarse sand and varying bathymetry. This indicates that the distribution of fish to a high degree is correlated with many other influential factors besides the presence of the wind farm.

In general, it has also been reported that oceanic pelagic zones and fish aggregations are associated with mesoscale hydrographic features such as fronts, eddies and discontinuities (Mann and Lazier, 1991; Bertrand et al., 2005; Robinson and Gómez-Gutiérrez, 2005).

5.2.2. Local variations

Fish density was expected to be higher inside the wind farm and especially higher in the vicinity of the turbine foundations because scour protection has a potential attraction effect on reef fish. However, no general statistical significance was found in the pelagic and semi pelagic fish aggregation compared to distribution patterns of fish between turbines. In previous studies at Nysted (Hvidt et al., 2005b) and Horns Rev Offshore Wind Farms, significantly higher fish abundances have been found in the vicinity of turbines than between turbines (Hvidt et al., 2005a). A close association of fish near hard structures around oilrigs was also demonstrated in the North Sea (Soldal et al., 2002) and in the northern Gulf of Mexico (David et. al., 1996). The study in the northern Gulf of

Mexico also found a decreasing gradient of fish density reaching the background level at a distance of 16 m from oilrigs besides a strongly seasonal fluctuation in density.

In the vicinity of the wind turbine foundations, the presence of current boundaries might play a role in the distribution pattern of the pelagic fish species. Noticeable current turbulence with associated fronts and eddies was at several occasions recorded by the hydroacoustic system registering turbulence up to 150 metres from the turbines, Figure 5.1. However, the hydroacoustic registration of fish at Horns Rev Offshore Wind Farm did not confirm that there was an unambiguous aggregations of pelagic fish in connection to the turbine created turbulence as found at Nysted Offshore Wind Farm (Leonhard et. al., 2006). Thought, it is common knowledge that fish do utilize the differences in currents both to preserve energy and to get easy access to drifting food items.

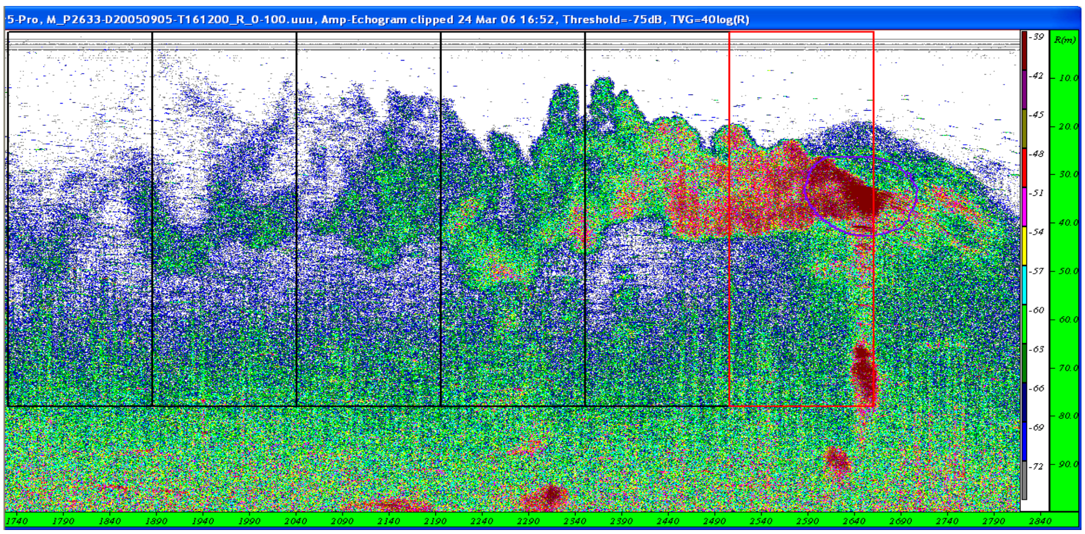


Figure 5.1. Turbulence from turbine foundation registered by the hydroacoustic echo sounder system at turbine site no. 74 September 5th 2005.The turbine foundation and the innermost part of the sour is encircled by a purple line.

Diurnal behavioural variations in the presence of different fish species might also affect the local hydroacoustic variation. As shown in other studies, dermersal or semi pelagic fish species hiding in hard structures during the day disperse throughout the water column at night so their distribution was suitable for acoustic biomass estimations (Soldal et al., 2002).

Hydroacoustic noise from the turbines could also be a factor influencing the local spatial and temporal distribution pattern, although Atlantic cod and whiting have a restricted hearing threshold range (Popper and Fay, 1993; Engell-Sørensen and Skytt, 2001; Nedwell and Howell, 2004).

Differences in the local variation might also develop over time with the development in fouling communities at the foundations. The deployed artificial substrates are still young of age, which might contribute to the high variability in the temporal and spatial dispersal pattern. Abundance and diversity of fish is expected to increase as sessile organisms become more abundant on the foundations (Birklund and Petersen, 2004).

5.3. Methodological considerations – lessons learned

Using the horizontal hydroacoustic methods, the validity of the results is highly dependent on the cross filtering and single target tracking technique used during the post processing. However, the strength of the acoustic signal is much larger if fish are oriented perpendicular rather than parallel to the acoustic axis. Marine fish will mostly be oriented parallel to the local current but random orientation will occur for a substantial amount of time. This results in difficulties predicting the origin of the echo or in an echo below the selected threshold value and thereby difficulties in determining the fish size. In some instances the result will be an underestimation of the fish density and biomass.

To comprehend this barrier, the single target tracking technique is used. It is designed to extract the strongest echo signal in a track, which is then transformed into a fish length measurement. This feature diminishes the underestimation, but does not remove it. The conversion of the acoustic signal measured in dB to length is preformed by a dorsal target strength (TS) view, which might differ slightly from a lateral view.

A TS value of -54 dB is equal to a fish that has a swim bladder, like most pelagic fish except e.g. mackerel (*Scomber scombrus*), with a length of approximately 5.6 cm. This TS value will then be the minimum target strength generally used for fish detection. However, in areas where mackerel, sandeels and flatfish can be encountered (fish without swim bladders), data should be interpreted carefully because a swimming mackerel with a length of 25 cm returns an echo with a TS value of only approximately -60 dB. Also, sandeels return a TS value below the threshold of -54 dB and have a target strength of -68.9 dB for a fish with a mean length of 12.44 cm (Mackinson et al., 2004a). Tracks of fish with these low target strengths could be confused with acoustic signals from other organisms having a low target strength e.g. jellyfish, crustaceans, algae etc.

Mutlu (1996) found that TS values of jellyfish (*Aurelia aurita*) ranged between -54 dB to -67 dB at 120 kHz depending on disc diameter. A jellyfish with a disc diameter of 15.5 cm has an average TS value of -57.1 dB . These results are supported by Brierly (2001) describing an average TS value of -68.5 dB at 120 kHz for jellyfish (*Aequorea aequorea*) with a disc diameter of 7.4 cm. However, using TS thresholds in the spectrum between -75 dB and -63 dB in this study minimises the risks of contaminating the tracks of sandeels with tracks of jellyfish because the size of disc diameter during the autumn is generally large. Excluding sandeels is a great disadvantage of the method because sandeels are important species displaying temporary pelagic activity in the area around Horns Rev Offshore Wind Farm.

More likely, the acoustic signal from brown shrimp (*Crangon crangon*) interferes with that of sandeel. Brown shrimp have frequently been registered in the area (Leonhard and Pedersen, 2005a) and is known to be important to the local commercial shrimp industry. The supplementary fishing and visual observations also revealed a high abundance of brown shrimp and harbour crab (*Lionocarcinus depurator*) in both impact and reference areas. The target strength of either of these two species is not found in the literature. In comparison, the target strength of Arctic krill is reported to range from -73 dB to -67 dB (Hewitt and Demer, 1996). However, the target strength of the red crab (*Pleuroncodes planipes*), which is approximately the same size as the brown shrimp, has a distinctly higher target strength varying between -54 dB and -50 dB (Gómez-Gutiérrez et. al., 2000). Because of the diverged measurements of target strength it will remain unknown if the presence of the brown shrimp interferes with the hydroacoustic registrations of sandeels.

Photo 7-8. The weather was unusual calm during day as well as night offering the best conditions for the horizontal hydroacoustic survey.

Apparently, the fish communities at Horns Rev are influenced by many abiotoc as well as biotic factors besides a possible effect of the wind farm itself. It is obvious in analysing effects from the wind farm, that there is a need to gain knowledge on the influence by other natural factors and map the spatial and temporal variations in the study area. Before very specific descriptions of the natural background variation is available, it does not seem possible to obtain statistical evidence of an effect from the wind farm without the implementation of time series.

The high variability in the spatial and temporal distribution of both pelagic and semi pelagic fish populations has shown that the description and assessment of impact with use of statistical methods requires a huge sampling programme (Hvidt et al., 2003). It is also very difficult or impossible to achieve statistically useful representative replicates and geographical representative reference areas, as was the case in this study. The use of hydroacoustic methods, however, is the an appropriate method to achieve substantial datasets for analysing the distributional patterns in pelagic and semi pelagic communities as olso mentioned by Mackinson et al., (2004b).

6. Conclusion

The horizontal hydroacoustic survey performed at Horns Rev Offshore Wind Farm has shown a high temporal and spatial variation in fish density, biomass and length distribution in the pelagic and semi pelagic fish communities with significant cross effects between areas inside and reference areas outside the wind farm.

No unambiguous diel variation pattern could be revealed from the hydroacoustic data. There was a trend, though not significant, of a higher fish density at night.

No general or clear regional effects from the presence of the wind farm were demonstrated when comparing impact and reference areas. In contrary, there was an indication that the distribution of fish generally was influenced by other biotic and abiotic factors like sediment characteristics.

No local statistically significant differences were found in the temporal and spatial distribution of the fish communities inside the wind farm due to the presence of the turbines.

Before very specific descriptions of the natural background variation are available, it does not seem possible to obtain statistical evidence of an effect from the wind farm without the implementation of time series.

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