Distribution and density of harbour porpoises in Dutch North Sea waters

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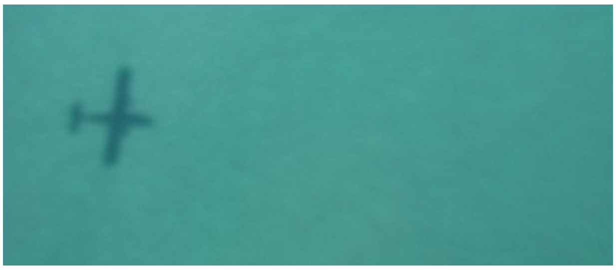

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Contents

Summary

Aerial surveys were conducted to investigate harbour porpoise density and distribution in Dutch waters. Surveys were conducted following standard line transect distance sampling methodology on tracklines providing a representative coverage of the study area which ranged from the Dutch coast to about 120 km offshore thus covering about half of the Dutch EEZ. Within this overall study area two sub-areas were defined. One sub-area (from Texel to the German border) was covered in on 29 November 2008 and 3 April 2009. Density was 1.02 animals per km^2 during the November survey and 0.52 animals per km^2 during the April survey. An overall survey, covering both sub-areas, was conducted on 3 February, 18 March and 3 April 2009. The resulting density was 1.12 animals per km^2. This corresponds to an estimate of harbour porpoise abundance for this study area of 36 825 animals (95% C.I. 19 090 – 68 130; 0.33 C.V.). Distribution patterns of porpoises in the surveys waters were patchy and seemed variable between surveys. Applying this abundance estimate, a range of potential mortality limits were calculated for the Dutch harbour porpoises.

1 Introduction

The harbour or common porpoise (Phocoena phocoena) is the smallest cetacean species inhabiting temperate and cold waters throughout the northern hemisphere (Reid et al. 2003). Due to its occurrence, mainly in coastal or shelf waters, the porpoise is threatened by a variety of anthropogenic impacts including by-catch in fishery (Vinther 1999, ASCOBANS 2000) and habitat degradation due to, for example, chemical and acoustical pollution (Jepson et al. 1999, Siebert et al. 1999, Madsen et al. 2006).

In EU waters, this species is listed in Appendix II of the Bern Convention (implemented in 1982), in Appendix II of the Convention on the Conservation of Migratory Species (CMS; implemented in 1983), in Annex II and IV of the EU Habitats and Species Directive (implemented in 1992) and in Annex V of the Convention for the Protection of the Marine Environment of the Northeast Atlantic (Oslo and Paris Convention OSPAR, implemented in 1998). The Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas (ASCOBANS) was concluded in 1991 under the auspices of the CMS (or Bonn Convention) and entered into force in 1994.

Harbour porpoises are the most common and resident cetaceans in Dutch waters. Several studies have investigated their coastal distribution along the Dutch coast (Addink & Smeenk, 1999, Camphuysen 1982, 1994, 2004, Reijnders et al. 1996) and have shown that there has been an increase in occurrence over the last decade (Camphuysen 1994, 2004, Witte et al. 1998). At the same time two potential threats to harbour porpoises have become evident. First of all, the observed increase in strandings with a high percentage of animals showing evidence of by-catch could indicate an increased mortality of porpoises (Camphuysen & Oosterbaan 2009). Secondly, the ongoing development of offshore construction sites such as wind parks causes concern as they might impact the distribution of porpoises (Carstensen et al. 2006, Gilles et al. 2009).

The objective of this project was to conduct aerial surveys in the Dutch North Sea to obtain density and distribution data of harbour porpoises. The data analyzed here is based on two projects, each covering different areas. Within an ongoing study "area D" (figure 1) is surveyed within a project funded by the Dutch Ministry of Agriculture and Food Quality (LNV) (table 1, figure 1). The additional flights funded by Rijkswaterstaat (RWS) were conducted in "area C". Area C was successfully covered in November 2008 and April 2009. Area D was surveyed in February and March 2009 which, in combination with area C (subsequently called "early spring survey"), effectively covered a large part of the Dutch EEZ ranging from the coast to about 120 km offshore (figure 1). Two additional offshore areas were defined (areas A and B), but have not yet been covered.

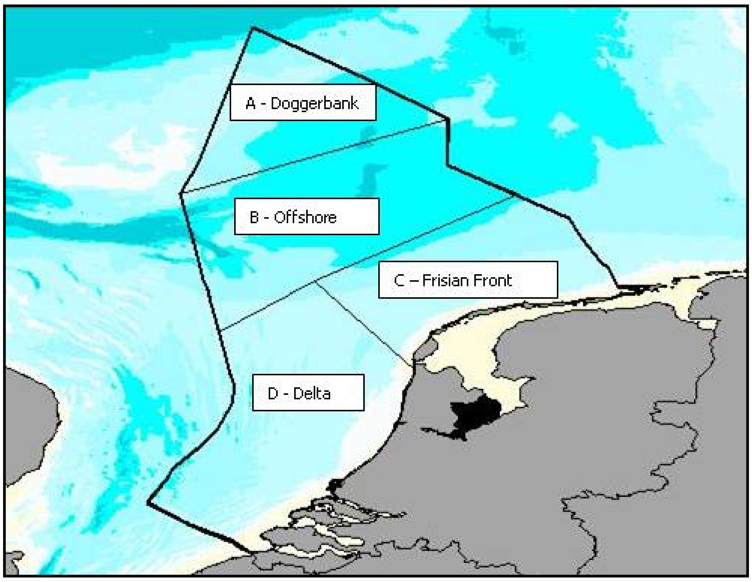


Figure 1: Overview of the four defined study areas: A – Doggerbank, B – Offshore, C – Delta, D – Frisian Front

2 Materials and Methods

2.1 Study area

The overall study area ranged from the coast to about 120 km offshore, thus covering about half of the Dutch EEZ (exclusive economic zone). The Dutch EEZ is divided in 4 areas: A, B, C and D (figure 1). The focus study area of this study ranges from the German border to the island of Texel (area C, 12023 km²). The second area that was covered within the ongoing LNV study ranges from the coast to about 120 km offshore (area D, 20797 km²) (figure 2).

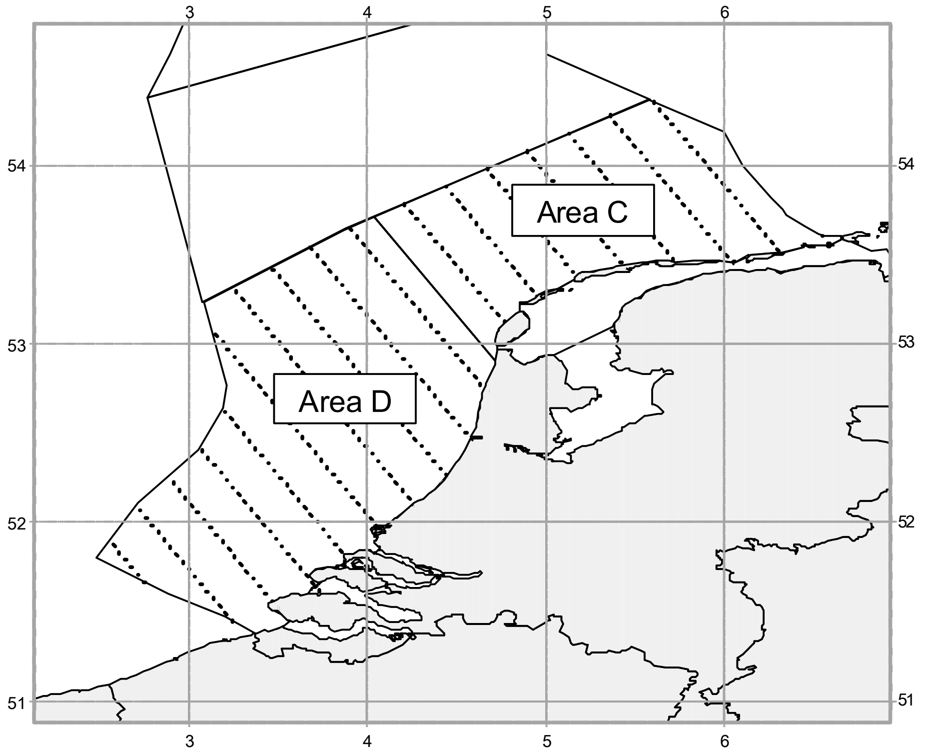
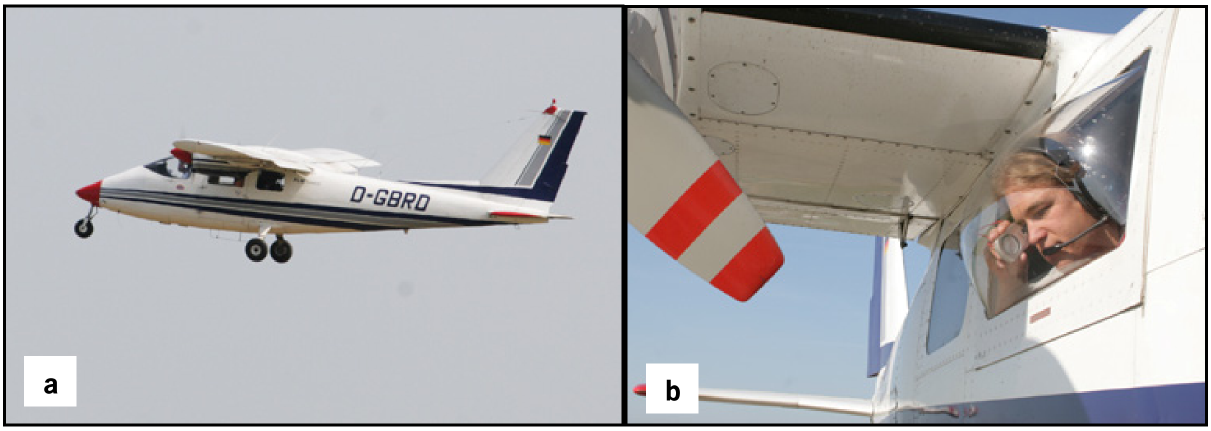


Figure 2: Overview of the study area C and study area D in Dutch waters. The dotted lines show the tracklines.

2.2 Survey Design and Data Acquisition

Surveys were following standard line-transect methodology for aerial surveys (Hiby & Hammond 1989, Buckland et al. 2001). In the study area C the first survey was conducted on 29th of November 2008 and the second survey was conducted on April 3rd 2009. Surveys were flown along a predetermined, systematic set of parallel transect lines with a random starting point, superimposed on the study area (figure 1). The direction of transects was in such a way to follow depth gradients, in order to minimize variance in encounter rate (Buckland et al. 2001). To ensure an adequate chance of harbour porpoise sightings, surveys were only conducted in weather conditions with good visibilities (> 3 km) and Beaufort sea state equal or less than 3. A complete survey for area C and D was planned for November 2008. During that time weather conditions were not good enough in the southern study area of D to complete this survey. In particular the presence of icy fog prevented safe flying and led to the abandonment of the survey. The survey attempt was repeated in early spring 2009 and the survey was conducted on 4th February, 18th March and 3rd April. The survey could not be completed during a shorter time frame (which would have been preferred) because of problems in obtaining a survey plane during the short windows of good enough survey weather.

Figure 3: Aerial surveys were conducted with a Partenavia 68. The high wings (a) allow a good visibility of the area under the plane. The plane is equipped with "bubble windows (b) allowing the observers to search the area under the plane.



The aircraft used was a high-wing two-engine Partenavia 68 (figure 3a), equipped with bubble windows (figure 3b), flying at an altitude of 183 m (600 feet) with a speed of 167 to 186 km/hr (90 to 100 knots). Data collection was based on the "VOR" software designed by Lex Hiby and Phil Lovell and described in Hammond et al. (1995). Every two seconds the aircraft's position and time (to the nearest second) were recorded automatically onto a laptop computer connected to a GPS. Sighting information and details on environmental conditions were entered by a third person, the data recorder. Sea state (according to the Beaufort scale), glare, cloud cover (parts of eight), turbidity (judged visually: 0 - clear water with several meters of visibility to 2 - very turbid water with no visibility under the surface) and subjective sighting conditions ("good", "moderate" or "poor") were entered at the beginning of each transect and whenever any environmental condition changed. Sighting data were acquired by two observers located at the bubble windows left and right of the aircraft (figure 3b). Sighting data included declination angle measured from the aircraft abeam to the porpoise group, group size, presence of calves, behaviour, swimming direction, cue and reaction to the survey plane. The perpendicular distances from the transect to the group were later calculated from aircraft altitude and declination angle.

2.3 Data analysis

During previous surveys conducted in German waters we used the "racetrack" method (Scheidat et al. 2005), which involves some doubling-back to re-survey previously flown transect segments for the estimation of total Effective Strip Width (ESW) (Burnham et al. 1980), including the detection probability of porpoises on the trackline (g(0)). Further details of the race-track method and the analyses are described in Hiby & Lovell (1998) and Hiby (1999). During the study presented here the observer team, methodology and the survey plane were consistent with the one used in the German study. Thus no racetracks were conducted and the g(0) values obtained from the German study were applied in the abundance calculations.

Only transects flown in "good" or "moderate" conditions were considered in the analysis. Animal abundance in stratum was estimated using a Horvitz-Thompson-like estimator and details on this method can be found in Scheidat et al. (2008) and is added as an appendix to this report.

Coefficients of variation (C.V.) and 95% confidence intervals (C.I.) were estimated by a non-parametric bootstrap (999 replicates) within strata, using transects as the sampling units. The variance due to estimation of ESW was incorporated using a parametric bootstrap procedure which assumes the ESW estimates in good and moderate conditions to be normally distributed random variables.

3 Results

3.1 Area C: November 2008 and April 2009

3.1.1 Effort and overview of sightings

Table 1 summarizes the overall effort as well as the effort on tracklines in area C during the November and April surveys. In November only 5 tracklines were covered due to difficult weather conditions. In April effort was higher and 7 tracklines were covered. Figures 5 and 6 give an overview of all sightings of cetaceans made during both surveys.

Table 1: Overview of effort and harbour porpoise observations during the November 2008 and April 2009 survey. Total effort includes transits between tracks or non-designated tracks.

Area	Survey	Total sightings	Total animals	Total effort (km)	Track sightings	Track animals	Track effort (km)	Number of tracks
C	Nov 29th 2008	39	45	459	36	41	411	5
C	April 3rd 2009	38	47	722	35	42	616	7

Total number of sightings and animals were almost identical between both surveys (table 1). However, survey effort was higher during the April survey than the November survey.

Average group size in area C was 1.24 animals in November and 1.15 in April, with a maximum group size of 8 animals in April. Figure 4 shows the distribution of group sizes for both surveys. No calves were seen during either survey.

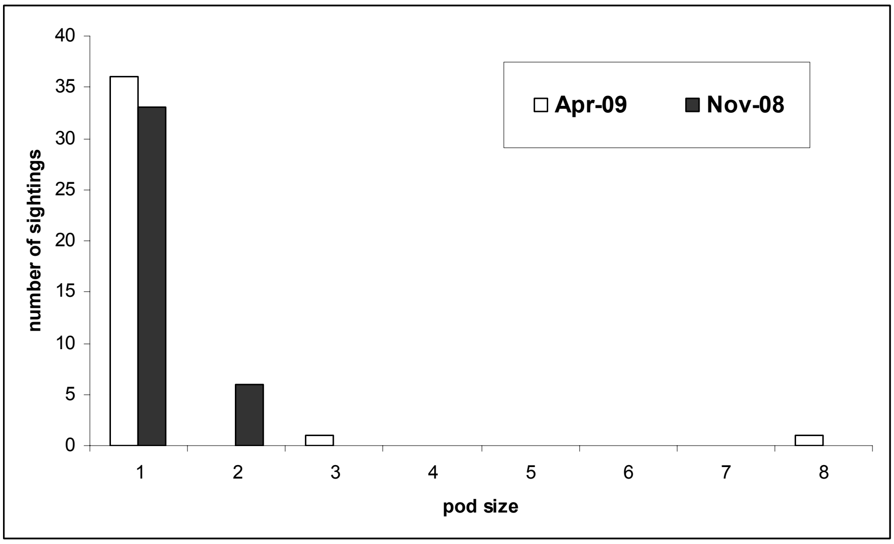


Figure 4: Group sizes of harbour porpoises sighted during the aerial survey in November 2008 and April 2009 in area C.

3.1.2 Distribution

Distribution of animals differed notably between the two surveys in the study area (figures 5 and 6). In November harbour porpoises seemed to be more evenly distributed over the study area with no obvious pattern visible. In April most harbour porpoises were sighted in the northern part of the study area close to the German border. Figures 5 and 6 show the distribution of all effort (on and off tracklines) as well as sightings.

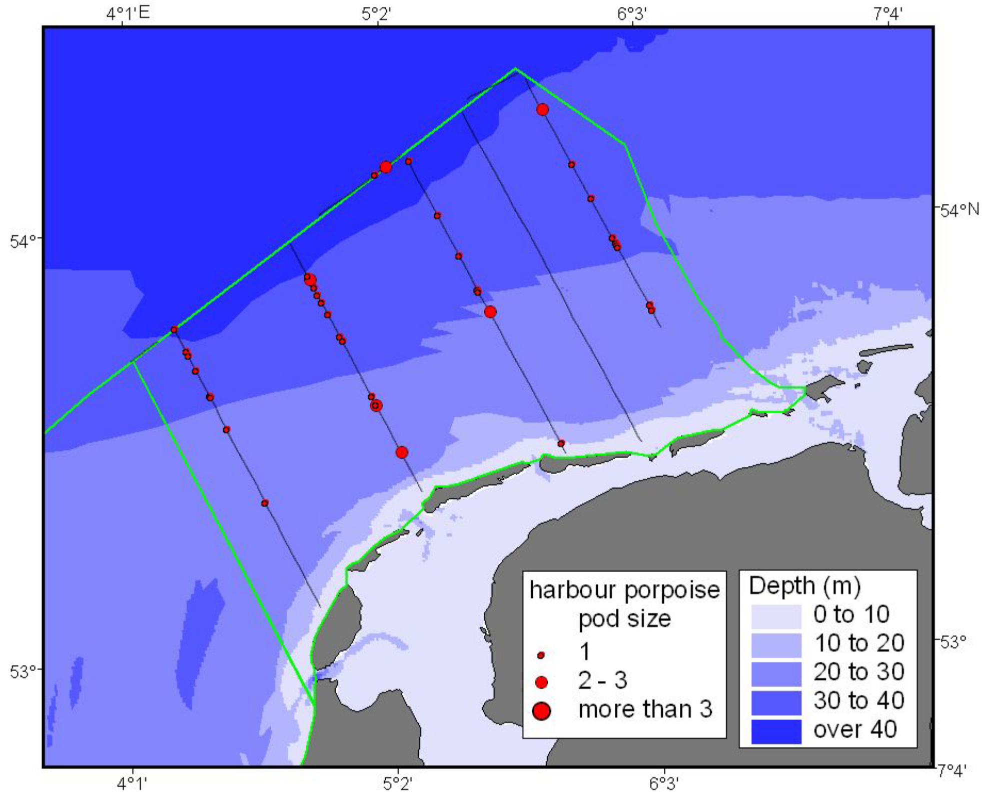


Figure 5: Overview of tracklines flown and harbour porpoises sighted during the November 2008 survey (November 29th) in area C.

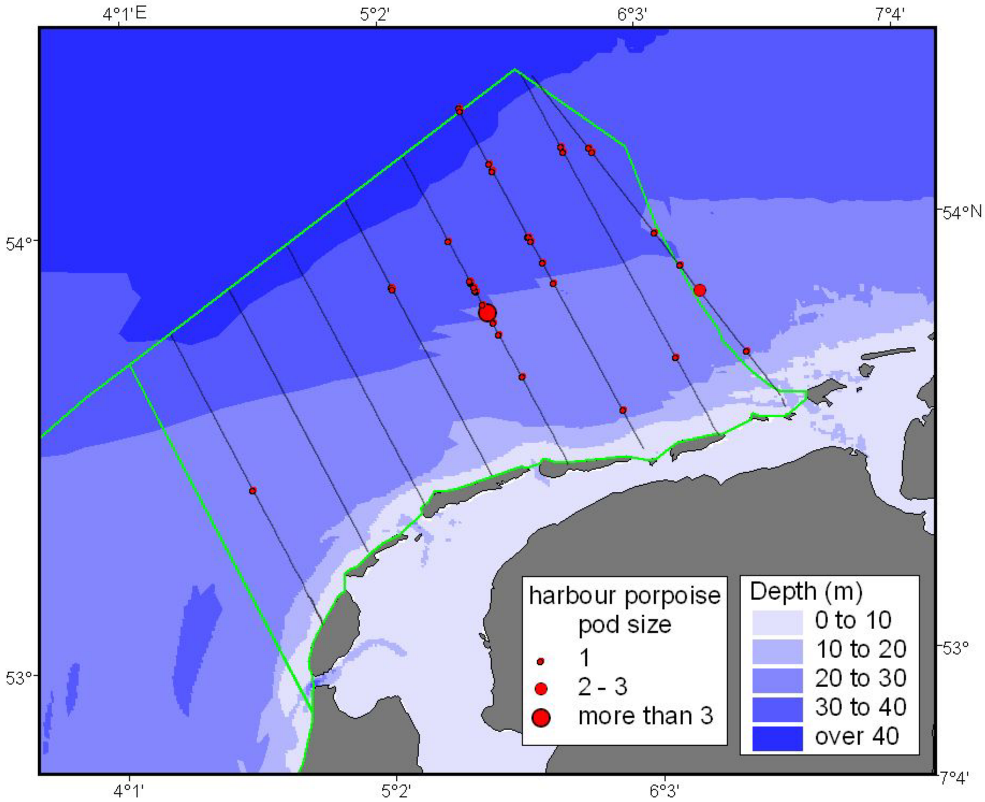


Figure 6: Overview of tracklines flown and harbour porpoises sighted during the April 2009 survey (April 3rd) in area C.

3.1.3 Density estimates

Density estimates could be made for area C for November 2008 and April 2009. Density was half as high in April as in November (table 2).

Table 2: Abundance and density estimates for harbour porpoises in the study area C for November 2008 and April 2009. Only survey effort under good or moderate conditions were included in the analyses. 95% Confidence Interval (C.I.) and Coefficient of Variation (C.V.) were calculated using bootstrap analyses.

Area	Dates of survey	Abundance (95% C.I.)	Density (95% C.I.)	C.V.
C	**29th November 2008**	**12 227** (4 038 – 25 285)	**1.02** (0.34 – 2.10)	0.42
C	**3rd April 2009**	**6 291** (1 366 – 15 159)	**0.52** (0.11 – 1.26)	0.53

3.2 Area C and D "early spring survey"

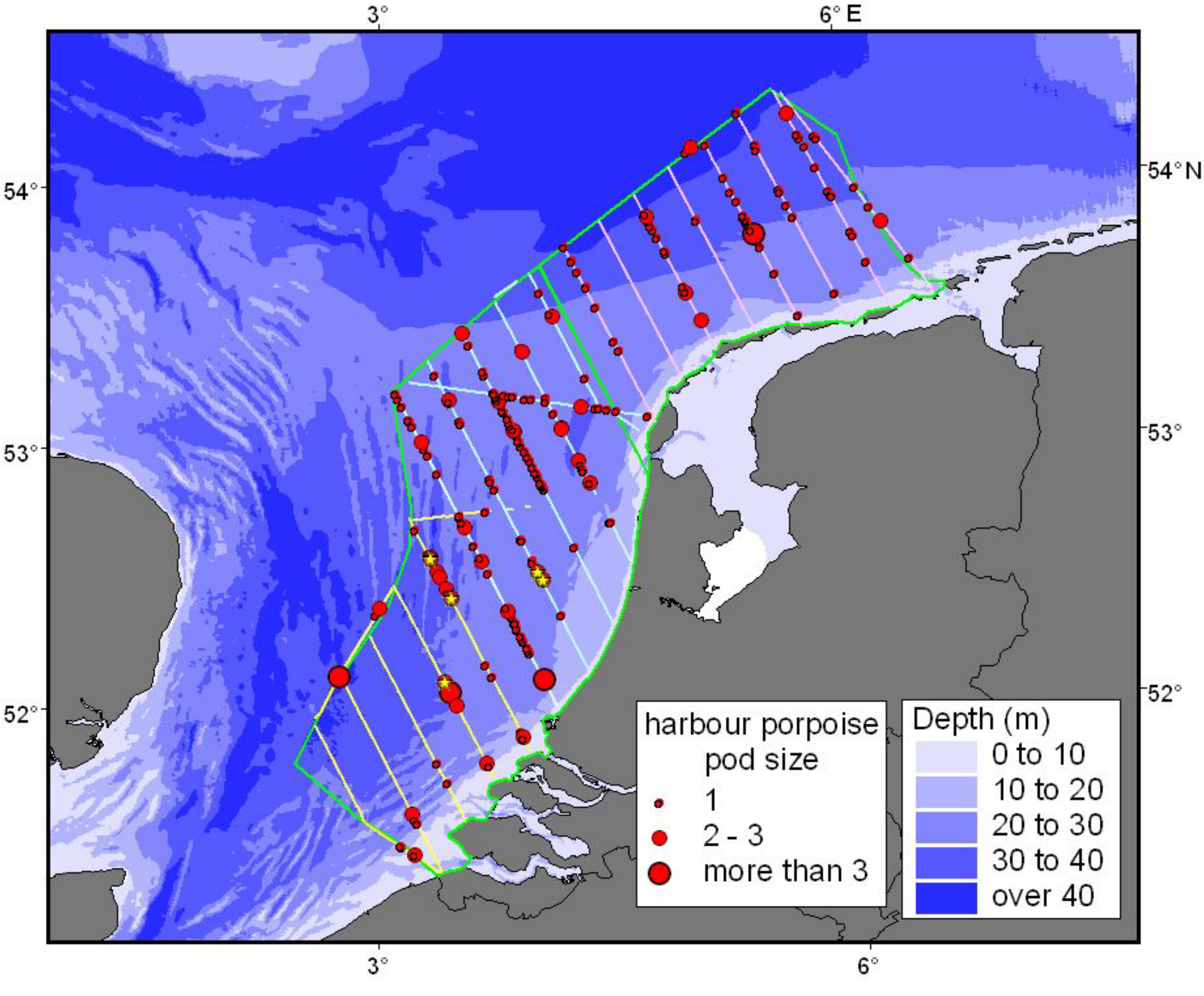
Effort and overview of sightings

Figure 7 gives an overview of all effort and all harbour porpoise sightings made during the "early spring survey" in area C and D. During the "early spring survey" (see table 3) a total of 2198 km were covered on effort. In total, during 202 sightings 252 animals were observed. Six sightings consisted of a mother calf pair (figure 7).

3.2.1 Distribution

Distribution of porpoises was not homogenous over the study area. High sighting rates of porpoises were recorded in the offshore waters of area D. All sightings of mother-calf pairs were made in area D.

Figure 7. Overview of tracklines flown and harbour porpoises sighted during the "early spring survey" 2009. Flown tracks are coloured in yellow (3rd February), blue (18th March) and pink (3rd April). Sightings including a calf are marked with in yellow. Map is projected as GRS80; UTM 1983 Zone 31.



3.2.2 Density estimates

For the early spring (3rd February to 3rd April) an overall estimate of density for area C and D was calculated together (table 3).

Table 3. Abundance and density estimates for harbour porpoises in the study areas C & D for early spring 2009. Analyses are based on tracklines covered on effort only. Only survey effort under good or moderate conditions were included in the analyses.

Area	Dates of survey	Abundance (95% C.I.)	Density (95% C.I.)	C.V.
C & D	**Early spring (03/02/09; 18/03/09; 03/04/09)**	**36 825** (19 090 – 68 130)	**1.12** (0.58 – 2.08)	0.33

3.2.3 Potential mortality limits

Worldwide a number of different approaches are used to calculate allowable annual anthropogenic mortality to cetacean stocks. Under the US Marine Mammal Protection Act the Potential Biological Removal (PBR) calculations are used (NMFS 2000), for the North Sea and adjacent waters the ASCOBANS recommendations are applied (ASCOBANS 2000). The PBR calculations vary with the amount of information available for this stock, including its conservation status. Based on only this one abundance estimate for harbour porpoises in part of the Dutch North Sea, we can not adequately judge the status of this stock. Therefore, a range of calculations were applied, ranging from the assumption of a "healthy well studied stock" to an "endangered stock" (table 4). The current estimates do not include the complete EEZ of the Netherlands. However, as far as is known, most anthropogenic impact (e.g. by-catch, offshore construction, shipping) occurs in the area surveyed and therefore, until more complete data is available, can be considered a useful management unit when calculating potential unsustainable mortality limits for harbour porpoises.

Potential Biological Removal

The analyses was conducted using the default guidelines for assessing marine mammal stocks in US waters (Wade and Angliss 1997), and are described as follows:

$$PBR = N_{\min} x 0.5 (R_{\max}) x F$$

Where F is defined as the maximum theoretical or estimated net productivity rate (default value for cetaceans = 0.04), R_{max} as the recovery factor, set to

a) 1.0 for a healthy stock (or "optimum sustainable"),

b) 0.5 for stocks with an undetermined status or threatened status,

c) 0.1 for endangered stocks (Wade and Angliss 1997, NMFS 2000) and N_{max} as the 20th percentile of a log-normal distribution surrounding an abundance estimate (equivalent to the lower limit of a 60% 2-tailed confidence interval) (Barlow et al. 1995):

$$N_{\min} = N / e^{(0.842 x (\ln(1+CV(N)^2))^{1/2})}$$

where N is the abundance estimate and CV(N) is the coefficient of variation of the abundance estimate.

ASCOBANS

The ultimate aim of ASCOBANS is to reduce anthropogenic removals to zero within a, yet to be specified, timeframe, and "to restore and/or maintain biological management stocks of small cetaceans at a level they would reach when there is the lowest possible anthropogenic influence" (ASCOBANS, 2000). However, a suitable and practical interim objective is to restore or maintain populations to 80% or more of their carrying capacity. In 2000, an annual by-catch of equal or higher of 1.7% of the estimated harbour porpoise population size was considered unacceptable and the immediate precautionary objective of ASCOBANS was stated as "the reduction of by-catch to 1% of the best available population estimate" (ASCOBANS, 2000).

Table 4: Overview of potential mortality limits for harbour porpoise in the Dutch North Sea applying different existing conservation aims

Values used for calculations		
N_{best} – point abundance estimate		36 825
CV - Coefficient of Variation		0.33
N_{min} (20th percentile)		28 092
R_{max} – maximum net productivity rate for cetaceans		0.04
F – recovery rates depending on status of stock		1.0, 0.5, 0.1
Application of different conservation aims and related mortality limits		
ASCOBANS "unacceptable"	1.7% of N_{best}	626
ASCOBANS "precautionary"	1% of N_{best}	368
PBR "healthy status"	0.5 x R_{max} x N_{min} x 1.0 (F)	562
PBR "uncertain status"	0.5 x R_{max} x N_{min} x 0.5 (F)	281
PBR "endangered status"	0.5 x R_{max} x N_{min} x 0.1 (F)	56

4 Discussion

Density and abundance

The results of this study show that the distribution and density of porpoises varies within the study area and between surveys. The estimated densities for Dutch waters range from 0.52 – 1.12 animals/km² and lie well within range of comparable studies from bordering areas like the southern German North Sea (Thomsen et al. 2006, Gilles et al. 2009) and large scale SCANS surveys (Hammond et al. 2002, SCANS II).

Data from Gilles et al. (2009) reveal that the highest densities in the German North Sea EEZ were obtained in spring with an overall density of 1.34 animals per km² and a density of 0.85 animals per km² in the area closest to the Dutch border (East Frisia). This corresponds well to the densities estimated in this study. The SCANSII survey provided the only porpoise abundance estimate available for the whole North Sea. Those data revealed that the total (North Sea) abundance of porpoises has not changed since the first SCANS survey in 1994. However, changes in the distribution of the animals were evident: the average density in survey blocks north of 560N was about half as high as in 1994, whereas for the survey blocks south of 560N the density was twice the one estimated in 1994 (SCANS II 2008). Hammond et al. (2002) estimated a density 0.09 individuals/km² for SCANS-block H (coast of Belgium, Netherlands, and Eastern Frisia) between June and July 1994. In 2005 during the SCANS II survey block H (with a reduced size covering the northern Dutch and German coast) a density of 0.36 individuals/km² was estimated (SCANS II 2008). In the Channel (SCANS area B) no animals had been sighted in 1994 but a density of 0.33 was estimated for 2005 (Hammond et al. 2002). These findings suggest increasing porpoise numbers in Dutch waters. They are supported by studies using stranding data indicating a comeback of harbour porpoises in the southern North Sea, most notably along the Dutch and Belgian coast (Camphuysen 1994, 2004). Additionally, the sea watching data set also evidently demonstrates that the increase in harbour porpoise sightings in Dutch coastal waters mentioned in Reijnders et al. (2005) continued (Haelters et al. 2004, 2008).
It should be noted that the density data obtained in SCANS I and II can not directly be compared with those from this study, because of the seasonality in porpoise occurrence. The SCANS surveys were done in summer and in this study in November and early spring.

Distribution patterns

The two aerial surveys conducted in the northern part of the study area (C) in November 2008 and April 2009 revealed that porpoises occurred more evenly distributed and in an overall higher density in November compared to April. In April the animals showed a patchy distribution with high local densities close to the German border. These results are supported by data from German aerial surveys conducted along the eastern German Bight (Scheidat et al. 2004). Estimates of density for the area of the eastern Frisian coast surveyed by Thomsen et al. (2006) between 2002 and 2004 ranged from 0.38 to 1.26 animals per km², with highest densities found during surveys conducted in March with 1.26 and 1.62 animals per km². During surveys between 2002 and 2006, Gilles et al. (2009) detected a re-occurring aggregation of porpoises in the area of Borkum Reef Ground, located in the southwestern part of the German EEZ, approx. 60 km offshore the East Frisian Islands. This aggregation could be observed from 2004 onwards and only during spring, thus supporting a patchy occurrence of porpoises in the southern North Sea during spring. Gilles et. al (2009) suggest, that porpoises move into German waters in early spring, reach high numbers in early summer and move out of the German waters in autumn. It is thus possible, that high densities in Dutch waters observed in November correlate with lower densities in German waters in autumn.

The Gilles et al. (2009) data further showed that the spatial distribution in German waters is not homogeneous. Harbour porpoises showed clear preferences for discrete areas and apart from Borkum Reef Ground (close to the Dutch border) another hotspot was identified around the Sylt Outer Reef. Teilmann et al. (2008) similarly identified high density areas in Danish waters. The Danish monitoring data showed that the highest densities were found in the southern part of the Danish North Sea along the German border. Also here hot spots were identified, with one close to the Danish Wadden Sea (Teilmann et al. 2008). The Danish data also showed a strong seasonality in sightings, with maxima in the summer period. The Dutch survey data shows several areas of high porpoise density. However, if these are consisted between years of seasons can only be determined with future survey work.

Application of results
For a more detailed picture of seasonal movements of harbour porpoises in Dutch waters, surveys on a monthly or at least 2-monthly basis over at least a whole year would provide valuable insights. In combination with the temporally and spatially explicit data from the German surveys, both data sets could possibly elucidate harbour porpoise seasonal movements in the southern North Sea. Data on the distribution of harbour porpoises in the southern North Sea is of great interest with respect to the observed density shift (SCANS II) and even more concerning recent by-catch events in Dutch waters. A patchy distribution and relative high numbers coinciding with locally high fishing effort could have lead to the observed high by-catch numbers in the winter months.

The south-eastern North Sea is an area with a wide range of human activities (Ducrotoy et al. 2000, OSPAR Commission 2000, Halpern et al. 2008). Various corresponding pressures on harbour porpoises have been identified, such as by-catch (Kock & Benke 1996, Vinther & Larsen 2004), prey depletion (Smeenk 1987), potential resource competition (Herr et al. 2009), noise (Simmonds et al. 2003) or habitat degradation due to chemical pollution (Siebert et al. 1999), causing presumably a Multi-factorial impact (Reijnders 1992). There is an indication that dense sea traffic and maybe especially the traffic separation zone in the southern North Sea influence the distribution of harbour porpoises (Herr 2009). During this study, while the aerial surveys where taking place close to the Dutch - German border, the building of an offshore wind park was under way (pers. comment A. Gilles). The distance to the construction site was only tens of kilometres and if and in what way the pile driving impacted the observed porpoise distribution in Dutch waters is not known. With the amount of anthropogenic activities going on in the North Sea it will be difficult to obtain true “baseline” information on where porpoises would be in the absence of disturbance.

Within Dutch waters several areas have been proposed as Natura 2000 sites (Anonymous 2005, Lindeboom et al. 2005, Bos et al. 2008). Reliable und unbiased information on porpoise distribution and seasonal movements is necessary to determine whether these areas are also important for the harbour porpoise. Aerial surveys also provide information on the occurrence of calves and as such give an indication of areas that are especially important for reproduction. During the flights in February and March 2009 a total of six harbour porpoise mother and calf pairs were sighted in study area D. It is most likely that these calves were born in the summer months of 2008. If this area is of special importance for reproduction can only be determined if surveys continue over a longer time period.
As porpoises are a wide ranging species, larger scale surveys in cooperation with adjacent countries such as Belgium and Germany would allow a better understanding of the movements and habitat use of porpoises in the southern North Sea. This is necessary to develop adequate management and protection measures for harbour porpoises in the future.

At the moment the most important anthropogenic threat of harbour porpoises is incidental by-catch in fishery (e.g. Reeves 2003, Reijnders 1992). Concerning Dutch North Sea waters there is currently no comprehensive information on the size of by-catch of harbour porpoise. This study provides the first unbiased abundance estimates for a large part of the Dutch North Sea for spring months. This now allows a preliminary calculation of what range of by-catch take can be considered unacceptable under the ASCOBANS agreement and unsustainable according to the PBR approach. The resulting numbers can guide future actions to determine the potential impact of fishery interactions on the Dutch harbour porpoise. When applying the ASCOBANS precautionary 1% level the potential removal levels would be 368 animals per year. Using the PBR approach for stocks with an uncertain status the resulting number would be 281.

Independent observer schemes are considered the only way to obtain reliable quantitative by-catch estimates (Northridge 1996, CEC 2002); recommendations for the design of monitoring schemes and for the best practices are given by Northridge (1996). At this moment we do not have a by-catch estimate for porpoises in Dutch North Sea waters. However, a minimum estimate of by-catch can be derived from strandings data. In 2006, stranding data revealed the, to this date, highest number of porpoises ever recorded. A total of 536 porpoises were found stranded on the Dutch coastline (Anonymous 2009), of which 62 were necropsied (ICES 2008). When the cause of death was identified, 57% of porpoises were considered to be bycaught (ICES 2008), amounting to 306 specimens in 2006. Considering that not all bycaught animals will be found on the beach, this number can only be considered a minimum estimate. Comparing this number with the calculated mortality limits it is clear that it is in the range of both the PBR and the ASCOBANS precautionary level. Given the preliminary survey data, the inter-annual variation in percent of porpoises bycaught and the unknown fate of porpoises bycaught in areas outside the surveyed area, this outcome has to be considered tentatively. Nevertheless, it demonstrates that the current by-catch levels are of great concern for the harbour porpoise stock occurring in Dutch waters.

5 Acknowledgements

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Appendix I

Detailled description of methodology adapted from Scheidat et al. 2008:

Survey design and data acquisition.

Surveys were carried out following standard line-transect methodology for aerial surveys (Hiby & Hammond 1989, Buckland et al. 2001). Surveys were flown along a predetermined, systematic set of parallel transect lines with a random starting point, superimposed on the study area. The direction of transects was following depth gradients, in order to minimize variance in encounter rate (Buckland et al. 2001). To ensure an adequate chance of harbour porpoise sightings, surveys were only conducted during good weather conditions with good visibilities (>3 km) and a sea state according to the Beaufort scale of ≤3. The aircraft used was a high-wing 2-engine Partenavia 68, equipped with bubble windows, flying at an altitude of 183 m (600 feet), with a speed of 167 to 186 km h–1 (90 to 100 knots). Data collection was based on the 'VOR' software designed by Lex Hiby and Phil Lovell and described in Hammond et al. (1995). Every 2 s the aircraft's position and time (to the nearest second) were recorded automatically onto a laptop computer connected to a GPS. Sighting information and details on environmental conditions were entered by a third person, the data recorder. Sea state (according to the Beaufort scale), glare, cloud cover (parts of 8), turbidity (judged visually on a scale of 0 [clear water with several meters of visibility] to 2 [very turbid water with no visibility under the surface]) and subjective sighting conditions ('good', 'moderate', or 'poor') were entered at the beginning of each transect and whenever any environmental condition changed. Sighting data were acquired by 2 observers located at the bubble windows left and right of the aircraft. Sighting data included declination angle measured from the aircraft abeam to the porpoise group, group size, presence of calves, behaviour, swimming direction, cue and reaction to the survey plane. The perpendicular distances from the transect to the group were later calculated from aircraft altitude and declination angle.

The aircraft surveyed using the 'racetrack' method, which involves some doubling-back to re-survey previously flown transect segments for the estimation of effective strip width (ESW; Burnham et al. 1980). The synchronous recording of GPS data, abeam times and declination angles allows the positions of pods sighted on the first and second sweeps of the plane ('overflights') to be calculated. When deciding which of the pods seen on the first and second overflights were duplicates, the likelihood of the observed positions can be maximised with respect to (1) the parameters of models for the distribution of intervals between successive pods; (2) the succession of a pod's near-surface and diving phases; (3) its horizontal displacement between the times it comes abeam of the first and second overflights; and (4) the probability of it being detected as a function of its perpendicular distance from the aircraft. However, as it is impossible to determine which pod sightings on the first and second overflights are duplicates, it is necessary to sum the likelihood over all possible pairings. Some of the sighting times from the 2 overflights are too far apart to be duplicates. The remaining sightings form groups within which pairs of sightings from the first and second overflights may or may not be of the same pod. A recursive code was used to generate all possible pairings of sightings within each group (including the special case of no duplicates at all). These arrangements form an exhaustive set of mutually exclusive events so that the probability for the observed sighting positions equals the sum of the probabilities for each possible arrangement. In this way we calculated the likelihood for the data on each section of the survey conducted under consistent conditions; the log likelihood for the entire survey was obtained as the sum of the log likelihood for each section. Further details of the racetrack method and the analyses are described in Hiby & Lovell (1998) and Hiby (1999).

Synchronous recording of GPS data and sighting conditions allows the sighting locations to be assigned to sections of effort completed under consistent conditions (good and moderate) and, hence, allows the estimates of ESW appropriate to those conditions to be applied to those sections. The large number of free parameters involved in estimating ESW meant that it was not possible to derive estimates for >2 levels of sighting conditions. Subjective assessment of 'good' and 'moderate' conditions, assessed separately to the left and right of the transect, was chosen to define the sections completed under consistent conditions.

Data analysis

Only transects flown in 'good' or 'moderate' conditions were considered in the analysis. Detection curves and estimates of ESW were found to be similar under similar conditions in different years, so aerial survey data from 2002 to 2006 were pooled to provide an estimate of ESW for good and for moderate conditions.

Investigation of possible school size-bias indicated that no such bias was present. The mean school size was therefore estimated using the mean of the observed school sizes separately within each stratum. Animal abundance in stratum v was estimated using a Horvitz-Thompson-like estimator as:

$$\hat{N}_v = \frac{A_v}{L_v}\left(\frac{n_{\mathrm{gs}v}}{\hat{\mu}_{\mathrm{g}}} + \frac{n_{\mathrm{ms}v}}{\hat{\mu}_{\mathrm{m}}}\right)\bar{s}_v \qquad (1)$$

where A_v is the area of the stratum, L_v is the length of transect line covered on-effort in good or moderate conditions, n_{gsv} is the number of sightings that occurred in good conditions in the stratum, n_{msv} is the number of sightings that occurred in moderate conditions in the stratum, $\hat{\mu}_{\mathrm{g}}$ is the estimated total effective strip width in good conditions, $\hat{\mu}_{\mathrm{m}}$ is the estimated total effective strip width in moderate conditions and $\bar{s}_v$ is the mean observed school size in the stratum.

Group abundance by stratum was estimated by $\hat{N}_{v(\mathrm{group})} = \hat{N}_v / \bar{s}_v$. Total animal and group abundances were estimated by

$$\hat{N} = \sum_v \hat{N}_v \text{ and } \hat{N}_{(\mathrm{group})} = \sum_v \hat{N}_{v(\mathrm{group})} \qquad (2)$$

respectively. Densities were estimated by dividing the abundance estimates by the area of the associated stratum. Mean group size across strata was estimated by $\hat{E}[s] = \hat{N} / \hat{N}_{(\mathrm{group})}$.

Coefficients of variation (CV) and 95% confidence intervals (CI) were estimated by a non-parametric bootstrap test (999 replicates) within strata, using transects as the sampling units. The variance due to estimation of ESW was incorporated using a parametric bootstrap procedure that assumes the ESW estimates in good and moderate conditions to be normally distributed random variables. For each bootstrap pseudosample of transect lines, a bivariate lognormal random variable was generated from a distribution with a mean and a variance–covariance matrix equal to those estimated by L. Hiby (pers. comm.), i.e.

$$\hat{\mu} = (0.153, 0.054) \text{ and } \hat{\Sigma} = \begin{pmatrix} 0.0452^2 & 0.000721 \\ 0.000721 & 0.0162^2 \end{pmatrix} \qquad (3)$$

This was used as the ESW for the pseudo-sample. The 95% CIs were calculated using the percentile method.

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The scientific quality of this report has been peer reviewed by a colleague scientist and the head of the department of Ecology of Wageningen IMARES.

Approved: Dr. O.G. Bos
Researcher

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