Impact assessment of an off-shore wind park on sea ducks

Magella Guillemette
Jesper Kyed Larsen
Ib Clausager

Department of Coastal Zone Ecology

Data sheet

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ABSTRACT

As part of the plan of the Danish government to expand off-shore wind energy production, The Ministry of Environment and Energy, in collaboration with ELSAM (an energy consortium), initiated a three-year study of the potential conflict between the Tunø Knob off-shore wind park and aquatic birds in 1994-97. Danish coastal waters support very large, internationally important concentrations of moulting, migrating and wintering sea ducks which depend on shallow water areas as major feeding habitats. Denmark is committed, in relation to international conventions and EU directives, to protect and maintain these populations of aquatic birds and such shallow coastal areas are precisely the type of areas in which future wind parks are planned.

Two general approaches were adopted for the investigation: the before-after-control-impact design (BACI) and *After* studies conducted around the wind park. The aim of the BACI studies was to compare bird abundance and distribution before and after the construction of the wind park and between the area presumably affected by the development and a control area. This was carried out on three spatial scales: *i*) conducting aerial surveys in two large zones (about 5,000 ha), Tunø Knob and Ringebjerg Sand, while controlling the total number of birds in Århus Bay (88,000 ha), *ii*) conducting ground surveys of two areas of about 700-800 ha coverage at Tunø Knob and Ringebjerg Sand, using the latter as a control area and (*iii*) within Tunø using three subareas (160-250 ha) as controls compared to the construction area. The *after* experiments were conducted around the wind park with the aim of controlling the confounding effect of food supply and to establish (a) the short-term possible effects of noise and rotor movements generated by the turbines on the distribution and abundance of sea ducks and (b) the long-term scaring effect of the wind park (the impact of revolving rotors and the presence of the standing towers). Finally, an experiment was conducted in order to quantify the scaring effect, if any, of the wind park on flying sea ducks.

The wind park is constructed on Tunø Knob, a shoal in Århus Bay, and consists of ten 500 kW turbines erected in 3-5 m of water during the late summer of 1995. All studies were carried out during the winter period, and results are reported for common eider *Somateria mollissima* and common scoter *Melanitta nigra* which composed 97.2 % of the bird numbers. The BACI investigations started in the winter before construction of the wind park (base line year = 1994-95), and extended to two winters after its completion (year 2 = 1995-96 and year 3 =1996-97). The main study period was February - April. In addition to counts and localisations of the birds on the study areas, aerial surveys were conducted to monitor the trends in regional bird numbers. Furthermore, the benthic community was sampled each year to assess variation in the potential food supply. The *After* investigations were conducted during the third winter from November to April, and focused on the area within 600 m of the wind park.

Eider numbers declined by 75% and common scoters by more than 90% at Tunø, from the winter prior to construction (base line) compared to the third year of the study. In contrast, eider numbers at Ringebjerg Sand and for the whole Århus Bay showed no decrease during the same period. Amongst common scoter, the pattern depicted for Tunø Knob only slightly deviated from that at Ringebjerg Sand. During the same period, the biomass of blue mussel *Mytilus edulis*, a favourite prey species, decreased from the base line year to the third year of the study with a marked difference between Tunø Knob and Ringebjerg Sand in the size available. This was associated with a general impoverishment of the whole benthic community. This suggests that the decrease observed in sea duck abundance over the three years was caused by the availability of food supply and not by the wind park.

Within Tunø Knob, eider numbers decreased markedly within the subarea which included the wind park from *Before* to *After* periods. However, a similar decline was observed in the three other subareas. Furthermore, detailed mapping showed a high degree of annual and seasonal variation in spatial distribution of eiders over the area which was not consistent with an effect caused by the wind park. These results suggest that the observed changes in abundance of common eiders in the wind park area were due to natural variation.

In one experiment conducted around the wind park, we used three groups of 30 decoys each at different distances from the wind park to test the impact of the wind park on flying eiders. It was found that rates of landing and flying were significantly lower 100 m from the turbines than at distances of 300 and 500 m. In a second experiment, switching the turbines on and off, no detectable effect of revolving rotors and noise on the abundance and spatial distribution of common eiders was found. This was supported by another set of observations showing that 10 flocks of eiders within 600 m of the wind park did not take off and did not swim away when the turbines were switched on again. In a third experiment, food abundance and eider exploitation over the entire winter were determined for four experimental quadrates (4 ha each) positioned at different distances from the wind park (from 0 to 600 m). The data showed that more than 92% of the variation in common eider numbers in these quadrates could be accounted by food supply. This result alone suggests that the turbines had no effect on the exploitation of food resources around the wind park over a long time scale (a whole winter).

In summary, the decline in the number of common eider at Tunø Knob could not be attributed to the presence of the wind park as no effect of the wind turbines could be detected on the abundance and the distribution of that species. Indeed, the results of benthic surveys suggest that, at intermediate spatial scale, the observed changes in the abundance of eiders were driven by natural variations in the food supply. Since the probability of a negative impact decreases with increasing distance from the wind park, the above interpretation is further supported by the experiments conducted in the immediate vicinity of the wind park. Altogether these results should, however, be used with caution because flocks of eiders were small during that study and it is known that sensitivity to disturbance increases with

flock size. Finally, the present study did not address all aspects of the potential conflict between bird life and off-shore wind parks. Further information is needed about (1) other periods of the annual cycle (especially moulting), (2) the effect on other species, (3) the risk of collisions under varying weather conditions, (4) the effect of disturbance from maintenance ships and (5) the effect of large scale wind parks.

ACKNOWLEDGEMENTS

1 INTRODUCTION

In its most recent energy plan, Energy 21, the Danish government has confirmed and maintained its national goal to reduce CO_2 emissions and at the same time promote the development of sustainable energy production by the use of renewable energy sources. The goal is that renewable energy sources shall provide 12-14% of the Danish energy demand in the year 2005 and about 35% in the year 2030. This development of renewable energy sources is based mainly on wind power. In acknowledgement of the increasing difficulties in finding locations on land, reinforced by the development of larger turbines, the major part of the expansion is expected to take place off-shore. It is planned that off-shore wind parks shall be set up with an installed capacity of 4,000 MW by the year 2030. This requires that between two and three thousand turbines will be erected in Danish waters. These turbines will be distributed over four large areas and will be erected in shallow waters (< 10 m) (EEAH 1997).

The environmental impact most often reported in relation to wind parks is the bird problem (Gipe 1995). Danish coastal waters support some of the largest concentrations of moulting and wintering sea ducks of the world. Between one and two million sea ducks may be counted in winter and about half a million during the moult period (Pihl et al. 1992, Laursen et al. 1997). Apart from sea ducks, large numbers of divers, grebes, mergansers and alcids can also be found. Denmark is committed to protect and maintain these populations of waterbirds under the international agreements, the EU bird protection directive and the Ramsar convention. While Danish waters undoubtedly are of international importance for sea ducks, most of these species use shallow waters for feeding (Nilsson 1972, Stott & Olson 1973, Goudie & Ankney 1986, Guillemette et al. 1993, Bustnes & Lønne 1997) which apparently is related to the fact that highest food biomass are found in shallow waters in the northern hemisphere (reviewed by Guillemette et al. 1993). Therefore, the potential for conflict between the future development of off-shore wind parks and populations of wintering and moulting sea ducks is a genuine concern.

Midtkraft, an energy power company, in collaboration with ELSAM, an energy consortium, built an off-shore turbine park about 400 m north of the Tunø Knob reef in summer 1995. The park is composed of ten turbines of 500 kW each erected within the 3-5 m depth range. Tunø Knob is used mostly by sea ducks as a moulting and wintering area, the common eider *Somateria mollissima* and the common scoter *Melanitta nigra* being the most important bird species (Joensen 1973, NERI unpublished data). In order to investigate the impact of such industrial development, the National Environmental Research Institute of Denmark (NERI) in collaboration with ELSAM and Midtkraft started a three year study in February 1995. The null hypothesis was that this wind park would not influence the abundance, distribution and behaviour of these marine birds.

In this study, our aim was to quantify the potential impact of the Tunø Knob wind park on sea duck abundance and distribution in winter. This report is composed of three main parts, the before-after-control-impact (BACI) experiment where (1) Tunø Knob (TK) and Ringebjerg Sand (RS) areas are compared, where (2) the construction area and three subareas are compared within TK and finally (3), a set of three experiments conducted around the wind park. We followed a 'naive' approach in the sense that we started to look at the problem from a large spatial scale (Århus Bay, TK and RS), an intermediate (within TK) and then a small (around the wind park) scale. The BACI study was conducted on two species of sea ducks for which sufficient data on abundance and distribution were obtained by (i) aerial surveys and (ii) ground surveys. We also conducted (iii) benthic surveys to follow the abundance of food in order to find out whether this factor could have a major influence on sea duck abundance and distribution. Within TK we compared data for the Before and *After* period for four large subareas (one including the wind park). The experiments conducted around the wind park included (a) the on-off experiment investigating the impact of revolving rotor and noise on the spatial distribution and abundance of eiders, (b) the exploitation experiment designed to exclude the effect of food supply from our analysis and to measure eider distribution on a winter basis in relation to the wind park and finally (c) the decoy experiment looking at the scaring effect of the turbines on flight paths and landing frequency of eiders. Note that a Danish summary of the results can be found in Guillemette et al. (1997).

2 CONCEPTUAL APPROACH

In many environmental impact assessment studies, a before-after comparison of the (potential) impact site is made. In this case, the null hypothesis is that no impact occurs and that no difference in the abundance (or any other variables) of a species, comparing the Before and *After* periods, will be observed. A rejection of that null hypothesis leads to two alternative possibilities: the abundance of that species is increasing or decreasing under disturbance. This design is not very powerful given that natural variations in abundance may occur (it could be seasonal or between-year or even cyclic with phases of 5-20 years) at the putative impact site. Thus the presence or absence of a difference between Before and *After* periods can be due solely to these variations and confound any potential impact that may occur. This problem can be addressed by using a control area where it is known that no impact occurs. Such natural variation would probably appear in the control area and one could conclude that the observed difference is not caused by the industrial perturbation. This design, the before-after-control-impact (BACI) study was first proposed by

Green (1979). In our study, the presumed impact site is TK and the control area is RS.

Some years later, Hulbert (1984) criticised that design on the basis that the control site would need to be very similar to the impact site in order to come up with a sound conclusion. This is because that any difference in abundance between the impact and the control sites could be explained by *a priori* differences in the two sites and that no causal relationship of presence/absence of an impact could be derived from this design (note that a similar statement can apply for *a posteriori* differences). In the case of sea ducks, the abundance of food has been shown to be the determining factor in explaining their distribution within and between habitats (Guillemette et al. 1993, Guillemette & Himmelman 1996). Benthos density and biomass may well differ naturally between the impact and the control area because, for example, recruitment probability of prey would be associated with some physical factors that differ between the sites or alternatively, the level of predation differed between the two areas. If such differences occur, food will tend to be higher or lower at one site in some years and the abundance of the target species will follow accordingly. In our study, we measured food supply (benthos) at both sites for the three years of the study. Thus if any differences between the control (RS) and the presumed impact area (TK) appear in this respect, the final conclusion should be framed accordingly.

The criticisms of Hulbert (1984) about the BACI design were convincing and that is probably why a burst of conceptual work followed. Stewart-Oaten et al. (1986) argued that Green's design was not completely flawed and suggested that if the control and the impact site are sampled repeatedly in time during Before and *After* periods and simultaneously at both the control and the impact sites, then one could infer with confidence some causal relationship from this design. The crucial step here is that they proposed to get an estimate of this natural variation by sampling repeatedly and by looking at the trajectory of the *difference* between sites in the abundance of the target species. In our study, the abundance of sea ducks were sampled repeatedly during the base line year (1994-95) and during the *After* period (1995-96 and 1996-97) and we tried to sample both sites simultaneously.

Although the proposal of Stewart-Oaten et al. (1986) was a major step in the right direction (in terms of being able to detect impacts if any), the BACI design can be considered a quasi-experiment in the sense than neither the control nor the putative impact site are replicated under this design. Although replication in time may record the variability of the system under investigation, it needs many independent measures which may require several years of base line data. This is incompatible with the constraints of time and finance usually associated with impact assessment studies. Of course, it is virtually impossible to replicate the presumed impact site but there is no reason (apart from the logistics of such a task) not to replicate the control sites (Underwood 1992, 1994). Strictly speaking, control areas should be chosen randomly in order to fulfil the assumptions of inferential statistics. In this study, we divided the TK area into four different sectors, one including the wind park and three others that were used

as 'controls'. These three 'sister control' areas were not chosen randomly and are probably not independent from each other. However, they probably share similar oceanographic and biological features with the putative impact area simply because they are adjacent to it. Therefore, these subareas should show some similarity with the presumed impact area which is suitably characteristic of a control area (Hulbert 1984). Clearly, the requirements of similar (to the impact area) but randomly selected control areas are incompatible.

With the information gathered after the second year of the project, we felt that results of the BACI design would be difficult to interpret and we designed three other experiments in order to complement our approach. It is very likely that the abundance of food may be a major confounding variable of the system under study. Thus disentangling natural variability from any impact of the wind park is difficult unless we control for this variable in our investigation. One possible way is to randomise the possible effect of food supply by applying treatment and control conditions to the same area. We did so with the on-off experiment where the wind turbines were switched off (= control) and switched on (treatment) alternately. We thus compared for each condition the abundance and spatial distribution of common eiders. This experiment was complemented by another one called the flock experiment in which we observed the behaviour of a group of eiders when the turbines were switched on again after being stopped for one day.

The second possible approach to get rid of the confounding effect of food supply is actually to measure this parameter and use this information in the analysis. To do so, we used one prediction of the ideal free distribution theory stating that the proportion of birds in one area should be equal with the proportion of available food in that area (hereafter called the habitat matching rule). A detailed account of this approach and its application to sea ducks is presented elsewhere (Guillemette & Himmelman 1996). Our rationale was that any departure from the value predicted by the amount of biomass measured in areas located at varying distances from the wind park should be related to the presence of the wind turbines.

Finally, the experiments presented above are looking solely at the possible impact of the wind park on the distribution and abundance of sea ducks. Eiders generally fly every morning and, to a lesser extent, during the day, to locate suitable areas for feeding. It is only during flying that eiders are prone to collisions with wind turbines. We looked at this problem using their natural attraction to conspecifics and patches of decoys located at different distances from the wind park for which we measured the frequency of landings and flying birds.

3 METHODS

3.1 Study sites

TK and RS are located in Århus Bay (ÅB) about 14 km from each other (Fig. 1). TK is located 3 km west of Tunø island and 6 km from the mainland and is characterised by sandy, muddy and gravel bottoms. The choice of a control area was based on a correlation analysis in sea ducks abundance between TK and six other areas and logistical constraints. Since sea ducks abundance at RS, which is easily accessible by ferry (Fig. 1), was highly correlated with abundance at TK, this site was chosen as the control area.

3.2 Description of the wind park

The wind park was built during summer 1995 some 400 m north of TK. The park is composed of ten 500 kW turbines arranged in two
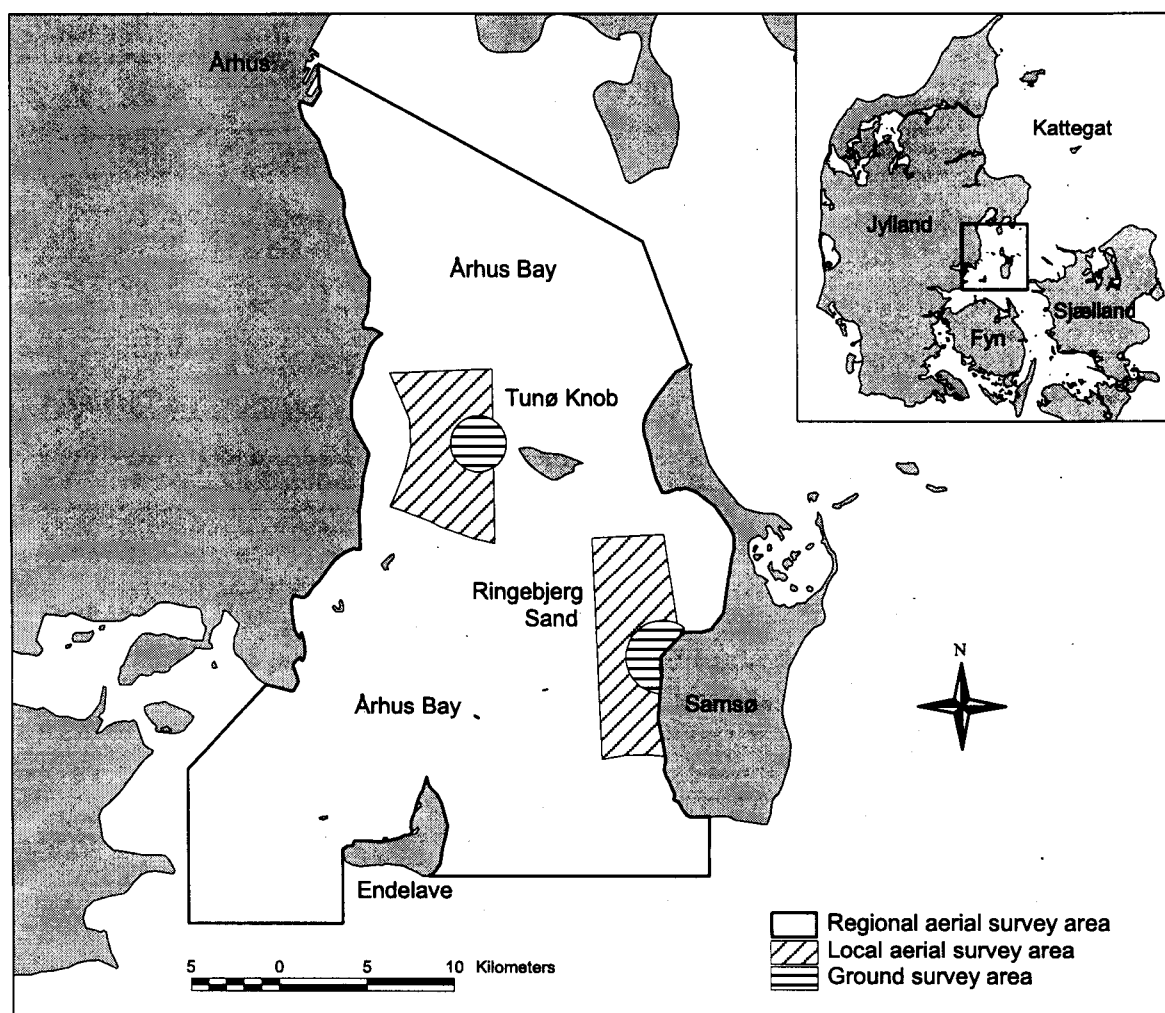
Figure 1. The region covered by aerial and ground surveys in this study. The region referred to as Århus Bay (ÅB) in the text includes all the area within the thick line. Both Tunø Knob (TK) and Ringebjerg Sand (RS) areas were covered by aerial and ground surveys as shown on the map.

rows facing north-south. The distance between the turbines and the rows is 200 m and 400 m respectively and they are located between three and five m depth. Each turbine was erected on foundations of the box caisson type made of reinforced concrete of about 100 m² area and weighing approximately 1,000 tonnes (Madsen 1997). Each tower of 40.5 m height is mounted with a 19.5 m diameter rotor (total height = 60 m) giving a total swept area of 1,195 m². Finally, these turbines can be switched off and on from a remote control centre using radio communications.

3.3 Data collection

3.3.1 Aerial surveys

The methodology of aerial surveys followed the method described by Laursen et al. (1997). The aeroplane used was a Partenavia P-68 Observer flying at 250 feet above sea level at a speed of 90 knots. Two observers, one located in the co-pilot seat and the other one behind the pilot seat, estimated bird numbers visually for each species and the time of observation. Since each observer was recording from each side of the aeroplane, both counts were summed to obtain the total number of birds present in one area. The flying route was determined in such a way to cover the area completely and to minimise double counting of birds during a survey. We covered the whole ÅB region from Århus to the island Endelave (Fig. 1) by flying linearly between fixed points using global positioning system. For all flights, the same route was followed and the position of the plane between two points were estimated using the (constant) flight speed of the engine and by recording the time lapse from the last reference point. Using this approach, we were able to determine the positions of each flock of birds with each of the sub-regions considered in that study. The area covered by aerial surveys at TK was about 5,000 ha and about 4,700 ha for RS (Fig. 1).

3.3.2 Ground survey and spatial distribution of sea ducks

Distribution of birds was determined by conducting censuses from a large (wet) tower standing on the bottom of the sea at a depth of about three metres in the TK area and, from one (dry) tower located on the shore of RS (Fig. 2). The surveys started during mid-February 1995 and ended during mid-April 1995 during the base line year and this period will be refereed to as the 'study period' used in our comparison with 1996 and 1997. Since benthos surveys (see below) were conducted in November and thus preceded each study period, we are using the following writing convention: 1994-95 as the base line year or *Before* period and 1995-96 and 1996-97 as the *After* period. In addition to these periods, ground surveys were conducted in November-December 1995 (second year of the study) and from September 1996 to mid-February 1997 during the third year of the study. Finally, we tried to conduct surveys in a concomitant manner from TK and RS. The study area at TK includes all the area from the observation tower within a circle of 1.6 km radius (804 ha) and half-circle at RS of 2.1 km radius (693 ha, Fig. 1).
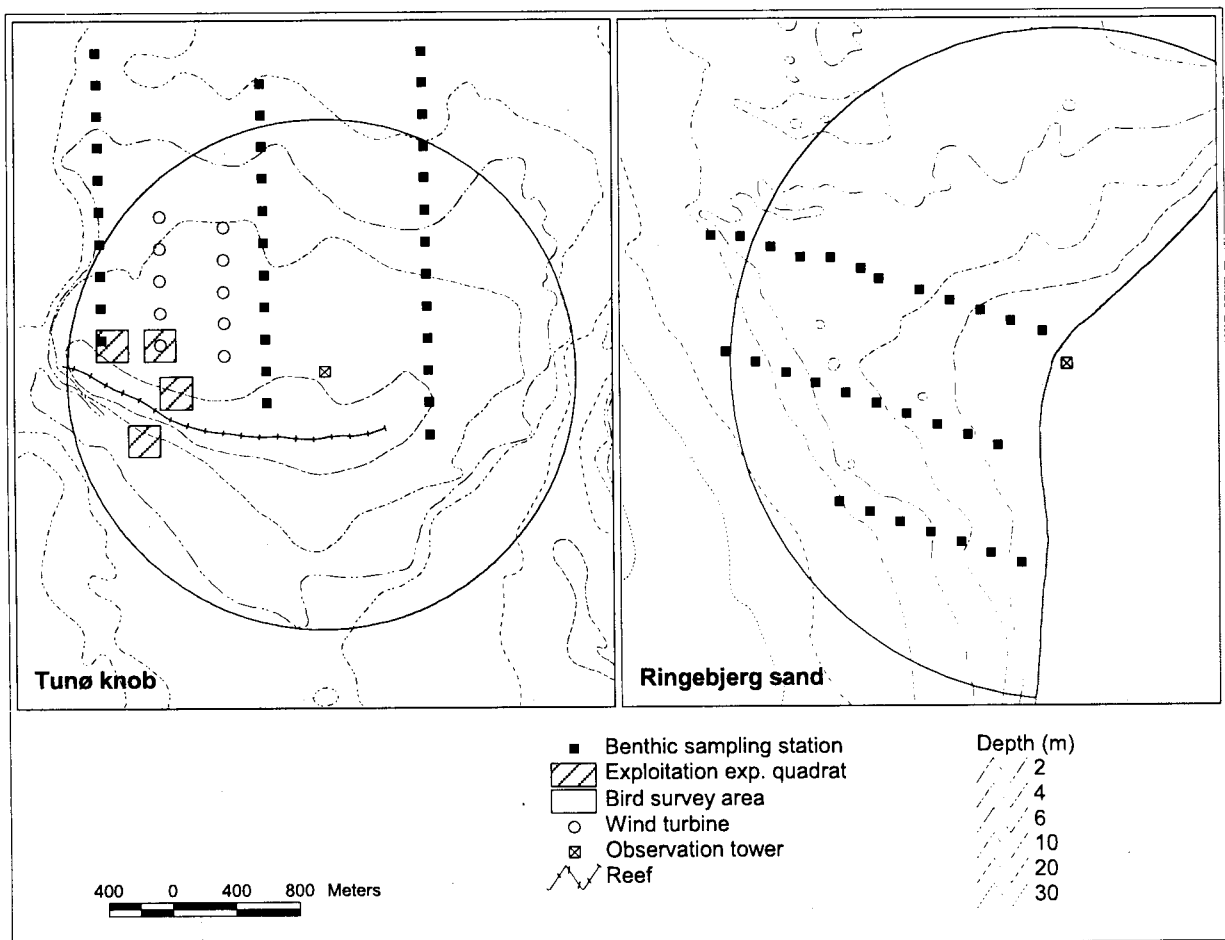
Figure 2. Location of observation towers and benthic sampling stations used for Tunø Knob and Ringebjerg Sand. Note for Tunø Knob the location of four 200 x 200 m quadrats used for the exploitation experiment.

Every flock was localised with the aid of a laser binocular (Zeiss Halem II) or a military range-finder and with a compass binocular. The laser binocular was used at TK only and allowed distance estimates of flocks with an accuracy of 5 m. In flocks of less than 100 birds, birds were counted individually, whereas the number of birds in larger flocks were estimated visually by counting subsets of either 10 or 100 individuals within the flock. Position of the flocks was plotted on a grid system composed of 100 m^2 squares using GIS. At TK, the study area was divided further in four different sub-areas (NW, NE, SW and SE) using the reef and the observation tower as the dividing marks.

3.3.3 Benthic surveys

We measured the abundance of benthos in the study because food is the major factor explaining the distribution and abundance of eider ducks in winter (Guillemette et al. 1993, Guillemette & Himmelman 1996). The benthic fauna of the presumed impact site (TK) and the control site (RS) was described and quantified using transect sampling. These transects were laid out for each site perpendicular to the coasts using DGPS (Fig. 2). Stations were marked with orange buoys at 200 m intervals along the transects lines. The same stations were

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used during the three years of study. At each station, a SCUBA diver reached the bottom with sampling bags, a writing pad, a depth recorder and two (20 cm x 20 cm) metal frames. On the bottom, the diver placed the two frames always in the same position in relation to the anchor (of the buoy) position. Information on water depth and brief descriptions of substrate types was recorded for each quadrate before any digging activity took place. Then the diver dug out all the benthic organisms (down to 15 cm) present in a quadrate of 0.04 m^2. All benthic organisms were sampled in November 1994 and November 1996. In November 1995, samples were collected only when blue mussels were present in a quadrate. Each sample was placed in a plastic bag and frozen for later analysis.

In the lab, each sample was thawed and sorted according to the different species present. For each species, the number of individuals present in one sample and the total wet mass (to the nearest g) was obtained. The length of all individuals present in a sample was measured to the nearest mm with a ruler with the exception of *Mytilus* where about 10% of all individuals found in one sample (excluding mussels less than 3 mm in length) were measured. Sub-sampling was conducted by homogenising the sample and mixing all sizes of mussels evenly in the tray (although for most samples, large mussels were not present with small mussels). The content was divided into 20 equal parts of which 2 were drawn at random and measured. In order to report the biomass for different size categories of blue mussel, we multiplied the total number of individual mussels by the proportion of each size class of one mm increment in size. The biomass of each size class b_i was obtained by estimating the mass of each size class from an equation relating size and weight. The linear equation relating the total wet mass (in g) of an individual mussel with its length (mm) expressed as a power function is BIOMASS = -9.511 LENGTH $^{3.072}$. Finally, the biomass of each size category was obtained by summing all b_i pertaining to three size categories, 3-15 mm, 16-40 mm and > 40 mm.

No data on the food eaten by common eiders was collected in the course of the study. From the literature we know, however, that common eiders and sea ducks in general are benthic predators which means that they are consuming molluscs, echinoderms and crustaceans. Extensive investigations have shown that the main prey of eiders and scoters are molluscs (Cottam 1939, Madsen 1954, Guillemette et al. 1992). In the Kattegat 85% of the 261 common eiders collected by Madsen (1954) had consumed molluscs of which 69% had consumed the bivalve *Mytilus edulis*, (the blue mussel or for some authors the common mussel) whereas 22% had consumed bivalves of genus *Cardium*, *Mya* and *Spisula*. Amongst the common scoters 96% of the 219 individuals collected by Madsen (1954) in the Kattegat had ingested molluscs. The blue mussels was found in 51% of the scoters collected while the frequency of occurrence for other bivalves like *Cardium*, *Mya* and *Spisula* was 43%, 8% and 7%, respectively.

3.3.4 On-Off experiment

In order to disentangle the impact of revolving rotor from the standing towers, we performed an on-off experiment. In this case, the

treatment was when the turbines were operating and the control was when they were stopped (although a slight movement of the rotor was observed even when turbines were off). The experiment involved two observers alternating regularly and operating from the wet tower. Based on the fact that eider abundance was higher during mornings than during afternoons in 1996-97 and that numbers from one survey tended to be correlated with adjacent surveys (see below), we used the following design. The treatment and the control were always compared on *adjacent* days (dates following each other) and during the same part of the day (e.g. mornings were compared with mornings).

3.3.5 The exploitation experiment

The idea of this experiment was to test the potential impact of the wind turbines on a long term basis (a whole winter) and to get rid of the confounding effect of food supply by measuring it. To do so we positioned, during the winter 1996-97, four quadrates of 200 m x 200 m each at different distances from the turbines (0, 300, 320 and 600 m) within which we recorded the number of eiders and the amount of food present. If the wind turbines have a scaring effect we should observe, for the quadrates closest to the turbines, a lower proportion of birds than predicted by food biomass.

We faced two major constraints in relation to positioning the quadrates. The first one was to keep all quadrates in the same type of habitat, in this case a sandy substrate. This type of habitat was limited and occurred in very shallow waters (< 3-4 m) which made it difficult to position quadrates at systematic distances from the turbines. The other constraint was the reef itself which precludes an orthogonal arrangement (Fig. 2). We used a DGPS to position 12 stations of 6 samples each within each quadrate (72 samples per quadrate). Each sample was obtained with the aid of a core sampler of 95 cm^2 mounted on a 3 m long pole in order to obtain the samples from the surface. The sampling was carried out on October 22 1996 and repeated on April 24 1997. All eiders present in the experimental region over the winter were counted and localised as described above.

At the beginning of that experiment we did not know the prey upon which the eiders were feeding in this habitat. We first used the difference in biomass between fall and spring to infer the type of prey eaten by eiders. The bivalves were the main species found in terms of density and biomass varying between 195 g/m^2 on average for quadrate 1 to about 25 g/m^2 for quadrate 3. The second most important group, the polychaetes, never exceeded 25 g/m^2 on average. Differences in biomass between fall and spring were apparent for all quadrates for the bivalves but were found to be significant only in quadrate 1 and 4. Within the bivalves, the most important available prey in terms of biomass were *Spisula* and *Cardium* sp. while the other species had negligible biomass at the beginning of the winter. Paired t-test showed that biomass of *Spisula* differed significantly for quadrate 1, 3 and 4 whereas for *Cardium* a significant difference was found in quadrate 1, 2 and 3. No significant difference was found between fall and spring for the other species of bivalves. Finally, information collected about the diet of common eiders wintering in the Kattegat sea

in the 1950s (Madsen 1954) and during the late 1980s (NERI unpublished data) indicates that *Spisula* and *Cardium* were frequent prey species. We thus concluded from this analysis that *Spisula* and *Cardium* were the prey eaten by eiders when diving within the four experimental quadrates.

3.3.6 The decoy experiment

The decoy experiment was performed in order to find out if common eiders were scared by the wind park when flying and landing. In this experiment, we used the fact that turbines represent a (potential) concentrated source of disturbance and the fact that common eiders are highly attracted by conspecifics. We thus used two lines of decoys positioned in a perpendicular fashion from both sides of the wind park. Each line was composed of three groups of 30 decoys each (15 males and 15 females) positioned at 100 m, 300 m and 500 m from the wind park (see Fig. 3).
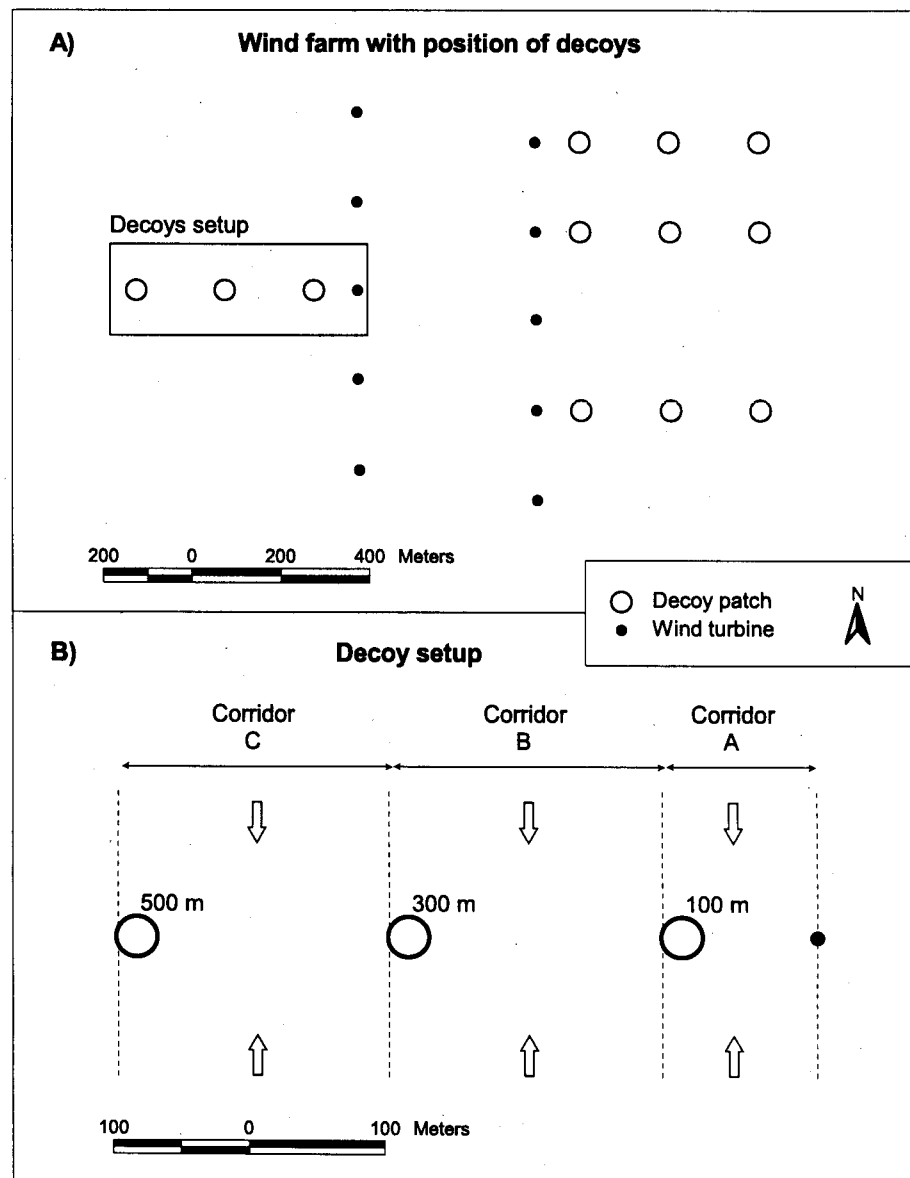

Figure 3. Experimental set-up for the decoy experiment. A) Positions of decoy lines (composed of three groups of 30 individuals each) used in the experiment. Note that three line positions were used on the eastern side of the wind park whereas only one position was used on the western side. B) Decoy set-up and flying corridors used in the experiment.

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Each decoy was made of robust plastic simulating a male common eider in nuptial plumage or an adult female. We recorded three types of behaviour during the experiment: flying birds which consisted of individuals flying at a constant speed and height and not showing any interest in the decoys, birds attempting to land i.e. birds which decreased their speed and/or showed flight manoeuvring toward the decoys patch but did not land, and landing birds which consist of birds who have landed in the vicinity of the patch. The landing birds did not change the experimental conditions (e. g. 30 birds in each patch) by increasing the numbers of individuals inside a group-patch because in almost every case, individuals flew away few seconds after they landed. Finally, we grouped birds attempting to land and landing birds under reacting birds for the analysis.

The observations were conducted from the slightly elevated (2 m) wind turbine base in line with the three group of decoys. An observer watched the three group-patches simultaneously and every focal bird or flock of birds was recorded and ascribed to a patch or a corridor. Not all the birds within the experimental set-up could be recorded because each flock of birds had to be followed until a clear response was obtained and frequently many individuals or flocks would fly fast in close succession to each other. The observer instead picked-up a new flock as soon as he was finished with the current focal flock. In the case of flying birds, individuals were ascribed to a flying corridor of 200 m width except for the corridor A which was 100 m wide (see Fig. 3). The recording of flying birds versus birds attempting to land and actually landing was an attempt to discriminate the mechanism involved in the observed differences.

3.4 Data analysis

This section is divided into four parts dealing with (1) two important assumptions of the statistical tests, the BACI experiment where (2) TK and RS are compared, (3) the construction area is compared with three sister subareas and, finally, (4) experiments performed around the wind park. For all statistical tests performed in this study, we used an alpha value of 0.100 as the significance threshold.

3.4.1 Assumptions of the statistical tests

Using the BACI design, we planned to use the analysis framework proposed by Stewart-Oaten et al. (1986) to detect if any impact occurred in our study. In short, this method tests for difference in delta's comparing Before and *After* periods, an observed delta being defined as the simultaneous difference (requiring that both sites are sampled at the same time) between the presumed impact and control areas. Usually, a t-test is used in order to test the null hypothesis of no impact. Alternatively, an ANOVA can be used for more complicated design. One assumption that needs to be fulfilled, when using this family of statistical models, is to check if the effects are additive (Stewart-Oaten et al. 1986, Stewart-Oaten et al. 1992). A second assumption that needs to be fulfilled for all the statistical tests used in this report is that the samples are independent from each other. We

checked these two assumptions for the common eider and for each data set in turn.

The additivity assumption

A crucial assumption of t-tests and ANOVAs is that the effects of the model used are additive. Translated into ecological terms, this assumption equates to the fact that any presumed impact would be constant whatever the abundance level of the population observed. In contrast, if an impact is proportional to the size of the population we would say that the effects are multiplicative (Stewart-Oaten et al. 1986, Stewart-Oaten et al. 1992). We used the Tukey test for additivity which is similar to testing the significance of slope of a linear regression relating the average number and the differences in the number of birds at the two sites (Stewart-Oaten et al. 1986). We found that the deltas, expressing the simultaneous differences between controls and presumed impacted areas, strongly violated the additivity assumption for the ground survey data (1995: $P = 0.009$, $n = 9$; 1996: $P = 0.001$, $n = 9$ and 1997: $P = 0.0001$, $n = 8$). A similar situation applied when comparing subareas within TK and, only for the aerial data, was the additivity assumption fulfilled (slope not different to zero for the *Before* period $P = 0.762$, $n = 8$ and the *After* period $P = 0.108$, $n = 7$). Transformations (log $(y + c)$, $\log_2 (y)$, square root (y), cubic root (y) etc.) were used to correct that situation for ground surveys but none of them were successful. When we look at the frequency distribution of all ground surveys (which is the parent distribution of the simultaneous surveys) for common eiders (Annex 1), we note that the distribution could be bi-modal (TK 94-95, RS 96-97) skewed to the right (TK 95-96) or to the left (TK 96-97). This suggests that even if successful transformations would have been found for one of the distributions mentioned above, we would have need of using different transformations for different years or sites which would, of course, invalidate comparisons. For this reason, we rejected the plan to analyse the data using deltas and t-tests.

The independence assumption

The major problem caused by serial correlation (also called autocorrelation) in a data set is that it inflates the nominal alpha level which makes the statistical tests (or parameter estimates) less conservative. In other words, one is more likely to reject H_o because the nominal alpha level chosen by the investigator is lower than the real alpha level (Stewart-Oaten et al. 1992, Hatfield et al. 1996).

Aerial survey data were not checked for serial correlation because of low sample size. Nevertheless, we believe that a high level of autocorrelation is unlikely in this case because each survey was conducted at approximately one month intervals. In addition, these surveys were conducted in different years: of eight aerial surveys of the Before period, four surveys were conducted in 1994 and four in 1995. Similarly, of seven aerial surveys conducted during the *After* periods, four surveys were made in 1996 and three in 1997.

Ground surveys were conducted in the morning and usually repeated in the afternoon from both the presumed impact area (TK) and the control area (RS). Afternoon counts of eiders were highly correlated with morning counts at TK in 1995 ($r = 0.992$, $n = 5$, $P <$

0.01) and in 1997 (r = 0.919, n = 38, P << 0.001) but not in 1996 (r = 0.660, n = 5, P > 0.100). For RS, mornings and afternoon counts were highly and significantly (P < 0.01 in all cases) correlated for the three years of the study (1995: r = 0.878, n = 8; 1996: r = 0.987, n = 9; 1997: 0.953, n = 21). Therefore, when two surveys were done the same day from the same site, we always used the morning survey in the computation and deleted the afternoon one. In cases where no morning surveys was conducted (because of weather condition), we used the afternoon count for that day.

When we consider all the surveys made during one year (using only one survey per day), the first order autocorrelation level is 0.751 (n = 16), 0.687 (n = 16) and 0.700 (n = 19) for 1995, 1996 and 1997, respectively. We thus decided to pool the data for adjacent dates which did not solve the problem as the autocorrelation level remained high (0.322-0.641). Pooling the data further was not considered a good solution since the sample sizes would have been too low for the calculation of confidence intervals.

Nine surveys in 1995, nine in 1996 and eight in 1997 were conducted simultaneously at both TK and RS. We calculated the deltas for each year and checked if they were autocorrelated. Although the level of autocorrelation coefficient (first-order) ranged from 0.291 to 0.564, none of them was significant (P > 0.100) which may have been caused by small sample sizes (=low power).

In lieu of a t-test on the simultaneous differences between the presumed impact and control area, we used confidence intervals and correlation analysis to detect any impact. To circumvent any problem related to serial correlation when calculating confidence intervals, we used a low alpha level in the computation. Hatfield et al. (1996) proposed to use a lower nominal alpha level to mitigate any impact of serial correlation. From simulations of the effect of serial correlation on randomisation t-test, Stewart-Oaten et al. (1992) showed for sample size of 15 and a correlation coefficient of 0.600 that a nominal alpha level of 0.010 corresponds to a real alpha level of about 0.120. In our calculation of confidence intervals of mean number of birds, we thus used a nominal level of 0.01 in order to get an alpha level of about 0.100. Although the computation of confidence intervals and correlations with non-normal distributed data (see annex 1) is awkward, it was considered the best method with the data at hand. Finally, in the case where we could not use statistics (because the assumptions of the tests were violated) we arbitrarily set at 50% the effect size between two samples to be declared *biologically different*. For example, two samples differing by 52%, and for which we could not apply statistics, will be declared biologically significant although it will not be possible to know if this effect size is the result of random variation or not.

3.4.2 Comparing TK and RS

For the aerial survey data, we used a correlation and regression analysis in the first instance in order to see if fluctuation in the abundance of sea ducks at a large spatial scale would influence the numbers counted at one site (control and impact area). The slopes of

model II regressions for *Before* and After periods were compared. The slopes were compared using a Z-test (Scherrer 1984) even though sample sizes were small. Since the aerial survey data conformed to the additivity assumption, we also used a t-test on the simultaneous differences between TK and RS to compare the *Before* and After periods.

For the ground survey data, we computed confidence intervals of mean abundance of birds including all surveys and then including only simultaneous surveys. When confidence intervals of the mean of one data set included the mean of the comparative data set, we conclude that these two samples were not different. Otherwise they were considered different. Although useful in our context, we do not know the level of significance associated with this approach, which would need further development (e.g. an analytical solution or computer simulations). However, the application of the confidence intervals approach and the t-test on the same set of (aerial) data (for which the assumptions of the t-test were not violated), suggests that it corresponds to a P value of about 0.200 (see section 4.2).

Although the sampling design used for benthos surveys is convenient to reduce logistical constraints and to show any pattern in benthos distribution in relation to depth (Guillemette et al. 1993), it is very likely to generate serial correlation in the data. However, we do not use inferential statistics in our analysis mostly because we compare the same transects among years and assumed that our sampling covered on average (at 34 stations at TK and 29 at RS) the same habitat and conditions. Therefore, any substantial trend in the data (an effect size of at least 50%) was interpreted as of biological importance.

3.4.3 Comparisons within TK

We used a correlation analysis to compare sub-areas within TK. The general idea of this analysis was to evaluate if the abundance of birds at both observation sites are influenced similarly (positive correlation), in an opposite fashion (negative correlation) or are not related at all (no correlation) in relation to environmental factors. For correlation analysis, the problem of autocorrelation in the data is more complex because it is not only within an x or a y variable that you have to look at this problem but you also need to evaluate if xy are autocorrelated in the time series (Swihart & Slade 1985). Although techniques do exist to assess this problem, the solutions to solve it are not simple and we therefore decided to use the following rationale. The problem of serial correlation occurred in our data set because the intervals between surveys were not long enough. Since the rate of sampling was the same during all three years (the number of surveys is similar and the study period is the same for the three years), we assumed that the serial correlation level would be comparable from year to year. We therefore examine the variation in the coefficient of correlation between two sites referring to its effect size only (using the 50% effect size rule).

3.4.4 Around the wind park

For the on-off experiment, a paired t-test was applied to the data to test the null hypothesis that there is no difference in the number of common eiders when controls (turbines stopped) and treatments (turbines operating) are compared. The total number of paired comparisons was 22 for the park-200 m zone and 29 for the 200-600 m zone. The reason for a lower sample size in the former is because seven pairs of zero comparisons have been deleted. The normality assumption was checked by plotting the frequency distribution of the differences between controls and treatments. For the two zones considered (park-200 m and 200-600 m) a bell shaped curve was evident without any apparent skew.

For the exploitation experiment, we first checked our working assumption that food biomass was linearly related with the abundance of eiders. To do this, we used regression analysis and the total amount of food in each quadrate (of 4 ha) as the independent variable and the total number of eiders counted as the dependent variable. The total amount of food in a quadrate was obtained by extrapolating the average biomass of food, derived from 12 stations of 6 samples each, to 4 ha. The total amount of eiders using a quadrate in one winter was obtained by the cumulative count of their numbers throughout the 38 surveys conducted in the morning from November 1996 to April 1997. As a cross-check, we did a similar analysis with the 38 counts conducted in the afternoon. In order to check if the data showed any deviation from an expected slope of 1 (that would be caused by the wind park), we computed the proportion of birds and the proportion of food associated with each quadrate and performed a regression analysis separately for morning and afternoon counts. If the confidence intervals of the observed slope included the theoretical slope of one, it was concluded that no significant departure from the habitat matching rule (see section 2) was observed.

With the decoy experiment, the sample unit was each trial or observation period lasting 90 min. When the variance of the number of reacting (landing + attempting to land) birds of patch 1 (100 m from the wind park) is compared with the variance of patch 3 (500 m from the wind park), a significant difference (F = 203.7, P << 0.0001) is found. We thus log-transformed the data to reduce the problem of unequal variance (F = 3.1, P = 0.099). Secondly, we checked if we could use the absolute (as opposed to relative) numbers recorded in our analysis of reacting eiders on patches either side of the wind park. To do this, a two-way ANOVA was performed with the total numbers of reacting birds in one trial as the dependent variable and patch and line location as the two independent factors (see results). The fact that we conducted simultaneous trials on both sides (n = 7 for each side) of the wind park allowed us to discard any effect of weather conditions in our analysis.

Finally, the number of eiders entering each corridor was analysed using a one-way ANOVA on log-transformed values with corridor locations as the independent factor. As the corridor A was half the size of corridor B and C, we doubled the number of eiders recorded in corridor A before analysis.

4 RESULTS AND DISCUSSION

4.1 Seasonal abundance and bird diversity at TK

The seasonal abundance of birds over a complete annual cycle at Tunø Knob was depicted using data from ten aerial surveys conducted from February 1994 to January 1995. As shown in Fig. 4, the total number of birds of all species was highest during the period January-March and then decreased dramatically in April-May and increased to a medium level in July-September. These large fluctuations in bird numbers are largely explained by the presence of com-

A   **Seasonal variation in the abundance of birds at TK**

B   **Species composition**
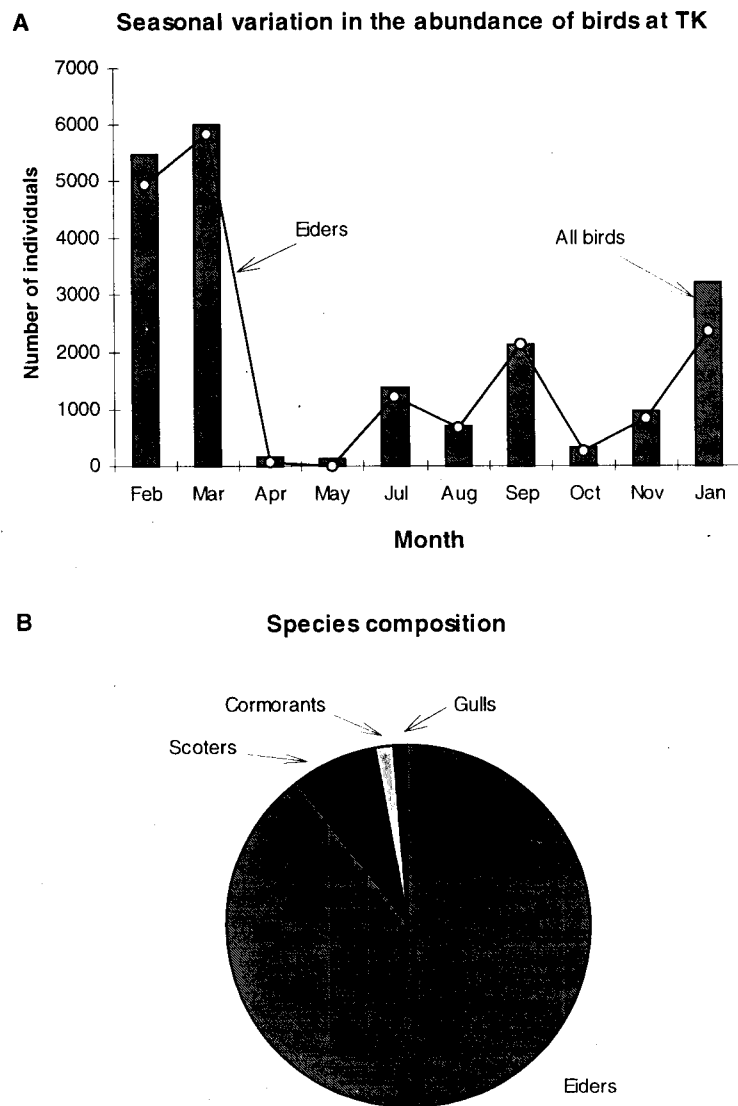
Figure 4. A) Seasonal variation in the abundance of birds counted at Tunø Knob during 10 aerial surveys and conducted over a complete annual cycle (February 1994-January 1995). The figure shows the total number of individuals of all species (histograms) and the number of common eiders (line). B) Relative importance of different group of birds at Tunø Knob over an annual cycle estimated from the total number of birds counted (20,460) over 10 aerial surveys.

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mon eiders where the three periods mentioned above correspond approximately to winter, breeding and moulting seasons, respectively. The common eider represents 90% of all birds surveyed in the area whereas the common scoter represents almost 8% (Fig. 4). The two other main groups of birds were cormorants (1.6%) and gulls (1.1%) while the other species represented only 0.1% of all birds surveyed. For this reason, we deal only with common eiders and common scoters in the following sections.

4.2 Abundance of eiders: comparing TK and RS

4.2.1 Aerial surveys

The total number of eiders in ÅB during the *Before* period ranged from 10,700 individuals to 81,400. For TK it ranged from 70 to 5,826 while for RS it varied between 204 to 6,800 individuals (Fig. 5). We plotted the number of eiders at TK or at RS against the total number present in the ÅB and we obtained a significant (P < 0.100) relationship in both cases. This means that as more birds were present in the bay, more birds were found at TK or at RS. The slope b is 0.102 (R^2 = 0.457, n = 8) for ÅB-RS and 0.096 (R^2 = 0.683, n = 8) for ÅB-TK.

The total number of eiders in ÅB during the *After* period ranged from 15,100 individuals to 66,600 (Fig. 5). For TK it ranged from 38 to 2,800 while for RS it varied between 40 to 4,638 individuals. The two relationships (Fig. 5) mentioned above remained significant (P < 0.100)

Figure 5. Linear regressions (Model II) relating the number of eiders counted from an aeroplane in Århus Bay (88,000 ha) and the number of eiders counted at Ringebjerg Sand (4,700 ha) and Tunø Knob (5,000 ha). Note that the slope is similar for Ringebjerg Sand and tends to decrease for Tunø Knob when *Before* and *After* periods are compared.

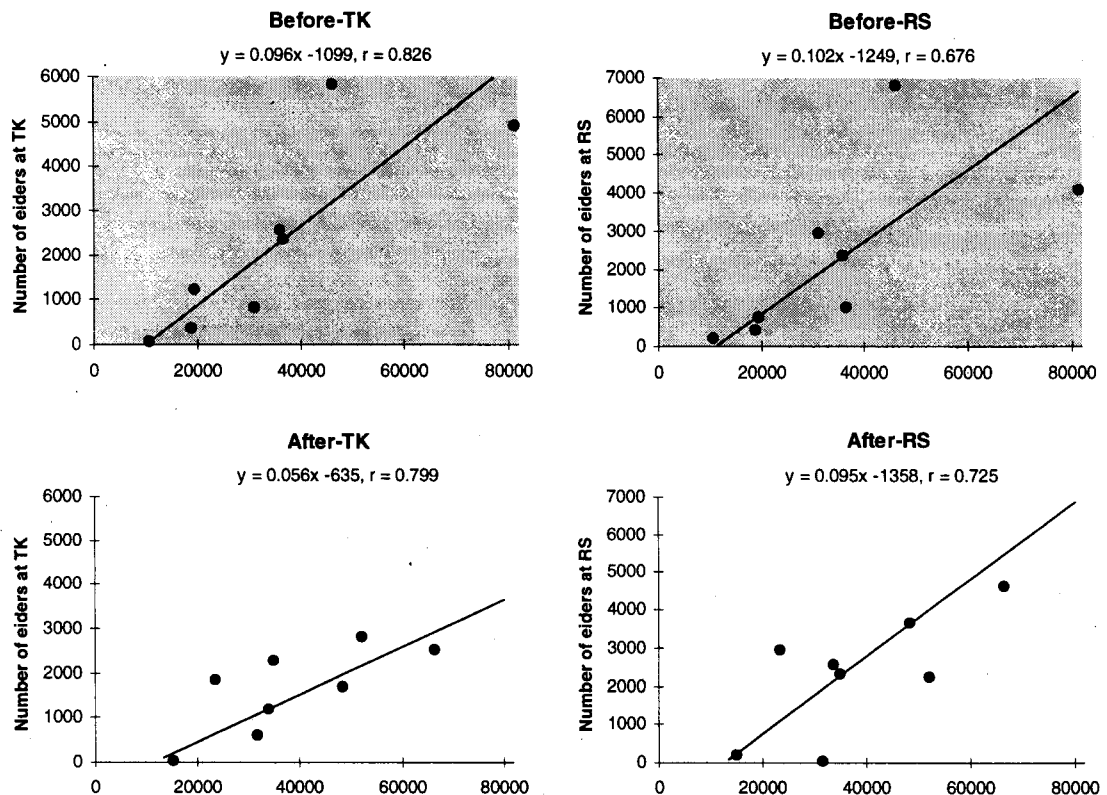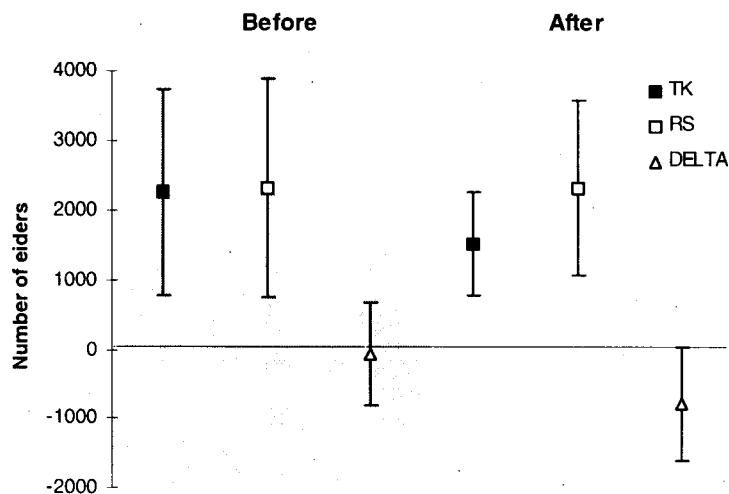*Figure 6.* Average number of eiders and 90 % confidence intervals (see methods) for Tunø Knob (TK) and Ringebjerg Sand (RS) obtained from eight aerial surveys *Before* and seven surveys *After* the construction of the wind park. Average deltas corresponding to the average difference between TK and RS in number of eiders are also shown. Note that confidence intervals of the *After* delta include the mean of the *Before* delta.

during the *After* period. While the slope for ÅB-RS (b = 0.095, R^2 = 0.526, n = 7) was similar (Z = 0.172, P >> 0.100) to the *Before* period, the trend was a decrease for ÅB-TK (b = 0.056, R^2 = 0.639, n = 7) although it was not significant (Z = 1.505, P = 0.135). This suggests that TK was supporting a smaller proportion of the birds found in ÅB in the *After* period.

This last result was depicted in a different way using confidence intervals of the mean number of eiders and of the mean deltas between the two sites (Fig. 6). The mean number of eiders at TK decreased by 32% from *Before* (= 2,266 individuals) to *After* (= 1,532 ind.) periods while it was similar for RS (*Before*= 2,327 ind., *After* = 2,326 ind.). The confidence intervals of the deltas overlapped largely, including the mean of the other state in both cases. For example, mean of the *After* delta (mean = -780) felt within the confidence interval of the *Before* delta (mean = -60, CI = 740) which suggests no statistical difference despite the substantial difference between mean deltas. Since the data for aerial surveys conform to the assumption of additivity (see methods), we also performed a t-test on the deltas comparing the *Before* and *After* periods. We found that no statistical differences existed between *Before* and *After* deltas (t = 2.160, df = 13, P = 0.218).

Thus when comparing the *Before* and *After* period, the aerial surveys showed (1) that the total number of eiders in ÅB was similar, (2) that the apparent (but not significant) decrease in slopes relating TK and ÅB suggests that TK supported a smaller proportion of birds during the *After* period, (3) that the relationship ÅB-RS remained the same and (4) that the decrease in eider numbers at TK was substantial (32%) although it was not statistically significant.

TK 1994-95

RS 1994-95

TK 1995-96

RS 1995-96

TK 1996-97

RS 1996-97
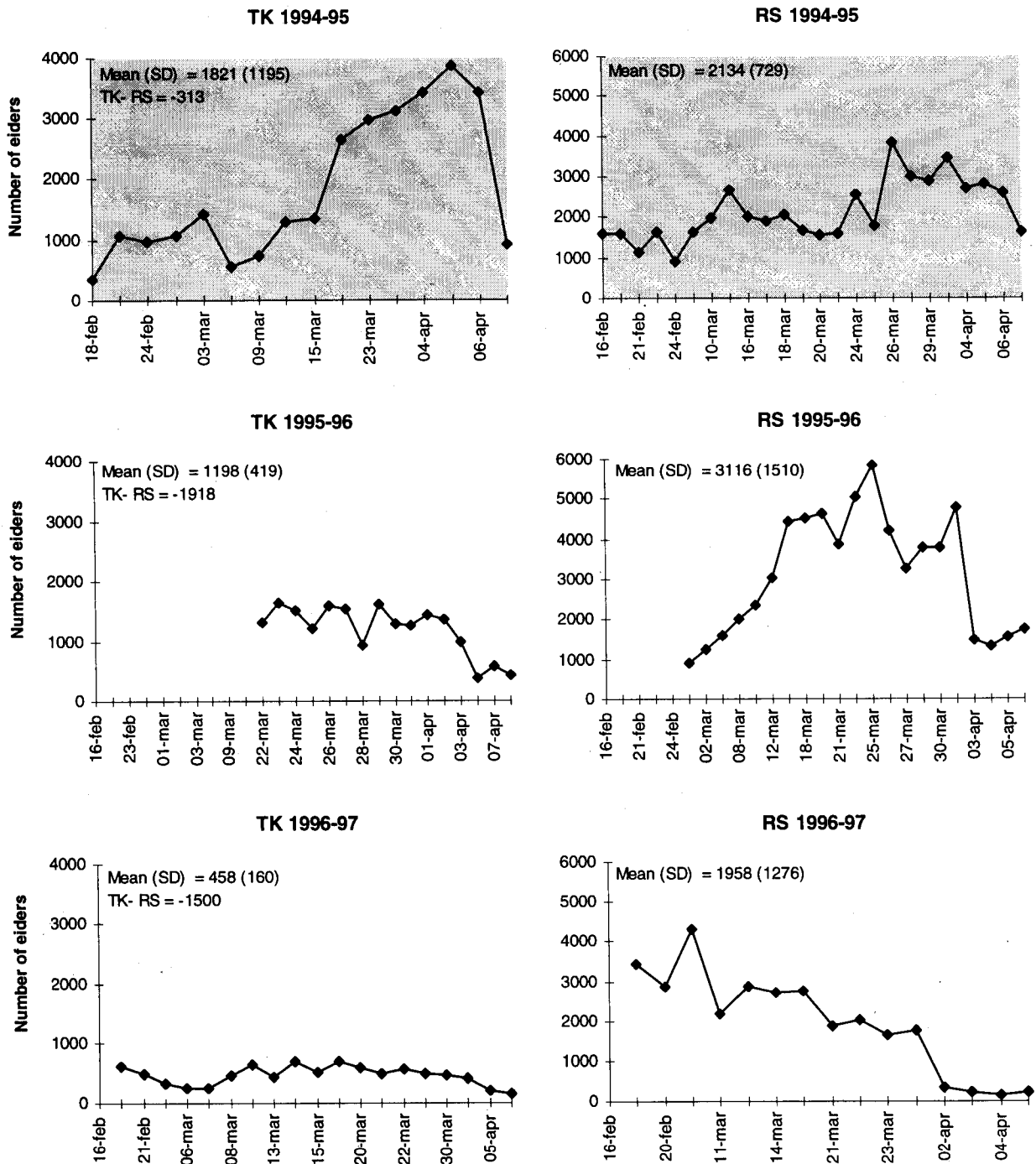
Figure 7. Abundance of common eiders at Tunø Knob (TK) and Ringebjerg Sand (RS) as counted from observation towers during three years (baseline year shaded). The mean (SD) number of individuals is written for each year and site. Note that the study period used in this investigation spans from mid-February to mid-April, except for TK in 1995-96 where ground surveys were conducted only from mid-March to mid-April. Also shown is the difference between average number of eiders observed at TK and RS.

4.2.2 Ground surveys

In the analysis presented here, we will first look at the between year variation in eider abundance for each site in turn which will be followed by a comparison between TK and RS. During the base line year at TK, eider numbers remained around 500-1,000 individuals from mid-February to the first week of March and then increased to a peak of almost 4,000 birds at the beginning of April (Fig. 7). In 1995-

A   **Average numbers for all ground surveys**

B   **Average deltas for simultaneous ground surveys**
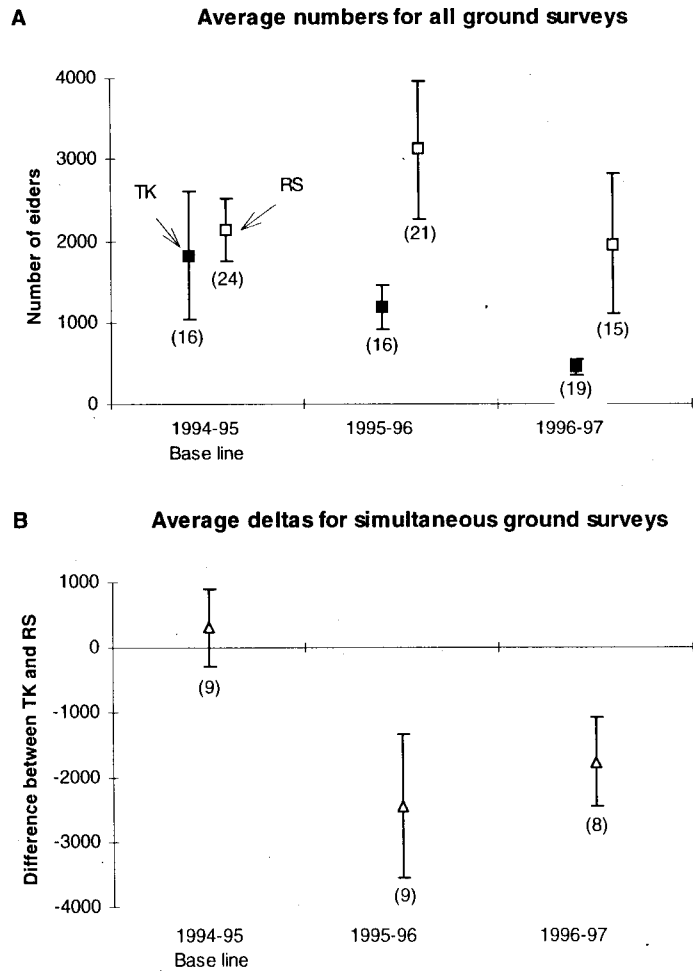
Figure 8. A) Average abundance of common eiders and 90% confidence intervals (see methods) for Tunø Knob (TK) and Ringebjerg Sand (RS) over three years (1994-95 = baseline year) based on all ground surveys. Numbers in parentheses are sample sizes for each year and site. B) Average difference in eider numbers between TK and RS (= delta) and 90% confidence intervals for simultaneous ground surveys.

96, we were unable to start the surveys before March 22 (because of ice cover) and an average of 1,198 eiders were counted during that period, 34% lower than during the base line (1,821 eiders). In 1996-97, the average number of eiders was only 458 individuals, 62% lower than 1995-96 and 75% lower than the base line. Using the confidence interval approach (Fig. 8), only the base line and 1996-97 were statistically different.

At RS, a similar pattern of seasonal abundance was apparent in 1994-95 with the lowest numbers (800-1,500) from mid-February to the beginning of March (Fig. 7). Numbers remained at a plateau just below 2,000 individuals until the third week of March when numbers increased during the last week of March and the beginning of April to 2,600-3,800 eiders (Fig. 7). The average number of eiders increased by 46% from 1994-95 (2,134 ind.) to 1995-96 (3,116 ind.) and then decreased from 1995-96 to 1996-97 (1,958 ind.) by 37% whereas eider numbers in 1994-95 (2,134 ind.) and 1996-97 (1,958 ind.) were similar (8% difference). The confidence interval approach (Fig. 8) indicates, (1) that eider numbers increased significantly in 1995-96 when com-

pared to the base line, (2) that it decreased significantly in 1996-97 when compared to 1995-96 and (3) that it was similar during the base line and 1996-97.

In summary, the ground survey data show that eider abundance (1) was similar between TK and RS during the base line year, (2) decreased at TK while it increased at RS in 1995-96 and (3) decreased at TK and remained the same at RS when 1996-97 was compared to the base line year.

If we now compare the average deltas between TK and RS for the three years, there is a clear difference between base line year and the two next seasons as the deltas decreased nine fold in 1995-96 and seven fold in 1996-97. In conclusion, the results from the ground surveys confirmed the trends observed from the aerial surveys and can be interpreted in two ways. The wind park had an impact on the abundance of eiders and/or it was a manifestation of the natural variability of the system.

4.3 Abundance of potential prey: comparing TK and RS

In Table 1 is presented the frequency of occurrence of potential prey based on 34 stations for TK and 29 stations for RS for the base line and 1996-97. Bivalves was the most important benthic group during the base line (100% of relative frequency) with four common (> 40%) species (*Mytilus edulis*, *Cardium* spp., *Mya arenaria*, *Macoma* spp.). Gastropods (*Littorina littorea*, *Acmea testudinalis*), Echinoderms (*Asterias rubens*) and unidentified polychaetes were also common. However, when considering the benthic community in general the blue mussel (*Mytilus edulis*) was the most common potential prey during the base line year with 85% of frequency of occurrence at TK and 90% at RS. In 1996-97 the frequency of blue mussels dropped to 32% at TK and 21% at RS. Although a general decrease in frequency of occurrence was observed for many species of bivalves, gastropods and echinoderms, the frequency for *Cardium* spp. and *Macoma* spp. remained stable when comparing the base line year with the 1996-97 season while *Spisula subtruncata* increased (using the 50% effect size rule).

When expressed in relative density, it is clear that blue mussel formed the bulk of potential prey at both TK and RS (Fig. 9). This was particularly true in 1994-95 with more than 95% of individuals counted. In 1996-97, the absolute and hence the relative density of blue mussel was much lower for both sites revealing the other bivalves (22-36%) as the second most important group of potential prey followed by polychaetes (9-10%), gastropods (6-8%), crustaceans (4-6%) and echinoderms (2-5%) being less important (Fig. 9).

Table 1. Frequency of occurrence (%) of all benthic species or groups of species for samples collected in 1994-95 and 1996-97 at Tunø Knob and Ringebjerg Sand.

Potential prey	Tunø Knob (n = 34)		Ringebjerg Sand (n = 29)	
	1994-95	1996-97	1994-95	1996-97
Bivalves	**100**	**91.2**	**100**	**82.8**
Mytilus edulis	85.3	32.4	89.7	20.7
Cardium spp.	88.2	79.4	79.3	44.8
Ensis spp.	20.6	5.9	3.4	0.0
Mya arenaria	64.7	20.6	69.0	10.3
Macoma spp.	58.8	47.1	51.7	41.4
Spisula subtruncata	14.7	26.5	0.0	6.9
Other bivalves	61.8	14.7	34.5	6.9
Gastropods	**73.5**	**41.9**	**55.2**	**31.0**
Littorina littorea	47.1	23.5	48.3	31.0
Acmea testudinalis	47.1	20.6	13.8	10.3
Other gastropods	29.4	0.0	0.0	0.0
Echinoderms	**67.6**	**38.7**	**65.5**	**34.5**
Asterias rubens	50.0	20.6	48.3	34.5
Ophiura spp.	26.5	5.9	20.7	3.4
Echinicyamus pusillus	32.4	5.9	20.7	3.4
Other echinoderms	20.6	2.9	6.9	0.0
Polychaetes	**82.4**	**82.4**	**75.9**	**55.2**
Crustaceans	**32.4**	**35.3**	**51.7**	**41.4**

Not only the abundance of blue mussels decreased over the years. The whole benthic community decreased in terms of absolute density of individuals from the base line year to 1996-97 (Fig. 10). Indeed, for the five groups of potential prey a marked decrease in density was observed. This observation applies to both TK and RS and suggests that the settlement of new recruits in the benthic community did not occur between the base line and 1996-97.

In terms of biomass, the blue mussel completely dominated the whole benthic community since this bivalve represented more than 95% of the total biomass for the base line year and the 1996-97 season for both TK and RS. We thus assume, for the following analyses, that
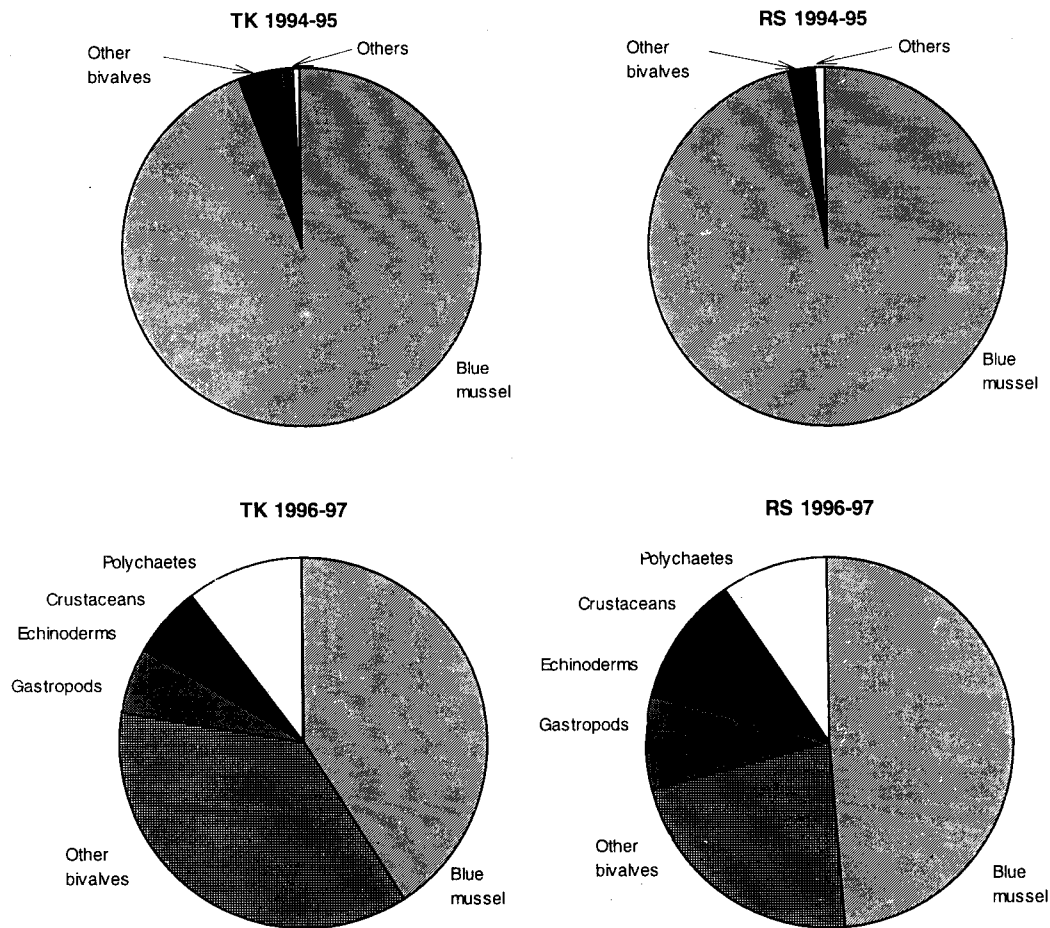
Figure 9. Relative density of benthic groups and species for two years at Tunø Knob (TK) and Ringebjerg Sand (RS). The relative density was calculated as the total number of individuals of one group or species found in all stations (34 for TK and 29 for RS) divided by the total number of individuals of all species. The baseline year (1994-95) was compared here with the last year of the study (1996-97).

the blue mussel was the main prey sought by common eiders and common scoters on the two study sites.

4.3.1 Size of blue mussels

The size of mussels available is important to consider because not all mussel size classes can be considered as favoured prey for the eiders and scoters. During the base line year, many stations at TK were characterised by small blue mussels of 3-15 mm in length and large mussels (> 40 mm) (Fig. 11). These two size categories were spatially separated, the small mussels being present predominantly from 3 to 7 m whereas the large ones were found between 6 and 10 m. During 1995-96 and 1996-97 the frequency of blue mussels in the area decreased compared to the base line as shown by the number of stations with the presence of mussels for each year (Fig. 12). This decrease in frequency was due mostly to the decrease of small mussel stations that appeared in 1995-96, followed by their disappearance in 1996-97 (Fig. 11).

Tunø Knob
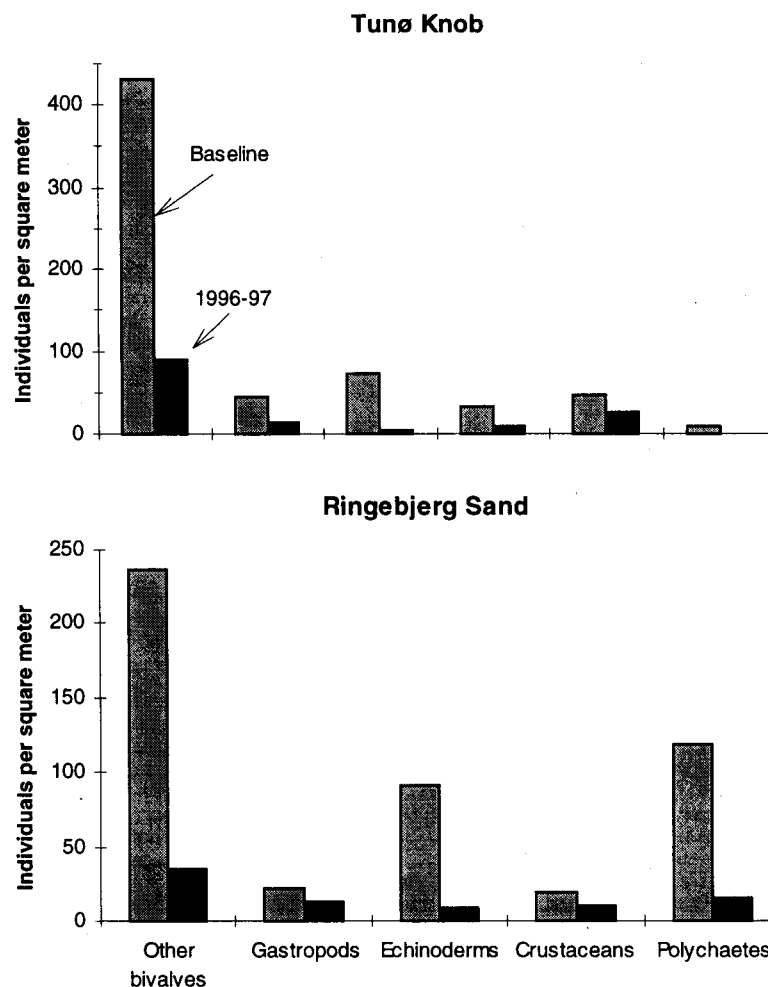
Ringebjerg Sand

Figure 10. Absolute density of all group of species, excluding the blue mussel Mytilus edulis, for 34 stations at Tunø Knob and 29 at Ringebjerg Sand. When the baseline year (1994-95) was compared to 1996-97, a general decrease in density of individuals is noted for all groups of species.

A similar situation occurred at RS where the frequency of blue mussel stations decreased from 1994-95 to 1996-97 (Fig. 13) due largely to the disappearance of the small size cohort. Two major differences, however, arose when we compared TK with RS. Intermediate sized (16-40 mm) mussels were present at RS whereas large (>40 mm) mussels were absent. This was especially true in 1995-96. In 1996-97, most of the remaining mussels were intermediate sized individuals. Therefore, TK and RS differed considerably in terms of blue mussel sizes in 1995-96 and 1996-97 while the two sites were more similar during the base line year, which was caused by the presence of a cohort of small sized individuals at both places.

4.3.2 Biomass of blue mussels

Although the confidence intervals overlapped completely among years (Fig. 11), there is a trend of decreasing mean biomass over the years at TK (from 3.9 to 1.4 kg. m^{-2} wet mass). This trend is real in the sense that it follows the disappearance of mussels from stations throughout the area which increases the variance because of the

Figure 11. Size and biomass (wet mass) of blue mussels in relation to depth at Tunø Knob over three years. The same number of stations (n= 34) with approximately the same positions (accuracy about 10 m) were sampled for each year. For comparative purposes, the biomass of mussels was averaged over all stations (All s.) and averaged for stations with mussels only (Mussel s.). SD are given in parentheses.

many zeros in our computation of average biomass. To offer a different perspective on that situation, we averaged the biomass of blue mussels only when they occurred at a station. For TK the 'exclusive' average biomass seems to be rather constant over the years varying between 4.31 and 6.05 kg/m² even though the small mussels decreased in 1995-96 and disappeared in 1996-97. This is mostly because the large mussel stations are associated with very large biomass and were present in the area for all three years. Therefore, the main event that occurred at TK in the course of the study is the disappearance of small mussels whereas mussels of large size persisted throughout all three years (Fig. 11).

A   **Blue mussel frequency (%)**

B   **Average blue mussel biomass**
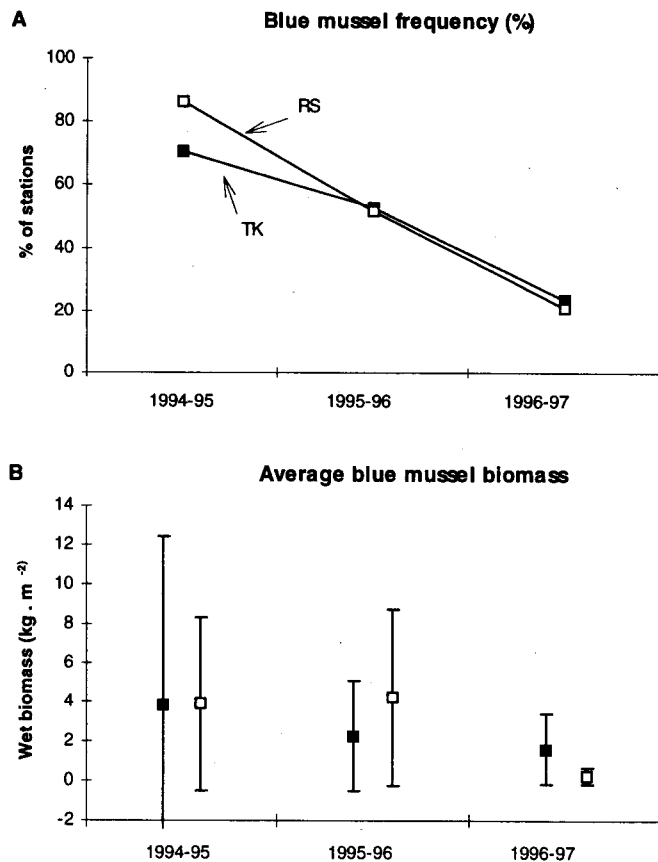
Figure 12. A) Relative frequency of occurrence (% of stations) of blue mussels at Tunø Knob (TK = 34) and Ringebjerg Sand (RS = 29) over three years. B) Average biomass (wet mass) of blue mussel (including all stations) for TK (filled squares) and RS (open squares) over three years with 90 % confidence intervals (computed as described in methods).

At RS, the biomass of blue mussels (all size classes) was stable when the base line year was compared to 1995-96 (about 4 kg/m² for both years, Fig. 12). Although the frequency of stations with mussels decreased markedly between these two years, the data indicated that small mussels increased in size (Fig. 13) which would have maintained the biomass at the same level for both years. However, a dramatic decrease in biomass of blue mussel occurred in 1996-97 with only 0.27 kg. m⁻² on average (Fig. 12). Based on our estimate of biomass on a station basis (Fig. 13), it is clear that the main variation in biomass was due to the occurrence of the intermediate sized class individuals whereas small mussels played a less important role. When we compute the exclusive average biomass of blue mussels (excluding the zeros), this was around 6 kg/m² during the base line, but which increased to 10 kg/m² during the second year and then decreased to 1.5 kg/m² in 1996-97. This means that even though the frequency of mussels decreased considerably at RS from 1994-95 to 1996-97, a foraging common eider would be able to find patches of food of high biomass. Indeed, in the Gulf of St. Lawrence Canada, an average biomass of blue mussels of about 2 kg. m⁻² supported a large population of wintering eiders (Guillemette et al. 1996).
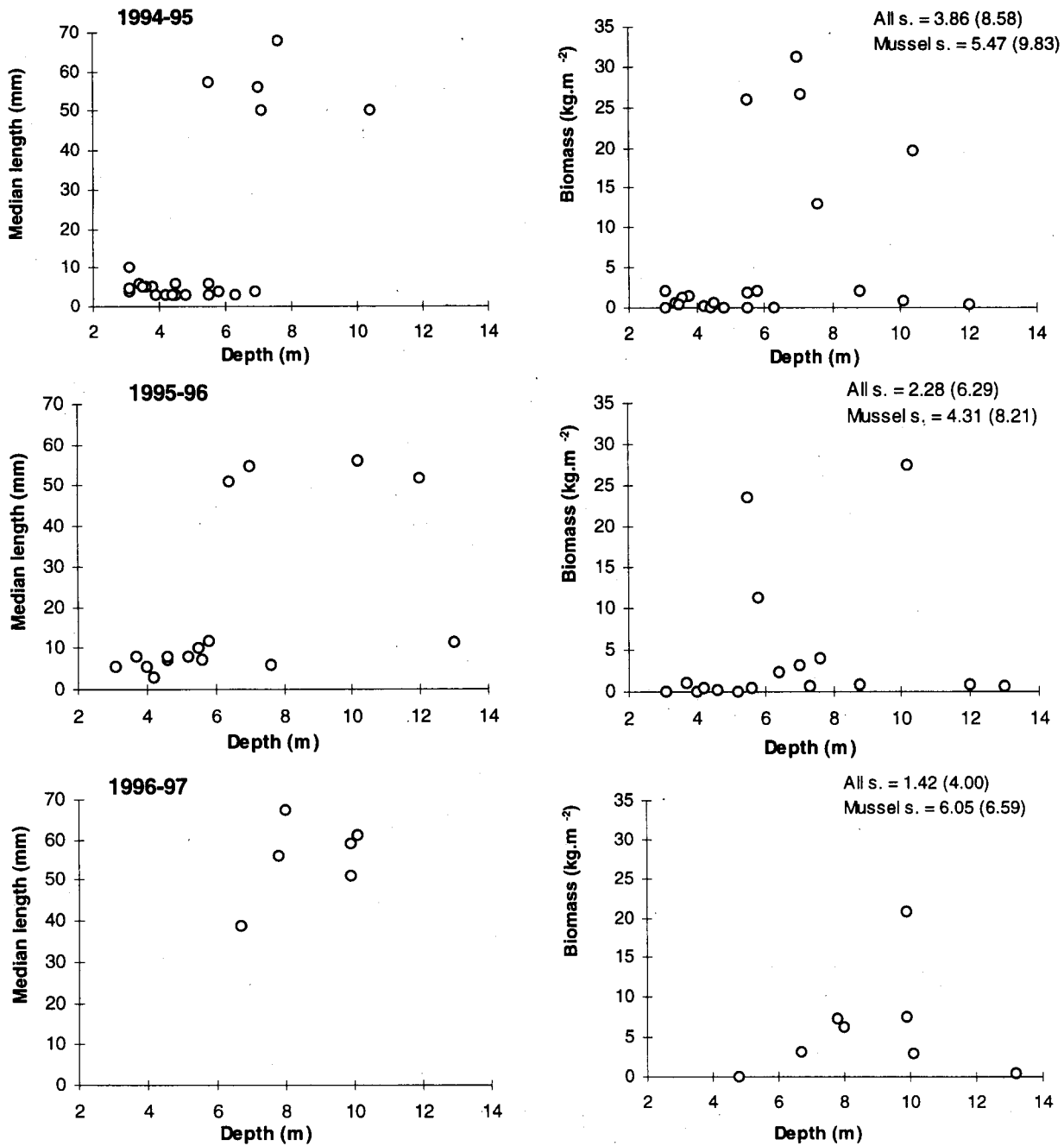
33
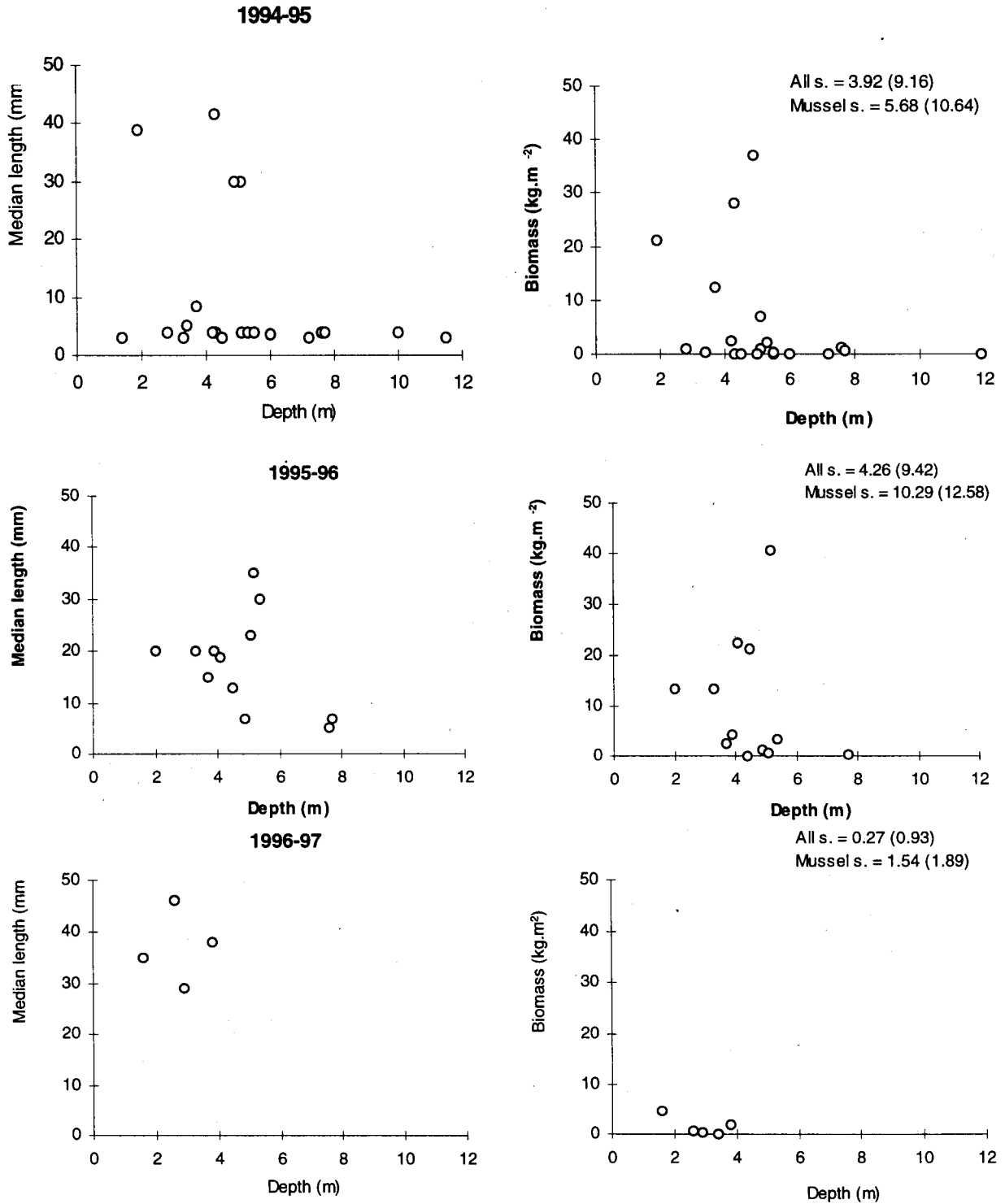
Figure 13. Size and biomass (wet mass) of blue mussels in relation to depth at Ringebjerg Sand over three years. The same number of stations (n= 29) with approximately the same positions (accuracy about 10 m) were sampled for each year. For comparative purposes, the biomass of mussels was averaged over all stations (All s.) and averaged for stations with mussels only (Mussel s.). SD are given in parentheses.

Altogether, these results indicate strong differences in the size and biomass of blue mussels available at TK and RS during the three years of the study with the base line year being the most similar. This result is of considerable importance in the sense that not all the mussels present can be considered potential prey. There are two reasons for this. The first one is related to a physiological limit; eiders are not

able to swallow mussels larger than a certain size. Based on circumstantial evidence, this limit is probably around 70-80 mm in length. The second reason is that mussels larger than 25 mm can be considered as poor quality food (Guillemette in press). This is related to the fact that above a certain point (about 25 mm) shell mass increases faster than flesh mass which means that the relative flesh content is decreasing with shell length. In other words, an average eider feeding on mussels < 25 mm would need to ingest about 2 kg of mussels each day (of which 1.3 kg is shell) while another with the same energy requirement feeding on 40 mm sized mussels would need to ingest around 3.5 kg of mussels of which 2.5 kg is shell. In the light of this, feeding on small mussels would be greatly advantageous.

4.3.3 Relationships between mussel biomass and abundance of eiders

It is interesting to note at this point that the fluctuation in mussel biomass of small and intermediate size seems to match the pattern of fluctuation in eider numbers described above. Large biomass of small sizes were found at TK during the base line decreasing in 1995-96 and decreasing again to a negligible amount 1996-97 while the average eider number decreased from 1,821 individuals during the base line, to 1,198 individuals in 1995-96 and 458 individuals in 1996-97. At RS, the eider numbers increased from the base line to 1995-96 and then decreased in 1996-97 following the fluctuation in biomass of small and intermediate sized mussels. To show to what extent the amount of blue mussel biomass influenced the number of eiders on the study site, we first computed the amount of available biomass for small and intermediate size categories (see methods). In a second step, we related the biomass of these two size categories with the average number of eiders counted during the study period for both sites. We obtained a significant and very high correlation coefficient ($r = 0.958$, $P < 0.001$, $n = 6$). This suggests that differences in the fluctuation of abundance of eider numbers observed at the experimental (TK) and at the control (RS) area were caused by differential fluctuations in their main food supply, the blue mussel.

4.4 Abundance and spatial distribution of eiders within TK

We divided TK into four sub-areas (North-West, North-East, South-West and South-East (Fig. 14). Although this sub-division of the study area seems arbitrary, we feel that it offers a useful benchmark from which we can compare the variation in abundance of eiders occurring in the NW sub-area where the wind park is located. Note that the average position of any bird distributed at random within the NW area would be at approximately 300 m from the centre of the wind park and thus, may well be influenced by the presence of the wind turbines.
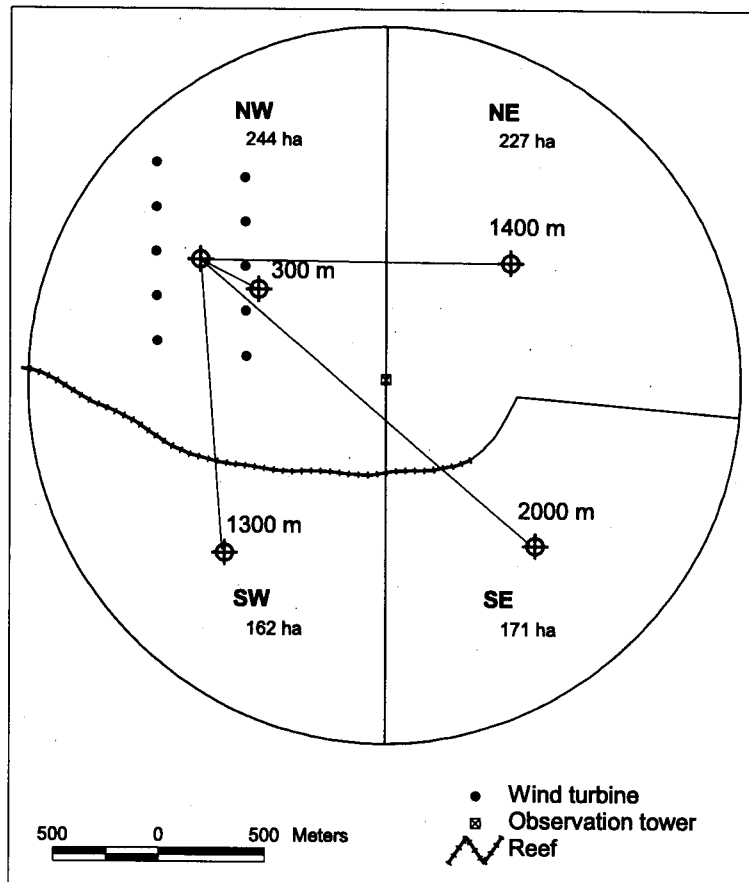
Figure 14. Map showing the four subdivisions. Also shown are the approximate distances between the centre of each area and the centre of the wind park.
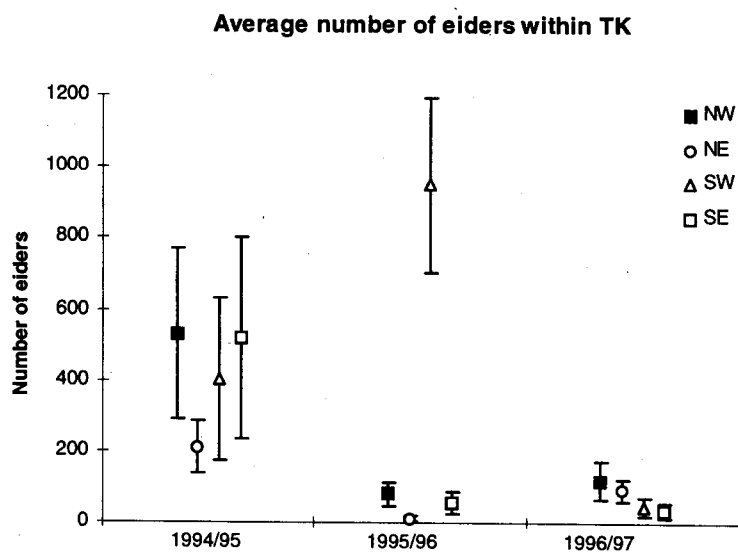
Average number of eiders within TK

Figure 15. Average abundance of common eiders within Tunø Knob and 90 % confidence intervals based on ground surveys over three years (baseline year = 1994-95) and four subareas (see Fig. 14).

4.4.1 Abundance

The average abundance in each area is presented in Fig. 15 for the three years of the study. It was shown for the NW area that eider numbers were highest during the base line year (average number of eiders = 531, CI = 290-772) and then decreased in 1995-96 (average number = 79, CI = 44-114) and remained stable in 1996-97 (average number = 120, CI = 68-172). As mentioned above this may have been due to (1) an impact of the wind park and or (2) to natural variation in food supply. A similar pattern of fluctuation was observed for the most distant (2.0 km) SE sector and to a lesser extent for the NE area. The pattern for the NE area was that eider abundance decreased there from the base line year (average number = 210, CI = 137-283) to 1995-96 (average number = 13, CI = 3-23) but increased again in 1996-97 (average number=90, CI = 59-123). The increase observed in 1996-97 at NE area is thus not consistent with the pattern observed in the NW area. Another difference from the NW area pattern of fluctuations was the case of the SW area where eider numbers increased from the base line year (average number = 404, CI = 173-635) to 1995-96 (average number = 950, CI = 703-1197) and then decreased in 1996-97 (average number = 47, CI = 21-73). Nevertheless, given that the fluctuations in abundance were nearly similar for two sister subareas (NE and SE) and partially similar for the SW subarea (1994-95 compared to 1996-97) where no wind turbines are located, this suggests that the decrease observed at the NW area was caused by natural variation.

A good way to synthesise the fluctuations occurring at the NW area in relation to the three others area is to build a correlation matrix (Table 2). The correspondence between abundance of eiders at the NW area and the three other areas is very high during the base line year, the coefficient of correlation ranging from 0.756 to 0.934. Those correlations decrease markedly in 1995-96, ranging from 0.299 to 0.638 and even becoming negative in 1996-97 for the NE and the SW areas. Although these negative correlations may suggest some 'displacement' effect caused by the wind park, the pattern is not consistent (i.e. it was not negative in both 1995-96 and 1996-97). Nevertheless, the fact that the strong relationship between the NW sector and the three others in 1995 vanished the subsequent years may indicate that the wind park was the cause of a such breakdown.

Table 2. Pearson correlation coefficient for three years among four subareas located within Tunø Knob.

Area and year	NE	SW	SE
NW 1994-95	0.756	0.840	0.934
NW 1995-96	0.638	0.299	0.488
NW 1996-97	-0.309	-0.365	0.315
NE 1994-95		0.618	0.755
NE 1995-96		0.252	0.447
NE 1996-97		0.430	0.291
SW 1994-95			0.846
SW 1995-96			0.213
SW 1996-97			0.269
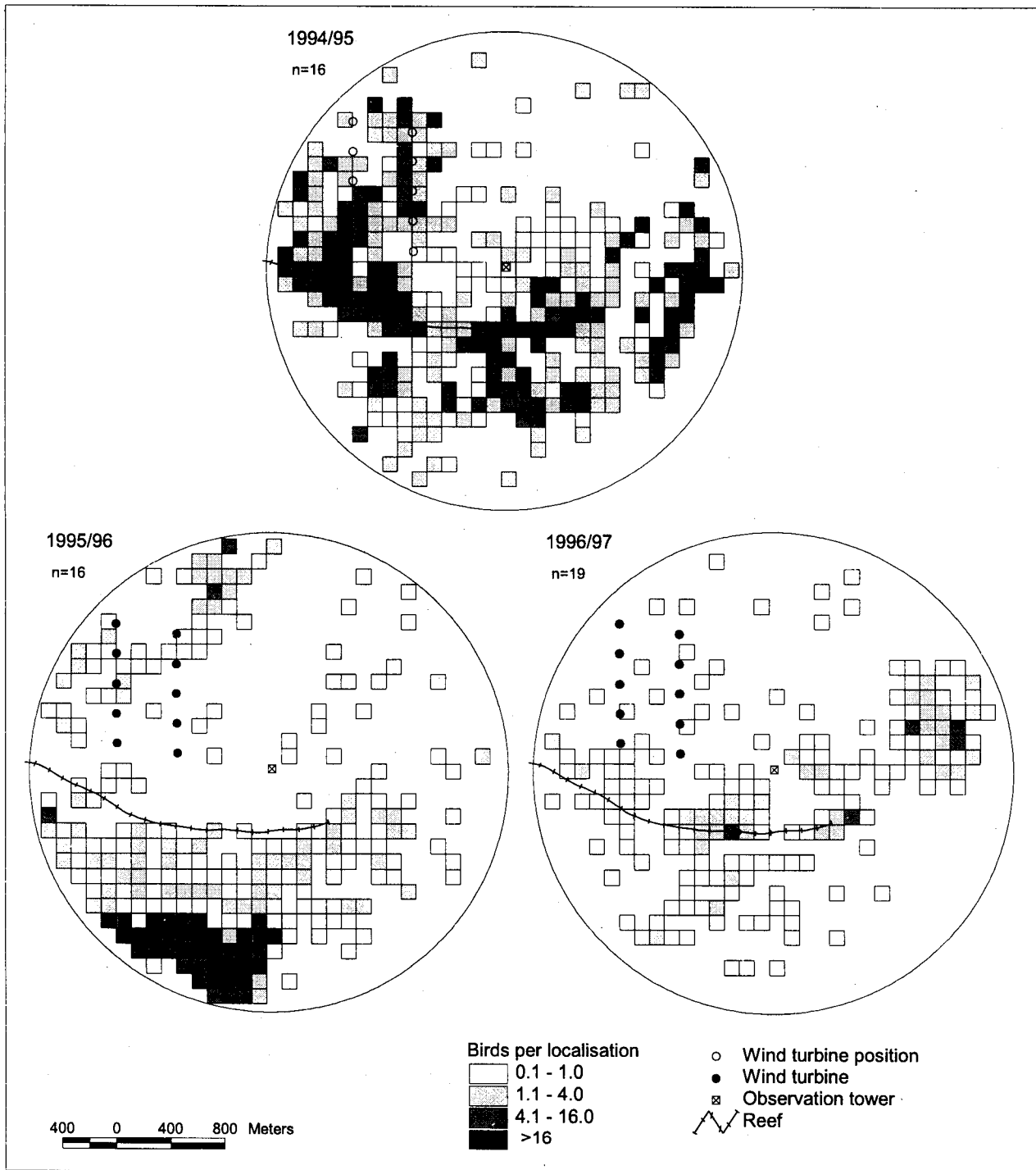
Figure 16. Spatial distribution of common eiders localised from the observation tower at Tunø Knob over three years (baseline = 1994-95). The number of localisations (n) is the number of surveys conducted within the study period (mid-February to mid-April). The density of eiders shown on these maps is calculated as the number of individuals per ha (each grid is 100 x 100 m) per localisation.

Considering the correlation among sister subareas, we note similarly that the correlations were fairly high (0.618-0.755) between NE, SW and SE during the base line year and then decreased during the second year of the study (0.252-0.447), being similar in the third year (0.291-0.430) (Table 2). This suggests that the decrease in correlation level between the NW and the control subareas from the base line year to 1995-96 was due to natural variation. One could argue, however, that the NE subarea is adjacent to the wind park and was also affected and thus, should not be used as a control. If we consider

Figure 17. Spatial distribution of common eiders localised from the observation tower at Tunø Knob during the second year of the study (1995-96). The right circle (presented in Fig. 16) is included for comparison.

only the subareas found south of the reef now, we found a similar pattern, the correlation coefficient between SW and SE being 0.846 in 1994-95, 0.213 in 1995-96 and 0.269 in 1996-97. We conclude from this that the decrease in the level of correlation between the NW area and the three other subareas from *Before* to *After* the construction of the wind park was the result of natural variation.

4.4.2 Spatial distribution

The spatial distribution of common eiders changed radically among years at TK (Fig. 16). In the baseline year, eiders were widespread over the study area with some concentrations of birds in all subareas (though eiders were not present in the northern half of the NE area). However, most of the birds were found in the NW area of which concentrations were found at the present location of the wind park. In contrast, almost no birds were localised in the NW sub-area in 1995-96 where the largest concentrations of eiders was present in the SW sub-area. In 1996-97, the number and density of eiders decreased again with the main concentration of eiders found in the NE subarea.

The absence of eiders in the NW sub-area in the wind park area in 1995-96 suggests that it may be caused by the presence of wind turbines erected during the summer of 1995. In both 1995-96 and 1996-97 we did observations outside the study period (mid-February-mid-April) which showed that eiders used the south-west part of the NW subarea and even the south-west part of the wind park in November-December 1995, three months after the construction was over (Fig. 17).
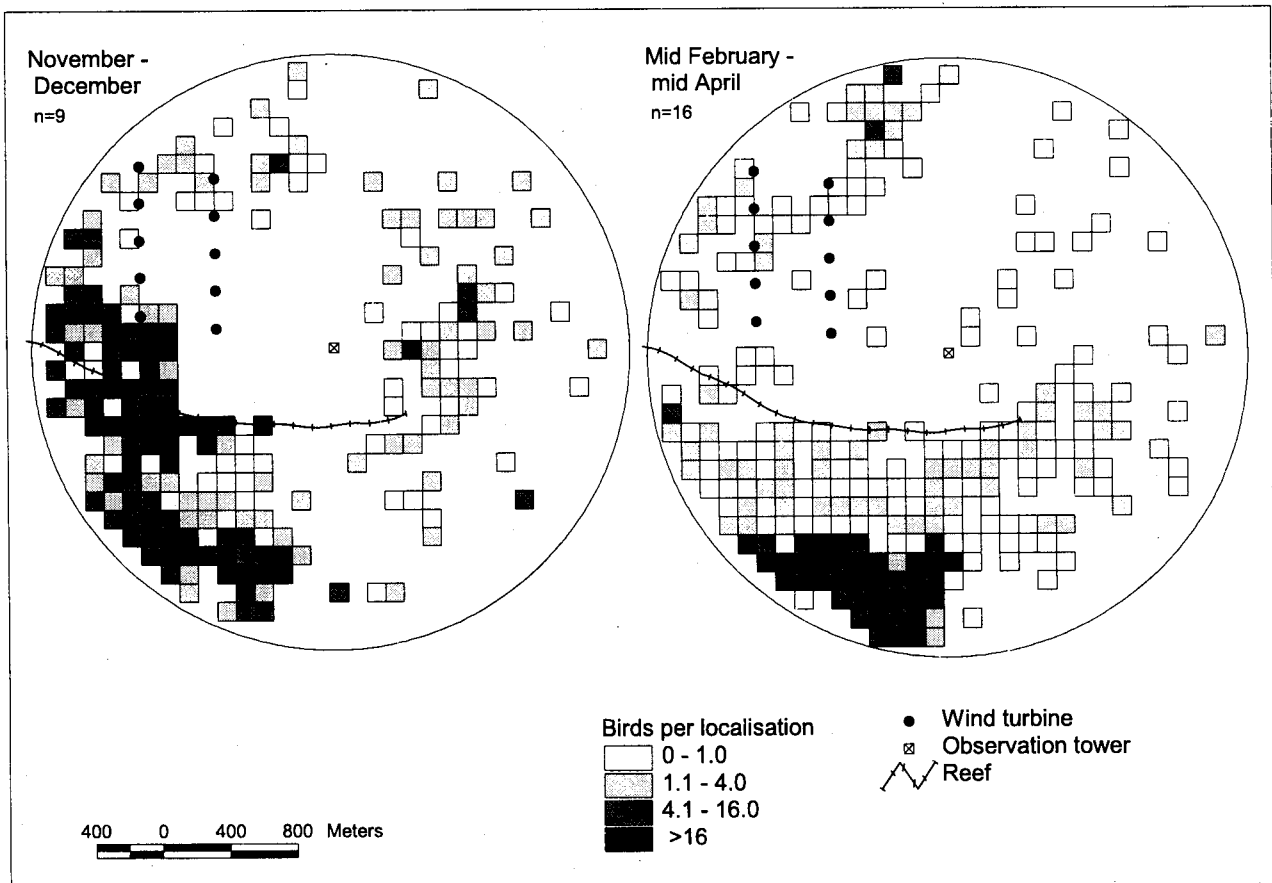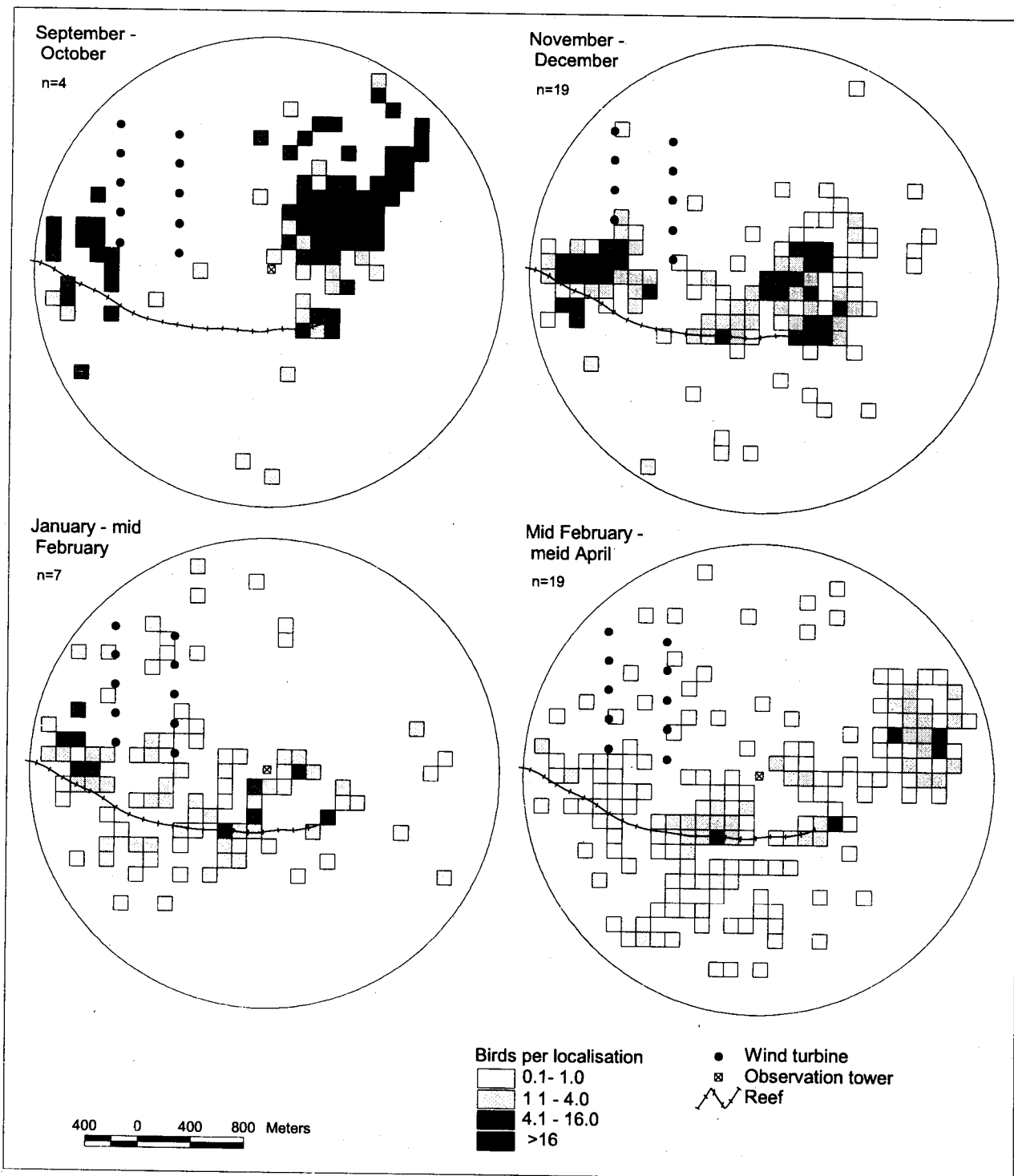
Figure 18. Spatial distribution of common eiders localised from the observation tower at Tunø Knob during the third year of the study (1996-97). The lower right circle (presented in Fig. 16) is included for comparison.

Moreover, in September-October and November-December 1996, the NW subarea was used with some concentrations of birds close to the turbines (Fig. 18). The largest concentration of eiders at this time was localised in the NE sub-area, about 800 m east of the park (Fig. 18). In January-February 1997 the density of eiders decreased, although the distribution of eiders was similar to the one observed for November-December 1996. If the avoidance of the NW area after the base line year was the result of the wind park, it is unlikely that we would have observed eiders in this subarea in November-December 1995 (Fig. 17) and in September-December 1996 (Fig. 18). When taken to-

gether, these results indicate that the distribution of eiders is uneven and varied within and between years. This variability in habitat utilisation may well confound any impact of the wind turbines. One hypothesis to explain such variation in the abundance and distribution of common eiders is that they track food on large spatial and time scales.

4.5 Abundance of scoters: comparing TK and RS

The abundance of common scoters at TK during the base line year was below 200 individuals until mid-March, increased to a peak of about 700 individuals for the second half of March and then decreased until mid-April (Fig. 19). In 1995-96 it decreased considerably, the number of individuals fluctuating around 60 individuals and decreased even further in 1996-97 with only seven individuals on average. For RS, the average number during the base line was 222 individuals with a more stable pattern of fluctuation than at TK (Fig. 19). The fluctuation in abundance was greatest in 1995-96 with a similar average number of individuals (272) whereas no scoters were seen at RS in 1996-97. Using the confidence interval approach, the number of scoters at TK decreased steadily and significantly from the base line to the third year of the study compared to RS where numbers were somewhat stable the two first years but nevertheless decreased to none the last year (Fig. 20). Looking now at simultaneous surveys, a similar conclusion is reached in the sense that the confidence intervals of the deltas overlapped completely during the three years (Fig. 20). This means that the deltas in scoter abundance remained the same when the base line year is compared with 1995-96 and 1996-97 and suggests, despite the low numbers recorded, that the wind park did not have an influence on the abundance of scoters.

4.6 Investigations around the wind park

Our objective at this point of the investigation is to look at a possible impact at closer distances around the turbines. As we get closer to the wind park in our investigation, the probability of detecting a negative impact increases.

4.6.1 The on-off experiment
The objective of this experiment was to disentangle any effect of the noise and revolving rotors generated by operating turbines from the standing towers on the abundance and the distribution of common eiders. In total 29 pairs of control-treatment were obtained during the third winter of the study from November 11 1996 to March 31 1997 on which 15 pairs started with the treatment (operating the first day and then stopped the second), the remainder 14 starting with the control. The results of this experiment are presented in Fig. 21. We plotted the number of birds counted during the running treatment (x-axis) with the number of birds counted during controls (motionless rotor on y-axis). The line drawn for each zone considered is theoreti-

TK 1994-95

Mean (SD) = 338 (304)

Number of scoters

1200
1000
800
600
400
200
0

16-feb 23-feb 02-mar 07-mar 14-mar 22-mar 24-mar 05-apr 11-apr

RS 1994-95

Mean (SD) = 222 (195)

1200
1000
800
600
400
200
0

16-feb 21-feb 24-feb 10-mar 16-mar 18-mar 20-mar 24-mar 26-mar 29-mar 04-apr 06-apr

TK 1995-96

Mean (SD) = 62 (62)

Number of scoters

1200
1000
800
600
400
200
0

16-feb 28-feb 09-mar 15-mar 22-mar 25-mar 28-mar 31-mar 03-apr 08-apr

RS 1995-96

Mean (SD) = 272 (325)

1200
1000
800
600
400
200
0

16-feb 24-feb 02-mar 08-mar 12-mar 18-mar 21-mar 25-mar 27-mar 30-mar 03-apr 05-apr

TK 1996-97

Mean (SD) = 7 (10)

Number of scoters

1200
1000
800
600
400
200
0

16-feb 21-feb 06-mar 08-mar 13-mar 15-mar 20-mar 22-mar 30-mar 05-apr 11-apr

No scoters at RS in 1996-97

Figure 19. Abundance of common scoters at Tunø Knob (TK) and Ringebjerg Sand (RS) as counted from observation towers during three years (baseline year shaded). The mean (SD) number of individuals is shown for each year and site. Note that the study period used in this investigation spans from mid-February to mid-April, except for TK in 1995-96 where ground surveys were only conducted from mid-March to mid-April.

cal and shows perfect correspondence between numbers on x and y axes (i.e. equality).

Therefore, more points above the equality line would mean more individuals in that zone when the turbines are stopped whereas more points below the equality line would mean more birds during the running treatment. For the zone including the park itself and a distance of 200 meters around it no significant difference were found between the treatment and the control (t = 1.58, P = 0,137, n = 29), although there was a tendency for more birds to occur during the

A   **Average numbers for all ground surveys**

B   **Average deltas for simultaneous surveys**

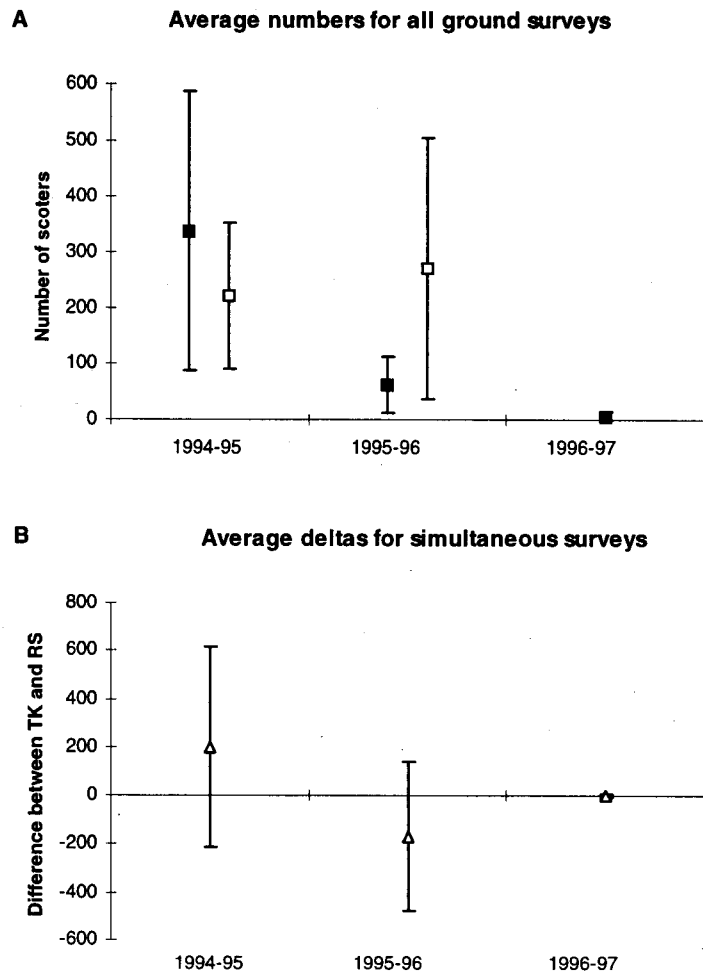*Figure 20.* A) Average abundance of common scoters and 90% confidence intervals (see methods) for Tunø Knob (TK) and Ringebjerg Sand (RS) over three years (1994-95 = baseline year) based on all ground surveys (sample sizes as in Fig. 8). B) Average difference in scoter numbers between TK and RS (= delta) and 90% confidence intervals for simultaneous ground surveys.

operating treatment (mean = 14.5 eiders) than during controls (mean = 10.7 eiders) (Fig. 21). A similar result was obtained for the zone 200-600 m around the wind park as no significant ($t = 0.670$, $P = 0.508$, $n = 29$) difference was found between controls (mean = 60.4 eiders) and treatments (mean = 72.4 eiders), the points being loosely clustered around the equality line.

We looked further at the results of this experiment by mapping the distribution of eiders around the wind park for the two experimental conditions (Fig. 22). It is clear from these maps that the distribution of the birds did not differ between treatments (operating turbines) and controls (stopped turbines). For example, grids with intermediate density of eiders (0.1 -16 eiders per ha) were located in the same region of the 200-600 m zone, that is in the south-west and south-east corner. The similitude is less obvious for the park-200 m zone where there is a tendency to have more birds within the park during the treatment than during controls (Fig. 22). Nevertheless, we conclude
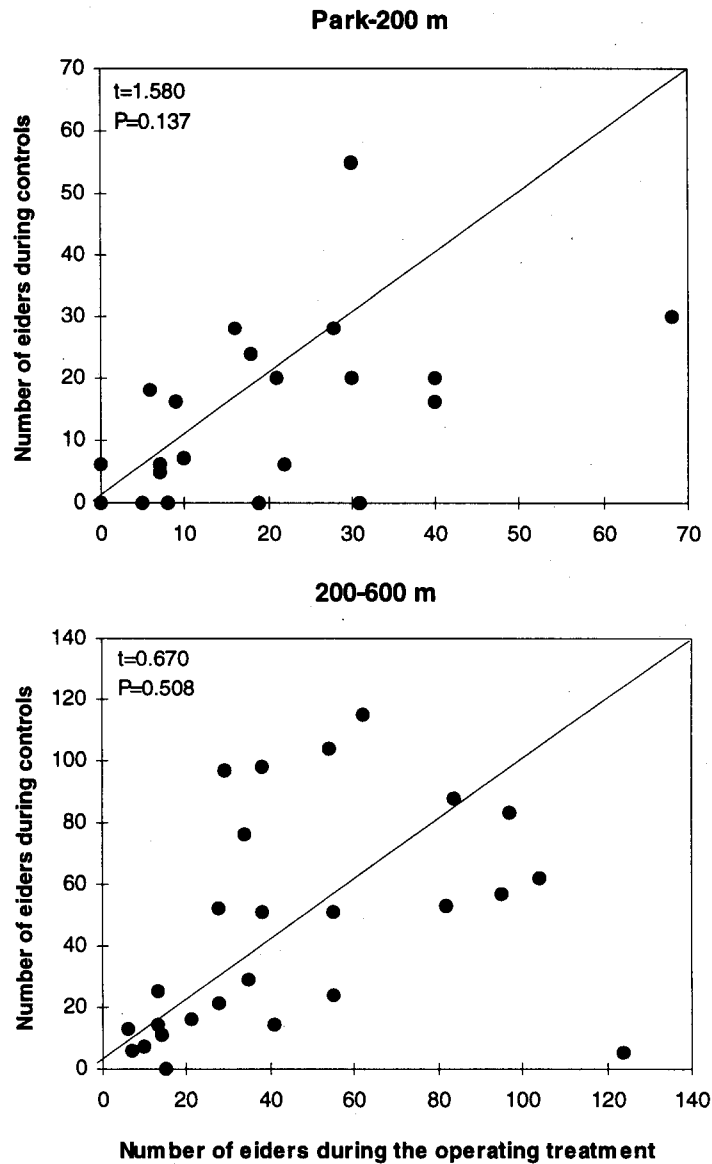
Figure 21. Relationship between the number of eiders during the operating treatments and the number of eiders during controls (motionless rotor) for two zones. Shown on each graph is the line of equality which represents a perfect match between treatment and control conditions and the results of a paired t-test testing for a departure from the equality line.

from this, that operating wind turbines do not negatively affect eiders abundance nor their spatial distribution.

In order to complement this experiment, we looked at behavioural reactions of eiders when turbines were switched-on again after being switched-off for at least one full day. To do this we chose a focal flock that was followed continuously for half an hour before and half an hour after the conditions of the turbines changed. During these one hour interval the focal flock was localised at least every 5 min. in order to find out if the flock was moving away from the wind park. The first important result of this experiment is that none of the ten flocks (from one to ten individuals) sampled flew away when the turbines were switched on again.
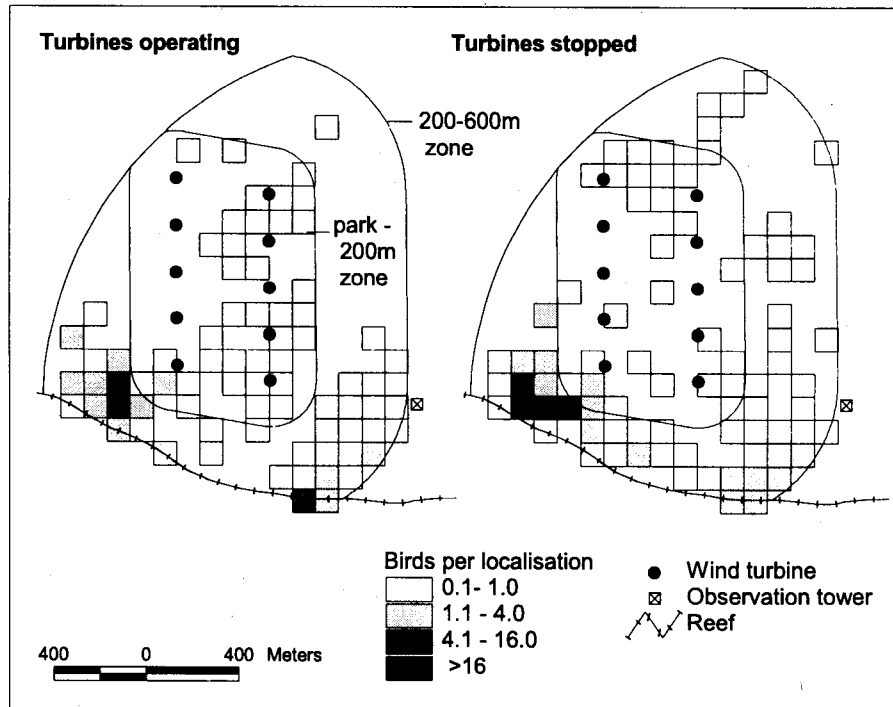
Figure 22. Spatial distribution of common eiders during treatment (operating turbines) and control (motionless rotor) conditions.

This applies in a similar fashion to the six flocks within 200 m of the wind park and the four others that were observed between 200 and 600 m from the wind park. Looking at their behaviour on the water, we observed that the distance from their original position (before the turbines were switched-on) to five minutes after the turbines were switched on did not differ for both categories of distance (Fig. 23). A similar conclusion is reached when longer time intervals are considered. Thus, these results indicate that eiders found in small flocks were not scared when the turbines were switched-on again and support the result of the on-off experiment shown above.

Figure 23. Movements of common eider flocks located within two zones around the park when turbines were switched-on again from a motionless condition. Shown here is the distance (in m) swum for each focal-flock from its original position five min. after the turbines were switched-on.

45

4.6.2 The exploitation experiment

Another way to remove the confounding effect of food supply is to measure its abundance.

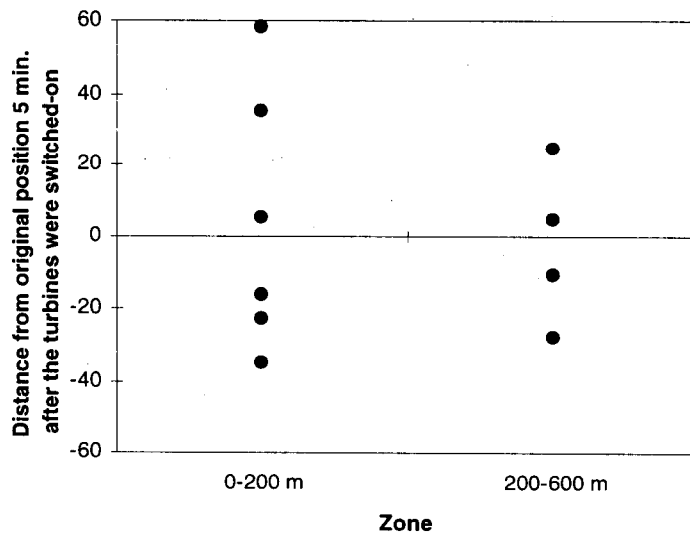From 76 surveys, the total number of eiders in each quadrate on morning counts (n = 38) varied between 744 and 23 individuals whereas it varied from 103 to 0 individuals during afternoon counts (n = 38) (Fig. 24). Thus, for some unknown reason the total number of birds differed greatly between morning and afternoon counts. Nevertheless, we used the morning and afternoon counts separately to look at the relationship between the amount of food and the number of eiders using one quadrate. For both morning and afternoon counts, the total number of eiders using one quadrate followed closely the total biomass of *Cardium* and *Spisula* estimated, which varied between 1 and 12 tons fresh weight. In both cases the coefficient of determination is extremely high, explaining 98 % of the variation for the morning counts and 93 % for the afternoon counts (Fig. 24).
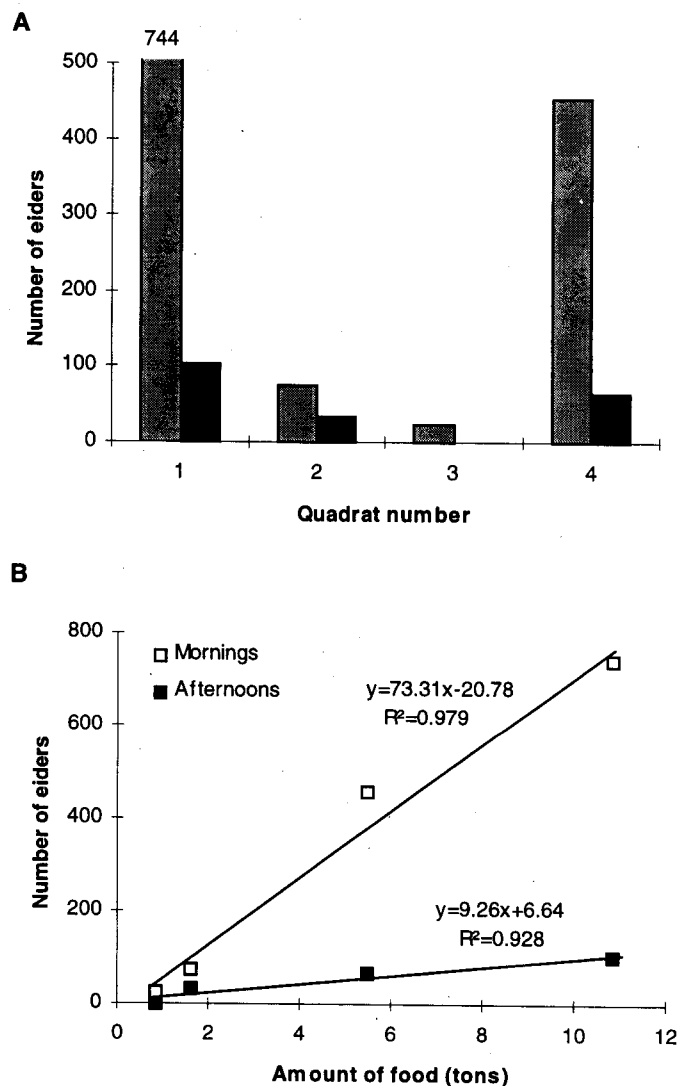

Figure 24. A) Total number of eiders for each quadrate as counted during 38 morning and 38 afternoon surveys from November 1996 to April 1997. B) Relationship between the total number of eiders and the total amount of food estimated in each quadrate.

A

y=0.966x+0.009
R²=0.948

(Y-axis: Proportion of eiders, values 0,0 0,1 0,2 0,3 0,4 0,5 0,6)
(X-axis: Proportion of food, values 0,0 0,1 0,2 0,3 0,4 0,5 0,6)

□ Mornings
■ Afternoons

B

(Y-axis: Selection index, values 0 0,5 1 1,5 2)
(X-axis: Distance (m) from wind turbines, values 0 100 200 300 400 500 600)

1   2 3   4

Quadrat number
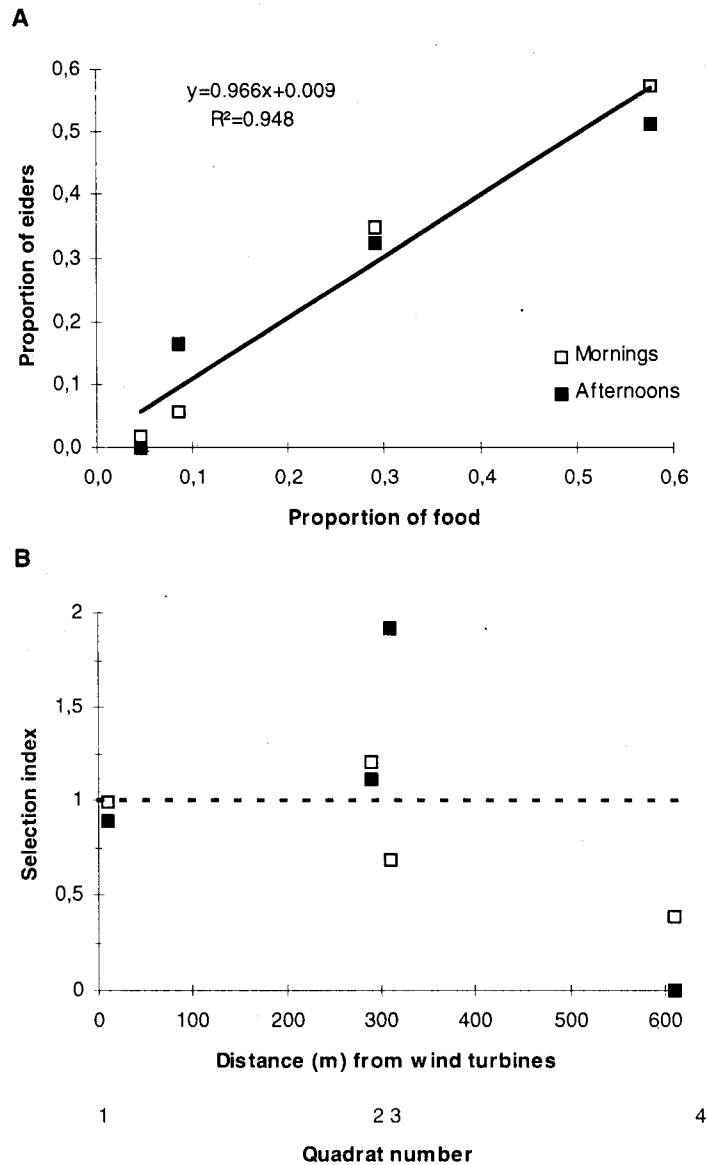
Figure 25. A) Relationship between the proportion of food and the proportion of eiders in each experimental quadrate. The regression equation for morning counts (squares) is Y = 0.920x -0.019 and for afternoon counts (circles) is Y = 1.069x -0.017. The regression equation shown on the graph was calculated with eight data points. B) Selection index (proportional use/proportional availability) for the four quadrates in relation to distance from the wind park. The average selection index for both years is 0.94, 1.15, 1.30 and 0.20 for quadrate 1, 2, 3 and 4, respectively.

In other words, the variation in eider numbers counted in one quadrate is almost entirely explained by the amount of food present, thus leaving very little room for any effect of the wind turbines.

When expressed in relative values, the match between the proportional use and the proportion of food biomass is very good (Fig. 25a). Both morning (slope = 0.920, intercept = 0.019, R^2 = 0.979, n = 4) and afternoon (slope = 1.069, intercept = -0.017, R^2 = 0.923, n = 4) counts gave similar slopes and intercepts. Indeed, the 90% confidence intervals of the two slopes overlapped greatly and included the theoretical slope of 1 as predicted by the habitat matching rule (morning

counts CI = 0.640-1.200, afternoon counts CI = 0.458-1.680). If we compute now the patch selection index, which is the ratio of proportional use by eiders divided by the proportion of food present, we show how it varied for the four quadrates in relation to the distance from the wind turbines (Fig. 25b). The quadrate positioned with one windmill in its centre (quadrate 1, distance = 0) obtains an average value of 0.94 which is very close of the theoretical value of one. Quadrates at distance of 300 and 320 m from the wind turbines also obtained average values close to one with 1.15 and 1.30, respectively. In contrast, the quadrate at 600 m from the turbines obtained a value of 0.20 which suggested that this quadrate was under-used (Fig. 25b). This last quadrate was characterised by the lowest amount of food found among all quadrates which could explain this result; low levels of food should attract a low number of eiders which approaches levels which are difficult to detect (i. e. it would need a greater number of surveys). Nevertheless, we conclude from these results that when we take into account the confounding effect of food supply on a long time scale (a whole winter), the wind turbines do not play any role in the abundance and the distribution of eiders within the studied distances.

4.6.3 The decoys experiment

In this experiment, we measured the rate at which eiders attempt to land or actually landed (= reacting birds) within any particular group of decoys (see Fig. 3). The results of seven trials conducted simultaneously on the western and eastern side of the wind park are presented in Fig. 26a. It shows clearly that the frequency of landing was much reduced in the 100 m patch compared to the further patches. Indeed, the average frequency of reacting birds (when back-transformed) was 20.4 birds per trial in the 500 m patch and 20.7 birds per trial in the 300 m patch while it was only 4.8 birds per trial in the 100 m patch. In addition, the similitude of the eider response for both sides of the wind park is striking (Fig. 26a). Not surprisingly, a two-way ANOVA indicates that the location of a line of decoys (western or eastern side of the wind park) had no effect on eider response ($F = 0.082$, $P = 0.776$), that no interaction between line location and patch positions was significant ($F = 0.321$, $P = 0.728$) and that only patch positions had an effect on the flying behaviour of eiders ($F = 10.44$, $P < 0.001$).

These results do not tell us, however, if eiders are reluctant to land or to fly at close distances of the wind park. In other words, where to fly and where to land may represent two different decisions taken by the birds. We thus looked at the flying rates of eiders entering three corridors located at increasing distances from the wind park (see Fig. 3) and succeeded in performing 4 simultaneous trials on both sides of the wind park. The pattern observed is very similar to the one observed for reacting birds (Fig. 26b) and we pooled the data for the two sides of the wind park to increase the power of our analysis (total of 8 trials). A one-way ANOVA indicates that these three corridors were significantly different in terms of flying rate ($F = 5.27$, $P = 0.014$, df = 2 and 23). Indeed, it was much lower for the closest corridor A (= 18.7 eiders in average per trial of 90 min) compared to corridors B (=37.0) and C (= 35.0) which had a similar flying rate.
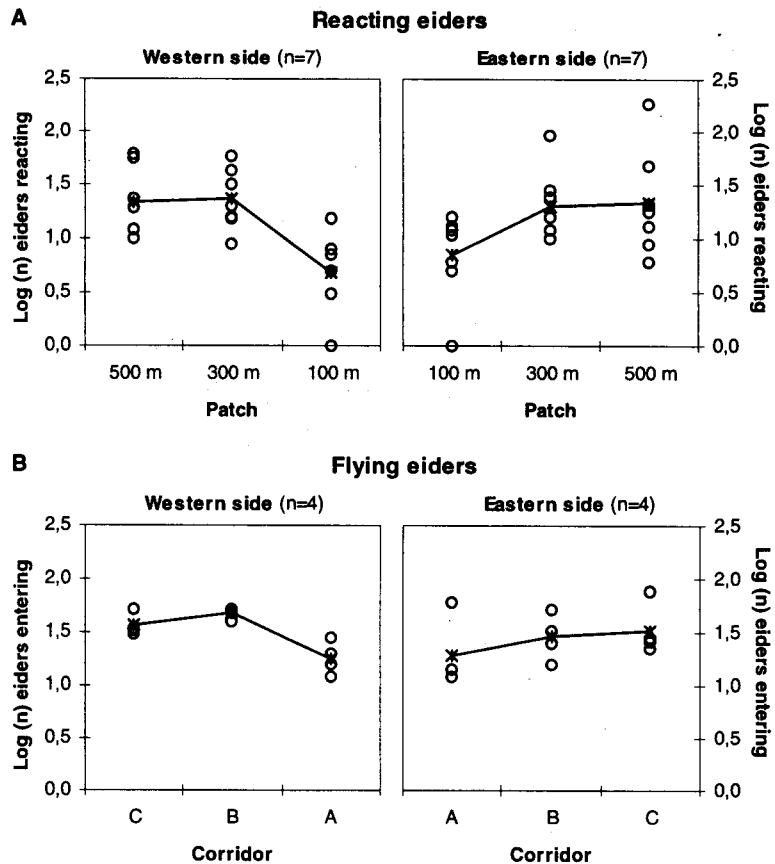
Figure 26. Behavioural responses of flying and reacting (landing and attempting to land) eiders at different distances from the wind park. A) Absolute number of eiders reacting to patches of decoys. Data presented are from seven trials (of 90 min each) conducted simultaneously on the western and the eastern side of the wind park (total number of trials = 14). B) Absolute number of eiders flying within corridors as defined in Fig. 25.

However, the decrease in flying rate from corridor B to A is less (50%) than the decrease in the reacting rates from 300 m patch to 100 m patch (80%). This indicates that the birds reacting rate observed above is caused partly by a flying rate decreasing from off-shore toward the wind park. We thus conclude from this experiment that eiders both avoid to fly and to land in close proximity (100 m) to the wind park.

5 SUMMARY and CONCLUSIONS

Several approaches have been used to test the impact of the Tunø Knob off-shore wind park on sea ducks. A summary of the different investigations conducted and conclusions obtained during this study is presented in Table 3 and in the following sections.

Table 3. Summary of the approaches used and conclusions of this study.

Investigation	Spatial scale (ha)	Design characteristics	Conclusion
Aerial surveys of the whole of Århus Bay comparing the abundance of eiders at TK and RS Before and After the construction of the wind park.	88,000 to 5,000	BACI controlling for the abundance of eiders in the whole of Århus Bay.	Tendency to have fewer eiders at TK *After* the construction while it remained stable at RS. The results are suggestive of an impact (see ground surveys below).
Ground surveys comparing the abundance of eiders at TK and RS Before and After the construction of the wind park.	700 to 800	BACI 'controlling' for the abundance of food at both study sites.	Much lower number of eiders at TK *After* the construction while it was almost stable at RS. This was associated with qualitative and quantitative differences in the biomass of blue mussels between the two sites. The results suggest that the decrease in eider abundance was caused by food supplies and not by the wind park. This interpretation probably also applies to the results of aerial surveys.
Ground surveys comparing the abundance and distribution of eiders within TK.	160 to 245	BACI with three sister areas.	Much lower number of eiders in the presumed impact subarea (NW) *After* the construction of the wind park and similar fluctuations in the sister subareas. Large inter-annual and seasonal variations in the distribution of the eiders. The results suggest that fluctuations in eider numbers were caused by natural variation and not by the wind park. This interpretation also applies to their spatial distribution.
On-off experiment comparing the abundance and distribution of eiders.	40 to 230	Experiment randomising the effect of food supply.	Similar number of eiders when controls and treatments are compared. The noise and the movements of the rotor do not affect negatively the abundance and the distribution of eiders.
Exploitation experiment comparing the proportion of eiders at different distances from the wind park on a winter basis.	40 to 230	Manipulative experiment controlling for the influence of food supply.	Similar proportion of eiders (corrected for food supply) at different distances of the wind park. Both, the standing towers and the revolving rotors did not influence the abundance of eiders on a winter basis.
The decoys experiment testing the impact of the wind park on flying eiders.	40 to 230	Manipulative experiment 'attracting' eiders to land at different distances of the wind park.	Eiders avoided flying and landing within 100 m of the wind park. This should decrease the probability of collision with the standing towers (in good weather conditions).

5.1 Comparison between TK and RS

The results from the aerial surveys showed a clear tendency to have less eiders at TK during the *After* period when the data are 'controlled' (using a regression approach) for the abundance in the whole of Århus Bay. Although this tendency was not statistically significant a similar trend was observed amongst ground surveys. Indeed, we showed that eider numbers decreased considerably at TK from the base line year to the *After* period. It was also shown that eider numbers differed greatly between the control (RS) and the pre-

sumed impact area (TK). These results were highly suggestive of a negative impact of the wind park. The data relating to the abundance of blue mussels indicate, however, that mussels of small (0-15 mm) size decreased from the base line year to 1995-96 for both sites and that TK and RS differed markedly in 1995-96 and 1996-97 in terms of biomass of suitable mussels. When the biomass of mussels of 3-40 mm length is estimated from our data and is related with the average number of eiders found at both sites (n = 2 sites x 3 years = 6), a strong relationship is found between the two variables. This suggests that the variation in eider numbers at both sites among the three years was a result of the variation in the amount of food supply and not of the wind park. However, this correlation between food supply and average eider numbers must be taken with caution, mainly because our measure of mussel biomass was estimated at the beginning of the winter whereas our measure of eider abundance was estimated for the study period which corresponds roughly to the spring season. Therefore, this hypothesis could be tested properly only by measuring again eider abundance and distribution during a year of high mussel abundance. Nevertheless, it cannot be concluded, at this large spatial scale, that the presence of the wind park is having an effect on eider abundance. In light of this and the observation that the density of many benthic groups decreased during that study, we speculate that a similar interpretation could apply to the results of the aerial surveys.

5.2 Comparison between years within TK

One of the weaknesses of the TK-RS comparison made above is that only one control site was used. In our *Before-After* comparison made within TK, we were able to use three sister sites. Our data indicate that eider abundance within these sites (NE, SW and SE) and the presumed impact area (NW) varied in a similar fashion (positive correlations) during the base line year. Subsequently, these correlations decreased in 1995-96 to become negative in 1996-97. When a similar correlation analysis was applied among the sister subareas only, we obtained a similar drop in the correlation level from the base line year to 1996-97 suggesting that variation in the abundance of eiders was natural and not caused by the wind park.

When we look at the spatial distribution, the data suggest that eiders avoided the presumed impact subarea (NW) after the construction of the wind park. This observation is misleading and may have occurred by chance as the localisations made outside the study period (mid-February-mid-April) showed. Indeed, we observed that eiders were using the NW area in November-December 1995, 3 months after completion of the construction. In addition, large densities of eiders were observed in September-October 1996 and during November-December 1996, sometimes within a short distance of the wind park. When comparing the spatial distribution of common eiders between and within years, the overlap in habitat (grid) utilisation is small. This suggests that eiders are tracking food supply on large temporal scales and that the 'history' of benthic communities may play a role in this respect. For instance, benthic species are very often long-lived organisms with irregular recruitment (which may be much reduced

or completely absent for few years in a row) while the occurrence of predation and physical factors may have a cumulative effect on population sizes over the years.

5.3 Around the wind park

Because the variability of the system is so large it is worthwhile (1) to randomise the potential effect of food supply or (2) to get rid of that effect in our analysis by measuring it. We thus used these two approaches at distances close to the wind park (0-600 m) by designing two specific experiments. The on-off experiment showed, by alternating observations between periods of motionless wind turbines and periods of operating turbines, that eider abundance and spatial distribution was not negatively affected by the movements and noise generated by the active turbines. This applied to the zone between 200 and 600 m from the wind turbines and to the zone including the park itself plus a zone of 200 m around the wind park.

The approach with the exploitation experiment was to get rid of the confounding effect of food supply by measuring food abundance for four quadrates of similar size. We positioned these quadrates at different distances from the wind park with one of them at distance zero with a turbine at its centre. We found a very strong relationship between the number of eiders counted during a whole winter (November-April) and the amount of food estimated in a quadrate. The fact that the variation explained by this relationship exceeded 92% indicates that there is little room for any other major influence (e.g. the wind turbines). Moreover, for each quadrate taken separately the selection index is also very close to one, except for the furthest (600 m) quadrate (and also with the lowest amount of food), indicating that overall, the three closest quadrates closely followed the prediction 'more food more birds'. Altogether, this indicates that the wind turbines, during the winter 1996-97, did not have any effect on the distribution and abundance of common eiders.

5.4 Power of statistical tests

One of the main problem often discussed in the field of environmental impact assessment (EIA) is the low power of the studies which is related to poor design and small sample sizes. Simply expressed, the concept of power is how confident a scientist can be when he accepts the null hypothesis of no effect or no impact in the case of EIA. Thus, concerns about the power of an experiment arise when one uses inferential statistics. This is an important question and it lies at the root of the scientific inquiries (see the recent contributions of Hayes & Steidl 1997, Reed & Blaustein 1997, Thomas 1997) and also because the lack of negative impact, as documented here, is likely to occur in EIA. The power of statistical testing is related to sample sizes, the variability of the phenomenon studied and the effect size (Toft & Shea 1983, Rotenberry & Wiens 1985, Peterman 1990). Investigations conducted in the course of this study that may be subject to low power (where we accept the null hypothesis) are the

aerial surveys, the on-off experiment and the exploitation experiment. We deal with each of these investigations below.

Aerial surveys
One way to find out *a priori* about power of an experiment is to compute what would be sample sizes required to detect a particular effect size associated with a sample of known variability. We used this approach and computer simulations with the Before aerial data where it was found that 9 surveys would have been necessary after the construction of the wind park to detect a significant (P was set at 0.10) difference of 50% (= effect size). Since we judged that such a large difference was unlikely to occur, we decided to conduct a limited number of surveys during the *After* period (we finally conducted seven additional surveys where eider abundance at TK was 32% lower when compared to the Before data, see Fig. 4). Therefore, the low power of aerial survey approach was 'accepted' *a priori* in our investigation considering that ground surveys were also conducted at a smaller spatial scale.

The on-off-experiment
We accepted the null hypothesis of no difference between controls and treatments in this experiment (Fig. 21) with a P value of 0.137 for the park-200 m zone and 0.508 for the 200-600 m zone. One could argue that the power of the paired t-test used (especially of the park-200 m zone) was low given the variability of the phenomenon. One point must be kept in mind with these results however. If any tendency exists for the park-200 m zone it is for more eiders being present during the running treatment, which is contrary to what one would expect from an impact of the operating turbines. Therefore, whatever the power of our statistical test the conclusion will stay the same, operating wind turbines do not decrease the abundance and do not affect *negatively* the spatial distribution of common eiders.

The exploitation experiment
For this experiment, we tested if the observations for the four experimental quadrates fitted a theoretical slope of one translating the habitat matching rule, that is the proportion of eiders in a quadrate should be equal to the proportion of food estimated in that same quadrate. Ninety percent confidence intervals of the observed slopes included that theoretical value of one and one could argue that four points (=quadrates) is a low sample size and thus subject to low power. Two reasons led us to believe that low power is not a problem in our analysis. The first one is that the relationship between the abundance of food and the abundance of eiders is highly significant and characterised by a very high coefficient of determination, thus leaving very little room for other factors (e. g. the wind park) to play a role. The second reason is that the value of the observed slope (0.97) and the values of patch selection index are very close to one which is what we should expect under the null hypothesis.

Finally, except for the aerial surveys we did not perform power analyses. Instead, we tried to falsify the null hypothesis of no impact with five different approaches and experiments (Table 3) which is, in our opinion, much stronger than any power analysis done on a single set of data.

5.5 Comparison with other studies

In two recent reviews of the impact of wind turbines on bird life, it was concluded that collision with such structures does not occur at an alarmingly high rate, being less than 2 birds killed/year/turbine (Benner et al. 1993, Clausager & Nøhr 1995). No data on bird collisions has been gathered in our study, although we showed that flying and landing rates of common eiders were lower at close distances from the wind park. This should decrease the probability of collision with each turbine. This interpretation applies, however, only to good weather conditions since Still et al. (1994) recorded 9 collisions of common eiders during conditions of low visibility compared to none in good conditions. Since foggy conditions are frequent in Danish waters and often associated with the absence of wind and motionless rotors, this aspect requires a thorough investigation. This is particularly true if one consider the (very large) size of the population at risk and the scale of future development of off-shore wind energy.

Although Benner et al. (1993) judged all the disturbance studies reviewed by them as of questionable value, disturbance effects on resting and foraging birds are considered to be the main impact caused by wind turbines (Benner et al. 1993, Clausager & Nøhr 1995). For example, Clausager & Nøhr (1995) reported that the distances at which birds reacted varied between 100 and 800 m from the wind park depending on the species concerned (the waders being the most sensitive), the size and the location of the turbines. This contrasts sharply with the findings reported here (see results of the on-off and exploitation experiments). Assuming that results reported by Clausager & Nøhr (1995) are correct, there are two possibilities to explain this apparent disparity. The first one is that common eiders easily and rapidly adapt themselves to this type of potential disturbance in contrast to other species. The second one is that the experiments conducted around the wind park were performed only with (the existing) small-flock individuals which are less sensitive to disturbance than large-flock individuals (M. Guillemette personal observation).

5.6 Conclusions

As a final conclusion, it was impossible to show any influence of the wind park on the distribution and abundance of common eiders at the large (TK and RS) and intermediate (within TK) spatial scales. The results of benthos surveys suggest that the decrease in abundance of eiders from *Before* to *After* the construction of the wind park was driven by the food supply which varied differently in the TK and RS study sites. Given the low number of scoters observed during that study and the difficulty to conduct specific experiments with them, our study is thus inconclusive for this species. Within TK, the fact that eider abundance and distribution on three sister subareas behaved in similar fashions to the presumed impact area suggest that the decrease in common eiders observed from *Before* to *After* the construction of the wind park was caused by natural variation. Experi-

ments conducted at a small spatial scale (around the wind park) showed that wind turbines did not have a negative influence on the distribution and the abundance of small-flock common eiders. Because we could not detect any impact in close proximity to the park, it is less likely that an impact would occur at intermediate and large spatial scales which thus supports the interpretation presented above. The only impact detected in the course of that study was that common eiders avoided flying and landing close within 100 m to the wind park (a conclusion that applies only in presence of wind). Of course, all these observations and conclusions apply to the conditions (park size, species of bird, phases of annual cycle etc.) under which that study was conducted. It must therefore be remembered that many aspects of this problem were not covered by our study (listed below).

6 ASPECTS NOT COVERED BY THIS STUDY

This study did not consider all the aspects that need to be covered if a more general decision is to be taken about the potential impact that off-shore wind parks may have on sea ducks and aquatic birds in general.

6.1 Other species and different phases of the annual cycle

Current knowledge does not permit extrapolating the results of the TK study to other sea ducks species. For example, the scoters have a different flock structure and seem to be more easily disturbed. Depending on the area chosen for a new park, the target species may change which may differ in their relation to the presence of a wind park.

The results of this study do not apply either to different parts of the annual cycle of common eider or other species. We are especially concerned about moulting (flightless) birds. It is known that aquatic and moulting birds are extremely sensitive to disturbance compared to individuals with the capacity to fly. There are large populations of moulting marine birds in Danish waters, mostly sea ducks, divers, grebes and alcids.

6.2 Flock sizes

We worked mostly with small groups of eiders for the experiments while large groups were present only during the base line year. It is

known for waterfowl that large-flock individuals are more easily disturbed than small-flock individuals. Therefore, the conclusions only apply to small flocks or small groups of common eiders. Since most of the wintering population is found in a few very large flocks, it would be imperative to look more closely at the effects of flock size on reactions to such developments.

6.3 Flight behaviour and collision probabilities

In the light of the results obtained, we suggest that any future research related to wind turbines park should look how sea ducks and other marine birds react to large off-shore wind park using radar equipment. These data could be used to calculate a collision probability for sea birds. For example, one study (Dirksen et al. 1997) has showed that flying distances of birds in relation to a wind park decreased under bad weather conditions and during the night. Observations of flight behaviour are difficult or impossible to conduct under these conditions without radar equipment.

6.4 Disturbance by the travelling ships

Both during the construction of off-shore wind parks and later during the maintenance phase a lot of associated boat traffic will occur, which may disturb the birds. In fact, the amount of construction and maintenance work will be proportional to the number of wind turbines in the park and larger park should generate disturbance more often. This is an important aspect since we know, at least, that ships cause disturbance to aquatic birds at close distances. Thus it would be imperative to quantify how detrimental ship traffic may be to aquatic birds.

6.5 Size of the wind park

Tunø Knob is a small wind park compared to planned future projects. Larger wind parks may create impacts which are not possible to detect with small wind parks. For example, it may make a large difference to birds foraging (or flying) below a small group of wind turbines like Tunø Knob compared with a 'forest' of wind turbines extending over 15-20 km^2. In this respect, it would be imperative to conduct studies looking if the area within large wind park is used by the birds.

6.6 Mitigation and prediction of impacts applied to sea ducks

Evidence gathered here (e.g. the exploitation experiment) and elsewhere (Guillemette et al. 1993, Guillemette & Himmelman 1996) suggests strongly that the best way to mitigate any potential impact on sea ducks is to avoid the building of off-shore wind parks on bottoms characterised by large biomass of prey. Thus, any mitigation procedure should incorporate long term measurements of bottom fauna in

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order to quantify the importance of such sites in terms of food supply for sea ducks. This should be associated with censuses of resident populations (winter or summer).

From what is known about the wintering ecology of sea ducks, we would like to make simple predictions about the impact that may arise in the context of building large scale off-shore wind parks. Sea ducks are extremely gregarious and react strongly to the presence of conspecifics by flying toward foraging flocks and then crowding over available food supplies. There are two potential conflicts between wind turbines and birds; the first one is the collision of individuals with the structures itself when flying and the second one is the disturbance effect. We could not demonstrate any impact of the Tunø off-shore wind park on the distribution and abundance of small-flock eiders in this study. Such a conclusion remains to be made for large-flock individuals, for moulting individuals and for other species of sea ducks. If for specific phases of the annual cycle or some species a disturbance effect would be detected, we could consider such disturbances as direct habitat losses for these populations because wind parks would force sea ducks away from potential food supplies on a constant basis.

On the other hand, the lack of disturbance could increase the probability of collision with the turbines. This is because aggregations of sea ducks around turbines (as for eiders in quadrate 1 in the exploitation experiment) would attract conspecifics and therefore increase the probability of collisions. This could be particularly true under foggy and snowy conditions when sea ducks seems to use vocalisations as a cue to find conspecifics (M. Guillemette personal observation). As a conclusion of this speculative discussion we would like to highlight the inverse relationship between two potential negative impacts. The presence of disturbance from off-shore wind parks could potentially lead to important habitat losses for such species. In the absence of disturbance, it could potentially lead to an increase of collisions with turbines. Clearly, more studies are required to document any effects on sea ducks and aquatic birds in general and mitigate potential impacts that may arise from future off-shore wind energy production.

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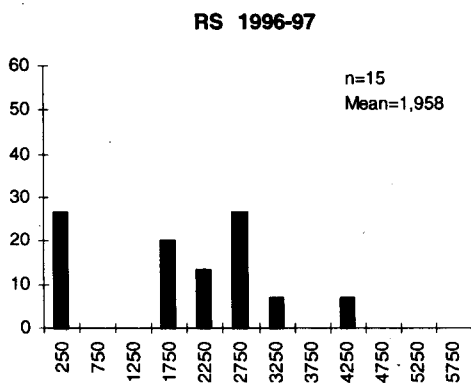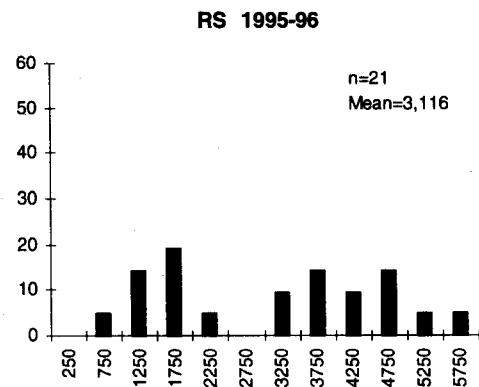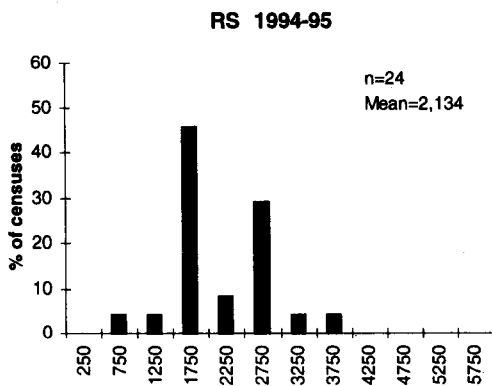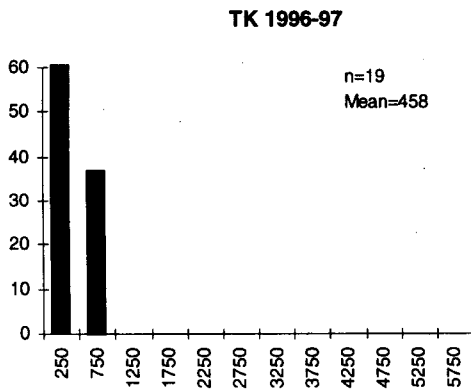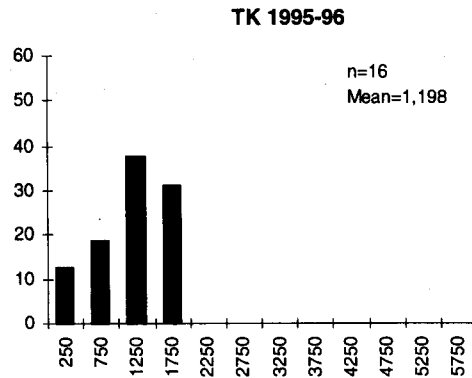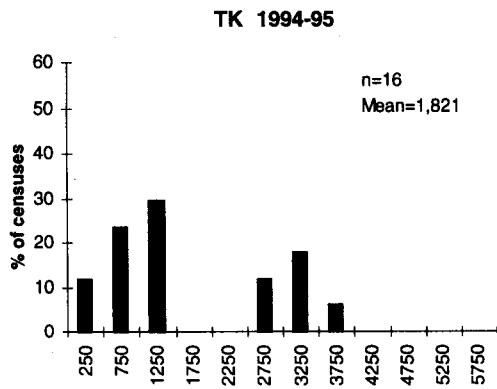
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Annex. Frequency distribution data of common eider abundance based on ground surveys over three years at Tunø Knob (TK) and Ringebjerg Sand (RS).

TK 1994-95

n=16
Mean=1,821

TK 1995-96

n=16
Mean=1,198

TK 1996-97

n=19
Mean=458

RS 1994-95

n=24
Mean=2,134

RS 1995-96

n=21
Mean=3,116

RS 1996-97

n=15
Mean=1,958

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Addresses:

URL: http://www.dmu.dk

National Environmental Research Institute
Frederiksborgvej 399
PO Box 358
DK-4000 Roskilde
Denmark
Tel: +45 46 30 12 00
Fax: +45 46 30 11 14

Management
Personnel and Economy Secretariat
Research and Development Section
Department of Atmospheric Environment
Department of Environmental Chemistry
Department of Policy Analysis
Department of Marine Ecology and Microbiology

National Environmental Research Institute
Vejlsøvej 25
PO Box 413
DK-8600 Silkeborg .
Denmark
Tel: +45 89 20 14 00
Fax: +45 89 20 14 14

Department of Lake and Estuarine Ecology
Department of Terrestrial Ecology
Department of Streams and Riparian areas

National Environmental Research Institute
Grenåvej 12, Kalø
DK-8410 Rønde
Denmark
Tel: +45 89 20 17 00
Fax: +45 89 20 15 14

Department of Landscape Ecology
Department of Coastal Zone Ecology

National Environmental Research Institute
Tagensvej 135, 4
DK-2200 København N
Denmark
Tel: +45 35 82 14 15
Fax: +45 35 82 14 20

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