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Optimizing Habitat Models as a Means for Resolving Environmental Barriers for Wind Farm Developments in the Marine Environment

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1. Introduction

The recent, rapid growth of offshore wind energy has highlighted significant gaps in our ability to properly assess impacts on wildlife species and habitats. Despite the reported and conceived small and local impacts at small and medium-sized offshore wind farms, the experience with future large-scale wind farms may show otherwise. At the same time the industry now faces daunting logistic and scientific challenges as the construction sites move offshore both in relation to the assessment of the status of habitats and species, and in relation to the estimation of environmental effects.

The key problems are lack of reliable models both of the distributional dynamics and of the habitat displacement and related impacts on populations of the species in question. This situation has hampered decision-making in relation to the management of the offshore wind energy sector by introducing unnecessary conflicts with conservation interests. As shown in this paper habitat models may offer solutions to many environmental barriers by providing data in high spatio-temporal resolution about the distribution of sensitive species.

Detailed data about the distribution of sensitive species is required in order to:

- Predict likely changes in distribution arising from natural dynamic change in the marine environment;
- Evaluate more accurately the potential loss of habitat arising from exclusion (displacement) of priority and sensitive fauna from offshore wind farm areas as induced by disturbance and underwater noise emissions;
- Assess the impact of cumulative habitat loss on priority and sensitive species arising from wind farm construction;
- Avoid conflicts in future offshore wind energy schemes associated with environmentally sensitive areas.

The programmes of biological sampling that are typically carried out for the offshore industry have documented problems associated with biological sampling in a dynamic environment. Even benthic habitats are not stable, and as the weather windows during which sampling of species and habitats is typically undertaken are relatively small interpretation and generalisation of results from baseline surveys is often constrained. Examples of such constraints are the lack of information on the distribution of food supply to higher trophic levels like birds, and the lack of information on the variation of habitats at

the site. Thus, the next generation of habitat models does not only require inclusion of dynamic variables, but also requires the application of a process-based approach which integrates ecosystem models and statistical models.

This paper highlights some examples of integrated, dynamic ecosystem and habitat models, which have been applied in relation to recent offshore wind farm projects in Denmark. Time will tell whether dynamic, process-driven habitat models will form the benchmark for future impact assessments in offshore areas, and whether developers and regulators will have access to solid descriptions of local environmental conditions with lower risks for the appearance of unforeseen impacts and environmental barriers (ON/OFF News, 2010).

2. Limitations of biological sampling in offshore environments and the role of habitat models

Integrated models can enable offshore wind farm projects to better demonstrate ecological sustainability in offshore waters, even in the presence of tight time schedules for baseline investigations. Due to the variability of environmental effect parameters in dynamic offshore environments, the risk exists that major dynamics and changes remain undetected by traditional measurements and monitoring, even following prolonged and intensive sampling campaigns. In most cases, developers will be requested to provide solid descriptions of the environmental baseline conditions based on investigations carried out over a relatively limited period of time. Thus, results of baseline investigations in offshore environments are often constrained due to the following factors:

- Uneven coverage;
- Short weather windows;
- Short baseline period;

This situation may have pronounced financial consequences and may give rise to speculations on the scale of possible effects. The experience from the most recent constructions of offshore wind farms shows that the time schedules under which baseline investigations have to be undertaken will be very tight. In some countries like Germany two years of baseline sureys is mandatory, however in other countries like Denmark baseline studies related to the last large-scale projects (Horns Rev 2, Rødsand 2 and Anholt) were undertaken over just one year. Ecological conditions for many offshore sites on the basis of one year of investigations may not be sufficient to detect major dynamics, and may lead to flawed conclusions on the presence of priority habitats and species at or near the site.

3. From static to dynamic habitat models

Optimization of habitat models in the marine environment requires the development of models which are both sufficiently detailed to describe the realized niche occupied by the species in focus and at the same time sufficiently generalized and parsimonious to be able to predict distributions for a range of environmental scenarios. In other words the next generation of marine habitat models needs to include predictor variables which reflect the whole range of scale-dependent processes which form the basis for the distribution of the species at the site. Since marine processes are dynamic by nature marine habitat models need to be designed in a way which describes the range of dynamics of the key processes driving the distribution of the species.

In the environmental programmes related to two of the latest large-scale offshore wind farm project; Horns Rev 2 (2008-2010) and Anholt (2009-2010) DHI used the MIKE modelling framework (Rasmussen, 1991) to facilitate easy and seamless linking of all models required for the full implementation of a local model in relation to the various aspects of the feasibility, construction and operation of the wind farm. The MIKE modelling framework links the basic hydrodynamic and wave modules to the different modules applied for sedimentation processes, water quality, and benthic pelagic environmental conditions. The water level variation and flows are simulated in response to a variety of forcing functions using a stratified model, MIKE3 (DHI Water & Environment, 2000). The water levels and flows are resolved on an array of nested regular grids.

Benthic habitat models have been developed reflecting the links between the variability of the long-lived elements and bio-coenoces of benthic communities in the regions surrounding the sites in the central Kattegat and the North Sea, and measured/modelled parameters like water depth, sediment, sediment grain size, water temperature, oxygen level, contents of organic matter, light attenuation, plankton density, density of suspended material in the water column etc. The resulting statistical species distribution models are directly coupled to the refined hydrodynamic models which produced temporally resolved predictions of local distribution changes of benthic fauna and flora resulting from natural changes in oceanographic conditions. The statistical models could then be used as a basis for evaluating the change in the distribution of target animals and communities, and the relation to the natural variability of the local ecosystem.

The baseline, impact assessment and monitoring studies carried out in relation to the Horns Rev 2 (Leonhard, 2006; Skov & Thomsen, 2006; Skov et al., 2008) and Anholt (Møhlenberg, 2009; Skov et al., 2009) projects highlighted the benefits of adding model data to the results from traditional surveys. The baseline conditions are used as a yardstick to evaluate the permanent changes in benthic habitats following establishment of the wind farms, and temporal effects related to earth works. The merits of using combined hydrodynamic, sediment and biological models as a basis for estimation of environmental impacts can be summarised as:

- Estimation of the realistic scale of impacts;
- Identification of hydrographic and geomorphologic structures and habitats and estimation of their variability;
- Increase of power of sampled data by provision of physio-chemical data;
- Improvement of understanding of the local dynamics of project site and hence interpretation of changes - especially in relation to regional scale events;
- Evaluation of the similarity of reference and impact sites, incl. re-assessment of the location of the reference areas;
- Evaluation of the extent of the monitoring design in relation to the (modelled) level of impact in monitored areas.

4. Application for offshore wind farm developments

The model design applied for the Horns Rev 2 and Anholt offshore wind farms is based on four model elements:

1. A regional and local hydrodynamic model;
2. An ecological model;
3. A deterministic filter-feeder model;
4. A habitat suitability model.

4.1 Hydrodynamic model

Several numerical 3D flow models have been established within the MIKE modelling framework covering the North Sea and Kattegat. Each of these models has individual strengths. With the purpose of water quality modelling, the so-called BANSAI model (DHI, 2006) was chosen as it has been running operationally since 2001. The model provides input data with regard to the flow field and water quality, and consists of two parts:

- A hydrodynamic module for calculating the evolution in water levels, currents, salinity, and water temperature.
- An ecological module that calculates the spreading of nutrients, the primary production, the biomass, and other ecological parameters.

The main objective of this integrated model system is to calculate the environmental status in the area of the wind farm sites. This includes source apportioning, transport, dispersion, transformation and removal in the coastal and open sea marine waters of nutrients inputs to the North and Baltic Seas. Originally the BANSAI model was created in a collaboration between the Swedish Meteorological and Hydrological Institute (SMHI, Sweden), Finnish Institute of Marine Research (FIMR) and DHI.
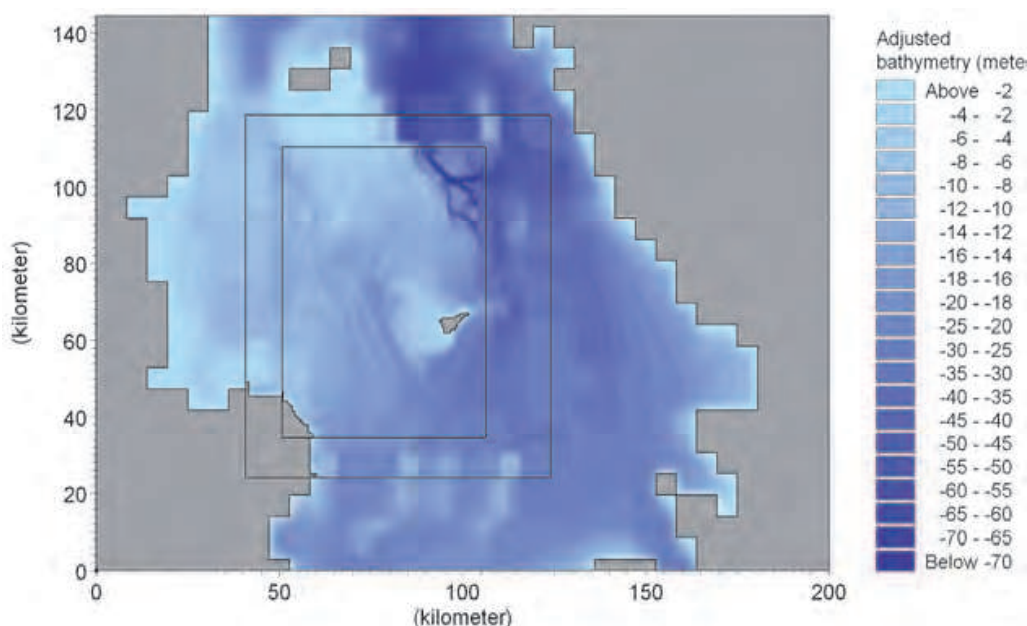

Fig. 1. Example of boundaries and nesting used in the habitat model system for the Anholt offshore wind farm.

The model is using DHI's 3-dimensional model system MIKE3 Classic, which is a fully three-dimensional, non-hydrostatic, primitive equation model (Rasmussen, 1991). It is based on the Reynolds-averaged Navier-Stokes equations and the conservation of mass, salinity and temperature. The prognostic variables are fluid pressure, the three velocity components and the two scalar quantities salt and temperature. In the waters nearest Denmark (the eastern part of the North Sea, Skagerrak, Kattegat, the Belts and the western Baltic) a 3 nautical miles grid is used while a 9 nautical miles grid is used in the North Sea and in the eastern Baltic Sea. The local model applied has this resolution in the outer mesh but by use of the nesting technique this is downscaled by a factor 9 to a resolution of app. 600 m in the area of interest where the wind mills are located. The distance between the wind mills is 600

m – 700 m which means that there will be approximately one wind turbine in each cell in the model area.

The model represents the water column with a 2 m resolution. The model is operational and based on:

- Meteorology;
- Tide, salinity-, temperature and nutrients on the edge of the Atlantic (tide from tidal constituents, salinity and temperature from monthly climatology (ICES), nutrients from climatology supplied with national monitoring data from Denmark and Germany;
- Runoff and nutrient loadings from land (runoff from monthly climatology from HELCOM, OSPAR, national monitoring data) and nutrient loadings from climatology supplied with national monitoring data.

The model was first calibrated based on measurements from the year 2000 and has been continuously improved since then. The representation of salinity in the Belts is extremely important for ecological modelling in the Kattegat, whereas the representation of currents is the key to obtain correct ecological conditions in the eastern part of the North Sea.

4.2 Ecological model

The ecological model consists of an eutrophication model describing the pelagic system with 13 state variables, and seven state variables describing the exchangeable Nitrogen and Phosphorous pools in the sediment (Rasmussen et al., 2009). The pelagic system includes phytoplankton, described in terms of their concentration of carbon (C), nitrogen (N) and phosphorus (P), chlorophyll-a, zooplankton, detritus (C, N & P), inorganic nutrients (dissolved inorganic nitrogen—DIN & PO4–P), total N and P nutrients (including dissolved organic N and P compounds) and dissolved Oxygen (DO). Due to the depth in the wind farm development areas benthic vegetation (i.e. macroalgae) is poorly developed or not existing, and accordingly benthic vegetation is not included in the model. In addition to state variables a large suite of derived variables such as water transparency and secchi depth is modelled and stored during the modelling process. Benthic organisms are not modelled explicitly, but are included as a forcing in the water quality model. Filter-feeding bivalves constitute on average 93% of the entire biomass of benthic invertebrates in the areas, and their filtering activity can exert a significant grazing loss on phytoplankton. Their effect is included in the model by imposing a filtration loss on phytoplankton and detritus in the near bed model layer according to the filtration capacity calculated from length distribution and total biomass of the different species. Because bivalves are not included as a state-variable they do not participate directly in nutrient cycling and accordingly, 50% of filtered algae (C,N,P) are returned as inorganic solutes to the near-bed layer and 50% are entered into the detritus pool subject to sedimentation and remineralisation. Figure 2 shows the state variables and processes for carbon (C) for the pelagic system.

The ecological model was built using the generic equation solver ECOLab that functions as a module in the MIKE 3 simulation software, and ECOLab is linked to the advection-dispersion term of the hydrodynamic flow model, enabling transport mechanisms based on advection-dispersion to be seamlessly integrated into the ECO Lab simulation.

Forcings and boundary conditions of the water quality model follows the line of the forcings and boundaries of the hydrodynamic model, but in addition values for all pelagic state variables at boundaries (Øresund, Southern Kattegat and north of Læsø) and nutrient concentrations in freshwater loads (monthly basis) in addition to atmospheric loads are

included. Boundary values are forced with water quality data extracted from the BANSAI model.
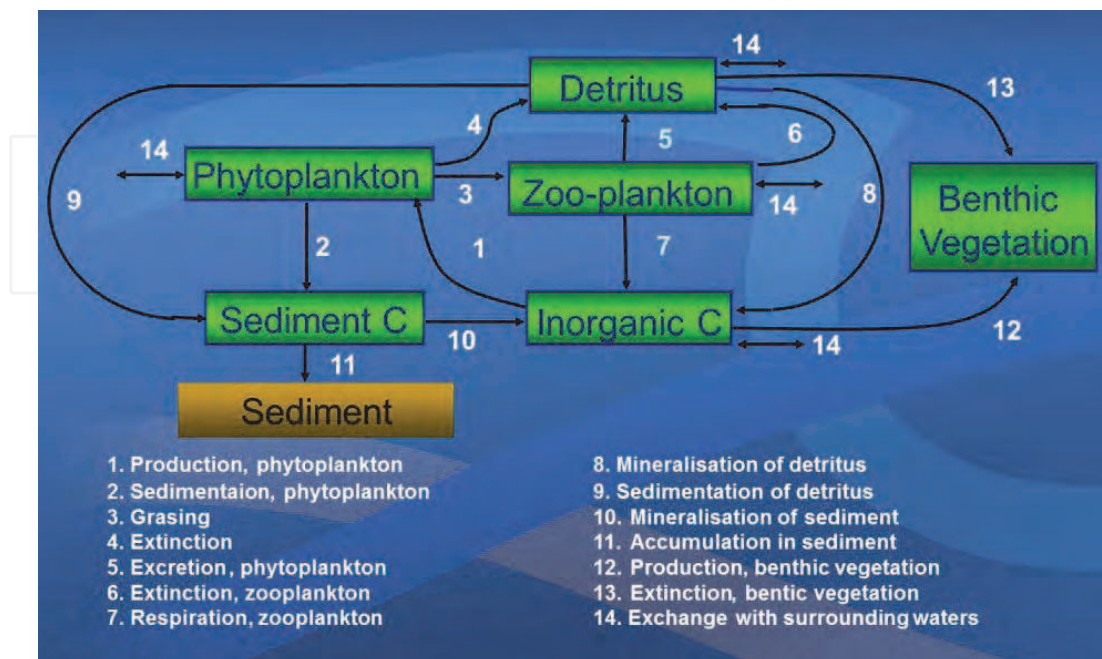

1. Production, phytoplankton
2. Sedimentaion, phytoplankton
3. Grasing
4. Extinction
5. Excretion, phytoplankton
6. Extinction, zooplankton
7. Respiration, zooplankton
8. Mineralisation of detritus
9. Sedimentation of detritus
10. Mineralisation of sediment
11. Accumulation in sediment
12. Production, benthic vegetation
13. Extinction, bentic vegetation
14. Exchange with surrounding waters

Fig. 2. Schematic diagram showing state variables and processes for carbon in the ecological model established to simulate water quality.

4.3 Filter-feeder model

Carrying capacity models for filter-feeders (FF) were established for epibenthic filter-feeding bivalves exemplified by *Mytilus edulis* and *Modiolus modiolus* and infauna filter-feeding bivalves exemplified by *Arctica islandica* and *Spisula subtruncata* in the Kattegat and infauna filter-feeding bivalves in the North Sea exemplified by *Ensis americanus* and *Spisula subtruncata* using the output from the hydrodynamic and water quality models. The FF models build on the same concept by combining a physiology-based growth and survival model for a standard individual with an advection term that replenish the food ingested by filter-feeders. On a large scale benthic FF for filter-feeders depends on the local primary production and on smaller scale current speed plays an increasing role for FF.

The energy balance of a filter-feeding bivalve can be expressed as: $I = P + R_t + F$, where I = ingestion; P = growth, R_t = total respiration (sum of maintenance respiration, R_m, and respiratory cost of growth, R_g), and F = excretion. Rearranging, growth is expressed as $P = I \times AE - (R_m + R_g)$ or $P = (F \times C \times AE) - (R_m + R_g)$, where $AE = (I - F)/I$ = assimilation efficiency, F = filtration rate, and C = algal concentration. In the individual bivalve growth depends on the quantity (C) and quality of suspended food particles including different species of algae, ciliates and zooplankton organisms along with suspended inorganic material (silt). The maintenance food concentration (which just is sufficient for zero growth) and the maximum growth rate for a standard-sized bivalve differs between species and between populations within species as result of adaptation to local composition and concentration of food (Kiørboe & Møhlenberg, 1981). Energetic growth models are available for many filter-feeders, including *Spisula subtruncata* (Kiørboe et al., 1980) and *Mytilus edulis* (Møhlenerg & Kiørboe, 1981, Kiørboe et al., 1981).
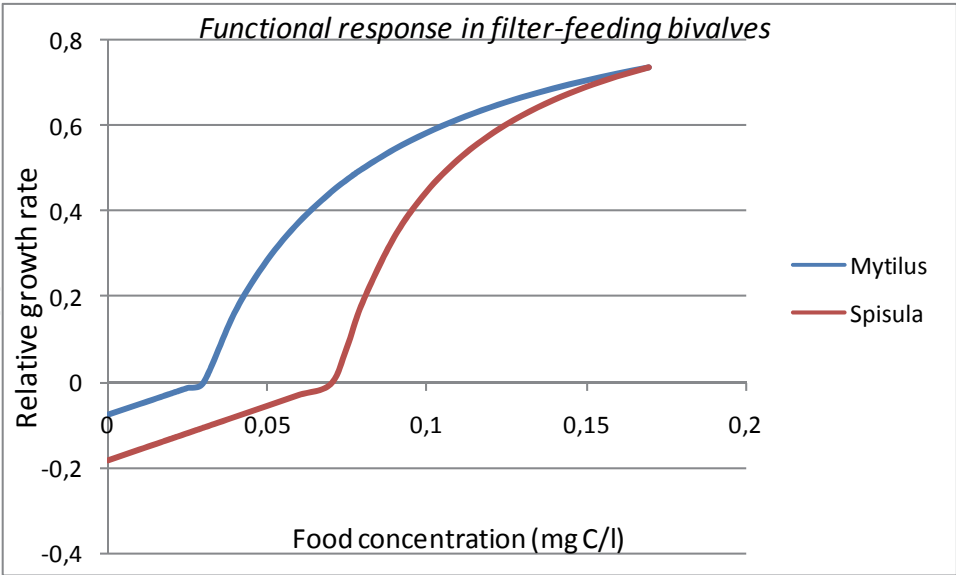
Fig. 3. Comparison of functional response in *Spisula subtruncata* and *Mytilus edulis*.

Important documented evidence for food requirements for *Spisula subtruncata* (Figure 2) includes a rather high maintenance food concentration of 0.072 mgC/l, and that suspended bottom material (i.e. detritus) can constitute up to 30% of assimilated food (Kiørboe et al. (1981). Based on the modelled detritus concentration in the model areas 5% of detritus was assumed to be available for assimilation, hence a growth equation fitted to observed data was developed using non-linear curve-fitting:

For food concentration (PC +0.05*DC) less than 0.072 mg C/l:

Gf = 2.55*(PC+0.05*DC-0.1833)

For food concentration (PC +0.05*DC) above 0.072 mg C/l:

Gf = (PC+0.05*DC-0.072)/(PC+0.05*DC-0.057))

The growth functions described above relate to individual bivalves surrounded by food at constant concentrations. In nature, filter-feeding bivalves aggregate in dense assemblages if current speeds are high, e.g. in tidal areas such as in the Wadden Sea. In low-current environments plankton algae removed by filtration are only slowly replenished and such environments cannot sustain dense populations. Therefore, the growth functions need to be supplemented by an equation that describes the replenishment of food. In *Mytilus* the *in situ* growth rate increases with current speed (Riisgård et al., 1994) and wind-induced turbulence (Sand-Jensen et al., 1994). As bivalves in benthic environments consisting of erodible substrate such as sand cannot maintain their position at current speeds larger than 0.6-1.0 m s^{-1} a bell-shaped current function with an optimum speed at 0.3 m s^{-1} was constructed (Figure 4).

The individual growth function can then be combined with the current function to a 'carrying capacity' index reflecting both individual growth conditions and the density of bivalves that can be sustained:

'CC'-index = Gf * Vf

Controlled experiments of the effects of current speed on growth have only been carried out on oysters, which showed an increase until an optimal current speed of 15 cm s^{-1}, after

which the growth started decreasing. Other bivalve species such as blue mussels increase growth in the field with increasing current speed and wind-induced turbulence until a plateau. This is generally interpreted as a consequence of increasing food availability. Mussels which are settled on substrate like cliffs, stones and foundations may survive and grow in even very energy rich environments (e.g. in current speeds > 60-80 cm s^{-1}), while blue mussels on sandy sediments are unable to establish long-living populations at current speeds exceeding 40-50 cm s^{-1}, probably as a result of erosion.
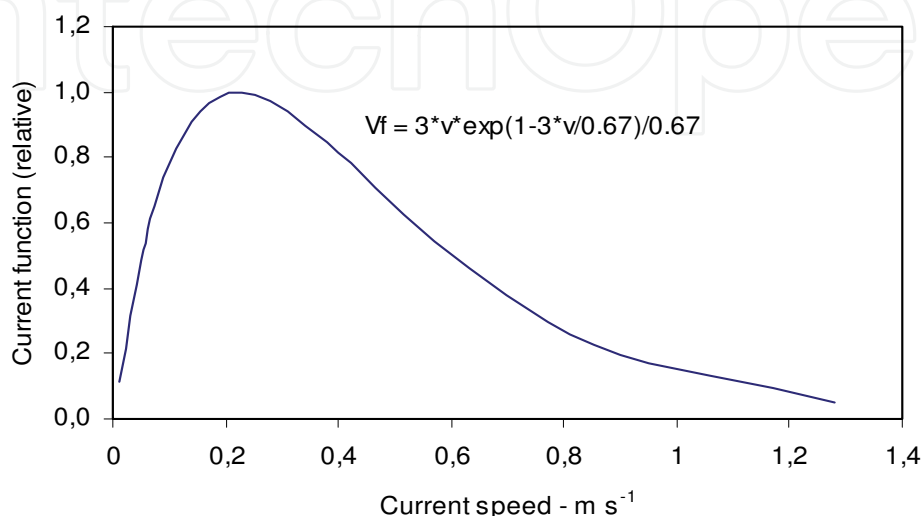
Fig. 4. Current function to describe food replenishment and physical stress in filter-feeding bivalves.

Extended periods with low oxygen concentration can reduce growth and increase mortality in benthic invertebrates including filter-feeders. Such information is included numerically by multiplying the CC-index with a factor (0.8-0.9) for each day oxygen concentration is below 2 mg O_2/l but starting the reduction at day 7 with low oxygen. Also a salinity-dependent function (species-specific) is included in the combined index:

FF-Index=CC index* SF*OF

SF denotes a species dependent salinity index and OF denotes a species independent oxygen index. SF attains values below 1 at salinities less than 20 psu.

The final index for *Mytilus edulis* type in the central Kattegat is shown in Figure 5 for the six years between 2000 and 2005. In general, the index is rather high in the shallow areas at depths less than 12-13 m, whereas at depths larger than 15 m, i.e. where the seabed is located below the pycnocline, the index is rather low due to lower chlorophyll concentrations and lower current speeds. The time series documents a striking stability in the patterns of benthic productivity in the Central Kattegat, and underlines that despite variations the location of the planned Anholt offshore wind farm is always coinciding with the benthic areas of lower productivity.

The model time series of benthic productivity provided a solid basis for the assessment of the importance of the wind farm area to waterbirds. Both baseline and historic survey data unambiguously point at the fact that the waterbirds do not use the wind farm and associated areas with lower carrying capacity for filter-feeding bivalves to any great extent (Figure 6). The areas of high carrying capacity for mussel growth (> 0.15), which match

exactly the most sensitive areas to the waterbirds in the Central Kattegat are located at a minimum distance of 8 km from the wind farm site.
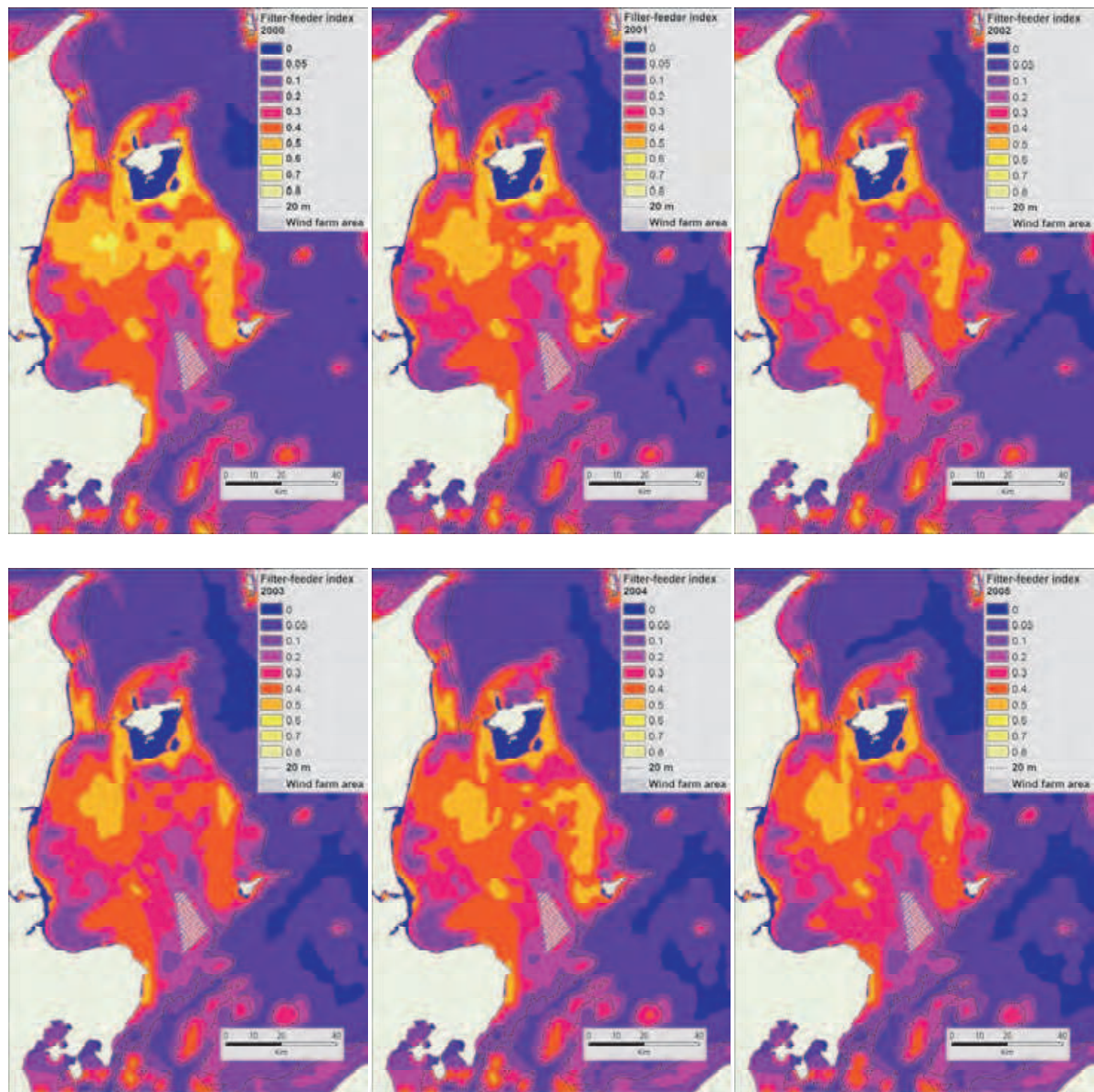

Fig. 5. Modelled mean and annual filter-feeder carrying capacity index for *Mytilus edulis* in the central Kattegat between 2000 and 2005. The planned site for the Anholt offshore wind farm is indicated.

4.4 Habitat suitability model

On Horns Rev, in the North Sea, habitat suitability models were developed on top of the filter-feeder models in order to estimate more precisely the distribution of the two in-fauna bivalves *Spisula subtruncata* and *Ensis americanus*; two key species in the benthic ecosystem of the eastern North Sea whose distribution can only be estimated by the addition of geo-morphological parameters. This was done within the frame of habitat suitability modelling using empirical samples of the two species as response variables and modeled filter-feeder indices, sediment data and data on the depth and relief of the sea floor as predictor

variables. All variables were standardized using 'Box-Cox' normalization (Sokal and Rohlf, 1981), and suitability functions were computed using Ecological Niche Factor Analysis (Hirzel et al., 2002).
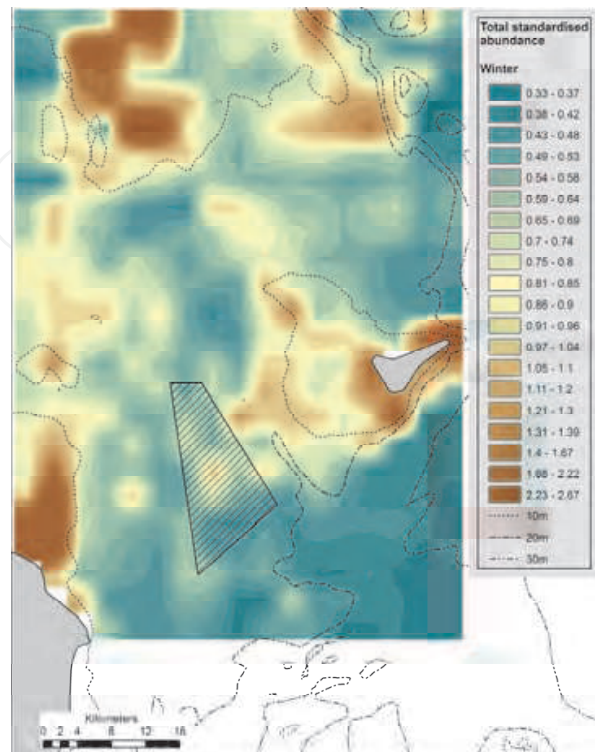

Fig. 6. Index of abundance of waterbirds during winter (species occurring in internationally important concentrations) in the Central Kattegat. The scale is arbitrary. The planned site for the Anholt offshore wind farm is indicated.

Suitability functions compare the distribution of razor clams and trough shells in the multivariate oceanographic space encompassed by the recorded presence data with the multivariate space of the whole set of cells in the modelled area (Hirzel, 2001). On the basis of differences in the bivalve and the global 'space' with respect to their mean and variances, marginality of bivalve records was identified by differences to the global mean and specialisation by a lower species variance than global variance. Thus, for large geographical areas like the part of the North Sea studied here, ENFA approaches Hutchinson's concept of ecological niche, defined as a hyper-volume in the multi-dimensional space of ecological variables within which a species can maintain a viable population (Hutchinson, 1957).

To take account of multi-colinearity and interactions among eco-geographical factors, indices of marginality and specialisation were estimated by factor analysis; the first component being the marginality factor passing through the centroid of all bivalve presence records and the centroid of all background cells in the study area, and the index of marginality measuring the orthogonal distance between the two centroids. Several specialisation factors were successively extracted from the n-1 residual dimensions, ensuring their orthogonality to the marginality factor while maximising the ratio between the residual variance of the background data and the variances of the bivalve occurrences. A high specialisation indicates restricted habitat usage compared to the range of conditions measured in the studied part of Horns Rev. A habitat suitability index was computed on the

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basis of the marginality factors and the first three specialisation factors, as a high proportion of the total variance was explained by the first few factors, by comparison to a broken-stick distribution. The habitat suitability algorithm allocated values to all grid cells in the study area, which were proportional to the distance between their position and the position of the species optimum in factorial space.
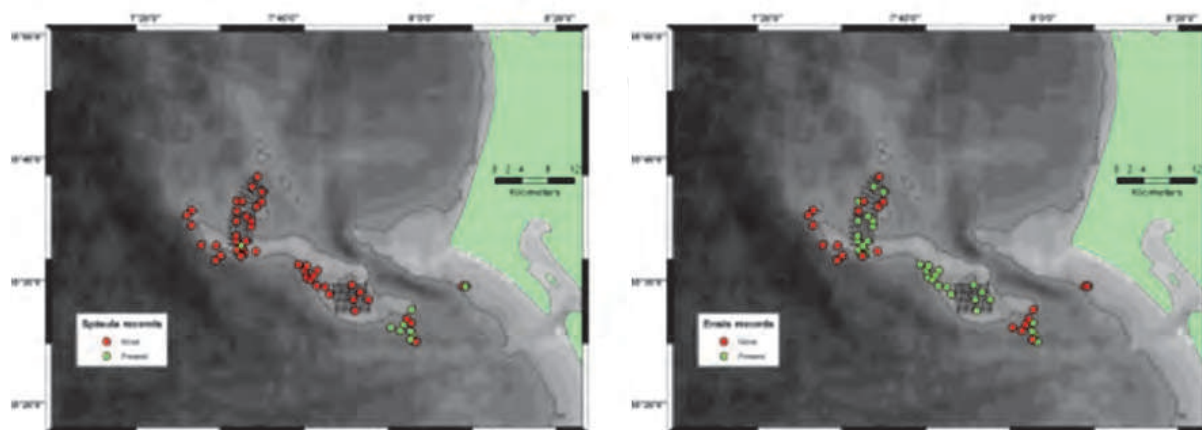
Fig. 7. Available empirical data on the presence/absence of Cut trough shells (left) and American razor clams (right) on Horns Rev.

Application of ENFA provided an overall marginality of $m = 3.92$ and an overall specialization value of $S = 2.734$ for Ensis and $m = 0.527$ and $S = 4.654$ for Spisula, showing that Horns Rev habitats for the two species during 2000-2007 differed markedly from the mean conditions in the studied part of the North Sea. The three factors retained accounted for more than 93 % of the sum of the eigenvalues (that is 100 % of the marginalization and 95 % of the specialization). Marginality accounted for 50.9 % of the total specialization in Ensis and 81.6 % in Spisula. The two first specialization factors accounted for 41 % of the total specialization in Ensis and 11.7 % in Spisula, indicating that the two species are moderately restricted in the range of conditions they utilize in the study area, with trough shells being more restricted.

Marginality coefficients showed that razor clams were (positively) linked to water depth, areas with relatively flat terrain and the carrying capacity index, while trough shells showed strong links to median grain size (negative coefficient) and the carrying capacity index. These scores can easily be interpreted on the basis of the plotted presence/absence data, which indicate that razor clams mainly use offshore areas and are found commonly around and on Horns Rev, whereas trough shells are mainly found in the eastern-most, near-coastal areas. The marginality and specialization scores lead to habitat suitability scores ranging from 0-100, the upper 33 reflecting suitable habitat (Figures 8, 9). The pixels indicating high habitat suitability for razor clams mainly lie within a coherent zone corresponding to the Horns Rev and moderate slope areas to the northwest and southeast, including the wind farm areas on Horns Rev (Figure 8). The pixels indicating high habitat suitability for trough shells (Figure 9) are confined to the area of fine sediments and high carrying capacity values in the south-eastern and eastern-most part. In most years, the wind farms areas have low suitability for trough shells, and intermediate suitability is only estimated for the Horns Rev 1 wind farm on the eastern part of Horns Rev.
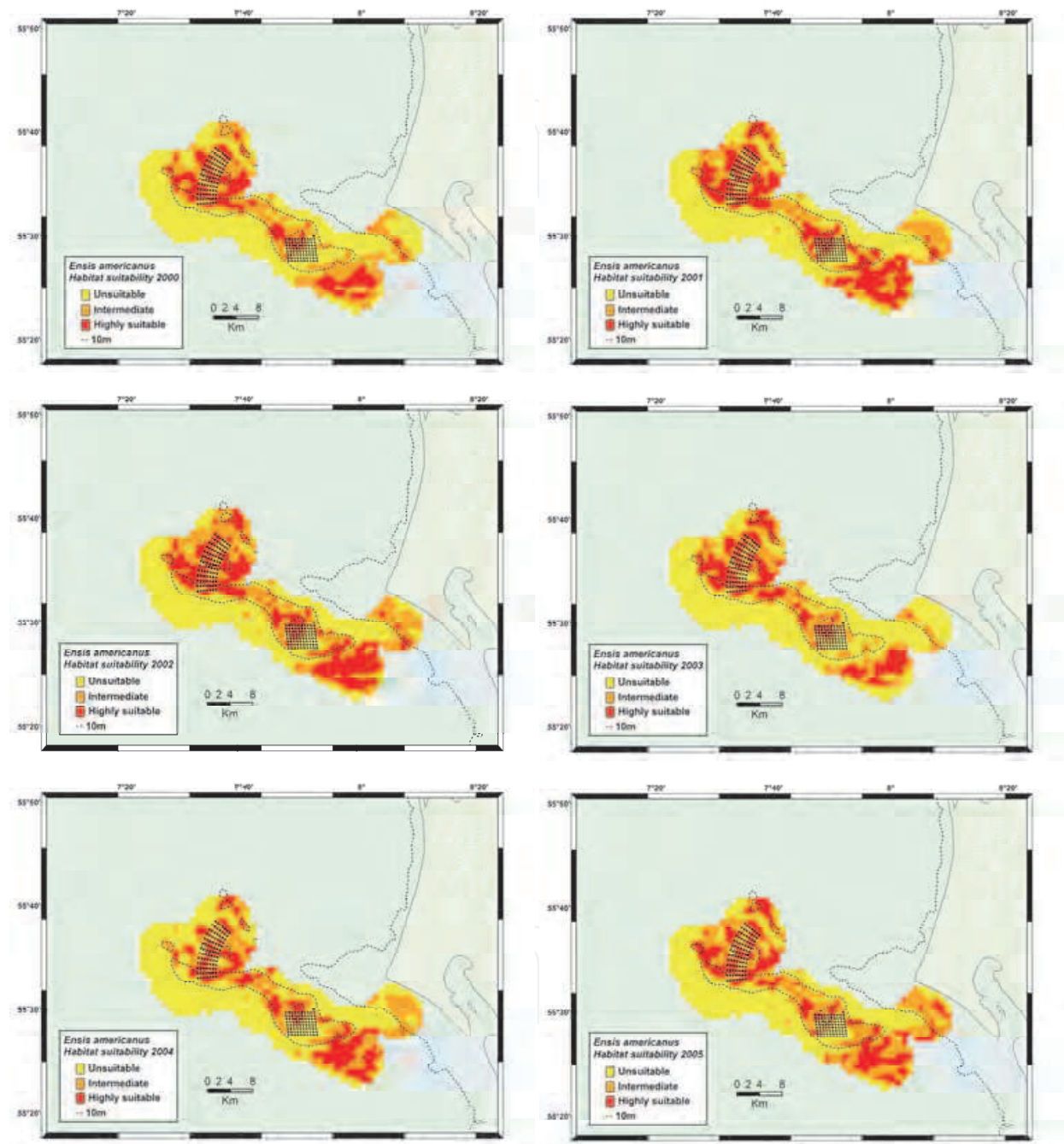
Fig. 8. Modelled annual habitat suitability for American razor clam *Ensis americanus* on Horns Rev for the period 2000-2005. The two offshore wind farms Horns Rev 1 and Horns Rev 2 are marked as black dots.
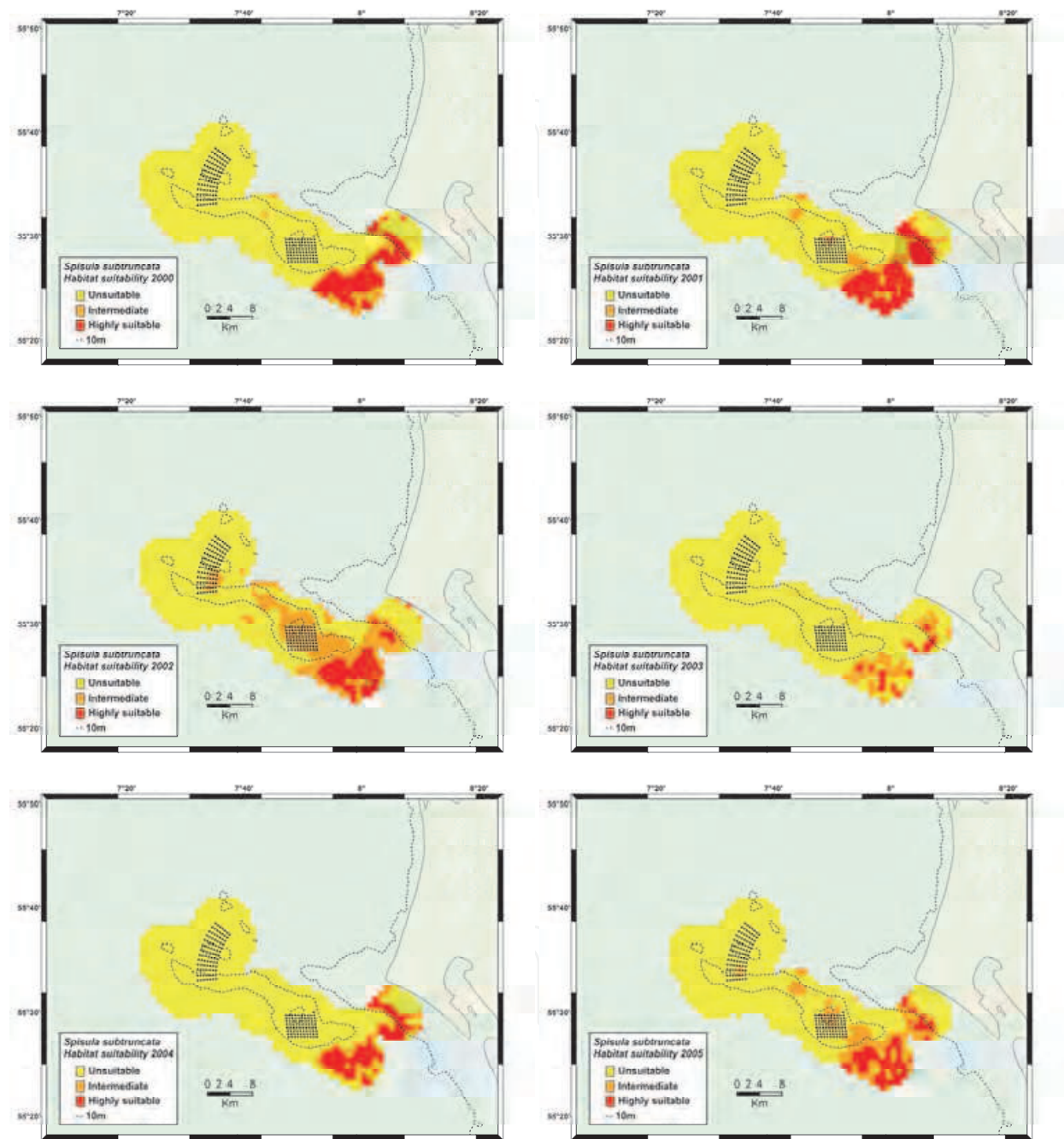
Fig. 9. Modelled annual habitat suitability for Cut trough shell *Spisula subtruncata* on Horns Rev for the period 2000-2005. The two offshore wind farms Horns Rev 1 and Horns Rev 2 are marked as black dots.

The time series of suitable habitat to razor clams and trough shells on Horns Rev enabled the prediction of the distribution of benthic-feeding waterbirds, and assessment of the importance of the wind farm area to sensitive species like Common Scoter *Melanitta nigra* (Figure 10). The predicted distribution of the Common Scoter shows the Horns Rev 1 wind farm area as of low importance, and the Horns Rev 2 wind farm area of medium importance.
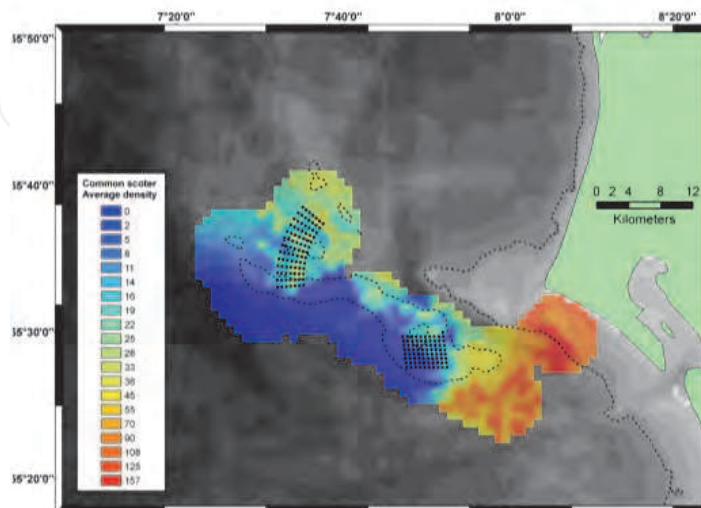
Fig. 10. The average density (number of birds/km²) of Common Scoter *Melanitta nigra* at Horns Rev modelled for six aerial surveys between December 2007 and April 2008. The two offshore wind farms Horns Rev 1 and Horns Rev 2 are marked as black dots.

5. Conclusion

The environmental investigations related to the Anholt and Horns Rev 2 offshore wind farm projects are illustrative examples of the fact that the integration of traditional sampling and advanced habitat modelling make it possible to achieve a robust assessment of baseline conditions and ecological impact within the relatively short period of time available. Time will tell whether these projects represent a benchmark for future impact assessments in offshore areas, and whether developers and regulators will have access to solid descriptions of local environmental conditions with lower risks for the appearance of unforeseen impacts and environmental barriers.

6. Acknowledgement

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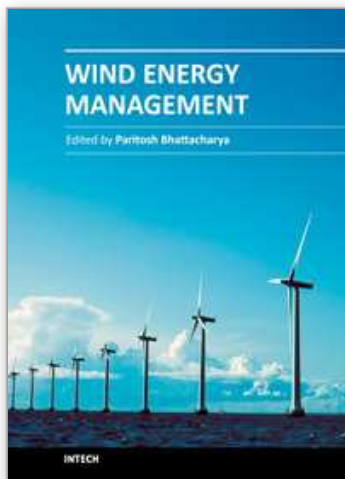
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Edited by Dr Paritosh Bhattacharya

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