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Ecosystem based modeling and indication of ecological integrity in the German North Sea—Case study offshore wind parks

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ABSTRACT

Human exploitation and use of marine and coastal areas are apparent and growing in many regions of the world. For instance, fishery, shipping, military, raw material exploitation, nature protection and the rapidly expanding offshore wind power technology are competing for limited resources and space. The development and implementation of Integrated Coastal Zone Management (ICZM) strategies could help to solve these problems. Therefore, suitable spatial assessment, modeling, planning and management tools are urgently needed. These tools have to deal with data that include complex information on different spatial and temporal scales. A systematic approach based on the development of future scenarios which are assessed by combining different simulation models, GIS methods and an integrating set of ecological integrity indicators, was applied in a case study in the German North Sea. Here, the installation of huge offshore wind parks within the near future is planned. The aim was to model environmental effects of altered sea-use patterns on marine biota. Indicators of ecological integrity were used to assess altering conditions and possible ecosystem shifts ranging from systems' degradations to the development of highly productive and diverse artificial reef systems. The results showed that some ecosystem processes and properties and related indicators are sensitive to changes generated by offshore wind park installations while others did not react as hypothesized.

1. Introduction

Coastal and marine regions have been of special interest for human activities due to their high potentials to provide ecosystem goods and services (UNEP, 2006; Peterson and Lubchenco, 1997). Besides more traditional uses like fishery or raw material exploitation, contemporary activities include rapidly growing shipping traffic and the implementation of offshore wind parks (OWPs) for electricity generation. The latter has become an issue in Germany due to its high demand for space and its political desire to mitigate the effects of climate change (POWER, 2005). Integrated Coastal Zone Management (ICZM) has the potential to aid in solving conflicts between competing forms of anthropogenic activities and their effects (Cicin-Sain and Knecht, 1998). In Germany, the Federal Maritime and Hydrographic Agency (BSH) has been authorized to carry out the planning and licensing of OWPs. Two reasons typically cited for refusal of respective approvals are: (a) the interference with shipping activities; and (b) possible threats to the marine environment. Until now, 16 applications for construction of OWPs have been approved in Germany's Exclusive Economic Zone (EEZ) of the North Sea and three in the Baltic Sea (www.bsh.de; December 2008) even though little is known about their environmental impacts so far. Two OWP applications in the Baltic Sea were declined due to nature conservation reasons. Appropriate tools and methods appear needed to assess potential impacts of OWPs on marine environments.

The framework and methodology presented in this paper link different models aiming to carry out a holistic assessment of diverse biotic and abiotic components and processes relevant for the functioning of marine ecosystems. Hypothetical installations of future OWPs were chosen as case study because they represent a new form of sea use likely to play a major role in future sea-use patterns. To date a huge number of methods for analyzing environmental impacts of human activities on coastal ecosystems are available (Bierman et al., 2011) and studies with special focus

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on offshore wind energy have been carried out (e.g. in Köller et al., 2006), but still there are many gaps in knowledge, especially with regard to long term and spatial effects and system dynamics. It is unclear if the insertion of new structures in the form of thousands of wind turbine foundations will cause a deterioration of marine ecosystems or the generation of new, artificial reef-like systems. To better characterize specific effects of human activities on coastal ecosystems a new approach was tested which combines theory with models that integrate best available data with scientific knowledge, as at 2008.

Two main questions arise from the issues mentioned above:

- Are the existing methodology, models and indicators suitable for the assessment of environmental components of ICZM? If "yes",
- will the construction of offshore wind parks cause a system shift towards a degradation of marine ecosystems, the development of artificial reef systems or will the system show a resilient behavior?

2. Materials and methods

The study is part of the research and development project *Zukunft Küste—Coastal Futures* which deals with aspects of ICZM in the German North Sea. In this interdisciplinary project, various future scenarios were developed following a systematic framework (Burkhard, 2006). Within these scenarios, characteristic patterns of anthropogenic use evolve according to certain combinations of socio-ecological driving forces. The individual patterns are dominated by one form of use (e.g. shipping, recreation, nature conservation, energy conversion), and are linked to distinctive intensities, areas and time steps of OWP installations in the German North Sea. For the purposes of modeling we assumed in the maximum OWP scenario, that in 2055 Germany will have installed 10,000 wind turbines in the North Sea with the capacity to generate 90,000 MW of electricity. This would be a massive increase over 2005 levels when no offshore turbines existed in Germany. An area covering almost one fourth of the German EEZ would be used by OWPs then. Time steps and single events like successive construction and operation of individual wind parks at particular sites were defined within the different scenarios. The conceptual framework, methods and results of the ecologically oriented sub-projects in *Zukunft Küste—Coastal Futures* for the assessment of environmental impacts of the different OWP scenarios are presented in this paper.

2.1. Ecological integrity—indicators and system dynamics

The concept of ecological integrity refers to the necessity to safeguard the self-organizing capacity of ecosystems (Barkmann et al., 2001). Such self-organized systems receiving a flow through of energy (e.g. sunlight) have the capacity to build up structures and gradients based upon spontaneously occurring processes (Bossel, 2000). It follows that the concept of ecological integrity does not focus on single species or parameters but rather on processes and structures. Consequently, significant processes like cycling and transformation of exergy (usable energy; Jørgensen et al., 2005) and matter, and the preservation of specific biotic structures and abiotic components have to be maintained to secure ecosystem functioning (Müller and Burkhard, 2007). Indicators for the assessment of ecological integrity have to reflect these processes and structures. The systematic derivations of ecological integrity indicators as they are used in this study also are described in detail by Müller (2005). Their applications in different case studies in terrestrial ecosystems are illustrated for example in Burkhard and Müller (2008) and in Müller and Burkhard (2006, 2007). Hence, this study about effects of offshore wind parks and the combination with different models is a new challenge to assess impacts of human action on the state of ecosystems. Table 1 gives an overview of the applied indicators, respective parameters for their quantification, and data sources and models that were applied for their quantification. Descriptions of the individual models are given below.

Different system dynamics can be hypothesized to be impacted as a consequence of the installation of offshore wind parks. During the erection phase of the turbines, existing processes and structures will be disturbed. This will result in alterations of integrity components and respective indicators. In particular the insertion of turbine fundaments into the seabed and associated scour protections in a previously rather homogeneous sandy and muddy sea bottom environment may have the potential to initiate remarkable system dynamics. How the system might react after disturbance during this construction phase is still unclear. First results of monitoring at Danish offshore wind parks showed that epifaunal communities establish relatively quickly following construction (DONG Energy et al., 2006; ELSAM Engineering & Energy E2, 2004). On the one hand, these findings support the hypothesis, that insertion of hard structures in sea bottom areas will provide substrate suitable for the emergence of artificial reef-like ecosystems. These systems have the potential to be more productive, more efficient regarding energy and matter cycling and they could maintain a high biodiversity. This would raise the self-organizing capacity of the system and thereby, increase its integrity. Of course this would mean a fundamental change in the state of marine ecosystems, but it is important to recognize that hard substrate communities were typical of marine environments into the 1970s, being substantially reduced by the stone fishing activities that were carried out in German coastal waters.

On the other hand, disturbances during construction phases could be so severe that essential ecosystem processes and structures are interrupted, leading to irreversible system degradation or even a continuation of degradation after the construction is finished. A third hypothesis would suggest a resilient behavior of the system. This would mean that following the disturbance, main attributes, structures and functions will be restored to their earlier states (Walker and Salt, 2006) (Fig. 1).

To test these hypotheses, different simulation models and existing monitoring data were linked and used to quantify the

Table 1
Ecological integrity groups and indicators, parameters and data sources applied for their quantification.

Orientor groups	Indicator	Parameter	Data source/model
Energy budget	Exergy capture	Net primary production	ERSEM
	Entropy production	C/year from respiration	Ecopath
Matter budget	Storage capacity	C stored in biomass	Ecopath
	Nutrient cycling	Winter turnover of nutrients	ERSEM
	Nutrient loss	Transport loss of nutrients	ERSEM
Structures	Biotic diversity	Diversity seabirds	GIS data
	Abiotic heterogeneity	Turbidity, sediment parameters	MIKE21
	Organization	Ascendancy	Ecopath

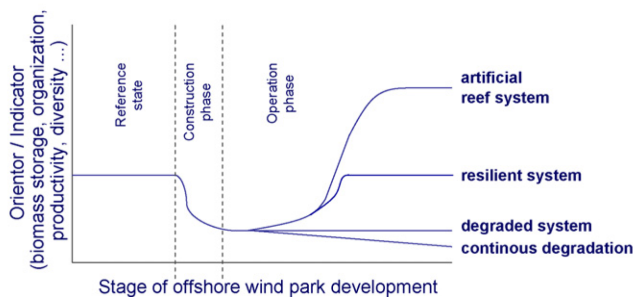

Fig. 1. Hypothetical dynamics of marine ecosystems with regard to the installation of offshore wind parks.

ecological integrity indicators. Due to the lack of OWPs in Germany up to 2008, modeling is the only way to assess impacts of such comprehensive offshore installations with regard to predictive management.

2.2. Model applications

The model applications were based on the future scenario assumptions described above. All scenarios developed in the scope of the *Zukunft Küste—Coastal Futures* project are linked to varying intensities and areas of OWP installations. To evaluate extreme conditions, the scenario B1 "the North Sea as a source for renewable energy" (Burkhard, 2006), representing the maximum intensity of OWP installations, was chosen as background for the simulations. For the simulation of the three developmental stages of OWP installation, different settings were applied. Due to varying technical requirements of the individual models, the simulations referred to different spatial scales:

(i) The ERSEM model is based on horizontal and vertical boxes of varying sizes. Hence, model results encompass the whole area respective volume of at least one box.
(ii) The Ecopath model was used to describe the hypothetical situation before and after construction of the OWP Butendiek, which is planned for construction 34 km west of the North Sea island of Sylt in the German EEZ.
(iii) For the abiotic modeling with MIKE21, the planned OWP DanTysk was chosen. DanTysk is located 70 km seaward of the island of Sylt with water depths between 25 m and 35 m.

Both OWP areas, Butendiek and DanTysk, are comparable in their natural settings and representative for the northern and deeper part of the German EEZ (Pesch et al., 2011). Conditions may be different in other areas, or closer to the coast. Of course it is always delicate to draw conclusions about larger areas from discrete area information, but given that no data are available for the whole North Sea area, best individual data sets are be used.

As reference state for all simulations, the situation without any wind park in the year 2005 was used. For the second stage, representing the construction phase of OWP, the main modification simulated in the models was an increase of suspended particulate matter (SPM), assumed to take place due to the insertion of OWP fundaments and cable connections. Here a threshold level of 2 g/m^3, as proposed in a study by the Danish Hydraulic Institute (DHI, 1999), was applied by adding this concentration on the SPM background concentration in the model. This addition of a higher SPM concentration represents the process contribution of stirring up the sea bottom and mixing this released SPM over the entire water column, on top of the existing background concentration. This additional SPM concentration was applied during the construction phase, representing a summer period with low wind activity from May till September. The simulation included a subsequent resting phase in October where the SPM concentration was linearly reduced towards the background concentration (Nunneri et al., 2008). For the simulation of the operation of OWPs as third stage of assessment, standard SPM values were used. The potential impacts of OWPs on resting seabirds were assessed by overlaying the varying areas of OWP installations, as assumed in the project future scenarios, with information on bird distributions. In the following, a short overview is provided of the models ERSEM, Ecopath, MIKE21 and the GIS data that were used and linked in this study.

2.2.1. European Seas Ecosystem Model ERSEM

The ecosystem model ERSEM (European Regional Seas Ecosystem Model) is used for assessing ecosystem changes related to defined scenarios concerning the construction of OWPs. ERSEM describes the North Sea ecosystem via the dynamic interaction between physical, chemical and biological processes (Baretta et al., 1995; Lenhart, 2001). The model represents biological and biogeochemical interactions in a unique complexity (Moll and Radach, 2003) within the pelagic and benthic system. In the box model version used for this study the physical features, as derived from the hydrodynamical HAMSOM (Hamburg Shelf Ocean Model) circulation model, are represented in a reduced but realistic form (Lenhart and Pohlmann, 1997).

The defined scenarios are transposed into the ERSEM model in the form of increases in the suspended matter concentration (SPM), referring to the construction phase of the OWPs. Changes are compared with a standard run, a hind cast simulation for the year 1995 under realistic forces. The scenario simulation applies the increased SPM concentration, but leaves the rest of the forces exactly as in the standard run. In this way the impact of the construction is made under comparable conditions, since there were no changes in the hydrodynamics between the different model runs. However, it should be noted that with the application of the increased SPM concentration for the whole ERSEM box, an effect of light limitation on the algae production has to be considered as an upper limit of the impact (Nunneri et al., 2008).

2.2.2. Food web simulation with Ecopath

Ecopath with Ecosim (EwE) (www.ecopath.org; Christensen and Pauly, 1992a,b) is a free ecological/ecosystem modeling software suite. EwE has three main components: (1) *Ecopath*—a static, mass-balanced snapshot of the system; (2) *Ecosim*—a time dynamic simulation module for policy exploration; and (3) *Ecospace*—a spatial and temporal dynamic module primarily designed for exploring impact and placement of protected areas. Amongst others the Ecopath software package can be used to address ecological questions, to model the effect of environmental changes, to explore management policy options, and to analyze impact and placement of marine protected areas.

The Ecopath procedure was used to construct two mass-balance models that quantify the structure and flows within the biocenosis at the wind park site Butendiek, both before and after its hypothetical construction. The construction phase itself with contemporarily higher SPM values in the water column was not modeled with Ecopath because it is a steady-state approach and not useful for modeling short term changes in ecosystem structure and flows of a highly dynamic system.

An application of Ecosim – the dynamic component of the model suite EwE – was not scheduled for the first phase of the *Zukunft Küste—Coastal Futures* project but is planned to be applied to more refined versions of the food web at the potential wind park sites Butendiek, DanTysk and Sandbank24 in 2009 as part of the third phase of the project. Ecospace, a third component of the EwE suite of models, was not applied as the changes referred only to a single wind park.

The basic equation of the modeling approach used in this work is: production + import = predation mortality + fishing mortality + other mortality + migration + biomass accumulation. It assumes mass-balance, i.e. it balances the flow to and from each biomass pool or compartment in the model. The predation mortality term is used to link predator and prey species, whereas consumption = production + non-assimilated food + respiration. A detritus compartment D receives flows originating from "other mortality M" and "non-assimilated food NA", so that D = M + NA.

One of the limitations of Ecopath is that only living and dead (detritus) organic components are included in the model; abiotic effects such as nutrient uptake by primary producers are not considered. ERSEM (as described in this paper) in contrast deals mainly with abiotic forcing functions and the lower parts of the food web (e.g. microbial cycle). Thus, outputs from ERSEM for lower trophic levels were combined with data on information of higher trophic levels resulting from environmental impact analyses and literature data. For each living group model inputs consisted of an estimate for biomass (B), production/biomass ratio (P/B), consumption/biomass ratio (Q/B). Gross efficiency rates (GE = production/consumption) were used in cases where no estimate was available for either P/B or Q/B. Additionally, a diet composition estimate (DC, in percentages of volume or weight of food items), an estimate of the percentage of food that is not assimilated (NA) were required as inputs for each "trophic" group. An additional parameter, ecotrophic efficiency (EE = predation mortality expressed as percentage of production), was then calculated by the model software. Changes in fishing pressure before and after the construction of the OWP were not considered since no reliable area related fishery data were available. This issue of impacts of altered fishery patterns on marine food webs in OWPs is part of ongoing research in *Zukunft Küste—Coastal Futures*. Model inputs were modified according to quality of input data until all EEs were below 1. Model outputs from Ecopath for Butendiek that were used as indicators to describe ecosystem integrity according to Windhorst et al. (2005) and Nunneri et al. (2007a) are given in Table 1.

2.2.3. Hydrodynamic modeling with MIKE21

MIKE21, developed by the Danish Hydraulic Institute, is a two-dimensional hydro numerical model, which takes into account wave, wind, tidal, current and sedimentological parameters (http://www.dhigroup.com/). This model calculates the influences of changing conditions like storm surges, coastal protection measures and other man-made structures in the littoral and near shore zone to given natural conditions (e.g. Johnson et al., 2005; Jones et al., 2007). MIKE21 was applied in comparable projects, for example in the Danish OWP Horns Rev, with good success (DHI, 1999). Offshore wind piles have an influence on the current velocity flow. They locally change current flow directions, velocity and turbidity, which in turn influences the sedimentary conditions like grain-size distribution, morphodynamics and compactness. Related change in the benthic community may also influence higher trophic levels. In the modeled OWP DanTysk, the projected turbines are of the monopile type. The sediment in this area can be characterized as fine to coarse sand with local gravel deposits. Good hydrodynamic data were available from a measuring pile seaward of the island of Sylt. The time series for one month (December 2005) at 1 h intervals, was used for hydrodynamic input, and a storm surge with a velocity of 50 m/s was used to model an extreme event.

2.2.4. Analysis of impacts on seabirds using GIS

Seabirds were chosen as one group of animals to investigate possible effects on biodiversity for two reasons: (i) birds are generally of greatest concern in assessments of wind park effects;

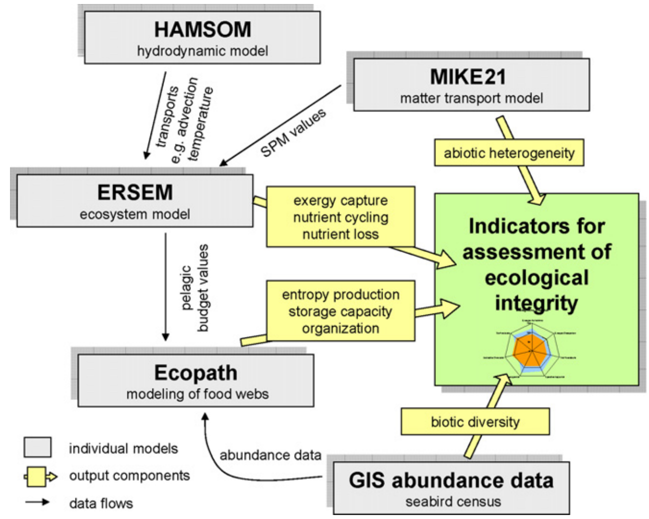

Fig. 2. Models used for the quantification of ecological integrity indicators, their linkages and data flows.

(ii) the relatively large number of bird species affected by OWPs (Garthe and Hüppop, 2004; e.g. in contrast to very few species of marine mammals in the region; Gill, 2005). Furthermore, comprehensive data sets are available from various studies, including data on the distribution and abundance of seabirds from the "seabirds at sea" database at the Research and Technology Centre West Coast (FTZ) in Büsum. This database holds data from both ship-based and aerial counts, following internationally standardized methodologies. For each geographic and temporal unit, abundance estimates can be derived. We analyzed data to derive current mean numbers per species and season for the area of the planned wind park Butendiek. From these numbers, values such as the Shannon diversity index were calculated. As few wind parks currently operate at sea, it is difficult to predict species responses for the period of wind park construction and operation (Garthe and Hüppop, 2004). We used the findings of a literature review regarding bird species responses to OWPs as a basis for our modeling (Dierschke and Garthe, 2006. They found that divers, scoters and auks avoided wind parks after construction while many gulls appeared to be attracted to these areas, probably because of their opportunistic foraging behavior. We modified the mean numbers per species and season for the construction/post-construction period (we assume no difference between these two) for the Butendiek area based on the assumed species responses, and recalculated the diversity index and other community parameters, then compared them with the situation before the wind park establishment.

2.2.5. Model coupling

With the objective of obtaining a more authentic representation of real conditions and matter fluxes, the individual models were linked by using output data from one model as input parameter for the other model. For example selected outputs from ERSEM for phytoplankton, zooplankton and detritus were used as inputs for Ecopath after moderate transformation. A more detailed description of this approach is under way. The whole concept of models, their interactions and linkages to ecological integrity indicators are given in Fig. 2.

3. Results

The modeling and GIS data analysis results were applied for assessing impacts of offshore wind park installations on marine biota. The particular ecological integrity components and respective indicators showed the following reactions: (i) Exergy capture was reduced during the construction of OWPs, indicated by decreased net primary production. This decrease was caused primarily by sun light limitations due to the higher amount of SPM in the water column. In the year after the construction, net primary production reached almost the same annual sum as before the construction. (ii) Entropy production, indicated by tons of carbon per year and m^2 produced by respiration, decreased significantly during operation of the OWP. (iii) Intensity of nutrient cycling, indicated by the turnover of nutrients available in winter, was reduced during the construction phase and showed a very slight increase in the first year of operation of the wind park compared to the intensity before the OWP was built. (iv) The transport loss of nutrients increased during the construction phase and reached almost the same amount when construction of OWP was finished. (v) Storage capacity, modeled with Ecopath, did not show significant differences before or after the construction of the OWP at Butendiek.

(vi) The MIKE21 simulations regarding current dynamics showed, that without wind turbine pile the maximum current velocity (*V* south to north) was 1.28 m/s. In the same area, far away from a pile, the calculated velocity with piles was 1.24 m/s. The maximum current velocity was calculated directly beside a pile with 1.34 m/s and directly behind a pile a reduction to 1 m/s was estimated. However, at a distance of 100 m from the pile, the reduction was 50 cm/s and in 600 m only 19 cm/s. No differences were calculated beyond 300 m of a pile, regarding the resulting vector of *U* (west–east) and *V* (south–north). The changes in current velocity also have consequences on the sediment distribution. But, compared with the complete area of the wind park, the influence is less than 0.3%. Taking into account additional effects due to scour protection measures (Ulrich, 2006), the influence on abiotic heterogeneity is more important, but still less than 3%.

(vii) Biotic diversity, indicated by analyzing the species composition of resting seabirds, was largely reduced during construction and operation of the wind park. Diversity index values decreased clearly for summer (from 1.53 before to 0.78 during construction and operation of the wind park), autumn (from 1.41 to 1.03) and winter (from 1.80 to 0.93), but increased slightly for spring (from 1.83 to 1.89). Mean values from the four seasons were used to derive indicator values. Evenness values showed the same tendency, while species numbers decreased throughout. (viii) Organization was indicated by ascendancy (see e.g. Ulanowicz and Norden, 1990) and was computed by Ecopath. The

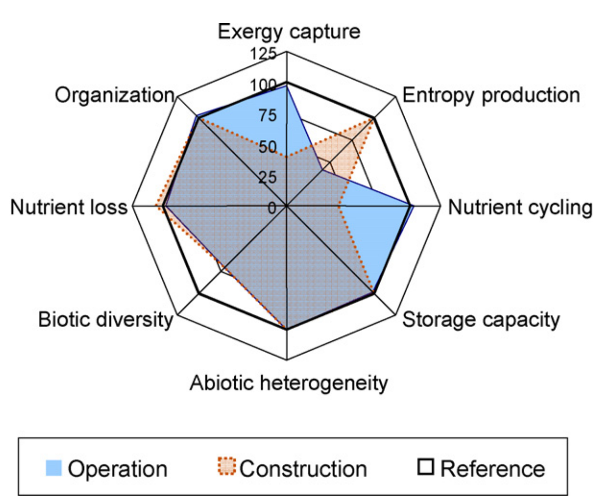

Fig. 3. Synoptic overview of results of the model and GIS based assessment of impacts of offshore wind park installation in the German North Sea.

ascendency-system throughput ratio in mg C/m^2/year × flow bits may be viewed as a measure of information, as included in Odum's attributes of ecosystem development (Odum, 1983). However, there is an upper limit for the size of the ascendency. This upper limit is called the 'development capacity' and the percentage of modeled ascendency of this capacity was used here to denote system organization. It showed a very slight decrease during the operation of the OWP.

Fig. 3 gives an overview of the results, showing the three stages of OWP installation. All values were normalized to a relative scale, where the reference state (without OWPs) corresponds to 100% and any positive or negative difference is indicated in % deviation from 100%. The results show that construction and operation of OWPs exert characteristic effects on the ecosystem. Of course it has to be taken into account that individual model applications refer to varying spatial and temporal scales. On the other hand, all analyses are based on comparable assumptions regarding reference state (without OWPs), construction of OWPs and operation of OWPs.

4. Discussion

Individual components of this assessment and related ecological integrity indicators showed characteristic reactions due to the pressure exerted by the construction and operation of OWPs. However, a truly consistent pattern of system behavior could not be revealed by the individual model applications. Regarding the ERSEM model results, the parameters used for the indication of exergy capture, nutrient cycling and nutrient loss returned within the first year after the construction to a state similar to that of the year before (Lenhart et al., 2006). Hence, the system was able to absorb this disturbance without flipping into another state with altered structures and functions. This would support the hypothesis of a resilient system dynamic. Also the Ecopath model results on storage capacity and entropy production showed rather minor alterations of the system. A slight increase of ascendancy may be interpreted as a first sign of an increased organization of the system.

Biotic diversity may comprise a large variety of parameters from the lower to the uppermost trophic levels. As experience from existing wind parks have documented that birds are one of the taxa most affected by the installation of wind parks at sea, the numerical composition of the seabird fauna was taken as a proxy for biotic diversity. Applying response patterns of the different species obtained from studies at marine wind parks in Denmark and other countries to the study site OWP Butendiek, a likely loss in species numbers, diversity and evenness during construction and operation of the wind park could be demonstrated. Hence, referring to the hypotheses of systems dynamics mentioned earlier, impacts of OWP installations might vary between above water and underwater marine environments. However, the loss of birds could possibly be counteracted by adaptation of species over longer periods to the wind parks, as has been indicated recently by Petersen and Fox (2007) for common scoters in the Horns Rev wind park.

The method presented here for the assessment of impacts of OWP constructions has been successfully used in another study to address the problem of marine eutrophication (Nunneri et al., 2007b). A number of the ERSEM parameters were applied in the same way as for the eutrophication study. Other parameters were added from the models and the GIS data described above. The selected parameters are dependent on (a) the data available to consider for the study and (b) the way these parameters are able to represent the impact of the distortion on the system under consideration. For example, since the net primary production was always lower in the respective eutrophication reduction scenarios (OSPAR, 1998; Lenhart, 2001), the upper value representing the reference value for the standard run was always set. This had to be adopted in the application of the OWPs, since lower net primary production in a neighboring box as a result of light limitation due to increased SPM values might lead to an increase in the net primary production elsewhere, since the nutrients not utilized are made available for production by the transport into the next box.

One problem not adequately addressed within this study was that impacts occurring during the construction and operation of OWPs are varying in relation to spatial and temporal scales. For example, in the ERSEM modeling, the assumption was made that the dispersal of increased SPM due to construction activities takes place homogeneously within the rather large two-dimensional boxes of the model. In reality, SPM concentrations are likely to vary locally and diminish with increasing distance from the emission source. On the other hand, looking at larger scales as for example the entire North Sea, effects of local disturbances will be diluted. Therefore, a downscaling of the ecosystem model is needed to look into these effects in detail.

Such scale-dependent effects were shown in the MIKE21 model simulations where altered current dynamics were visible on single piles, whereas on the whole wind park area only minor effects became obvious. At the scale of the whole North Sea no more effects could be identified. Hence, no significant effects on sediment dynamics and distributions are expected to occur, unless particularly sensitive areas would be taken into account.

The trophic network models produced with Ecopath showed very minor changes of total system biomass before and after OWP construction at Butendiek. This may be viewed as a preliminary indication against the hypothesis of the emergence of productive artificial reef systems. In the simulation carried out in this study, results from ERSEM modeling were used to "feed" Ecopath. Possibly due to the small size of biomass alterations at lower trophic levels, resulting values of ecotrophic efficiency did not show any changes. It is obvious that if ERSEM modeling ascertains a resilient system which returns quite quickly to its former state, related modeling of biocenotic structure will not simulate substantial variations. Thus, it was concluded that the additional substrate from piles available to sessile organisms after the construction of the wind park would not have a significant quantitative impact on the structure and flow pattern of the ecosystem in the modeled wind park Butendiek.

Regarding impacts on seabirds utilizing the sea for foraging, resting, and staging, effects shown in this study clearly illustrate the spatial conflicts that might arise between expansive human activities and natural habitats occupied by specialized species. More attention should be paid to the analysis of potential alternative habitats and the behavioral responses of the different species involved. Analysis should include indirect effects such as increased and altered ship traffic and the possible discontinuation of fishing activities in the wind park areas.

One major problem and limitation of this kind of assessment is the lack of "real" field and monitoring data due to the absence of OWPs in the German North Sea to date. Data and information are needed to supply the models, to calibrate their simulations, and to validate the outcomes. Hence, the best data at hand, e.g. from existing OWPs in Denmark were used. These produced results which are – to a certain extent – transferable to other conditions.

5. Conclusions

It was demonstrated that an assessment of key features and processes of ecosystem integrity in the context of establishing new forms of anthropogenic pressures on the environment is possible with the methods, models and indicators presented and discussed in this study. The evaluation of future developments using scenario techniques made an important contribution to ICZM in particular, and integrated management of natural resources in general. The application and integration of different models in order to quantify ecosystem-oriented indicators is a novel approach and a promising attempt for assessments of complex systems. However, the results presented did not show a consistent picture of systems dynamics with regard to initial hypotheses. This is due in part to the shortcomings of existing models and input data. To answer the question of whether installations of OWPs can trigger system shifts towards artificial reefs or degraded systems on a more comprehensive basis, improved input data and enhanced model applications based on real OWP installations would be needed.

In Germany, a test wind park of 12 wind turbines with a capacity of 5 MW each is planned in 2008. The wind park will be located in the North Sea 60 km from the mainland in a water depth of 30 m. It is expected to provide valuable insights into this new technology and its impacts on marine and coastal environments. Results and data anticipated from accompanying research will be used to improve the quality and applicability of the assessment framework described here. They will help to calibrate and validate the model applications, to assess long-term environmental impacts and the practical usage and improvement of indicators of ecological integrity.

Therefore, further research (e.g. in the project *Zukunft Küste—Coastal Futures*, but also by more specific case studies targeted at different biota) should focus on the integration of these additional data, the consideration of scale effects (e.g. by using higher spatial and temporal resolutions in the models and for special sensitive areas, for example those likely to be affected by oxygen deficiency), and the analyses of complex food web interactions. OWPs are expected to generate alterations at different trophic levels in the food web as for example the emergence of benthic communities on turbine foundations, variations in seabird communities, and also restrictions of fisheries in OWP areas. The methodological framework, models and indicators presented here allow the analysis of such complex processes, interactions and states and are thus an important tool to support decision making in the context of ICZM and a responsible planning of future sea-use activities.

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References

Baretta, J.W., Ebenhöh, W., Ruardij, P., 1995. An overview over the European Regional Sea Ecosystem Model, a complex marine ecosystem model. Neth. J. Sea Res. 33 (3/4), 233–246.
Barkmann, J., Baumann, R., Meyer, U., Müller, F., Windhorst, W., 2001. Ökologische Integrität: Risikovorsorge im Nachhaltigen Landschaftsmanagement (in German). Gaia 10 (2), 97–108.
Bierman, P., Lewis, M., Ostendorf, B., Tanner, J., 2011. A review of methods for analysing spatial and temporal patterns in coastal water quality. Ecol. Ind. 11, 103–114.
Bossel, H., 2000. Sustainability: application of systems theoretical aspects to societal development. In: Jørgensen, S.E., Müller, F. (Eds.), Handbook of Ecosystem Theories and Management. CRC Press, Boca Raton/London/New York/Washington, DC, pp. 519–536.
Burkhard, B., 2006. Nordsee 2055—Zukunftsszenarien für die Küste (in German). EcoSys Suppl. Bd. 46, 70–89.
Burkhard, B., Müller, F., 2008. Indicating human–environmental system properties: case study Northern Fenno-Scandinavian reindeer herding. Ecol. Ind. 8, 828–840.
Christensen, V., Pauly, D., 1992a. EcoPath II—a software for balancing steady-state models and calculation of network characteristics. Ecol. Model. 61, 169–185.
Christensen, V., Pauly, D., 1992b. A guide to the EcoPath II software system (version 2.1). ICLARM Software 6, 1–72.
Cicin-Sain, B., Knecht, R.W., 1998. Integrated Coastal and Ocean Management: Concepts and Practices. Island Press.

DHI, 1999. Horns Rev wind power plant—environmental impact assessment of hydrography. Baggrundsrapport nr. 8. Danish Hydraulic Institute report 50396-01.
Dierschke, V., Garthe, S., 2006. Literature review of offshore wind farms with regards to seabirds. BfN-Skripten 186, 131–198.
DONG Energy, Vattenfall, the Danish Energy Authority & the Danish Forest and Nature Agency, 2006. Danish Offshore Wind—Key Environmental Issues. DONG Energy.
ELSAM Engineering & Energy E2, 2004. The Danish offshore wind farm demonstration project: Horns Rev and Nysted offshore wind farm. Environmental impact assessment and monitoring. Review Report 2003. Copenhagen, Frederica.
Garthe, S., Hüppop, O., 2004. Scaling possible adverse effects of marine wind farms on seabirds: developing and applying a vulnerability index. J. Appl. Ecol. 41, 724–734.
Gill, A.B., 2005. Offshore renewable energy: ecological implications of generating electricity in the coastal zone. J. Appl. Ecol. 42, 605–615.
Johnson, H.K., Karambas, T.V., Avgeris, I., Zanuttigh, B., Gonzalez-Marco, D., Caceres, I., 2005. Modelling of waves and currents around submerged breakwaters. Coast. Eng. 52 (10–11), 949–969.
Jones, O.P., Petersen, O.S., Kofoed-Hansen, H., 2007. Modelling of complex coastal environments: some considerations for best practise. Coast. Eng. 54 (10), 717–733.
Jørgensen, S.E., Costanza, R., Xu, F.-L., 2005. Handbook of Ecological Indicators for the Assessment of Ecosystem Health. CRC Press, Boca Raton/London/New York/ Singapore.
Köller, J., Köppel, J., Peters, W., 2006. Offshore Wind Energy—Research on Environmental Impacts. Springer.
Lenhart, H.-J., 2001. Effects of river nutrient load reduction on the eutrophication of the North Sea, simulated with the ecosystem model ERSEM. In: Kröncke, I., Türkay, M., Sündermann, J. (Eds.), Burning Issues of North Sea Ecology, Proceedings of the 14th International Senckenberg Conference North Sea 2000. Senckenbergiana marit 31 (2), 299–311.
Lenhart, H.-J., Pohlmann, T., 1997. The ICES-boxes approach in relation to results of a North Sea circulation model. Tellus 49A, 139–160.
Lenhart, H., Burkhard, B., Windhorst, W., 2006. Ökologische Auswirkungen erhöhter Schwebstoffgehalte als Folge der Baumaßnahmen von Offshore Windkraftanlagen (in German). EcoSys Suppl. Bd. 46, 90–106.
Moll, A., Radach, G., 2003. Review of three-dimensional ecological modelling related to the North Sea shelf system. Part 1. Models and their results. Prog. Oceanogr. 57 (2), 175–217.
Müller, F., 2005. Indicating ecosystem and landscape organisation. Ecol. Ind. 5, 280–294.
Müller, F., Burkhard, B., 2007. An ecosystem based framework to link landscape structures, functions and services. In: Mander, Ü., Wiggering, H., Helming, K. (Eds.), Multifunctional Land Use—Meeting Future Demands for Landscape Goods and Services. Springer, pp. 37–64.
Müller, F., Burkhard, B., 2006. Beiträge zur Indikation der ökologischen Integrität auf verschiedenen Skalen (in German). EcoSys Suppl. Bd. 46, 53–69.
Nunneri, C., Lenhart, H.-J., Burkhard, B., Colijn, F., Müller, F., Windhorst, W., 2007a. The use of 'ecological risk' for assessing effects of human activities: an example including eutrophication and offshore wind farm construction in the North Sea. Landscape Online 5, 1–20, doi:10.3097/LO.200805.
Nunneri, C., Windhorst, W., Turner, R.K., Lenhart, H.-J., 2007b. Nutrient emission reduction scenarios in the North Sea: an abatement cost and ecosystem integrity analysis. Ecol. Ind. 7, 776–792.
Nunneri, C., Lenhart, H.-J., Burkhard, B., Windhorst, W., 2008. Ecological risk as a tool for evaluating the effects of offshore wind farm construction in the North Sea. Reg. Environ. Change 8, 31–43.
Odum, H.T., 1983. Systems Ecology: An Introduction. Wiley-Interscience, New York.
OSPAR, 1998. Report of the ASMO Modelling Workshop on Eutrophication Issues, 5–8 November 1996, The Hague, The Netherlands.
Pesch, R., Schmidt, G., Schröder, W., Weustermann, I., 2011. Application of CART in ecological landscape mapping: two case studies. Ecol. Ind. 11, 115–122.
Petersen, I.K., Fox, A.D., 2007. Changes in bird habitat utilisation around the Horns Rev 1 offshore wind farm, with particular emphasis on Common Scoter. Report to Vattenfall A/S, National Environmental Research Institute, Univ. of Aarhus, Denmark.
Peterson, C.H., Lubchenco, J., 1997. Marine ecosystem services. In: Daily, G.C. (Ed.), Nature's Services: Societal Dependence on Natural Ecosystems. Island Press, pp. 177–194.
POWER, 2005. Offshore Wind Energy in the North Sea Region. POWER and University of Groningen.
Ulanowicz, R.E., Norden, J.S., 1990. Symmetrical overhead in flow and networks. Int. J. Syst. Sci. 21 (2), 429–437.
Ulrich, U., 2006. Potential ecotoxicological effects of offshore wind parks. M.Sc. Thesis at the Christian Albrechts University of Kiel.
UNEP, 2006. Marine and Coastal Ecosystems and Human Wellbeing: A Synthesis Report Based on the Findings of the Millennium Ecosystem Assessment. UNEP.
Walker, B.H., Salt, D., 2006. Resilience Thinking: Sustaining Ecosystems and People in a Changing World. Island Press.
Windhorst, W., Colijn, F., Kabuta, S., Laane, R.P., Lenhart, H., 2005. Defining a good ecological status of coastal waters—a case study for the Elbe plume. In: Vermaat, J.E., Bouwer, L., Turner, K., Salomons, W. (Eds.), Managing European Coasts. Springer, pp. 59–74.