Ocean and Coastal Management 163 (2018) 401–416

Contents lists available at ScienceDirect

Ocean and Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

How to include ecological network analysis results in management? A case study of three tidal basins of the Wadden Sea, south-eastern North Sea

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ARTICLE INFO

Keywords:
Inter-ecosystems comparison
Food web models
Coastal ecosystems
Decision making
Holistic approach

ABSTRACT

Ecological network analysis (ENA) is an efficient tool to conduct holistic evaluation of the functioning and structure of ecosystems. ENA results can be used to support management decisions, but further development is needed to improve ENA application. We compared the food web functioning of three areas of the Wadden Sea: the Sylt-Rømø Bight, the Norderaue tidal basin and the Jade Bay, and present an example application of ENA indices in decision making processes. We used a sequential increase in uniform uncertainty from 50% to 99% using 10% increments to evaluate the robustness of the network comparisons. The results showed that the Jade Bay differed in its system functioning from the Sylt-Rømø Bight and the Norderaue tidal basin which represent the Northern Wadden Sea. The Jade Bay system, which is dominated by mudflats, had a heavier reliance on detritivory pathways, while the Northern Wadden Sea, which is dominated by *Arenicola*-sand flats, relied more on exchanges with the North Sea. Higher recycling, redundant pathways and flow diversity in the Jade Bay indicated that this system is probably more resilient against external perturbations than the Northern Wadden Sea systems which are more organized and specialized. This was related to the high standing stocks of suspension feeders in the Northern Wadden Sea, resulting from the establishment of several invasive suspension feeders, such as the Pacific oysters, the American razor clams and the common slipper shell. This study showed that 1- uncertainty analyses are crucial for the interpretation of ENA results and their use in management, 2- temporal measurable trends of indices which are robust to model uncertainty would be more appropriate for decision making than single reference values, 3- using ENA for assessment purposes in the Wadden Sea must be based on several representative sites taking into account their habitat types as well as morphological and physical characteristics, in terms of water depth, hydrodynamics and degree of enclosure of back barrier areas.

1. Introduction

In the current context of increasingly stressed ecosystems due to anthropogenic activities and global changes (Doney et al., 2012), holistic approaches are crucial to assess the status of ecosystems and to develop management and conservation strategies (Levin and Lubchenco, 2008; Samhouri et al., 2009; Longo et al., 2015). A holistic evaluation that considers direct and indirect interactions among multiple species will improve our knowledge about how the system may respond to environmental and/or anthropogenic stressors and thus provide valuable indications of possible impacts of management regulations on ecosystems (Carey et al., 2013). Ecosystem-based management has been proclaimed as the solution needed to improve the efficiency of management measures (Pikitch et al., 2004; Levin and Lubchenco, 2008; Levin et al., 2009), in the way that it defines management strategies for entire ecosystems rather than for single species (McLeod et al., 2005). In the last decades, food web models and ecological networks have become useful tools to represent large scale systems encompassing numerous compartments that interact with each other and respond differently to external stressors in both marine (Leguerrier et al., 2007; Ings et al., 2009; Kaufman and Borrett, 2010; Fath, 2015) and terrestrial systems (Heymans et al., 2002). Results from those models provide significant insight into the fundamental functioning of the ecosystem by quantifying properties that account for the

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https://doi.org/10.1016/j.ocecoaman.2018.07.019
Received 3 May 2018; Received in revised form 6 July 2018; Accepted 22 July 2018

direct and indirect interactions of these numerous compartments (Baird et al., 2004a; Fath, 2015). Ecological network analysis (ENA) was developed to holistically assess these complex environmental and biological interactions within ecosystem networks through a set of algorithms that analyse the structural and functional properties of these models (Finn, 1976; Ulanowicz 1986, 2004; Ulanowicz and Abarca-Arenas, 1997; Fath and Patten, 1999; Fath, 2015). Previous applications of ENA successfully evaluated the consequences of changes in ecosystems either due to 1- natural seasonal variations (Baird and Ulanowicz, 1989; Baird et al., 1998; Leguerrier et al., 2007; de la Vega et al., 2018), 2- direct anthropogenic impacts such as hypoxic events caused by eutrophication (Baird et al., 2004b) or the impact of dredging of estuarine channels leading to seawater intrusion (Hines et al., 2015), 3- decadal changes in ecosystem functioning due to changes in species community structure caused by invasive species (Baird et al., 2012) or climate change and eutrophication (Schückel et al., 2015) and 4- changed management practices such as decreased nitrogen loading on the eutrophication status of estuaries (Borrett et al., 2006; Christian and Thomas, 2003). ENA has also been used to compare the status of food webs within and across different ecosystems (Baird et al., 1991; Scharler and Baird, 2005; Leguerrier et al., 2007; Horn et al., 2017).

Until now, ENA has not yet been adopted as a management tool for multiple reasons. First, food web models are complex and require a large amount of data. Second, differences in model structure, degree of aggregation and topology makes inter-ecosystem comparisons difficult. Assessing the variability and sensitivity of ENA results to imprecisions and uncertainties in the model parametrization is essential for appropriate interpretation of ENA results and especially for comparison studies. These uncertainty analyses are therefore crucial for making ENA useful to decision makers, as they help to assess the strength of ENA conclusions (Hines et al., 2018). However, apart from some successful attempts to performed different types of uncertainty analysis on network flow models (e.g. Kaufman and Borrett (2010), Salas and Borrett (2011), Ayers and Scharler (2011), Mukherjee et al. (2015), Hines et al. (2015)), its application in ecology remains very scarce. Third, case studies that show specifically how ENA results can contribute to management decisions are highly missing. Niquil et al. (2012) and Heymans et al. (2014) demonstrated that ENA derived indicators vary by ecosystem traits (e.g. location, size, depth, type, physical typology). Both authors underlined that reference values for ecosystem indicators to define "good ecological status" should be developed for individual ecosystems or in defining sub-groups of ecosystems with similar typologies in which thresholds will have to be defined, but not benchmarked against all other ecosystems.

The Wadden Sea, extending along the south-eastern margin of the North Sea from the Netherlands to Denmark, is one of the largest continuous systems of intertidal sand and mudflats in the world (Lotze, 2007). Tidal basins and estuaries that differ in size or type (open Wadden Sea area, bay character or protected by barrier islands) are the natural sub-units of the Wadden Sea (van Beusekom et al., 2012). The Wadden Sea ecosystem is of great value and has supported coastal population for millennia, mainly with food, high water quality, natural coastal protection and recreation (Lotze et al., 2005). Intertidal flats are highly productive, diverse, and ecologically and economically important coastal ecosystems (Kabat et al., 2012). For example, these habitats provide high standing stocks and densities of benthic macrofauna that are essential food sources for higher trophic levels. Indeed, millions of migratory birds use the Wadden Sea as a stopover site in spring and fall on their annual migrations between southern wintering and northern breeding areas (Meltofte et al., 1994; Scheiffarth and Nehls, 1997). Several fish species (e.g. *Clupea harengus, Merlangius merlangus* and *Limanda limanda*) of high commercial importance from the North Sea use the tidal inlets and tidal flats of the Wadden Sea as nursery ground (Daan et al., 1990; Polte and Asmus, 2006; Tulp et al., 2008; Baumann et al., 2009). Finally, several species of marine mammals (e.g. *Phoca vitulina, Halichoerus grypu, Phocoena phocoena*) use the sheltered waters of the Wadden Sea to give birth, rest, feed and moult (Reijnders et al., 2009; de la Vega et al., 2016). The social and economic importance of this region, along with complex interspecies interactions, make this location an ideal spot to conduct a case study that demonstrates how network modelling and ENA can inform decision making.

In 2009, the Dutch and German parts of the Wadden have been declared UNESCO World Heritage Site which was extended to the Danish part of the Wadden Sea in 2014. In the Wadden Sea, effort has been made to implement holistic approaches in management decisions with international collaboration in protection plans. For instance a Trilateral Wadden Sea Plan that defines common management targets between the Netherlands, Germany and Denmark was adopted in 1997 and updated in 2010 (Kabat et al., 2012). The Wadden Sea is under the protection of several conventions and directives such as the Bonn Convention (1983) on the Conservation of Migratory Species of Wild Animals, the Bern Convention (1985) on the Conservation of European Wildlife and Natural Habitats and the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention 1998). In terms of European environmental directives, the EU Habitats Directive (1992), the EU Bird Directive (2009), the Water Framework Directive (2000) and the Marine Strategy Framework Directive (2008) are more relevant for the protection and sustainable use of the Wadden Sea property. However, most of these legislations focus on species-based management which uses monitoring data of populations and abundance of single species. Holistic approaches are still missing although the monitoring programs provide a large data set of most of the Wadden Sea ecosystem compartments which allow the construction of holistic models. Increasing global warming, invasion of non-native species, sea level rise and anthropogenic stresses, such as fisheries, eutrophication or pollution (Lotze et al., 2005; Oost et al., 2009) influence the Wadden Sea ecosystem at every trophic level but the effects will not necessarily be uniform across the Wadden Sea. A holistic appreciation of human impacts on natural processes and an assessment of ecosystem functioning across temporal scales would contribute to the management and protection of ecosystems worldwide (Shi et al., 2001; Apitz et al., 2006; Samhouri et al., 2009). The Wadden Sea case study is a good example application of implementing food web models by means of ENA in management decision processes, which is crucial to improve management, conservation and assessment as required by national and international legislations.

In this study, we examine and compare ENA derived results of three areas in the Wadden Sea (i.e. Sylt-Rømø Bight, Norderaue tidal basin and Jade Bay). We describe and quantify differences in the variability of standing stocks, interactions between living and non-living compartments as well as ecosystem functioning among Wadden Sea tidal basins. Similarities and differences are discussed in context of tidal basin traits, environmental characteristics and composition of habitats, as well as influence of invasive species, each of the three food webs comprising a different degree of invasive impact. In addition, we conducted an uncertainty analysis to evaluate the statistical significance of the differences observed in the ENA results, which is highly essential for ENA results to be used in a management context. This case study provides an example of how the insights gained from ENA can be useful to inform decision making.

2. Material and methods

2.1. Study sites

The three study sites are part of the Wadden Sea which extends along the south-eastern margin of the North Sea from the Netherlands to Denmark (Fig. 1). The most northern tidal basin considered in this study was the Sylt-Rømø Bight (54°52' - 55°10′ N, 8°20′ - 8°40′ E, Fig. 1). Further south, the studied Norderaue tidal basin is situated between the islands Amrum, Föhr, Langeness and the western coast of the federal state of Schleswig-Holstein (50°30′- 50°48′N, 8°15′- 8°50′E,