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Towards benthic ecosystem functioning maps: Quantifying bioturbation potential in the German part of the Baltic Sea

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ABSTRACT

This study aims to estimate, model and map the spatial differences of ecosystem functioning expressed by community bioturbation potential (BPc), an indicator of benthic faunal function based on bioturbation, in the German part of the Baltic Sea. The usefulness of bioturbation potential calculations was justified by its moderate but significant correlation with estimates of bioturbation rates derived from diagenetic models fitted to the *in situ* measured sediment depth profiles of naturally-occurring chlorophyll-a tracer. Seasonal and interannual variations of BPc were assessed and key species contributing to bioturbation in the study area were identified. To generate the most accurate map of BPc and to investigate its predictability based on abiotic parameters, we have tested 3 different methodological approaches: i) benthic macrofauna community bioturbation potential was initially calculated per station and treated as response variable for species distribution modelling technique (RandomForest, RF) with relevant available environmental layers used as predictors, ii) 35 key species were selected as the most contributing to BPc (responsible for 90% of total BPc), their population bioturbation potential (BPp) estimates were used as response variables and RF models were fitted on each of them to predict their full coverage distributions, that were subsequently summed up to the BPc, iii) BPc values at stations were interpolated to a raster surface using a natural neighbour technique. The comparison with observed values of BPc indicated that map derived by natural neighbour interpolation was the most accurate one given the considered resolution of 1 × 1 km.

1. Introduction

Biogenic activities that cause sediment reworking, including burrow and mound construction, lateral 'ploughing' of the surface (e.g. by heart urchins), particle ingestion and egestion during foraging, food caching and prey excavation, wallowing and trampling, and the infilling of abandoned burrow structures, are known as bioturbation (Meysman et al., 2006). In a broad sense the effects of bioturbation by benthic macrofauna that helps to illustrate multiple transport mechanisms include changes of sediments diagenesis, bioirrigation, displacement of microorganisms and non-living particles (Volkenborn et al., 2007). These fundamental processes have implications for ecosystem related functions ranging from alteration of sediment biogeochemistry, organic matter regeneration and nutrient cycling to the provision and maintenance of habitats for other organisms (Mermillod-Blondin, 2011; Birchenough et al., 2012). The mixing of sediment particles and solutes through the activities of infauna is one of the most important factors controlling the fate of contaminants in sediments, because these activities enhance pore water oxygenation and keep contaminants in contact with active fauna (Konovalov et al., 2010). It is important to understand these ecosystem functions and underlying mechanisms to insure that they are safeguarded and benthic function are not adversely affected as required by the European Marine Strategy Framework Directive (MSFD). A better understanding of the functional role of benthic fauna in relevant ecosystem processes will lead to the evaluation of the ecological services of the sediments.

When bioturbation is studied from the biogeochemical angle, bioturbation rates are often estimated using a family of diagenetic bioturbation/non-local exchange models that are fitted to the *in situ* measured depth profiles of naturally-occurring, particle-reactive tracers, such as ^{210}Pb, ^{234}Th, or chlorophyll a (e.g. Boudreau, 1986;

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Soetaert et al., 1996). These methods are beneficial in that they may distinguish between local and non-local sediment mixing. Local mixing is characterized by random transports over very short distances as well as by an exponential decrease of the tracer with sediment depth and is quantified by a biodiffusion coefficient Db. Non-local sediment mixing is defined by the occurrence of subsurface maxima due to e.g. discrete burrowing events or feeding behavior (Boudreau, 1986). Subject to the chosen tracer these methods will reflect rather short term and discernible small-scale spatial heterogeneity in mixing, as indicated by large variations in replicate cores. The values of Db reported for the marginal sediments of the Kara Sea by Mulsow and Povinec (2002) ranged between 0.03 and 27.4 $cm^{-2}\,yr^{-1}$ (based on single core collected per locations from 17 to 30 m water depth). Based on high sampling effort (with 4 cores at 6 locations few hundred meters apart collected at each of 6 stations) in the southern Baltic Sea Morys et al. (2016) suggested strong differences in modes of sediments reworking at replicate cores within one station; differences in Db estimated for replicate cores varied from factor 3 (at sandy stations) to factor 30 (at muddy Mecklenburg Bight). There was a factor of 20 between lowest injection flux ($J = 0.04\,\mu g\,cm^{-2}\,d^{-1}$) and highest estimate ($J = 0.8\,\mu g\,cm^{-2}\,d^{-1}$) for 24 cores collected in the Lübeck Bay. Based on mean chlorophyll profiles between-stations variability in local mixing (Db) showed a factor of 20 (with absolute values reported for Db ranging from 0.006 $cm^2\,d^{-1}$ in Lübeck Bay to 0.4 $cm^2\,d^{-1}$ in Stolteraa) and for stations characterized by non-local biomixing an injection flux differed by a factor of 6 (J ranged from 0.05 $\mu g\,cm^2\,d^{-1}$ to 2.1 cm depth (Oder Bank) to subsurface maximum injection flux of 3.9 $\mu g\,cm^{-2}\,d^{-1}$ in the Arkona Basin). According to Morys et al. (2016) non-local transport accounts for 33 to 50% of the investigated area in the west of the German part of the Baltic Sea and for 70–100% in the east, and there are first hints that the variability of DB, injection fluxes and amount of local versus non-local transports depend on the different compositions of the macrofauna population, the patchy distribution of the benthic organisms, and their adaptation to different salinities, as well as on food supply.

In situ quantification of bioturbation can be achieved by many methods, requiring not only technology and resources not always available, and not feasible in some settings but also conventional expert knowledge on species identity and associated biological attributes such as traits. Where dedicated biogeochemical research programmes do not exist, a practical alternative is the adoption of a trait-based approach. When trying to categorize and understand ecosystem functions conducted by benthic communities, bioturbation intensity can be quantitatively estimated from benthic quantitative data using the metric of bioturbation potential BPc (Solan et al., 2004; Birchenough et al., 2012). BPc provides an estimate of relative bioturbation intensity integrated over time of the development of macrofauna community at its sampled state. It is a simple value of the possible bioturbation activity and does not include any realistic measurements. It means that it is a sum parameter without consideration of temporal variability, intra- and interspecific interactions, individual fitness and behaviour. Neither the realistic contribution of species/individuals nor the temporal and spatial patterns are reflected. Yet, due to the paucity of data concerning mechanistic attributes of bioturbation (transport rates, activity, mixing depth), and the fact that the majority of this data is focusing on single species, artificially manipulated assemblages or sediment geology, until now the use of BPc may indeed be the only available option to investigate bioturbation at the regional scale. This was underlined in the recent study by Queirós et al. (2015), dealing with quantification of variability of community level bioturbation and association with seasonal drivers in the Western Channel. By calculating BPc over time, or for different locations or scenarios, changes in the efficiency of the organism-sediment coupling can be monitored for compliance in support of management and policy objectives (Queirós et al., 2013). Our present study provides a regional contribution to this thematic. Particularly important for managers and ecologists, large scale representation of BPc, complementing more information on species' ecological importance and providing a good test case to illustrate the uses of this metric, are lacking until now and are addressed in the present paper.

In order to create full-coverage spatial information of biological features spatial modelling techniques that link environmental parameters to biological information have become increasingly popular in recent years (Reiss et al., 2015). This work aims (1) to assess the seasonal and interannual variability of ecosystem functioning expressed by BPc in the German part of the Baltic Sea, (2) to identify key species contributing to bioturbation, and (3) to estimate, model and map its spatial differences in the study area.

2. Materials and methods

2.1. Study area

The sedimentary habitats in the south-western Baltic Sea (Fig. 1, study area amounts to about 14.8*10^3 km^2, average depth is 19 m) are mainly shaped by postglacial processes. Shallow areas along the shore and on top of the offshore glacial elevations are characterized by a mosaic of rocks, till, gravel and coarser sands. Substrate gets generally finer with increasing water depth. Organic-rich muddy sediments dominate in the basins and deeper part of trenches (Darr et al., 2014). Near-bottom salinity and oxygen concentration are the major factors influencing species richness and composition of macrozoobenthic communities in the area. Salinity declines from 20 to 25 in the western part of Kiel Bay towards 7 in the eastern Pomeranian Bay. The water exchange between the western Baltic and the Baltic Proper is inhibited by the Darss and Drodgen Sills, causing highest temporal variability of salinity in the western part of the study area. Aperiodic seasonal oxygen depletion events occur in the deeper areas of the Kiel Bay, the Bay of Mecklenburg and in the Arkona Basin, and have negative effects on the diversity and density of soft-bottom fauna (Arntz, 1981). An important food source is the inflow of freshwater from the larger rivers such as Trave, Warnow and Oder.

2.2. Macrozoobenthic data

Macrozoobenthic data from 1191 sampling stations located in the German part of the Baltic Sea (Fig. 1) were analysed (data sources: Leibniz Institute for Baltic Sea Research). Samples have been collected from 1999 to 2015. Sample data were averaged per stations and standardised to the area of 1 m^2.

The areal combination of functionally different sediment types and salinity conditions within a region determines the general functioning of benthic habitats. Large ranges of relevant environmental variables in the study area together with the availability of relatively large dataset that cover both the distribution of macrobenthic species and environmental variables makes the study area specifically interesting to assess the patterns of ecosystem functioning.

Even though spatial variability exceeds the temporal fluctuations on the regional scale, macrofaunal communities in the area have also shown high temporal variability in species abundance and shifts in species composition (Andersin et al., 1978; Perus et al., 2004; Zettler et al., 2008), often subject to changes in hydrodynamic processes, near-bottom oxygen or food availability (Kube et al., 1996). For example at monitoring station located on muddy sands of the Fehmarnbelt dramatic reductions associated with oxygen