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# Methodological elements for optimising the spatial monitoring design to support regional benthic ecosystem assessments

Gert Van Hoey  · Julia Wischniewski · Johan Craeymeersch · Jennifer Dannheim · Lisette Enserink · Laurent Guerin · Francisco Marco-Rius · Joey O'Connor · Henning Reiss · Anne F. Sell · Marie Vanden Berghe · Michael L. Zettler · Steven Degraer · Silvana N.R. Birchenough

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**Abstract** Benthic habitat condition assessments are a requirement under various environmental directives. The Marine Strategy Framework Directive (MSFD), for example, challenges member states in a European sea region to perform comparable assessments of good environmental status and improve coherence of their monitoring programmes by 2020. Currently, North Sea countries operate independent monitoring programmes using nationally defined assessment

areas. Lack of an agreed OSPAR or EU scale monitoring method and programme has been identified as a priority science need. This paper proposes a method for the development of a coherent and efficient spatial sampling design for benthic habitats on regional level and gives advice on optimal monitoring effort to get more accurate assessments. We use ecologically relevant assessment areas (strata) across national borders and test spatial sample allocation methods.

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Furthermore, we investigate the number of samples needed in each stratum to reduce the variance for estimating mean number of taxa and abundance. The stratification needs to take into account the spatial heterogeneity of the entire ecosystem. The total sample effort is optimal when sample allocation takes into account the size and benthic variability within those strata. Change point analysis helps to find a balance between sampling effort and precision of the benthic parameter estimate. A joint sampling design for the North Sea could be generated by combining current efforts, and where needed adapting existing national programmes. This serves a coordinated, region-wide, benthic condition status assessment and strengthens regional cooperation to fulfil multiple monitoring tasks, with a scientifically underpinned common approach.

**Keywords** Benthos · Monitoring · Sampling design · Stratification · Sample allocation · Coordination

## Introduction

The benthic system plays an important ecological role for the functioning of marine ecosystems (Braeckman et al. 2010; Birchenough et al. 2012; Stief 2013; Gogina et al. 2016a; Griffiths et al. 2017) and due to their sessile behaviour, benthic species are excellent sentinel species of temporal and chronic disturbances (Dauer 1993; Rees et al. 2007). The benthos is considered for the evaluation of the status of marine ecosystems under different European environmental directives such as the Marine Strategy Framework Directive (MSFD) (see Descriptors 1 [Biodiversity is maintained] and 6 [The sea floor integrity ensures functioning of the ecosystem]), Water Framework Directive (WFD) and Habitat Directive (HD) (Borja et al. 2010). In general, three aspects regarding the benthic ecosystem are considered in those directives; in relation to (1) benthic species distribution/occurrence (e.g. biogenic reefs, benthic species of conservation importance); (2) benthic habitat distribution; and (3) benthic habitat condition. The assessment of species distribution can be based on field data and/or modelling approaches (Reiss et al. 2015; Gogina et al. 2016b). The evaluation of benthic habitat distribution can rely on habitat (model) mapping, which can be determined by e.g. underwater acoustic techniques (Galparsoro et al. 2013). For determining the benthic

habitat condition, a wide variety of multimetric or multivariate indicators are developed to support obligations under the EU environmental directives (Borja et al. 2007; Borja et al. 2011; Birk et al. 2012; Rice et al. 2012; Van Hoey et al. 2013; Teixeira et al. 2014). These indicators rely on benthic samples taken in the field. The adoption of appropriate spatial and temporal scales whilst planning a monitoring programme is critical to derive a robust habitat status classification with high levels of confidence, regardless of the indicator type used (Van Hoey et al. 2010; Clarke 2013; Borja and Elliot 2013; Franco et al. 2015; Carstensen and Lindegarth 2016). Such confidence is related to the level of precision and sufficient statistical power where is strived for to detect a certain signal of change with those indicators (Rogers et al. 2008; Gray and Elliot 2009; Franco et al. 2015).

Member states are free to choose their own way of MSFD implementation (assessment method, sampling technique or design), which make it a challenge to perform comparable assessments of good environmental status and improve coherence of their monitoring programmes on a European sea region. We need for this a shift from local-orientated monitoring to basin- and/or system-oriented monitoring (de Jonge et al. 2006). Such design has the potential to deliver data, which can detect trends or non-compliance with a threshold or baseline value, leading to a well-defined management action towards good environmental status (GES) (De Jonge et al. 2006; Ferreira et al. 2007; Borja and Elliot 2013). These policy drivers have encouraged scientists to consider more robust survey designs, sampling and analytical methods with higher levels of confidence and reduced costs (Van der Meer 1997; Berg et al. 2015; Hayward et al. 2015; Patrício et al. 2016). The sampling resolution for a robust, regional monitoring is a complex issue, as it must standardise the spatial (all strata, size of strata, sample distribution, etc.) and temporal (season, year-to-year) conditions combined with the variability observed in ecosystem characteristics within a region. Nevertheless, designing efficient monitoring programmes on regional scale, which are still lacking, should be encouraged to limit expenses and effort. The level at which MSFD monitoring programmes experience regional integration varies between descriptors, ecosystem components and indicators. Commercial fish stock monitoring under the EU Common Fisheries Policy and its Data

Collection Framework (also relates to MSFD descriptor 3 [The population of commercial fish species is healthy]) is a good example, as there is a coordinated programme, with sampling designs defined on a regional scale (across national boundaries) and sampling protocols harmonised (e.g. IBTS manual; ICES 2015). In contrast, the available evidence for benthic biodiversity monitoring in the MSFD monitoring programmes of North Sea countries (Art. 11 reporting, 2015) suggests that there is a limited or non-existing level of co-ordination, as those programmes are nationally driven (Appendix). For benthos, there is still a clear lack of a common monitoring design and internationally agreed protocols (e.g. different devices, sampling times, sieve sizes). Nevertheless, there are two large-scale surveys, the North Sea Benthos datasets collected in 1986 and 2000 (Heip et al. 1992; Künitzer et al. 1992; Rees et al. 2007), which are valuable examples of how to start a coordinated benthic monitoring over representative spatial scales with national support of North Sea countries. The aim of this paper is to apply and evaluate some new methodological elements (e.g. stratification, allocation principles of sampling effort and change point analysis) (Hufnagl et al. 2014; Lavrakas 2008; Horvath and Rice 2014) to improve the design and development of spatial benthic monitoring over regional scales. This will provide already valuable input for the upcoming revision process of the MSFD monitoring programmes towards October 2020. The selection of the appropriate boundary conditions for those methodological elements is instrumental to support a cost-effective and ecologically meaningful regional benthic monitoring programme, which will support the development of large-scale seafloor assessments and the implementation of common regional indicators. The applicability of the methodological elements is tested in this paper for mean number of taxa and abundance of benthos. Those benthic parameters were selected as most of the ongoing benthic assessment methods rely on species diversity indices and abundance related measures (Borja and Dauer 2008; Van Hoey et al. 2013). The paper uses the earlier monitoring data of the North Sea (NSBP 1986 and 2000) to test and provide guidance for developing a spatial design of future regional monitoring programmes in such a way that a maximal precision and accuracy is strived for. Therefore, following elements of such

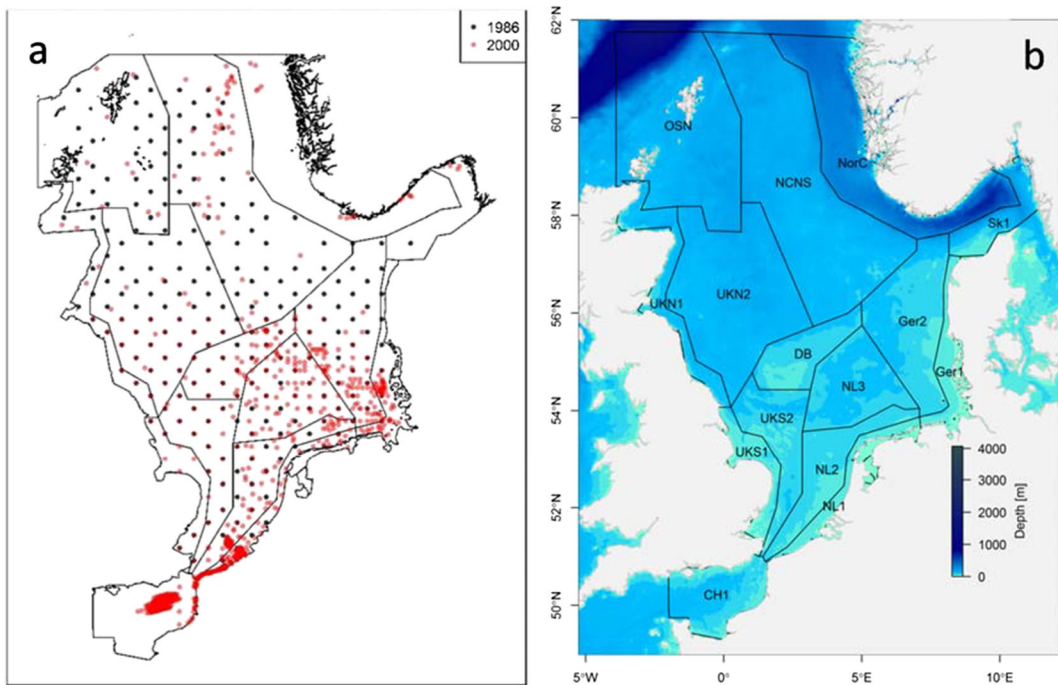
programme need to be optimised: (1) their stratification process; (2) the spatial allocation of samples; and (3) total sampling effort.

### Previous benthic monitoring programmes (NSBS 1986 and NSBP 2000)

The datasets of the North Sea Benthos Survey of 1986 (NSBS 1986) (Heip et al. 1992; Künitzer et al. 1992) and the North Sea Benthos Project of 2000 (NSBP 2000) (Rees et al. 2007) on benthic infauna are used (Fig. 1a). These datasets compiled by the International Council for the Exploration of the Sea (ICES) Benthos Ecology Working Group (BEWG) are publicly available (<http://www.emodnet-biology.eu/>). The early survey conducted in 1986 is carried out following a standardised sampling procedure for the central and southern North Sea (period April/May, grab sampling, 1 mm sieve) and an extensive grid survey of the northern part in 1980–1985 (grab sampling, 0.5 mm sieve) (Eleftheriou and Basford 1989; Heip et al. 1992; Künitzer et al. 1992). Later surveys conducted during 2000 were not possible to standardise (mainly due to different drivers related to national priorities and research needs) and resulted in a more uneven distribution of sampling stations (see details included in Rees et al. 2007). These datasets were collected mainly in spring and early summer, with several tools (box corers, Day or Hamon grab, Van Veen grab) and sieved on a 1 mm mesh. Additional harmonisation work on the taxonomy (synonymy, lumping of taxa, excluding non-benthic species or rare species) was performed during benthic expert workshops and integrated in the interface of the database to facilitate further data analysis and integration (Rees et al. 2007; Reiss et al. 2010). A broad comparison of data structure of the datasets was performed, which provide reassuring evidence of their integrity. Therefore, it provides a sound basis for an evaluation of the North Sea benthos, whilst recognising that sampling and analytical influence must also be accounted for in interpreting results.

### Evaluation of approaches to optimise spatial monitoring conditions

Here, the three methodological elements (e.g. stratification, allocation principles of sampling effort and change



**Fig. 1** **a** The sampling design of the NSBP 1986 and 2000; **b** the 15 modified strata delineated from the spatial domain structure of the North Sea ATLANTIS model (VECTORS project, Hufnagl et al. 2014), overlaid with bathymetry. NL, Netherlands; UKS, UK

south; UKN, UK North; CH, Channel; Ger, German strata; Sk, Skagerrak; DB, Doggerbank; NCNS, Norther Central North Sea; NorC, Norwegian Coast; OSN, Orkney/Shetland/Fladen Ground

point analysis) to guide the design and development of spatial benthic monitoring on regional scales are outlined. Stratification and a proper allocation of the sampling effort are essential aspects for obtaining a robust assessment of benthic habitat condition over large spatial scales (Van Hoey et al. 2010; Cabral and Murta 2004).

#### Stratification process

The goal of stratification is to divide the survey area into homogenous spatial units (strata) to obtain similar measurements within each stratum, and clearer differences among them (EUROSTAT 2008), increasing the reliability of the measurements. Suitable strategies for stratifying an area are well known, and can be based on several environmental parameters (Hufnagl et al. 2014; Kupschus et al. 2016) and/or benthic species communities (Rees et al. 2007; Reiss et al. 2010; Van Hoey et al. 2013), helping to optimise the sampling design for a single indicator type or ecosystem component. However, this stratification strategy could hamper the integration across other ecosystem components, which is a current

requirement under the MSFD (assessing 11 descriptors over a regional scale). Therefore, the ongoing challenge is to consider an appropriate scale and level of interaction for those descriptors. Particularly, when studying marine ecosystems, for some components (e.g. pelagic, benthic and fish), the habitats and scales are not entirely the same and some habitat variability is clearly observed across systems. Nevertheless, at sea-basin scale, the co-occurrence and habitat demarcation of different ecosystem components are often triggered by the same environmental drivers (e.g. Reiss et al. 2010; Kupschus et al. 2016), which therefore can eventually form the basis for a regional stratification. This is at least a more appropriate approach compared to the current administrative strata (ICES subareas and divisions, per ICES rectangles) for MSFD monitoring and assessment, as they hardly concur with the regional drivers determining the occurrence of species and habitats. Nevertheless, a stratification structure that forms a compromise between the need to account for spatial heterogeneity across the ecosystem and spatial management units is needed as basis for regional management (Link et al. 2010; Bossier et al. 2018). Such



type of stratification for the North Sea is developed in the EU project VECTORS, as the spatial domain structure of the North Sea ATLANTIS model (Hufnagl et al. 2014) and therefore taken forward in this paper. This structure consists of 25 strata, which are defined on a combination of using management units, species compositions, hydrographic features, bathymetry, sediment type and the influence of coastal processes such as river runoff. For executing this exercise appropriately, only 15 strata were used by pooling (3 English Channel polygons, the 5 Orkney-Shetland polygons [only southern part]) or excluding some of them (the boundary polygons) (Fig. 1b) to correspond with benthic data availability. The stratum NorC (Norwegian Coast) could not be used as the 1986–2000 dataset contain only data from the shallow coastal area, which is not representative for the deeper Norwegian trench. The boundaries of the main benthic habitats are in most cases in line with the North Sea ecosystem stratification (EUNIS habitat map; Reiss et al. 2010). For example, the discriminated benthic assemblages Oysterground (D22), offshore Southern North Sea-Doggerbank (D11) and Northern-central North Sea (D21) in Reiss et al. (2010) corresponds well with the respective strata NL3, DB and UKN2-NCNS, as they are largely influenced by large scale hydrodynamic variables, depth and sediment characteristics, even for the in-fauna communities (Reiss et al. 2010).

Such stratification created from an ecosystem perspective is likely to be more stable through time (Hufnagl et al. 2014; Kupschus et al. 2016), irrespective of population dynamics of species, and eventually introduced species. As such, they deliver similar units across ecosystem components, which is advantageous for a regional MSFD assessment and monitoring. Conversely, it is less specific for some distinct areas with species or habitats of conservation importance (e.g. certain gravel beds, muddy habitat near estuaries, *Sabellaria* or oyster reefs), as listed under the Habitats Directive or Regional Sea Conventions (Van Hoey et al. 2004; Pesch et al. 2008). Such distinct areas need to be considered separately, as subtypes, to minimise the influence on the monitoring requirements for the entire stratum. Nevertheless, the use of a stratification structure that is based on underlying general environmental drivers, which affect spatial patterns for the entire ecosystem to a similar extent, is put forward here to be the most suitable approach. The spatial domain structure of

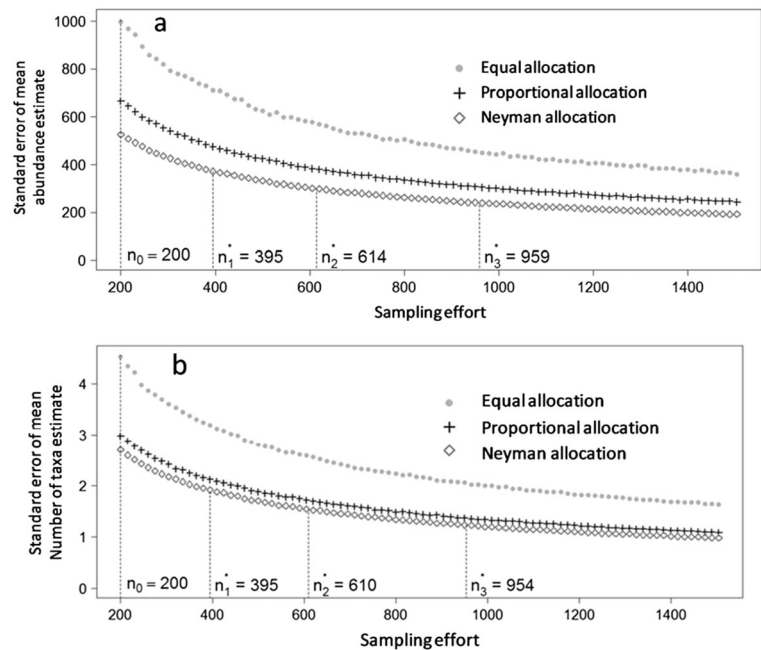
the North Sea ATLANTIS model seems to be an appropriate starting point for the benthic monitoring.

#### Allocation principles

Beside the selection of a stratification scheme, sample allocation to the strata is an important preliminary step for sample surveys (Lavrakas 2008). It determines how the samples are allocated to the strata, given a total sample size and it influence the accuracy of a stratified design. It can be undertaken in different ways, as (1) the ‘Equal allocation principle’ (E.a.), which allocates an equal number of samples to each stratum; (2) the ‘Proportional allocation principle’ (P.a.), which takes the surface area of strata into account (i.e. larger strata get more samples assigned than smaller ones); or (3) the ‘Neyman allocation principle’ (N.a.), which considers the proportional surface area of each stratum and the variability of the measured variable within each stratum. For the N.a. principle, more samples are assigned to a stratum with higher variability than to a similarly sized stratum with lower variability. For each allocation principle, the change in variance, as standard error of mean abundance or species richness (Fig. 2), is estimated by reducing the number of stations sequentially,  $n$  to  $N - 1$ ,  $N - 2, \dots, n_0$ , where  $N$  is the entire number of stations available from both benthic surveys and  $N_0$  the absolute minimum number of samples in a sampling scheme. There is worked with sample replacement during this procedure, in order to guarantee sufficient sample size in strata with few stations. For each sample size  $n$ , the estimates of total variance in mean number of species or abundance are computed as weighted sums of strata variances.

Our analysis revealed that the E.a. principle for sample allocation leads to a strong increase of variance for the same sampling effort, compared to P.a. and N.a. principle (Fig. 2). Using this principle for cost-effective monitoring would lead to an underestimation (e.g. offshore areas) or overestimation of sampling needs, and is therefore not recommended. The difference in variance level between the P.a. and N.a. principle are minimal for number of taxa, but slightly higher for abundance with P.a. compared to N.a. Nevertheless, the N.a. principle provides the best precision (lowest variance) for estimating the mean for number of taxa or abundance, given a certain total sample size. For example, the standard error of mean number of taxa estimate is higher by a factor 1 or more, if the total sampling

**Fig. 2** Standard error (SE) of the mean abundance (a) and number of taxa (b) in relation to sampling effort for the entire North Sea dataset (1986 & 2000). Indication of the change points in each graph ( $n_0$ ,  $n_1$ ,  $n_2$ ,  $n_3$ , see Table 1)



effort is allocated over the strata by another principle (i.e. E.a. or P.a.). This analysis illustrates that the selection of an appropriate allocation of your total sampling effort (N.a. principle, which take into account size of the strata and variability of the variables) can reduce the uncertainty of the benthic monitoring programme up to 50%.

#### Determination of total sampling effort

The determination of sampling effort within a monitoring programme is strongly driven by the available budgets (Borja and Elliot 2013; Carstensen 2014; Patricio et al. 2016). Nevertheless, it should mainly be based on the goal of the monitoring programme, the precision level (confidence) of the assessment strived for and the ability to detect a given amount of human induced impact (e.g. a threshold or a change of  $x\%$  in a parameter) (Rogers et al. 2008; Carstensen and Lindegarth 2016; Franco et al. 2015), and taking into account the natural variability of the biota (e.g. species richness, abundance) within a stratum. Therefore, a generic recommendation regarding the minimum number of samples is unrealistic. Instead, the aim should be an agreement on the minimum level of confidence and uncertainty that would allow for the reliable identification whether the target (e.g. Good Environmental Status) has been achieved (Borja et al. 2010). These targets

are still under development for several MSFD benthic indicators (Van Hoey et al. 2013; Teixeira et al. 2014; Van Loon et al. 2018). The objective for a regional monitoring programme is to obtain data on the entire area that minimise uncertainty in the assessment as much as possible, i.e. to distinguish between human induced change and natural variability. In this study, the change point approach is proposed to find a realistic compromise between sampling effort and precision of the benthic parameter estimate. Sampling effort-standard error graphs serve to explore the relationship between the number of samples and the considered variable standard error. Consequently, a multiple change point detection algorithm is executed to determine the optimal change point locations in the graph by transforming the continuous effort-variance graphs into segments with a consistent slope and intercept (Horvath and Rice 2014). The number of change points in the curve are validated statistically using the Bayesian Information Criteria (BIC) (Table 1). This segmented graph allows a sampling programmer to decide which segment and accompanied sampling effort is satisfactory. The multiple change point detection approach is realized in the R-package STRUCCHANGE (Zeileis et al. 2002).

The application of the change point algorithm on the previous North Sea benthic monitoring programmes showed that an increase of sampling effort above 954–

**Table 1** Bayesian Information Criteria (BIC) values for change point analysis (breaks) of the two parameters measured (species richness and density)

	0 break	1 break	2 breaks	3 breaks	4 breaks
Sp richness	- 1183.7	- 4555.4	- 6532.0	- 7338.7	- 7521.9
Density	12647.7	9279.4	7279.1	6455.2	6265.4

959 samples towards the total dataset (1525 samples) would be of little or no benefit to reduce the variability. The change of BIC is not significant in any of the variables, if more than four change points are included (Table 1). Moreover, the fourth break point is not further considered, as the decrease in BIC value from three to four breaks is rather small and to avoid overfitting. This results in four different sections of the curve (breakpoints at 395, 610–614 and 954–959 samples) where the highest benefit in increasing the confidence level can be reached. An effort lower than the first change point is not advisable because it is still accompanied with relative high variance values. These analyses and suggested sampling efforts give a direction on how many samples are needed to cover variability. It illustrates also that for estimation of number of samples, a proper prior knowledge of the area is helpful. Nevertheless, the obtained values are indicative, and new insights/data should be used continuously (or at least every 6 year, MSFD cycle) to re-evaluate the sample numbers and design. This is especially needed for the strata where the specific effort estimates are less confident due to the low number of available samples (< 20) (e.g. UKS1, Sk1, UKN1; Table 2).

**Spatial monitoring design**

The NSBP 1986 and 2000 show the benefit of executing a North Sea wide survey for observing the benthic ecosystem (Heip et al. 1992; Künitzer et al. 1992; Rees et al. 2007; Reiss et al. 2010; Kröncke et al. 2011). However, these designs (fixed gridded in 1986 and unbalanced in 2000) were not optimal for assessing benthic status on a regional scale (Rees et al. 2007). In 1986, the fixed gridded design led to an inadequate capturing of the benthic variability within the different benthic habitats, whereas in 2000, due to an individual institutional driven monitoring, the information is sometimes biased by

oversampling of a certain area. Our results demonstrate that an improved large-scale benthic sampling design needs to be developed by distributing the sampling effort across North Sea ecosystem strata by concurrent consideration of the variance of benthic characteristics and the strata’s surface area (based on the Neyman allocation principle). The analyses further showed that total sampling effort within a stratum becomes larger (e.g. change point two, 790 samples) compared to considering only one of them (e.g. species richness and abundance with 611 or 615 samples respectively), when considering the maximum effort of one of the variables needed per stratum (Table 2).

In comparison to 1986 and 2000, more sampling effort needs to be allocated to the deeper strata (NCNS, OSN, UKN2) compared to the shallower strata (GER1, NL1 and DB) for a regional monitoring (Table 2), which seems to be driven by another benthic parameter. In deeper areas (e.g. north-west North Sea area [UKN1, UKN2, OSN], English Channel [CH1]) a higher sampling effort is needed for species richness than for abundance to obtain a confident assessment. The opposite pattern is observed for some shallow strata, such as the German Bight (GER1, GER2), Skagerrak (SK1) and northern part of the Dutch shelf (NL3). For other strata (Southern North Sea [UKS1, UKS2, NL1, NL2] and Doggerbank [DB]), sampling effort for richness and abundance does not vary that much. It is obvious that there are differences in variance levels (standard error) between species richness and abundance across the North Sea strata, which must be taken into account for implementing a more cost-effective monitoring design, as also confirmed in other studies (Rogers et al. 2008; Franco et al. 2015).

**Way forward**

Robust ecological monitoring is relative costly (ship time, lab analyses, quality assurance/quality control [QA/QC] measures), especially for offshore sampling (Kingston and Riddle 1989; Eleftheriou and McIntyre 2005; Rogers et al. 2008; Gray and Elliot 2009; Borja and Elliot 2013). Therefore, efficiency will only be gained by integrating the suggested region-wide sampling programme into already ongoing monitoring at member states level, rather than starting an additional programme. At the North Sea scale, bordering countries already conduct benthic monitoring activities



**Table 2** Overview of the different strata, their weight (area proportion), the variance and the number of samples proposed to include for the two parameters measured (species richness, abundance), applying a Newman allocation at the first, second and third

change point. For comparison, the total number of samples during the two sampling surveys (1986–2000) is given for each stratum (last column). Area\* = stratum weight proportional to area

Stratum name	Area*	Required samples number (1th change point)			Required samples number (2th change point)			Required samples number (3th change point)			# samples 1986 + 2000
		Dens.	# spp	Total	Dens.	# spp	Total	Dens.	# spp	Total	
CH1	0.024	2	8	8	3	12	12	5	19	19	509
DB	0.042	13	11	13	20	16	20	31	25	31	57
GER1	0.029	23	5	23	36	8	36	56	12	56	63
GER2	0.091	42	19	42	65	30	65	102	47	102	106
NCNS	0.208	187	147	187	290	226	290	452	355	452	89
NL1	0.029	7	4	7	11	7	11	18	10	18	315
NL2	0.057	6	9	9	9	15	15	14	23	23	110
NL3	0.068	22	12	22	35	18	35	54	27	54	93
OSN	0.137	20	50	50	31	78	78	49	121	121	36
Sk1	0.031	29	10	29	43	16	43	67	25	67	4
UKN1	0.040	6	22	22	10	33	33	15	52	52	18
UKN2	0.159	23	68	68	36	105	105	56	165	165	66
UKS1	0.027	10	12	12	16	18	18	25	29	29	13
UKS2	0.058	6	9	9	10	29	29	16	45	45	33
<b>Total</b>	<b>1</b>	<b>396</b>	<b>396</b>	<b>501</b>	<b>615</b>	<b>611</b>	<b>790</b>	<b>960</b>	<b>955</b>	<b>1234</b>	<b>1512</b>

(Appendix); these are mainly national surveys to fulfil the demands under the ongoing EU Directives. In general, more benthic monitoring studies and datasets have become available, as benthic monitoring is also part of the Environmental Impact Assessment for specific activities (e.g. wind farms, aggregate extraction sites), which are mostly not considered as potential data source for MSFD (e.g. samples from control areas). Hence, the North Sea-wide sampling should be designed based on the available monitoring information or at least should consider the availability of this data, to meet the data needs per stratum (Table 3). Considering that the sampling of these studies is well spread within a stratum, they can be revisited on each sampling occasion to allow a better comparison over time. This temporal variability determination needs further attention once a spatial monitoring strategy is set up and should at least cover the time interval related to the EU legislation (6 years for MSFD assessment cycle). Therefore, the sample effort within this time interval will also depend on the level of change and precision you want to detect (cf power analyses) (Franco et al. 2015). This may include further

optimization of the functional design of existing monitoring locations, e.g. by shifted data needs per strata (Table 2), areas of interest (MPAs), inclusion of long-term monitoring stations and political or ecological constraints. Eventual extra costs (ship time) can be reduced by collecting benthic samples during other cruises (ships of opportunity, e.g. demersal fish surveys) (Shephard et al. 2015; ICES 2016). To achieve such an integrated benthic monitoring programme based on national initiatives, an official international coordination group, within existing regional frameworks (e.g. ICES, OSPAR, HELCOM), will need to be established to facilitate and integrate the discussion on how harmonisation of the monitoring designs and sampling protocols could be efficiently achieved. Common guidelines with incorporation of QC/QA, based on the existing ISO 16665 norm and Rumohr (2009), are sorely needed and have to ensure that the sampling, data management and the resulting datasets are comparable (Lampadariou et al. 2005; Kröncke et al. 2011). For supporting such process, a multinational dedicated funding scheme need to be set-up to ensure regional wide participation.

## Benefits and risks of coordinated monitoring

Implementing a coordinated monitoring for benthos on a regional scale could have a broad range of benefits as well as risks. The collected data can fulfil multiple purposes by coordinating and integrating existing monitoring (national survey's, long-term monitoring, industry monitoring) into a regional programme which increases the scientific and monetary value of each dataset. The newly acquired datasets will need to be stored in international data networks and comply with INSPIRE standards for easy access (e.g. <http://www.eurobis.org/>). The sampling designs, techniques and protocols used will also benefit from the knowledge exchange between countries. At the same time, agreeing on integrated and harmonised monitoring protocols (cf. ISO 16665 norm; Kingston and Riddle 1989; Lampadariou et al. 2005; Degraer et al. 2007; Rumohr 2009) before undertaking monitoring will lead to regional datasets of higher quality. This in turn will reduce the work and costs related to harmonisation or calibration of sampling methodologies (Rees et al. 2007; Vanden Berghe et al. 2009). This new set of integrating monitoring strategies will require changes in the common monitoring practices at institutional and member state levels. As such, standardised and quality-controlled datasets, with higher level of detail, could be made available for various initiatives such as modelling purposes, habitat mapping, species distribution and benthic indicator applications (Galparsoro et al. 2012; Reiss et al. 2015).

Regional scale-based monitoring programmes can depend on national initiatives, but will only be achieved if all countries and institutions support such an approach. The accuracy obtained with such an integrated programme depends if a common denominator can be found within those programmes and a certain level of harmonisation is acceptable (e.g. Appendix). At least, additional sampling costs would be minimised with such an approach, but some duplication of effort during sampling practices cannot entirely be excluded, due to

differing aims under the various ongoing monitoring programmes. Such integration processes are time-consuming, but the regional focus of the MSFD Directive and the regional conventions are the ideal driver for stimulating the development of efficient and robust monitoring programmes, integrating several ecosystem components, habitats and pressures through simultaneous monitoring. This will also enable a better scientific understanding of the benthic system on a larger scale, a thorough joint GES assessment and allow for a more effective response to pressures affecting it. Therefore, it is the perfect time and more than needed to make this step forward to strive for an improved, region-wide MSFD monitoring programme by 2020 for the benthic ecosystem. Nevertheless, those suggested methodological elements to optimise a regional monitoring programme are applicable worldwide.

We finally want to stress that a region-wide monitoring scheme for benthos aiming a region-wide assessment of the benthic condition does not exclude any more detailed extra monitoring effort targeting aspects of more local interest. Participating member states can of course always choose to do more as to target assets of local value or impacts of specific human activities. The critical point here is to agree on the minimum sampling scheme for region-wide assessments.

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## Appendix

**Table 3** Benthic subtidal soft sediment monitoring programmes for the European Union countries in the North Sea area. This information was collected in function of the project 'Towards a Joint Monitoring Programme for the North Sea and Celtic Sea' (JMP NS/CS) and the database from where these programmes were extracted can be found on <https://www.informatiehuismartien.nl/projecten/joint-monitoring/>. Those programmes can also be found on the official MSFD article 11 reporting portal (<http://cdr.eionet.europa.eu/>)

Name	Frequency	# samples	Coverage	Primary goal	Method	Official MSFD programme link	Linked to MSFD indicator
BE Environmental monitoring ILVO	Frequency depending on impact intensity	Between 190 to 270	EEZ of Belgium; sampling activity depending on the area occupied by a human activity (e.g. dredge disposal or sand extraction site)	Environmental impacts	Van Veen grab (0.1 m <sup>2</sup> ) follows the ISO standard (ISO 16665)	ANSBE-DI-4-6-Seabed-SP6	Benthic ecosystem quality index (BEQI); species richness, abundance, biomass, species composition
Environmental monitoring KBIN	Every 2 years; yearly	12	Gravel bed area in Natura 2000 area	Environmental state	Hamon grab	ANSBE-DI-4-6-Seabed-SP9	Not developed
NL Shellfish monitoring coastal area	Yearly	Around 800; 265 for MSFD	Coastal area Netherlands	Stock assessment, environmental state	Stratified, systematic sampling design; samplers: trawled dredge, hydraulic dredge.	ANSNL-D1346-Sub10-Benthos	'Smart' indicator species
MWTL infauna	Every 3 years	164	North Sea, H1110 b, H1110c, Oystergrounds, Frisian Front, Brown bank, offshore	Environmental state	Box-corer		MMI (OSPAR); Benthic Ecosystem Quality index-version2; species richness, Shannon diversity, AMBI
MSFD triple-D	Every 3 years	101	H1110c, Oystergrounds, Frisian Front, Brown bank,	Environmental state	Triple-D		'Smart' indicator species
MSFD Klaverbank	Every 3 years	42 + 39	Klaverbank (H1170)	Environmental state	Grab + video		Indicator species
DE Macrozoobenthos and Habitats	yearly	5-20	Eulittoral zone-sublittoral zone (coastal waters)	Environmental state	Van Veen grab (0.1; 0.2 m <sup>2</sup> ); Renneck corer; sieving 0.5-1 mm; Video and dredge	ANSDE_Sub_044	Not developed
Macrozoobenthos	yearly	5-20		Environmental state		ANSDE_Sub_007	m-AMBI: species richness, Shannon diversity, AMBI
DK Monitoring of zoobenthos	Yearly	35-50 coastal and 24 open water	North Sea -Wadden Sea-Skagerrak-Kattegat	Environmental state and impacts	HAPS bottom corer	NOVANA program; ANSDK-D06-04_- abundance_softbottomfauna	Danish Quality index (DKI)
FR RESOMAR-BENTHOS	Variable	845	Protected marine habitat areas	Environmental state	Van Veen grab		m-AMBI: species richness, Shannon diversity, AMBI
FR RESOMAR-BENTHOS	Variable	Variable	Coast of France (Manche-Mer du Nord, Mers Celtiques, Golfe de Gascogne, Méditerranée)	Environmental state and impacts	Methods (grabs, dredges, corers, sucker)	Not available	m-AMBI: species richness, Shannon diversity, AMBI
SE Soft-bottom macrofauna	Yearly	70	Coastal waters, territorial waters and EEZ; Skagerrak relevant for North Sea	Environmental state and impacts	Ekman (softer bottoms) or Ponar grab (sandy bottoms), drop video	ANSSE-BENT-D165-Bottenfauna	Benthic Quality Index (BQI);

Table 3 (continued)

Name	Frequency	# samples	Coverage	Primary goal	Method	Official MSFD programme link	Linked to MSFD indicator
UK UK WFD monitoring	Every 3 years	England +80 sites; 100 sites Scotland	Transitional and coastal waters	Environmental state and impact	Use of standardised methods (Sample type, sieve mesh, ISO 16665:2005)	ANSUK_D0146_03_subtidal_sediments_sub	Infaunal quality index (IQ)
UK SAC monitoring	Sampling spread over a six-year program	Variable per site	Transitional, coastal and territorial waters	Environmental state and impact		ANSUK_D0146_06_1_SAC_England_sub	

References

Berg, T., Fürhaupter, K., Teixeira, H., Uusitalo, L., & Zampoukas, N. (2015). The Marine Strategy Framework Directive and the ecosystem-based approach—pitfalls and solutions. *Marine Pollution Bulletin*, 96, 18–28.

Birchough, S. N. R., Parker, R., McManus, E., & Barry, J. (2012). Combining bioturbation and redox metrics: potential tools for assessing seabed function. *Ecological Indicators*, 12, 8–16.

Birk, S., Bonne, W., Borja, A., Brucet, S., Courrat, A., Poikane, S., et al. (2012). Three hundred ways to assess Europe’s surfaca waters: an almost complete overview of biological methods to implement the Water Framework Directive. *Ecological Indicators*, 18, 31–41.

Borja, A., & Dauer, D. M. (2008). Assessing the environmental quality status in estuarine and coastal systems: comparing methodologies and indices. *Ecological Indicators*, 8, 331–337.

Borja, A., & Elliot, M. (2013). Marine monitoring during an economic crisis: the cure is worse than the disease. *Marine Pollution Bulletin*, 68, 1–3.

Borja, A., Josefson, A. B., Miles, A., Muxika, I., Olsgard, F., Phillips, G., et al. (2007). An approach to the intercalibration of benthic ecological status assessment in the North Atlantic ecoregion, according to the European Water Framework Directive. *Marine Pollution Bulletin*, 55, 42–52.

Borja, A., Elliot, M., Carstensen, J., Heiskanen, A.-S., & van de Bund, W. (2010). Marine management – towards an integrated implementation of the European Marine Strategy Framework and the Water Framework Directives. *Marine Pollution Bulletin*, 60(12), 2175–2186.

Borja, A., Galparsoro, I., Irigoien, X., Iriondo, A., Menchaca, I., Muxika, I., et al. (2011). Implementation of the European Marine Strategy Framework Directive: a methodological approach for the assessment of environmental status, from the Basque Country (Bay of Biscay). *Marine Pollution Bulletin*, 62(5), 889–904.

Bossier, S., Palacz, A. P., Nielsen, J. R., Christensen, A., Hoff, A., Maar, M., et al. (2018). The Baltic Sea Atlantis: an integrated end-to-end modelling framework evaluating ecosystem-wide effects of human-induced pressures. *PLoS One*, 13(7), e0199168.

Braeckman, U., Provoost, P., Gribsholt, B., Van Gansbeke, D., Soetaert, K., Middelburg, J. J., et al. (2010). Role of macrofauna functional traits and density in biogeochemical fluxes and bioturbation. *Marine Ecology Progress Series*, 399, 173–186.

Cabral, H., & Murta, A. G. (2004). Effect of sampling design on abundance estimates of benthic invertebrates in environmental monitoring studies. *Marine Ecology Progress Series*, 276(1), 19–24.

Carstensen, J. (2014). Need for monitoring and maintaining sustainable marine ecosystem services. *Frontiers in Marine Science*. <https://doi.org/10.3389/finars.2014.00033>.

Carstensen, J., & Lindegarth, M. (2016). Confidence in ecological indicators: a framework for quantifying uncertainty components from monitoring data. *Ecological Indicators*, 67, 306–317.

- Clarke, R. T. (2013). Estimating confidence of European WFD ecological status class and WISER Bioassessment Uncertainty Guidance software (WISERBUGS). *Hydrobiologia*, *704*(1), 39–56.
- Dauer, D. M. (1993). Biological criteria, environmental-health and estuarine macrobenthic community structure. *Marine Pollution Bulletin*, *26*, 249–257.
- de Jonge, V. N., Elliott, M., & Brauer, V. S. (2006). Marine monitoring: its shortcomings and mismatch with the EU water framework directive's objectives. *Marine Pollution Bulletin*, *53*, 5–19.
- Degraer, S., Moulart, I., Van Hoey, G., & Vincx, M. (2007). Sieving alive or after fixation: effects of sieving procedure on macrobenthic diversity, density and community structure. *Helgoland Marine Research*, *61*, 143–152.
- Eleftheriou, A., & Basford, D. J. (1989). The macrobenthic infauna of the offshore northern North Sea. *Journal of the Marine Biological Association of the UK*, *69*, 123–143.
- Eleftheriou, A., & McIntyre, A. (2005). Methods for the study of marine benthos. 3rd edition. Blackwell Science, Oxford. 418 pp.
- Eurostat (2008). Survey sampling reference guidelines. Introduction to sample design and estimation techniques. European Commission, Eurostat, Luxembourg. 36 pp. <https://ec.europa.eu/eurostat/web/products-manuals-and-guidelines/-/KS-RA-08-003>.
- Ferreira, J. G., Vale, C., Soares, C. V., Salas, F., Stacey, P. E., Bricker, S. B., et al. (2007). Monitoring of coastal and transitional waters under the EU water framework directive. *Environmental Monitoring and Assessment*, *135*(1-3), 195–216.
- Franco, A., Quintino, V., & Elliott, M. (2015). Benthic monitoring and sampling design and effort to detect spatial changes: a case study using data from offshore wind farm sites. *Ecological Indicators*, *57*, 298–304.
- Galparsoro, I., Connor, D. W., Borja, A., Aish, A., Amorim, P., Bajjouk, T., et al. (2012). Using EUNIS habitat classification for benthic mapping in European seas: present concerns and future needs. *Marine Pollution Bulletin*, *64*, 2630–2638.
- Galparsoro, I., Borja, A., Kostylev, V. E., Rodriguez, J. G., Pascual, M., & Muxika, I. (2013). A process-driven sedimentary habitat modelling approach, explaining seafloor integrity and biodiversity assessment within the European Marine Strategy Framework Directive. *Estuarine, Coastal and Shelf Science*, *131*, 194–205.
- Gogina, M., Morys, C., Forster, S., Gräwe, U., Friedland, R., & Zettler, M. L. (2016a). Towards benthic ecosystem functioning maps: quantifying bioturbation potential in the German part of the Baltic Sea. *Ecological Indicators*, *73*, 574–588.
- Gogina, M., Nygard, H., Blomqvist, M., Daunys, D., Josefson, A. B., Kotta, J., et al. (2016b). The Baltic Sea scale inventory of benthic faunal communities. *ICES Journal of Marine Science*, *73*, 1196–1213.
- Gray, J. S., & Elliot, M. (2009). *Ecology of marine sediments. From science to management, 2nd edn*. Oxford: Oxford University Press.
- Griffiths, J. R., Kadin, M., Nascimento, F. J. A., Tamelander, T., Törnroos, A., Bonaglia, S., et al. (2017). The importance of benthic-pelagic coupling for marine ecosystem functioning in a changing world. *Global Change Biology*, *23*(6), 2179–2196.
- Hayward, M. W., Biotani, L., Burrows, N. D., Funston, P. J., Karanth, K. U., MacKenzie, D. I., et al. (2015). Ecologists need robust survey designs, sampling and analytical methods. *Journal of Applied Ecology*, *52*, 286–290.
- Heip, C., Basford, D., Craeymeersch, J. A., Dewarumez, J. M., Dörjes, J., de Wilde, P., et al. (1992). Trends in biomass, density and diversity of North Sea macrofauna. *ICES Journal of Marine Science*, *49*(1), 13–22.
- Horvath, L., & Rice, G. (2014). Extensions of some classical methods in change point analysis. *Test*, *23*(2), 219–255.
- Hufnagl, M., Fulton, E.J., Gorton, R., Keth, A., Kempf, A., Le Quesne, W.J., et al. (2014). ATLANTIS 1 – North Sea. In: *Holistic framework(s) for assessing multiple drivers*. Deliverable 5.1.3 of the EU project VECTORS. [www.marine-vectors.eu](http://www.marine-vectors.eu).
- ICES (2015). Manual for the International Bottom Trawl Surveys. Series of ICES Survey Protocols SISP 10 - IBTS IX. 86 pp. <http://www.ices.dk/publications/Pages/default.aspx>.
- ICES (2016). Report of the Workshop to plan an integrated monitoring Programme in the North Sea in Q3 (WKPIMP). ICES CM 2016/SSGIEOM:11, 44 pp.
- Kingston, P. F., & Riddle, M. J. (1989). Cost effectiveness of benthic faunal monitoring. *Marine Pollution Bulletin*, *20*, 490–496.
- Kröncke, I., Reiss, H., Eggleton, J. D., Aldridge, J., Bergman, M. J. N., Cochrane, S., et al. (2011). Changes in North Sea macrofauna communities and species distribution between 1986 and 2000. *Estuarine, Coastal and Shelf Science*, *94*, 1–15.
- Künitzer, A., Basford, D., Craeymeersch, J. A., Dewarumez, J. M., Dörjes, J., Duineveld, G. C. A., et al. (1992). The benthic infauna of the North Sea: species distribution and assemblages. *ICES Journal of Marine Science*, *49*(2), 127–143.
- Kupschus, S., Schratzberger, M., & Righton, D. (2016). Practical implementation of ecosystem monitoring for the ecosystem approach to management. *Journal of Applied Ecology*, *53*(4), 1236–1247.
- Lampadariou, N., Karakassis, I., & Pearson, T. H. (2005). Cost/benefit analysis of a benthic monitoring programme of organic benthic enrichment using different sampling and analysis methods. *Marine Pollution Bulletin*, *50*, 1606–1618.
- Lavrakas, P.J. (2008). *Encyclopedia of survey research methods*. Sage Publications Inc. 1072 pp.
- Link, J. S., Fulton, E. A., & Gamble, R. J. (2010). The northeast US application of ATLANTIS: a full system model exploring marine ecosystem dynamics in a living marine resource management context. *Progress in Oceanography*, *87*, 214–234.
- Patrício, J., Little, S., Mazik, K., Papadopoulou, K.-N., Smith, C. J., Teixeira, H., et al. (2016). European marine biodiversity monitoring networks: strengths, weaknesses, opportunities and threats. *Frontiers in Marine Science*, *3*, 161, 1–18.
- Pesch, R., Pehlke, H., Jerosch, K., Schröder, W., & Schlüter, M. (2008). Using decision trees to predict benthic communities within and near the German Exclusive Economic Zone



- (EEZ) of the North Sea. *Environmental Monitoring and Assessment*, 136, 313–325.
- Rees, H. L., Eggleton, J.D., Rachor, E., Vanden Berghe, E. (Eds) (2007). Structure and dynamics of the North Sea benthos. ICES Cooperative Research Report No. 288, 258 pp. <https://epic.awi.de/20067/1/Rac2007b.pdf>.
- Reiss, H., Degraer, S., Duineveld, G. C. A., Kroncke, I., Aldridge, J., Craeymeersch, J. A., et al. (2010). Spatial patterns of infauna, epifauna, and demersal fish communities in the North Sea. *ICES Journal of Marine Science*, 67(2), 278–293.
- Reiss, H., Birchenough, S., Borja, A., Buhl-Mortensen, L., Craeymeersch, J., Dannheim, J., et al. (2015). Benthos distribution modelling and its relevance for marine ecosystem management. *ICES Journal of Marine Science*, 72(2), 297–315.
- Rice, J., Arvanitidis, C., Borja, A., Frid, C., Hiddink, J. G., Krause, J., et al. (2012). Indicators for sea-floor integrity under the European Marine Strategy Framework Directive. *Ecological Indicators*, 12, 174–184.
- Rogers, S. I., Somerfield, P. J., Schratzberger, M., Warwick, R., Maxwell, T. A. D., & Ellis, J. R. (2008). Sampling strategies to evaluate the status of offshore soft sediment assemblages. *Marine Pollution Bulletin*, 56, 880–894.
- Rumohr, H. (2009). *Soft bottom macrofauna: collection, treatment, and quality assurance of samples*. ICES Techniques in Marine Environmental Sciences, 43: 20 pp. <http://www.ices.dk/sites/pub>.
- Shephard, S., van Hal, R., de Boois, I., Birchenough, S. N. R., Foden, J., O'Connor, J., et al. (2015). Making progress towards integration of existing sampling activities to establish Joint Monitoring Programmes in support of the MSFD. *Marine Policy*, 59, 105–111.
- Stief, P. (2013). Stimulation of microbial nitrogen cycling in aquatic ecosystems by benthic macrofauna: mechanisms and environmental implications. *Biogeosciences*, 10(12), 7829–7846.
- Teixeira, H., Berg, T., Fürhaupter, K., Uusitalo, L., Papadopoulou, N., Bizsel, K.C., et al. (2014). Existing Biodiversity, Non-Indigenous Species, Food Web and Sea floor Integrity GENs Indicators (DEVOTES Deliverable3.1) DEVOTES FP7 Project.198. <http://www.devotes-project.eu>.
- Van der Meer, J. (1997). Sampling design of monitoring programmes for marine benthos: a comparison between the use of fixed versus randomly selected stations. *Journal of Sea Research*, 37, 167–179.
- Van Hoey, G., Degraer, S., & Vincx, M. (2004). Macrobenthic community structure of soft-bottom sediments at the Belgian Continental Shelf. *Estuarine, Coastal and Shelf Science*, 59, 599–613.
- Van Hoey, G., Borja, A., Birchenough, S., Degraer, S., Fleischer, D., Kerckhof, F., et al. (2010). The use of benthic indicators in Europe: from the Water Framework Directive to the Marine Strategy Framework Directive. *Marine Pollution Bulletin*, 60, 2187–2196.
- Van Hoey, G., Permuy, D. C., Vincx, M., & Hostens, K. (2013). An Ecological Quality Status assessment procedure for soft-sediment benthic habitats: weighing alternative approaches. *Ecological Indicators*, 25, 266–278.
- van Loon, W. M. G. M., Walvoort, D. J. J., Van Hoey, G., Vina-Herbon, C., Blandon, A., Pesch, R., Schmitt, P., Scholle, J., Heyer, K., Lavaleye, M., Phillips, G., Duineveld, G. C. A., & Blomqvist, M. (2018). A regional benthic fauna assessment method for the Southern North Sea using Margalef diversity and reference value modelling. *Ecological Indicators*, 89, 667–679.
- Vanden Berghe, E., Claus, S., Appeltans, W., Faulwetter, S., Arvanitidis, C., Somerfield, P. J., et al. (2009). MacroBen integrated database on benthic invertebrates of European continental shelves: a tool for large-scale analysis across Europe. *Marine Ecology-Progress Series*, 382, 225–238.
- Zeileis, A., Leisch, F., Hornik, K., Kleiber, C., Hansen, B., & Zeileis, M. A. (2002). *Package 'strucchange'*. Vienna: R Foundation for Statistical Computing.

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