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Food for Thought

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The importance of long-time series of benthic data for science and management

Silvana N.R. Birchenough [1,*], Eivind Oug [2], Jan Beermann [3], Nicolas Desroy [4], Mats Blomqvist [5], Laurent Guerin [6], Urszula Janas [7], Céline Labrune [8], Paolo Magni [9], Henning Reiss [10], Jennifer Dannheim [3,11], Hilde Trannum [2,12], Annick Donnay [13], Ingrid Kröncke [14], Steven Degraer [15], Johan Craeymeersch [16]

[1]Sharjah Marine Science Research Centre, University of Khorfakhan, United Arab Emirates
[2]Norwegian Institute for Water Research, Region South, NO-4879 Grimstad, Norway
[3]Department of Benthic Ecology, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Am Handelshafen 12, 27570 Bremerhaven, Germany
[4]Ifremer, Unité COAST Laboratoire Environnement et Ressource Bretagne Nord, 38 Rue Du Port Blanc, 35800 Dinard, France
[5]Hafok AB, SE 179 61 Stenhamra, Sweden
[6]Office Francais de la Biodiversite. Station Marine de Dinard, Centre de Recherche et d'Enseignement Sur les Systèmes Côtiers (CRESCO), 38 Rue du Port Blanc, 35800 Dinard, France
[7]Faculty of Oceanography and Geography, University of Gdańsk, Al. Marsz. Pilsudskiego 46, 81-378 Gdynia, Poland
[8]Laboratoire d'Ecogéochimie des Environnements Benthiques (LECOB), Observatoire Océanologique de Banyuls, CNRS, Sorbonne Université, UMR 8222, 66650, Banyuls-sur-Mer , France
[9]National Research Council of Italy, Institute of Anthropic Impacts and Sustainability in the Marine Environment (CNR-IAS), Loc. Sa Mardini, Torregrande, 09170 Oristano, Italy
[10]Faculty of Biosciences and Aquaculture, Nord University, Universitetsalléen 11, 8026 Bodø, Norway
[11]Deep-Sea Ecology and Technology Department, Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Am Handelshafen 12, 27570 Bremerhaven, Germany
[12]Department of Natural Sciences, University of Agder, Centre for Coastal Research-CCR, Kristiansand, 422 4604, Norway
[13]Station de Recherches Sous-Marines et Océanographiques (STARESO), Pointe Revellata, 20260 Corse, France
[14]Dept for Marine Research, Senckenberg am Meer, Wilhelmshaven, Germany and Institute for Chemistry and Biology of the Marine Environment, Univ. of Oldenburg, Wilhelmshaven, Germany
[15]Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Marine Ecology and Management (MARECO), Vautierstraat 29, Brussels 1000, Belgium
[16]Wageningen University, Wageningen Marine Research, P.O. Box 77, 4400, AB, Yerseke, the Netherlands
*Corresponding author. Sharjah Marine Science Research Centre, University of Khorfakhan, United Arab Emirates. E-mail: silvana.birchenough@ukf.ac.ae

Abstract

Benthic organisms are important ecological receptors, playing fundamental roles across seafloor ecosystems, delivering some of the most important functions in the marine environment. Some of these key benthic functions include nutrient cycling, food provision for higher trophic levels, and carbon storage. Over the past 6 years, benthic monitoring has faced growing complexity, driven by diminishing funding and the constraints imposed by the COVID-19 pandemic. These challenges underscore the pressing need to recognize the enduring value of benthic time series in supporting monitoring, management, and modelling efforts. These long-term data sets have been critical to advance our current understanding into the areas of cumulative effects, conservation, management of Marine Protected Areas (MPAs), development of indicators, and assessment of climate-driven changes in marine ecosystems. Ongoing expert group discussions consistently affirm both the relevance and necessity of continuing to collect these vital data sets. However, the focus on emerging technologies and so-called '*cutting-edge*' approaches sometimes leads to the undervaluation and compromising some of these long-term series. We contend that a comprehensive understanding of benthic ecology, essential for robust marine management, reliable numerical analysis, and taxonomic consistency, cannot be achieved without the continuity provided by long-term data. Such time series are indispensable for tracking patterns of change and assessing responses across diverse human activities and seafloor ecosystems. While our research has concentrated on soft sediment environments, many of the key principles and recommendations outlined here are broadly applicable to other ecosystem types.

Keywords benthos, monitoring, time series, eDNA, seafloor, management, collaboration, and Directives

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Introduction

The assessment of natural ecosystem variability is of pivotal importance for the identification and discrimination of human influence on marine ecosystems. Consequently, marine management needs to incorporate: (1) knowledge of the ecosystems and their respective environmental drivers, (2) the assessment of anthropogenic effects, and (3) solutions to reduce their impacts. This commitment seeks to maintain and protect natural ecological characteristics and resources, delivering the ecosystem services and benefits required by society (see Elliott 2011, Elliott 2013). A multitude of observational systems and techniques have been designed and conducted to meet these demands. The concept is referred to as 'monitoring' (Elliott 2011, Elliott 2013, Karydis and Kitsiou 2013, Turrell 2018) and 'long-term data series'. However, there is no precise definition of marine monitoring. Therefore, our preference is to consider the definition of 'an activity that is routinely performed, assesses a pressure or impact on a marine ecosystem, with a sound design and is sustained over several years' (Turrell 2018).

The operation of long-term series is one of the fundamental activities in marine monitoring. By long-term series we consider data series carried out with uniform sampling strategies and measurement methods over extended time periods, i.e. 10–40+ years (see Wolfe et al. 1987). Long-term series mainly addresses the description of variation and changes in ecosystems over time. Their importance is twofold: (1) based on repeated sampling, reference values and sampling variability of ecosystem components can be developed into monitoring indicators and (2) depending on the length of the studies, any gradual changes or interannual patterns can be assessed and related to changes in environmental conditions. Series spanning several decades may reveal slow multidecadal ecosystem changes and demonstrate the effects of strong, but infrequent events that may affect ecosystems for extended periods (Frid et al. 2009, Kröncke et al. 2011, Kröncke 2011, Rousi et al. 2013, Pelletier et al. 2021, Dippner et al. 2025, Singer et al. 2025), including shifts in ecosystem state (e.g. 'tipping-points', see Reid 2016) and trophic cascades (Hughes et al. 2017). Edwards et al. (2010) illustrated from Continuous Plankton Recordings (CPR) series in the North Sea that interannual changes could be identified after 20 years, whereas relationships between plankton and climate signals were definable after 30–40 years and decadal regime shifts after 50 years. Climate-related tipping points were also found by Di Pane et al. (2024) and Marques *et al*. (2024) for zooplankton time series at LTER Helgoland Roads. Spencer et al. (2012) also demonstrated the importance of documenting the whole suite of changes across marine ecosystems with long-term series.

Monitoring *per se* could have different objectives depending on the purposes and/or questions needing to be addressed, which these time series should consider from the offset. These objectives could be aligned with scientific and/or management needs (Yoccoz et al. 2001). Scientific objectives primarily focus on learning and developing an understanding of the behaviour and dynamics of the systems studied. Monitoring designed for management purposes typically focuses on system state or provides information on a system response to a management measures (i.e. effect or compliance monitoring). Management-driven monitoring could fall under different categories, depending on the monitoring objectives, e.g. sentinel monitoring of long-term trends (type 1), operational monitoring of pressure-state relationships (type 2), and investigative monitoring to determine management needs and effectiveness (type 3) (JNCC 2016). When considering all these monitoring types, type 1 has the objective of measuring rate and direction of long-term change, and it is dependent on long-term time series data, while 'a long-term commitment to regular and consistent data collection is necessary, and time series must be established, as their power in identifying trends is far superior to any combination of independent studies' (JNCC 2016).

To date, not all long-term series have persisted continuously. An important consideration is to undertake a stocktake of dwindling funds, change of personnel, changes in scientific objectives, monitoring requirements, and policy support. These very important aspects will help to evaluate the need to keep these series running. Hughes et al. (2017) provided examples of long-term studies, even with highly invested studies with important scientific outcomes, some of them have been discontinued in recent years, primarily due to the declining funding. It is also a matter of concern that a steadily increasing share of funding for scientific studies is directed towards short-term studies addressing emerging and pressing environmental problems and are often financed by time-limited grants (Hughes et al. 2017), which may support short-term policy mandates. However, it is important to highlight the need for sustain observatories and time series. Globally, some of the most established networks such as '*Long-term Ecological Research* (ILTER)' (Mirtl et al. 2018) and '*The Global Observing System* (GOOS)'. The *Global Regional Alliances* (GRAs), which are integral to GOOS have reported discontinuity in their data collection and monitoring efforts due to their reliance on short-term, project-based funding (Moltmann et al. 2019). Other global and regional time series observatories, such as LTER HAUSGARTEN (Arctic deep sea benthic time series, see Soltwedel et al. 2020); the Porcupine Abyssal Plain (NE Atlantic abyssal plain); the Hawaii Ocean Time-Series-HOT (open -ocean with pelagic focus and with benthic links via coupling studies); the Bermuda Atlantic Time-Series—BATS (North Atlantic pelagic with contributions to benthic via coupling work); the Western Channel Observatory—WCO (NE Atlantic coastal benthic and biodiversity reference site); the integrated Observing system in Australia—IMOS (broad coastal-open ocean observing system with strong benthic component); LTER Helgoland Roads (North Sea plankton time series); LTER North Sea Benthos Observatory (benthic time series) all have reported on different types of funding models, with institutional, local, regional and in some instances with private sources (e.g. endowment funds). However, any type of sampling with strong dependence on high operational costs (e.g. ship time, benthic sampling, taxonomy, and analysis) has intermittently reported the ongoing challenges of funding cycles. These increasing issues due to patchwork funding, results in lack of data continuity, lack of experienced personnel (e.g. taxonomists), and data gaps.

Some new directions and drivers (e.g. EU WFD and MSFD) have provided the opportunity to initiate ongoing surveys as dedicated funds in support of direct management and policy needs. The opportunity to gather scientific data for the WFD and MSFD purposes, in which the main focus is to assess ecological status with reference to the variability of benthic communities has demonstrated its benefits (e.g. sampling annually or once every 3 years). These areas have acquired some background information and in some instances been subsidised with local research. The EU MSFD includes Descriptor 1 'biodiversity' and 6 'seabed integrity' (Van Hoey et al. 2010) and has helped to raise awareness over data needs, but with limited funds to collect the necessary level of time series to generate the assessments needed, as these are short term with greater needs (e.g. development of functional indicators).

It is important to acknowledge that many of the long-term series that currently provide invaluable data and information to underpin effective marine management were not funded for management purposes from the offset, as these investments were initiated out of scientific curiosity, essentially a 'let*'s see what happens*'approach. Nonetheless, long-term time series established out of scientific curiosity have been increasingly challenging to maintain overtime (see Al-Habahbeh et al. 2020). Particularly, when there is an increasing competition for funds or shifting priorities for other emerging areas. It is also important to highlight that dedicated reviews have noted that poorly defined underlying questions and inflexible sampling strategies have been a hindrance for some long-term series to address ecological and/or political issues of present concern. Some useful hints to support the future of long-term series could provide the ability to: (1) adapt established long-term series to address emerging ecological issues; and (2) implement and maintain new time series to provide purpose-built information for management.

Ultimately, the data sets that can be obtained through long-term series are important tools for marine monitoring and there is a clear need for integrating long-term series with other monitoring activities to support the requirements of marine management. This approach is becoming increasingly important in the context of shifts in marine ecosystems linked to climate change (see Elliott et al. 2015, Bindoff et al. 2019) as well as the development of more holistic ecosystem-based management strategies (Levin et al. 2009).

This contribution helps to document and provides tangible examples of the importance of long-time series of benthic data. The sections below will cover some important aspects, such as: (1) illustrate why long-time series are essential to our understanding of benthic ecosystems; (2) demonstrate what knowledge from long-time series studies is fundamental for management questions of ecosystem state and monitoring effects, leading to actions; (3) discuss how long-time series should be designed to provide maximum benefit for management objectives; and (4) assess how to inform managers and stakeholders of the benefits of long-time series with the aim to inform on the basic ecosystem knowledge to address emerging and current management issues.

The present viewpoint article is the result of the practical and conceptual work conducted by the ICES Benthic Ecology Working Group (BEWG) on why, what, and how to perform environmental monitoring in marine waters. Our contribution also highlights global efforts and new tools for considerations. The BEWG is one of the oldest working groups in ICES and has been instrumental in developing methods and strategies for assessing effects of human activities based on responses in benthic ecosystems. Presently, the BEWG works on some of the following topics: (i) long-term series and climate change (see Birchenough et al. 2015), (ii) benthic indicators and EU Directives (see Van Hoey et al. 2010), (iii) species distribution modelling (see Reiss et al. 2015 and Gogina et al. 2017), and (iv) the role of benthos in Marine Protected Areas (see Greathead et al. 2020).

Why are long-term series essential to our understanding of benthic ecosystems?

Benthic species and habitats are particularly suitable candidates for marine monitoring. Traditionally, most studies have applied quantitative or semi-quantitative methods to describe the composition and diversity of resident species and communities (e.g. infauna, epifauna, meiofauna, and macrofauna). The underlying rationale is that benthic species are mostly 'sessile' and must endure the conditions where they live. Any changes in the environmental conditions, either from natural causes or human influences, are considered to affect the species assemblages depending on the constituent species' sensitivity or tolerance to the changes. However, at the same time, all species assemblages are subject to intrinsic or stochastic variability that may confound patterns from environmental signals. The intrinsic variability can be biological (e.g. varying recruitment, competition, predation), be a result of stochastic environmental events, or be due to spatial random variation. Long-time series are instrumental to distinguish between the different sources of variation and describe their magnitude and potentially correlated effects. In Europe, the WISE Water Framework Directive Database captures dedicated sets of benthic data, habitat level (e.g. classified under the European Nature Information System—EUNIS (2004) at 3–4 levels), cataloguing with a hierarchical system the benthic communities sampled. The European Environment Agency (EEA) database (see https://www.eea.europa.eu/en) helps to inform the Habitat Directive needs, as it contains the reporting details from all contracting parties. These assessments have contributed to the OSPAR North-East Atlantic Environment Strategy (NEAES) 2025, helping to illustrate how benthic data, habitat assessments, were linked to measures or environmental objectives (NEAES for OSPAR, equivalent of MSFD for EU members) (OSPAR 2025). These reporting levels contain the current information over the reporting cycles with the accompanying trends of data. These reporting series have helped to document the state and trends observed. However, they have also flagged the ongoing knowledge gaps, the need to improve diagnostics and measures. In most instances, similar challenges were highlighted due to limited resources available to cover some of these wider areas and methodological constraints (OSPAR QSR 2023).

Table 1 provides a summary of monitoring strategies from fundamental scientific research and object-orientated research to applied science and management purposes. The sequence of objectives presented, outlines a progression considering a position of scientific research aimed at obtaining fundamental knowledge on species and ecosystems to a focused operational and investigative monitoring with dedicated aims. The overview of these considerations helps to showcase the knowledge required for designing specific monitoring programmes. For instance, when addressing ecosystem state or changes in system drivers, there are justified steps outlined in Table 1. Management-driven programmes could typically span from assessing ecological effects of pollution, eutrophication, or climate changes (Rees et al. 2006, Bacouillard et al. 2020) to surveillance of resources or ecosystem changes (Montagna et al. 2018). The documentation of ecosystem responses is essential in cases where actions are taken to mitigate unacceptable conditions or restore degraded systems (Yoccoz et al.

Table 1. Summary of objectives and main categories of marine benthic monitoring studies with long-time series as integrated elements.

Objective	Area type	Aims and scope	Importance
Scientific fundamental research	Pristine/low disturbed	Describe trends and patterns in ecosystem structure, functions, processes, and production; assess the importance of environmental drivers	Fundamental ecological knowledge, input to ecosystem models, and identify ecosystem services
Scientific object-orientated research	Pristine/low disturbed	Develop and test indicators for system state, describe natural state and reference conditions, and assess natural variability	Use quantitative indicators for ecosystem surveillance, assessment, and management purposes
Scientific and management	Pristine/low disturbed	Assess short-term and long-term variations in state indicators (variables), changes in effects of natural drivers	Surveillance of ecosystem state and changes provides baselines, and references for environmental impact assessments
Scientific and management	Human influenced	Assess persistent ecological effects of acute or gradual impacts from human activities (e.g. sewage, nutrient discharges, and climatic events)	Ecological consequences of eutrophication, contaminants, habitat loss, alien species, etc.
Scientific and management	Human influenced	Surveillance of exploited resources	Ecosystem resources to be kept at sustainable level.
Management	Human influenced	Surveillance of human activities that may affect ecosystem structure or functioning	Licence-based industrial activities to be kept within accepted limits, for sustainable economy.
Management (and public)	Human influenced	Assess effects of management actions to restore degraded systems	Inform managers of ecosystem responses, provide advice on continued or adjusted actions

2001, Karydis and Kitsiou 2013), which also requires sound baselines (Villnäs and Norkko 2011). However, robust and fundamental knowledge is needed for developing: (i) target-specific indicators, (ii) undertake their assessment and variability, and (iii) characterize reference conditions. It is important to acknowledge that '*reference conditions*' could, and probably will, change over time ('*shifting baseline*'; see Duarte et al. 2009, Elliott et al. 2015). Therefore, maintaining long-time series becomes essential when some of these changes may be caused by external and unmanaged factors (e.g. climate changes).

What is the fundamental knowledge from long-time series to support monitoring of ecosystem state and management objectives?

Management and policy goals are directly connected to ensure environmental protection. Several critical assessments of monitoring emphasize the importance of monitoring programmes supported by clearly defined objectives, based on hypotheses of system responses to ecosystem stressors or management actions. All in turn will help to assess the established levels for what constitutes unacceptable system changes (Segar and Stamman 1986, Wolfe et al. 1987, Yoccoz et al. 2001, Elliott 2011, Haase 2018). The science that underpins the monitoring programme must be fit for purpose and focused on elements that are accepted as important ecosystem components by managers and the public (Elliott 2011). Segar and Stamman (1986) pointed out that the design of cost-efficient and targeted programmes needs to be developed as a joint effort between scientists and managers with focus on suitability of hypotheses, appropriateness of monitoring parameters, and levels of undesirable effects. However, the reality of these processes often occurs in isolation leading to misinterpretation and uncoordinated efforts.

Wolfe et al. (1987) highlighted five scientific objectives of long-time data sets that are of potential importance to management purposes. These are: (i) detection and analysis of long-term trends, (ii) assessment of long-term variability, (iii) generation of hypotheses on observed patterns and relationships, (iv) field calibration of experimental test results, and (v) field validation of model predictions. It is important to add to these management purposes the capability of identifying targeted monitoring variables and the importance of determining their natural variability. To date, long-time series have been invaluable for the assessment of the natural state of benthic ecosystems, their natural variability, and the influence of natural drivers and human stressors. One clear example is the assessment based on species diversity in benthic habitats and presence or absence of selected species groups. These calculations have turned out to be useful elements for indicators of ecosystem state. For marine soft-bottom habitats, in particular, indices of species diversity from quantitative sampling programmes are extensively used for statutory ecosystem monitoring (e.g. European Union Environmental Directives), environmental impact assessments, and trend surveillance monitoring (Nygård et al. 2020).

For example, Greathead et al. (2020) assessed a total of 102 Marine Protected Areas (MPAs). The results showed that over 70% of the MPA case studies considered the benthos to some extent during the selection and designation processes. However, the research also evidenced lacking management measures and good practice as part of the implementation phase. Additionally, there was clearly poor spatial and temporal coverage of monitoring and ineffective indicators. There is concern that without adequate monitoring and adaptive management frameworks, these MPAs will be compromised. While this work highlighted the need to assess the representation and protection of the benthos in MPAs. The process also highlighted the need to expand the characterization and monitoring of benthic species or habitats of interest. Certain designated areas face the possibility of turning into so-called '*paper parks*' (Pieraccini et al. 2017).

Studies often find links between ecosystem changes and human stressors over time, but these associations do not directly prove causation. Confounding or correlations among several causal factors may impede the disentangling of their relative effects (Yoccoz et al. 2001, Zettler et al. 2017). In order to provide stronger inferences on relationships and interactions, hypotheses generated from long-time series may be tested in targeted short-term experiments in the laboratory or in the field with *a priori* predictions of alternative outcomes (Wolfe et al. 1987, Yoccoz et al. 2001, Peters 2010). Information from other external sources and general ecological knowledge may also be considered to support decisions about causal factors. The results may, in turn, be implemented in the monitoring programme to refine hypotheses for monitoring and adjust the programme to fit more closely to the management objectives. Wolfe et al. (1987) and Peters (2010) illustrated how long-time series may fit into a framework with data from multiple sources to support management needs.

How to design long-time series to meet management objectives

Firstly, understanding effects and/or operational monitoring helps when addressing what is economically achievable, technologically feasible, socially beneficial, and administratively possible to implement measures (Elliott 2011, Elliott 2013, Karydis and Kitsiou 2013). It is important that the results generated from the operational monitoring are accurate, as any doubts regarding the reliability of the monitoring results may be used as arguments against implementing management actions, especially in cases of high costs or undesirable social side effects. It is also important to integrate targeted indicators, defined baselines, thresholds for actions, and confidence limits. Furthermore, indicators need to be subject to strictly controlled sampling and measurement practices, avoiding any methodological challenges. Aspects related to quality control could only be ensured by a standardized set of methods (e.g. from sampling to the generation of species lists and abundance/biomass matrices). In some instances, institutions may be certified according to ISO standards. However, such certification does not grant uniform techniques. Therefore, intercalibration should be conducted, particularly, when there are changes in methods adopted over the life of a programme (see this document: 'guidelines for sampling of soft-bottom fauna' ISO 2014); either in the field or laboratory work. These aspects are particularly relevant to consider when different investigators are involved, e.g. the need to undertake 'ring tests' to ensure consistency. The NMBQC Scheme (see NMBAQC Scheme Coordinating Committee 2022). It is critical to define all methods and procedures, to ensure reproducibility and minimize bias. In some instances, biological and environmental samples should be preserved and stored over long periods in appropriately curated archives, for retrospective analysis in the future either by new methods or for previously unsuspected taxonomic components or chemical constituents (Wolfe et al. 1987).

The identification of monitoring variables should also consider their variability and determine potential error sources (Carstensen and Lindegarth 2016). For example, spatial variation and the use of different sampling methods are usually considered in monitoring programmes by developing systematic sampling strategies and routines for quality assurance. There will always be uncontrolled ('random') variation that needs to be known in order to make reliable assessments. Typical critique of monitoring underline that monitoring programmes should be based on *a priori* hypotheses about ecosystem responses to human influences that can then be tested for statistical significance (Yoccoz et al. 2001, Legg and Nagy 2006). Ideally, monitoring programmes should include power analyses with confidence limits for type I and type II errors. In most cases, there is a strong focus on type I errors to keep the chance of taking superfluous actions in managing the system as low as possible. However, for many management actions, the type II error (i.e. the statistical power to detect changes) may be equally or even more important if the resulting outcome indicates that no action needs to be taken while there is ongoing ecosystem change (Legg and Nagy 2006). It is important to consider that for any significance test or statistical power analysis, the parameters of the indicators (e.g. mean value, variance) must be known and based on sufficiently high number of events, as can be obtained from long-lasting time series. In some instances, many operational monitoring programmes are lacking proper consideration of indicator statistics and subsequently of type I and II errors, leading to ineffective monitoring programmes due to insufficient or misleading information (Legg and Nagy 2006).

Long-time series may provide information on regional or long-term variation from causes that cannot be monitored in the system that is the subject of operational monitoring ('exogenic unmanaged pressures' *sensu* Elliott 2011). Such exogenic unmanaged pressures have the potential to influence indicator responses; examples of these pressures include climate-based changes (Bindoff et al. 2019) or effects from long-distance transported nutrients or contaminants (Trannum et al. 2018, Delpeche-Ellmann et al. 2013, Macdonald et al. 2000). Climate change will act as a 'background variable', potentially interacting with factors or stressors of concern for the particular programme. Information on background noise or interacting factors may call for adjusting threshold levels for actions, as well as critically evaluating the confidence of the indicators. Where monitoring is standardized across larger spatial (and temporal) scales, these aspects will facilitate the characterization and disentanglement of exogenic unmanaged pressures, such as climate change, from local sources of variation. For a long-time series to be effective as part of a monitoring programme, the sampling scheme of the series needs to adequately cover the monitoring indicators, and the sampling activities within the series need to be coordinated (Elliott et al. 2020). If long-term series are already established, it may be expedient for operational monitoring to incorporate indicators that are already included in the long-term series to best utilize historical data collected through the long-term series. However, if these events are unfeasible, then long-time series should be extended with new complementary elements that can support the monitoring indicators. Whenever modifications are made to established long-time series, it is important to retain some of the original elements of the long-time series (e.g. biological parameters). By doing so, these aspects will ensure continuity of the series.

The ecosystems that are the subject of operational monitoring may change according to other drivers than the programme was originally designed to monitor, and additional monitoring objectives may arise as a result. In this case, adaptive monitoring should be considered, enabling monitoring programmes to evolve iteratively as the major drivers of the systems change (Frigstad et al. 2023). For example, several long-time series in operational monitoring were originally designed to detect changes due to eutrophication or pollution, and while some of these challenges have been reduced, climate-induced changes are now an emerging issue. In these cases, long-term series provide background information for assessing the performance of the monitoring indicators, enabling them to be adjusted on these new drivers of likely effects. It is an important consideration to carry out retrospective analyses on existing long-time series with substantial historical data (Yoccoz et al. 2001). In many cases, there will be time series data for drivers of present focus, either existing measurement data (e.g. temperature statistics, input of river-transported nutrients from land sources) or descriptors that can be constructed, which can be used in the search for correlations with the monitoring indicators (Yoccoz et al. 2001). Retrospective analyses can also help determine the environmental status in earlier periods that may be a basis for setting threshold levels for actions (e.g. Ecological Quality Objectives 'EQOs'; see MAFF 1991).

In recent status assessments, attempts have been made to reinforce the indices by including information on species performances, for instance, the use of sensitivity indices such as the AMBI (Borja *et al*. 2009) or BQI (Rosenberg et al. 2004, Leonardsson et al. 2009) and biological trait analysis (Magni et al. 2023). These approaches had varying success, due to different levels of uncertainty in the characterization of sensitivity as well as varying tolerance of single species from different geographical areas. While there is merit on such approaches, there is a constant need to continue with further developments and evaluations. Additional constraints, for ecological assessments, are often related on diversity indices. This aspect could lead to changes in species composition and distribution patterns, without resulting in significant changes to overall species diversity, for instance, following climate-induced changes in coastal waters (Frigstad et al. 2023). Changes in species composition are in present environmental studies routinely described and characterized by use of multivariate community analyses (Somerfield and Clarke 2013). These analyses are more sensitive to species changes than diversity indices (Olsgard and Gray 1995) and can be linked to long-time series for assessing background noise, but such analyses are only rarely included in operational monitoring programmes. Recently developed analytical techniques may help disentangling the effects of target and confounding factors and several methods allow for statistical testing of species changes according to specific factors (Borcard et al. 1992, Zuur et al. 2017). Over ecological assessments, there is always the ongoing challenge of how to set threshold levels for management actions, which will be an issue when systems are poorly understood. Bjørgesæter and Gray (2008) estimated threshold levels for effects of contaminants from multivariate analyses based on field data for more than 2000 species and found that threshold levels varied much with different sediment types and depths. Furthermore, the efficient use of community analyses requires consistent and reliable species identifications that may lead to increased analytical costs. It seems that community analyses up to now have been mostly used to support patterns in diversity indices, but the integration of long-time series and operational monitoring based on changes in communities is a field that warrants further study and development. Another advantage of multivariate methods is that the species patterns can be related to physical/chemical variables and used to generate hypotheses on causality between environmental variables and community responses.

The integration of multiple ecosystem indicators within the same monitoring programme could help to generate a robust and improved level of confidence in the monitoring results. In some instances, these combined efforts could help to align the monitoring programme with the '*Ecosystem approach to management*' (Edwards et al. 2010, Elliott 2011, Elliott 2013, Turrell 2018, Papadopoulos et al. 2025), where several ecosystem components, their environmental conditions as well as ecosystem processes and functions are incorporated in a coherent monitoring programme. An example of a formalized statutory system following up on these concepts is the EU Marine Strategy Frame Directive (Elliott 2011). As with present assessment based on species diversity or communities, indicators must fulfil basic requirements, including knowledge on their natural state (e.g. reference values), long-term or spatial variation, dependence on ecosystem drivers and stressors, and intrinsic variability. In such instances, a retrospective set of analyses of long-time series with different target organisms or environmental data may prove instrumental in similar ways as for adjusting present indicators (see Rees et al. 1989). Nevertheless, developing new indicators represents one of the major scientific challenges. Presently, there is ongoing work with designing targeted indicators for ecosystem processes and functioning for the Marine Strategy Framework Directive (functional indicators; see details in Birchenough et al. 2012, Queiros et al. 2013, Wrede et al. 2018). These new indicators could help to advance the existing knowledge and could be of public interest. To date, the need to consider indicators for ecosystem processes or functions will have more impetus than the traditionally used indices of ecosystem structure. However, the desire to develop and operationalize these indicators is still in its infancy. Furthermore, it may be considered to incorporate economic and social aspects into monitoring assessments (Harvey et al. 2020, Salaün et al. 2022). Peters (2010) and Gonzalez-Pola et al. (2024) proposed a framework that includes public involvement through citizen science. In any case, it is strongly recommended to establish routines that ensure long-term series data over time and that run in parallel with operational monitoring. The basic ecological knowledge required for decision-making is then gradually developed and will, in the long run, improve the confidence in environmental status estimates.

For management purposes, in some assessments, the need to combine biological and physico-chemical elements (from soft and hard bottom and water masses) could provide a much realistic environmental state of a given water body (i.e. in monitoring programmes run according to the requirements in the Water Framework Directive). At a higher level, there have been recent attempts to develop so-called 'nature indices' that combine monitoring from a suite of ecosystem components into one balanced estimate (e.g. the Nature Capital or Living Planet index, see ten Brink 2006) and the Norwegian Nature index (Certain et al. 2011, Oug et al. 2013). These indices are based on continued monitoring of each individual component, based on selected individual species or diversity of various organism groups. A combined approach of different sets of components from a long-time series, will provide a much-informed assessment and will gradually improve the confidence of the results.

A challenge for future monitoring is also the rapid development of new sophisticated techniques and cost-effective data sampling methods, for instance, molecular genetic methods, remote sensing systems, and autonomous data sampling devices. Many of the new techniques are repeatedly proposed for environmental assessments, to replace present costly and time-consuming methods. In some instances, the use of genetic methods (e.g. eDNA) is promoted to date with the potential for 'revolutionizing' environmental monitoring in terms of both costs and time efficiency (see the EU Interreg GEANS project comparing traditional and e-DNA methods, see https://northsearegion.eu/geans/pilot-studies/index.html). However, these opportunities are so far contrasting with the limitations concerning the building of reference libraries, sequencing methods, and lack of abundance estimates. Furthermore, it must be stressed that the basic requirements on knowledge of indicator behaviour and ability to detect significant departures from normal conditions apply equally well to these techniques if they are to be implemented in effect monitoring. For example, a background from long-time studies is generally not in place for the new techniques. However, genetic methods are highly (e.g. management-driven) relevant tools that result in the provision of important data (e.g. with focus on presence/absence of species) in support of management goals. For example, the need of tracing species extending their distribution limits following climate change (see Birchenough et al. 2015) and the introductions of marine invasive alien species (Katsanevakis et al. 2023) are gaining consideration.

These methods should be aligned carefully with traditional long-time studies to ensure consistency of results unless the objective is only under an exploratory level. In addition, remote sensory systems and autonomous data sampling systems provide easy access and detailed measurements of environmental factors that may reinforce the relationship between ecosystem indicators and system stressors. Some advocates of new techniques claim that time series of environmental factors are sufficient for ecosystem assessments. It is the biological elements, however, that constitute the core effect parameters to assess ecosystem state, but new sampling techniques may add broader information to the assessments made from the biological indicators. In addition, remote and autonomous systems are efficient in collecting detailed data from broad geographic areas or areas with limited accessibility (e.g. high Arctic waters). One common criticism of many long-time series is that the monitoring sites are fixed and may have limited relevance for larger areas. Nonetheless, new cluster monitoring designs will have relevance for analyses of areas instead of sites. This information will help to find more general area trends instead of site population trends and hence is more relevant for society's need for information. Integrating new techniques with fixed-site monitoring and running long-term series can greatly widen the spatial relevance of the monitoring results if relationships between observational data and monitoring indicators can be established. Peters (2010) outlined a framework for how integration of long-time series and spatial data from observation systems can be carried out. This work also pointed out the importance of long-time records of change as a background to offer complementary levels for observational data from new systems to forecast changes at larger geographic areas.

Challenges and opportunities for long-time series of benthic data for addressing current and emerging management needs

The pressing need to continue with dedicated monitoring and restoration activities of the marine and coastal environments has moved to the top of the agenda for scientists and regulators as human activities exert considerable and widespread pressure on the marine environment. Exploitation of new resources and development of activities into new areas may have unforeseen consequences. At the same time, there is increased public concern about the marine environment and growing political interest in reducing the human influence as much as possible. Nowadays, marine management has moved from a rather limited 'one-problem' objectives into more holistic approaches addressing interacting components of the ecosystems (Link 2013, Astruch et al. 2023, Personnic et al. 2014). International organizations such as the Convention on Biological Diversity (CBD) have established a series of targets for reducing the direct pressures on biodiversity and promoting sustainable use (CBD 2020). Upcoming issues, related for instance to the expansion of offshore wind farms and the development of seabed mining, will result in areas closed to data collection. For example, the restrictions on fisheries-independent surveys will have to be reconsidered, particularly across areas where offshore wind farms will be installed. The introduction of these hard structures (e.g. turbines and cables) over soft sediment areas will not be accessible as previously (Lipsky et al. 2025). However, historic assessments of some of these areas will become more critical when assessing sites closed to new activities. In the North Sea, earlier work to documented spatial patterns of infauna, epifauna, and demersal fish communities (Reiss et al. 2010) will become background evidence to support future observations and predictions. Luckily, the North Sea has been further studied with a combination of techniques to document epifauna from long-term by-catch studies (Craeymeersch et al. 1998, Callaway et al. 2007). These long-time studies will become fundamental sources to assess future changes of these systems. Similar benefits will continue to arrive from the Northern Ireland Ground Fish Survey (DATRAS 2023a), North Sea Sandeel Survey (DATRAS 2023b), North Sea International Bottom Trawl Survey (ICES 2020b), and the Beam Trawl Survey (ICES 2019) to suggest some established data sets.

The combined effects of several stress factors, for instance climate change and (de-)eutrophication, pose new challenges for management. Future management may face more multifaceted problems and be able to adapt monitoring to new situations. Presently, management according to the 'ecosystem approach' appears to gradually develop and may become an important part of national and international policies.

Managing new and emerging problems may be approached in different ways. In some cases, existing monitoring programmes with well-established indicators can address new or additional environmental problems. This would certainly be cost-efficient, but it must be ascertained that the indicators, for instance, through targeted studies or retrospective analyses, perform and respond to the new problems in line with new programme objectives (see section 'How to design long-time series to meet management objectives'). Else, the programme may risk being insensitive to what it is intended to measure and *de facto* becoming a waste of money. More often new problems or new management needs will call for changes in indicators, adding new indicators, or changes in programme structure. This is, for instance, the case for Skagerrak ecosystems, where monitoring programmes need to evolve iteratively as the major ecosystem drivers change (Frigstad et al. 2023). Changes in indicators may also come along with requests for entering new and cost-efficient methods. With regard to biodiversity indicators, the adoption of molecular tools, e.g. has become a more rapid and cheaper way to collect semi-quantitative data of species occurrences. But the integration of new tools introduces challenges of scales, taxonomic resolution, intercalibration, and new formatted data sets to support long-time assessments. It is important to stress that long-time series that have been administered with consistent methodologies over time need to be continued, e.g. to assess any decadal or longer gradual changes in the ecosystems (including exogenic unmanaged pressures; see Elliott 2011). Generally, new methods should not replace existing methodology but rather provide added information because of the risk of causing breaks in the series. Any breaks are detrimental to the confidence of trend patterns and may impair the interpretation of cause-and-effect relationships. It is an asset, however, that integrating existing monitoring with new elements evolves the monitoring programmes into more holistic approaches in line with the 'ecosystem approach to management' (Elliot 2011, Elliot 2013, Turrell 2018).

Despite some of the current challenges pointed out above, there are some examples of recent newly established benthic long-term time series being implemented. In France, for example, the recent coastal research infrastructure ILICO supervises nine national observation systems, dedicated to various oceanographic parameters (Cocquempot et al. 2019). The underpinning objectives are set to address several scientific concerns, but also to better understand and disentangle the effects at large temporal and spatial scales from more local causes or at a shorter time scale. Among several parameters observed, one is very recently dedicated to the benthos, in which 20 stations spread along the coast are sampled twice a year. The coordination and harmonization of similar existing national networks on a European scale or regional sea scale would improve our understanding of wider-scale changes, both in time and space, to support management objectives at these scales.

New questions may also call for establishing new monitoring programmes with new indicators. Queiros et al. (2016) have outlined a framework for developing indicators for the EU Marine Strategy Framework Directive (MSFD) that evaluates all information about potential indicators, including scientific basis, responsiveness to pressure, targets, quality of sampling, and links to long-term monitoring programmes. A favourable and profitable option will be to link new programmes to existing monitoring and long-term series. The programmes should then have either some correlated indicators or include some common monitoring sites. This ensures that the new programme can utilize information from the long-time series about trends and natural variability.

In areas without any trend data, any information from the area in question or information from monitoring elsewhere which could offer benefit to inform a new programme should be considered. The same requirements to indicator behaviour, responsiveness to pressure, and quality of sampling need to be complied to ensure the quality of the programme. It is important that the monitoring programme, or at least a part of it, is carried out according to a strict sampling programme in order to establish a long-time series that over time will have relevance for documenting any trend patterns in the area.

Another challenge for recent environmental management is to carry out monitoring with a broad geographical coverage. Many long-time series have been based on sampling from precisely fixed localities in order to minimize spatial 'noise' variation but at the price of limited geographical coverage. An option for broader coverage is to adjust indicator sampling from fixed localities to area-representative sampling, as has been done in the Swedish national monitoring programme after thorough statistical evaluation of indicator variability (Leonardsson and Blomqvist 2014, Leonardsson and Blomqvist 2015, Nygård et al. 2020). Even broader coverage but at increased costs can be obtained by establishing observational networks collecting similar data over distant geographical locations, i.e. essentially running parallel monitoring programmes with identical data acquisition (Peters 2010). Other and more cost-efficient options include applying autonomous data sampling devices or citizen science (Peters 2010, Bewley et al. 2015) in areas not covered by the long-time series but the success will depend on how well the observational units from these sources are linked to and intercorrelated with the indicators of the long-term series.

The various requirements for establishing efficient and purposeful monitoring programmes imply that the programmes are designed in cooperation between managers, stakeholders, and scientists (e.g. Yoccoz et al. 2001, Leonardsson and Blomqvist 2015). Managers and stakeholders should formulate clear objectives and assess the actions to be taken for alternative outcomes. The scientists should design the programme with regard to indicators, sampling, work-up, and reliability of results. Ideally, the scientists should make clear what the programme can show and what it cannot show within different cost scenarios. It is also necessary to recognize public concern about the environment and prepare dissemination plans.

Benthic long-time series provides the quantitative data (e.g. number of taxa, abundance, and species) as a basis for diversity and species assemblage indicators. This practice should be continued, despite all new methods, as sampling natural communities form the basis of ecosystem state assessment. The expertise of laboratories that are specialized on sample collection and services to support taxonomy and reliable data is still indispensable, many of which have adopted reliable and standardized methodologies (e.g. using dedicated laboratory protocols, the preservation of samples with ethanol for later comparative tests, ring tests and reference libraries to support taxonomic checks, dedicated preservation methods, etc.). Ultimately, the quality of the work relies heavily on the knowledge of expert taxonomists, helping to correct identification of species. Taxonomy is a steadily developing science, particularly since molecular genetic techniques currently contribute to clear up species complexes and distinguish between similar species with different geographic distribution and ecological requirements (Nygren and Pleijel 2011, Nygren et al. 2018). For long-time series addressing trends, the deposition of specimens that can be available for future taxonomic reanalysis is essential to meet questions about which species were present at earlier stages.

Over time, ecological discussions have repeatedly involved the shortcomings associated with missing information. In some instances, missing information hinders the assessments with unrealistic outcomes. It is important to document changes and patterns observed. It is important to document changes and patterns observed. It is also necessary to accept that missing information will result in a cost expressed in losing understanding of biodiversity, functions, and ecosystem services in a given system, downgrading our understanding by missing these details.

The study of benthic ecosystems continues to be paramount to detail and document marine environments. Therefore, the adoption of dedicated strategies (e.g. sampling scales, reduction of replicates to work around a reduced budget) will affect the outcomes of such efforts. To date, the maintenance of long-time series of benthic data remains a global challenge as climate change, pollution, and restoration needs are on the top of management and conservation drivers. There are current efforts on global networks (e.g. OBIS, EMODnet Biology, Jerico, ILTER, etc.) helping to advance these shortcomings. However, the most challenging issues remain for regional imbalances (e.g. Africa, South America, Southeast Asia), as these areas lack consistent support for benthic monitoring. These aspects weaken the global syntheses and models that currently depend on multi-site continuity and expertise.

Conclusions and recommendations

This viewpoint document has covered some of the current challenges associated with long-time series of benthic data for soft sediments. However, some of these general issues are also pertinent across many monitoring considerations across several ecosystem receptors. We concord with similar challenges raised by Lindenmayer et al. (2012). Their research covered the importance of long-term ecological studies (LTES) and their fundamental contribution for understanding ecological processes, managing ecosystems, and addressing global environmental issues (e.g. climate change, biodiversity loss, and habitat degradation) (Lindenmayer et al. 2012).

The interpretation of observed long-term changes is complex and multifactorial (Zettler et al. 2017, Bonifácio et al. 2019). Continuous dialogue between scientists and managers is essential to ensure that management needs are framed in terms of testable hypotheses with defined end points and limitations of scale. This should lead to the design of focused sampling programmes in order to test those hypotheses with adequate statistical power (Wolfe et al. 1987, Yoccoz et al. 2001, Legg and Nagy 2006). However, the continuous collection of long-time benthic series is often compromised by funding restrictions and emerging new technologies. Regarding new technologies, both scientists and managers may be eager to complement and often replace traditional long-time observations with rapid and inexpensive detections, which, however, may not deliver comparable data resolution power (e.g. optical, molecular and other methods). In the worst case, the original data series may be inadvertently, but in reality, discontinued as a tool to detect long-time changes, resulting from a mismatch of information from different data sources.

Considering long-time series of benthic data, it is important to highlight:

- The need to revise long-term monitoring in view of new (and presently unforeseen) technological, scientific, and management issues. Ensuring that these new methods are complementary rather than providing data sets, which will be of limited use, causing further challenges to data sets collected over time and space.
- The future of 'traditional' long-term monitoring in a world with new techniques for observing habitats and ecosystems (e.g. remote observing systems, autonomous submersibles, video recording) (Danovaro et al. 2016), as these new techniques could be tested alongside the current efforts to assess the added value rather than compromising existing efforts.
- The new legislative commitment will result in new demands and, in some instances, new parameters to consider and assess. Therefore, consideration of the current time series (e.g. spatial and temporal scales) will be important to assess and ensure that these data set remain 'fit-for purpose', as science-to-policy demands are often changing. The wider concept of ecosystem approach and inclusion of social and economic aspects imply that marine monitoring needs to be well-governed, cost-effective, and well-organized (work plan, sampling protocols, quality assurance), transparent, and communicative (Elliott 2011, 2013, Turrell 2018).
- Long-time series of benthic data are heavily reliant on taxonomists to ensure that the identification of species is updated and consistent, e.g. including relevant training and reviewing to ensure taxa and classification remains accurate. Inclusion of molecular genetic methods as new tools for species identification and discrimination must involve taxonomic expertise to be used properly and targeted.
- The UK government requests of 'collect data once and use many times' from the 'big data' initiatives have demonstrated the value of intensive data collection exercises (e.g. model validation, indicator development, trend analysis, etc.). However, the need to inform managers of data collection purpose, will help to demonstrate the context for data collection.
- Ecological changes have been studied over many decades across several areas (e.g. the North Sea Benthos project in the 80s and 2000s) and long-time series have demonstrated ecological knowledge, variability, and changes. Therefore, it is relevant to highlight the importance of international cooperation, transboundary assessments, and collaboration between researchers. This viewpoint contributes with knowledge and demonstrates the importance to continue with long-time series.

Therefore, as we openly call for action and maintenance of long-time series of benthic data, our plea encourages: (i) improved and active institutional and governmental commitments, (ii) open networks and collaboration among long-term research sites (e.g. the Long-Term Ecological Research Network, see https://lter.kbs.msu.edu/), and (iii) stronger data management and sharing frameworks to globally support these areas of work. As biodiversity losses continue to increase, there is even a more pressing driver to confidently describe and provide sound and robust management of our ecosystems globally.

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Author contributions

Eivind Oug (Conceptualization [equal], Investigation [equal], Visualization [equal], Writing – original draft [equal], Writing – review & editing [equal]), Jan Beermann (Conceptualization [equal], Investigation [equal], Writing – original draft [equal], Writing – review & editing [equal]), Nicolas Desroy (Conceptualization [equal], Formal Analysis [equal], Methodology [equal]), Mats Blomqvist (Conceptualization [equal], Writing – original draft [equal], Writing – review & editing [equal]), Laurent Guerin (Conceptualization [equal], Methodology [equal], Writing – original draft [equal]), Urszula Janas (Conceptualization [equal], Writing – original draft [equal], Writing – review & editing [equal]), Celine Labrune (Conceptualization [equal], Writing – original draft [equal], Writing – review & editing [equal]), Paolo Magni (Conceptualization [equal], Writing – original draft [equal], Writing – review & editing [equal]), Henning Reiss (Conceptualization [equal], Writing – original draft [equal], Writing – review & editing [equal]), Jennifer Dannheim (Conceptualization [equal], Writing – original draft [equal], Writing – review & editing [equal]), Hilde Trannum (Conceptualization [equal], Writing – original draft [equal], Writing – review & editing [equal]), Annick Donnay (Conceptualization [equal], Writing – original draft [equal], Writing – review & editing [equal]), Ingrid Kroncke (Conceptualization [equal], Writing – original draft [equal], Writing – review & editing [equal]), Steven Degraer (Conceptualization [equal], Writing – review & editing [equal]), Johan Craeymeersch (Conceptualization [equal], Writing – original draft [equal], Writing – review & editing [equal])

Conflicts of interest

None declared.

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