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# Marine monitoring in transition: On the verge of technological revolution?

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Efforts to renew marine ecosystem monitoring to include advanced technology and cost-effective methods have been repeatedly called for. The current environmental legislation in European Union (EU) requires also ecosystem monitoring beyond the scope of conventional methods and sampling strategies. Despite several studies showing the benefits of new methods, the progress to adopt the methods in national monitoring programmes under legal requirements has been slow. In this study, we have reviewed the current use of a set of methods in marine monitoring programmes under the EU marine strategy framework directive (MSFD), which calls for a holistic view of the marine environment and thus requires tens of monitoring parameters by different methods. Here we assess how widely the new methods are being adopted in the EU member states implementing the MSFD. Our results show a relatively high adoption rate for certain methods, while others are widely ignored. We compare the results also with the monitoring strategies of the four regional sea conventions. We argue that the adoption of methods in European and regional programmes may positively influence the national use of new methods.

KEYWORDS

**ocean observation, sampling, monitoring methods, monitoring programs, EU marine strategy framework directive**

## Introduction

Around the globe societies have established legislation to govern marine monitoring, assessment, protection and restoration to achieve healthy marine environment and prevent its further deterioration. Therefore, legislation, such as the Clean Water Act and Oceans Policy (USA), the Oceans Act (Canada, Australia), the Water Framework Directive, the Marine Strategy Framework Directive, and the Biodiversity Strategy for 2030 (European Union EU), mandate rigorous monitoring of aquatic environments to follow up achievements of the policy objectives (Borja et al., 2008; Borja and Elliott, 2013). While the economic benefits of healthy environment can be estimated (Hyvärinen et al., 2021) and are appreciated (e.g. Nieminen et al., 2019), the economic benefits of monitoring are hard to capture, leading to attempts to save monitoring expenses (Borja and Elliott, 2013). However, Nygård et al. (2016) and Koski et al. (2020) show that monitoring costs are minimal compared to the costs of measures taken to maintain or improve the status of the monitored system, and that monitoring can save money by helping focus the measures effectively.

Despite its advantages and clear legal requirements, Europe's marine monitoring has been found insufficient (European Commission, 2017; Kahlert et al., 2020), especially in terms of detecting tipping points (Hewitt and Thrush, 2019), threats and pressures (Painting et al., 2020), and status of the environment (Kahlert et al., 2020). The potential for improvements to monitoring programmes have been explored by Mack et al. (2020) with respect to novel marine monitoring methods. Mack et al. (2020) found several promising methods to improve the quality, quantity, or cost-efficiency of marine monitoring, and evaluated their applicability based on their reliability, environmental impact, added value, limitations and required expertise. In this study, we build on their result that the proposed methods have the potential to improve the cost-efficiency of monitoring and thus allow wider spatial coverage and temporal frequency with same resources.

In the age of global change and increasing human pressures affecting the seas, reliable information from the marine environment is valuable and much needed. Technological advances are providing ways to monitor marine environments with more spatial and temporal resolution and including more parameters than has been possible so far, and these advances need to be deployed to gain a better understanding of the state and evolution of the marine ecosystems. There has been a general call for improved coordination of ocean observation systems and plans to better understand and manage the marine ecosystems (Duarte et al., 2018; Davidson et al., 2019; deYoung et al., 2019; Révelard et al., 2022), yet their specific links to policy processes aimed at improving the state of the sea are not always clear. In this paper, we bring the results of Mack et al. (2020) closer to the reality of the management of marine monitoring by reviewing the formal marine monitoring programmes of the EU member states to get an overview of how these methods are implemented by individual member states, what plans there are for the new methods. We relate these findings to the international marine monitoring governance by reviewing whether the national implementation statuses have patterns that reflect coordination on a regional and continental level. We argue that this progress indicates how the marine monitoring is expanding and potentially approaching the requirements of the policy objectives.

## Materials and methods

The European Union's Marine Strategy Framework Directive (MSFD) requires member states to establish marine monitoring to assess eleven qualitative descriptors of environmental status. The requirements cover biological, chemical and physical components and are considered to provide a holistic picture of the marine environment (Borja et al., 2010). Moreover, the MSFD requires member states to coordinate their monitoring and assessments within the four European marine regions. A recent guidance report by the European Commission sets recommendations for harmonized assessment requirements (e.g. data products) on the EU level (European Commission, 2022). In this paper, we assume that the national MSFD monitoring programmes give the best basis for estimating the current use of monitoring methods in Europe.

The member states' marine monitoring programmes are updated every six years (2014 and 2020) and reported to the European Commission for a review. The national reports are available through the European Environment Information and Observation Network (EioNet; https://www.eionet.europa.eu/) within its Central Data Repository (https://cdr.eionet.europa.eu/).We downloaded the most recent monitoring programme reports from 23 member states with marine areas (incl. the UK) and analyzed the reports to identify countries that use or plan to use the selected novel methods (Table 1; Figure 1). We also noted the parameters used in the member state monitoring (Table S1 in Supplementary material). If the 2020 monitoring report was not available, we used information of the 2014 report instead (five countries; see Figure 1).

As most of the programmes were written in their respective national languages, we developed relatively broad search terms for each monitoring method, used Google Translator to search for hits from the reports, and translated longer passages among the search hits to see if the method was used or if the report explained plans for using the method in future updates of the programme. Despite common EU reporting templates, there were differences in the style of the reporting. Hence, it is likely that in some programmes the methods were not reported in sufficient detail which may have caused some underestimation in the results.

Secondly, we analyzed the monitoring programmes of the four European regional sea conventions (RSC): Oslo-Paris Convention (OSPAR), Helsinki Convention (HELCOM), Barcelona Convention (BARCON) and the Bucharest Convention (BSC). The OSPAR has Coordinated Environmental Monitoring Programme (CEMP, https://www.ospar.org/work-areas/cross-cutting-issues/cemp), the HELCOM has the monitoring manual and guidelines (https://helcom.fi/action-areas/monitoring-and-assessment/), the BARCON has the Monitoring and Assessment Protocol (MAP, https://www.rac-spa.org/sites/default/files/ecap/ig22_inf7.pdf; https://wedocs.unep.org/rest/bitstreams/45233/retrieve), and the BSC has the Black Sea Integrated Monitoring and Assessment Program (BSIMAP, http://www.blacksea-commission.org/_bsimap_description.asp). We compared the national monitoring methods

TABLE 1 A summary of the applicability of new methods and the use in current and planned monitoring in EU coastal member states and the regional sea conventions.

| | Monitoring method | Applicability[1] | Improves spatio-temporal resolution[2] | Creates new kind of data[3] | Number of EU countries using/planning to use the method[4] | Regional sea conventions using/planning to use the method |
|---|---|---|---|---|---|---|
| Citizen observations | Citizen observations | Very high | yes | | 8/0 (+2) | 3/0 |
| Field analysis | HydroFIA® pH | Very high | yes | | 0/1 | 0/0 |
| | Imaging Flow Cytometry | Moderate | yes | | ¾ | 1/1 |
| In site, research vessel independent | FerryBoxes | Very high | yes | | 7/2 (+2) | 2/1 |
| | Profiling Buoy/ Bottom-mounted profiler | Very high | yes | | 6/3 (+1) | 2/1 |
| | Artificial hard substrates (ARMS, ASU) | High | yes | yes | 1/0 | 1/0 |
| | Argo Float | High | yes | | 4/0 (+1) | 0/1 |
| | Gliders | Moderate | yes | yes | 2/3 | 2/0 (+1) |
| | Active biomonitoring | Moderate | yes | yes | 0/1 | 2/0 |
| In situ, research vessel dependent | Remotely Operat-ed Towed Vehicle | Very high | yes | yes | 8/1 (+2) | 1/1 |
| | Sediment corer (e.g. GEMAX) | Very high | yes | yes | 4/0 | 1/0 |
| | Moving Vessel Profiler | High | yes | | 0/0 | 1/0 |
| | Manta Trawl | High | yes | yes | 7/0 | 1/0 |
| Laboratory analysis | Stable Isotope Analysis | Very high | yes | yes | 5/0 | 0/0 |
| | (e)DNA Metabarcoding | High | yes | yes | 5/5 | 1/2 |
| | Computer-based identification | Moderate | yes | | 6/2 (+2) | 2/1 |
| Remote sensing | Passive Samplers | Very high | yes | yes | 0/2 | 0/0 |
| | Earth Observations | Very high | yes | yes | 15/1 (+7) | 3/0 |
| | Remote Electronic Monitoring for fishing activities | High | yes | | 2/3 | 0/0 |
| | Unmanned Aerial or Underwater Devices [5] | Low | yes | | 1/2 | 2/1 |

1) Table 2 in Mack et al. (2020). 2) Table 3 in Mack et al. (2020), (in gap type i). 3) Table 3 in Mack et al. (2020), (gap types ii -iii). 4) Based on member states reporting under the EU marine strategy framework directive during 2014-2022 (https://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/implementation/reports_en.htm). The list is indicative. 5) Mack et al. (2020). reported only aerial autonomous devices; there are underwater autonomous devices in use in one member state and planned to be used in another member state.
The number of countries currently using the method under the EU MSFD monitoring programmes is given first, then the number of countries reporting plans of using them. The figure in parentheses indicates the number of countries who already use the method but plan to use it for other parameters too. The same rationale is used for the regional sea convention monitoring programmes.

with the European RSC monitoring programmes to see whether the countries within the same RSC use similar methods.

Finally, we suspected that there is marine monitoring infrastructure in countries which is not utilized in the EU MSFD monitoring. Therefore, we analyzed the major marine infrastructure programme the 'European Global Ocean Observing System' (EuroGOOS, https://eurogoos.eu). Within EuroGOOS, we recorded whether the countries also used Argo floats, gliders or ferry boxes, which are listed as novel methods on our list. Observations of use of these methods is given as additional information in Figure 1, when a country failed to report its use in the official MSFD monitoring programme.

## Results and discussion

The EU Member States' MSFD reporting reveals that 16 of the 20 novel monitoring methods recommended by Mack et al. (2020) are used in the monitoring programmes by one or more EU member states (Table 1). Earth observation by satellites was

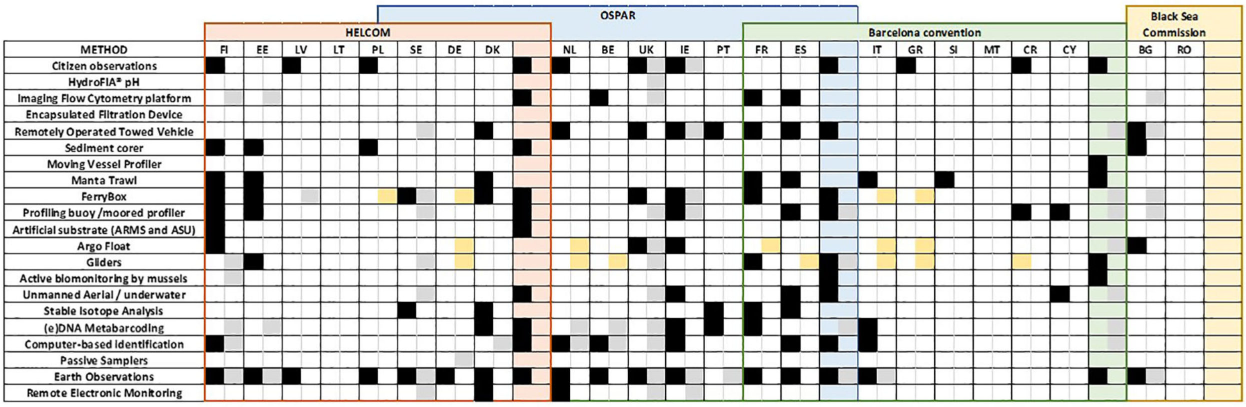


FIGURE 1
The reported use of the novel monitoring methods identified by Mack et al. (2020) by the EU member states (incl. the UK, an EU member at the time of reporting) and included in the regional sea conventions' monitoring programmes (coloured columns). The black cells indicate that the method was reported under the EU MSFD, the grey cells indicate reported plans to include into the EU MSFD (i.e. not yet in use), and the yellow cells indicate use in the EuroGOOS co-operation. The methods are in the same order as in Table 1. Country codes (use of the older 2014 monitoring report is indicated by an asterisk after the country code: FI, Finland; EE, Estonia; LV, Latvia; LT, Lithuania; PL, Poland; SE, Sweden; DE, Germany; DK, Denmark; NL, Netherlands; BE, Belgium; UK, United Kingdom; IE, Ireland; PT*, Portugal; FR*, France; ES, Spain; IT, Italy; GR, Greece; SI, Slovenia; MT*, Malta; CR, Croatia; CY*, Cyprus; BG*, Bulgaria; RO, Romania).

clearly the most often used method in the EU (15 of the 23 member states; Table 1). The second most commonly reported methods were citizen observations for larger species and non-indigenous species and ROVs mainly for plankton with eight member states implementing each. The ferry boxes (mainly chemistry and chlorophyll) and manta trawls (micro litter) were used by seven member states, whereas profiling buoys for chemistry and oceanography and computer-based identification for species, habitats and built-up area were used by six member states each. Also, metabarcoding from environmental DNA was reported by five countries mainly to detect non-indigenous species but also rare species and plankton (Table 1). All these methods increase spatio-temporal resolution/coverage and/or create new kind of data (Table 1), indicating improved outputs from the national monitoring programmes.

Despite the high applicability ratings by Mack et al. (2020), the monitoring programmes did not use passive chemical samplers (only two countries planning), towed profilers, active biomonitoring of contaminants or their effects by caged mussels (one country planning) or the pH measurements by HydroFIA (one country planning). Mack et al. (2020) had estimated the applicability of three of these as high or very high (Table 1).

The methods planned for implementation were related to automatic image interpretations (Imaging Flow Cytometry or computer-based imaging) (6 countries), gliders (3), profiling buoys/mounted profilers (3), remote electronic monitoring for fishing activities (3), unmanned aerial or underwater devices (2), ferry boxes (2) and the use of environmental DNA (metabarcoding) (2). The plans to use unmanned vehicles, computer imaging and remote electronic monitoring for fishing activities were all related to identification of benthic habitats or species of all sizes, whereas implementation plans for metabarcoding were directed towards phytoplankton and soft-bottom benthic fauna.

Interestingly, there seemed to be a trend that adoption of a novel method in a marine monitoring programme often was linked to simultaneous plans by the same country expanding its use to other parameters. This trend was most pronounced for earth observation (planned for new parameters by seven countries who already use it), ferry boxes and computer-based identification (Table 1). For example, Sweden used earth observation for monitoring of three parameters (see Table S1 in Appendix) but is planning to expand it to eight more.

Adoption of a new monitoring method into international monitoring programmes and using their data in indicators and other assessment products creates a strong push for the wide-spread adoption of it. An example of this are the introduction of marine litter and underwater noise to the formal state assessment under the EU MSFD (European Commission, 2022). The method development was part of a joint-EU implementation process and was the driving force to ensure pan-European coordinated methods and comparable outcomes. Also, the regional sea conventions (RSC) have an important role in supporting the adoption of new methods and ensuring their coordinated use. In this study, we expected that there would be correlation between countries sharing a marine region and the RSC in adoption of specific methods. Indeed, we found that the same methods were most often mentioned in the RSC and the national monitoring programmes. However, from our data we cannot discern whether the RSC monitoring is the driver for national method adoption or vice versa. In the Baltic Sea, adding earth observation methods as a test assessment for phytoplankton chlorophyll, water transparency and harmful algal blooms (HAB) to the HELCOM regional assessment was a steppingstone for later adoption of the method into routine monitoring in the region (Figure 1; HELCOM, 2018). In contrast, the Black Sea Integrated Monitoring and Assessment Program does not mention any of the new methods (Figure 1).

In this short overview of the current situation of the use of modern monitoring methods by European countries, we have shown that technologically advanced methods are being introduced into operational monitoring programmes. The results indicate a positive trend to modernize the marine monitoring and suggest that more data (in space and time) can be obtained with the same resources. However, the comparison of the method applicability rating (Mack et al., 2020) and the use of the method for the MSFD was not fully correlated (Table 1). For example, some of the methods rated "very high" did not have any applications in the EU MSFD monitoring, while some rated "moderate" and "low" had 1-3 applications. Reasons for this pattern may include that (i) the data from the 'highly applicable' novel methods are not explicitly needed to comply with the official marine monitoring (e.g., there is no legislative need for the produced data), (ii) there are sufficiently good and cost-efficient existing methods to fulfil the data needs, (iii) the method is not sufficiently known among marine managers, or (iv) there is reluctance to shift to a new method due to either lack of standards, general acceptance, high initial investments costs or required procedural changes.

The EU has made large economic investments into pan-European observation systems such as the earth observation programme Copernicus (https://www.copernicus.eu/), the Europe's Marine Observation and Data Network EMODnet (https://emodnet.ec.europa.eu/en) with its modules for marine physics, chemistry, bathymetry, geology, biology, seabed habitats and human activities, and the EuroGOOS. While member states have invested in the Copernicus, EMODnet products and the EuroGOOS infrastructure and these marine data products are available, our analysis seems to indicate that these products are not used in the reporting under the MSFD. Thus, our results indicate that current formal monitoring programmes may overlook potential augmenting data sources and would highly benefit of their more efficient use.

## Conclusions

Our review showed that the use of the novel methods is uncoordinated between countries and regions. We also found out that there is EU infrastructure which is not used to support formal monitoring programmes, and that novel methods are applied, but not in relation to the priority Mack et al. (2020) suggested. However, our results seem to indicate that the marine monitoring is expanding in terms of spatial and temporal data. Moreover, we noticed that once a method is successfully used by any country, the intentions to expand its use increase. Furthermore, there is evidence that collaboration on the EU or regional level to produce assessments can improve adoption of new methods and increase regional coordination between monitoring programmes. We argue that marine monitoring needs to be continuously improved, not only technologically, but also towards regional coherence. Both effectively used local method testing and adaptation phases as well as clear objectives and quality requirements for combined use of novel and current methods with longer local traditions are needed. While the development of methods is likely to remain technology-driven and hence "bottom-up", the deployment and adaptation process of the novel methods needs to be top-down coordinated. This requires relevant mandated entities that define policy objectives requiring novel assessment products. Also, novel method uptake can significantly be enhanced by method adoption through regional or inter-regional fora.

## Author contributions

SK: data analysis and writing; MK: writing and content expert; HK: writing and content expert; LM: content expert and writing; KM: coordination and conclusions; HP: writing and content expert; TP: interpretation of results; LU: original idea and conceptualization. All authors contributed to the article and approved the submitted version.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note



## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.1066769/full#supplementary-material

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