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An ecosystem-based system of variables to enhance marine species and habitat monitoring and conservation: The Adriatic Natura 2000 case study

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Implementing effective marine monitoring to detect and track ecosystem shifts, biodiversity alteration, and habitat loss is one of the most crucial challenges to meet the objectives set out by the Post-2020 Biodiversity Framework and by the United Nations Sustainable Development Goals. The lack of coordinated and harmonized monitoring frameworks at different spatial scales and their weakness in accounting for ecological processes, due to incomplete sets of monitoring variables, strongly hinder the achievement of conservation objectives. Here, we propose an approach to build a coherent ecosystem-based system of monitoring variables for target marine species and habitats. The approach is designed to integrate the existing monitoring frameworks set up by the Water and the Marine Strategy Framework directives, and the Essential Ocean and Biodiversity Variables, with the aim to contribute to their harmonization and implementation. Furthermore, by embracing a holistic vision, it aims to incorporate ecological processes and socio-ecological aspects, considering the benefits of public engagement through citizen science, and of the ecosystem services approach for policies' implementation. The study stems from the Ecological Observing System of the Adriatic Sea (ECOAdS), which was developed in the framework of the Interreg Italy-Croatia project ECOSS, using as exemplary monitoring test cases two relevant conservation targets for Natura 2000 sites of the Adriatic Sea, the common bottlenose dolphin and seagrass meadows. We test the potential of this approach in guiding the prioritization of monitoring variables under ecosystem-based criteria, and provide insights into the benefits delivered by an integrated system of observatories' networks and monitoring frameworks to support marine conservation at both local and regional scales. The proposed approach can be transferred to other contexts and scales to help build a common knowledge and monitoring framework for conservation and

management strategies, saving costs by relying on available resources and on consolidated and long-lasting approaches that might converge towards global initiatives.

KEYWORDS

essential variables, MSFD, WFD, natura 2000, marine ecological observatory, transboundary conservation

Tursiops truncatus urn:lsid:zoobank.org:act:1B8DC3EB-C5D4-42CE-AD8B-EB3A1E500E81

Cymodocea nodosa urn:lsid:catalogueoflife.org:taxon:2634e832-60a7-102d-be47-00304854f810:col20110201

Zostera marina urn:lsid:catalogueoflife.org:taxon:2637f144-60a7-102d-be47-00304854f810:col20110201

Zostera noltii urn:lsid:catalogueoflife.org:taxon:d2c6e5d4-2dc5-11e0-98c6-2ce70255a436:col20110201

Posidonia oceanica urn:lsid:catalogueoflife.org:taxon:f0c509a2-29c1-102b-9a4a-00304854f820:col20110201

Introduction

The marine environment is impacted by a multitude of anthropogenic stressors that, with an unprecedented speed, are impairing its status (Pinsky et al., 2013; Bryndum-Buchholz et al., 2019; Maxwell et al., 2020; Nicholson et al., 2021). Several initiatives are in place struggling to find a way to revert this deterioration trajectory and to ensure the conservation and restoration of nature—among the many, the Convention on Biological Diversity, the European Biodiversity Strategy 2030, and the Global Sustainable Development Goals (SDGs), especially SDG14 “Life Below Water” (Rees et al., 2018; Reimer et al., 2021; Gissi et al., 2022; Hermoso et al., 2022). However, both local and climate-induced pressures acting on marine ecosystems lead to unpredictable changes in their structure and functioning, and forecasting the effects of such changes on their resilience and capacity to provide ecosystem services is challenging (García Molinos et al., 2016; Lotze et al., 2019; Gissi et al., 2021). The most reasonable strategy to put in place for marine management and conservation to be effective is to embrace an adaptive and ecosystem-based approach, able to deal with fast-changing conditions (Magris et al., 2014; Frazão Santos et al., 2016; Rilov et al., 2019).

To operationalize such an approach, a baseline of knowledge and the continuous acquisition of up-to-date data are essential (Lombard et al., 2019). Thus, the monitoring of the marine environment is key and must be systematic and long-lasting to be able to provide the information needed to effectively feed evidence-based management (Addison et al., 2018; McQuatters-Gollop et al., 2019). Monitoring strategies should be coordinated

transnationally to favor the collection and sharing of data beyond the geopolitical boundaries to capture large-scale and interconnected ecological processes. Indeed, beyond characterizing species and habitat structure and their distribution within ecosystems, monitoring should depict the key processes that allow species to feed, move, reproduce, and interact among them and with the surrounding environment, thus supporting ecosystem functioning (Williams et al., 2018; UNEP, 2019). Such an approach would enable the advancement of our understanding of the driving forces that affect species, populations, and habitats and the identification of monitoring variables that might better inform anticipatory management strategies, such as describing early-warning signals (Scheffer et al., 2012; Pinsky et al., 2013; Clements et al., 2019). Additionally, to adequately interpret the observed ecosystems' conditions, due to the mutable and complex nature of the marine environment (Maxwell et al., 2015), the monitoring has to be performed by combining information coming from multiple variables to describe ecosystem shifts (Kroeker et al., 2020) and favor anticipatory conservation actions and management (Van Hoey et al., 2010). However, the vast array of variables that can be potentially monitored in marine environments (Turnhout et al., 2007), along with the complexity and amount of derived data, complicates the selection of the most relevant and useful information to effectively depict ecological processes and to inform management (Fischer and Grimes, 2012; Hayes et al., 2015); therefore, the identification of clear criteria for monitoring variable selection would be of great benefit.

Diverse initiatives that can satisfy these needs are in place, dictated by both legally binding European (EU) frameworks for monitoring (e.g., the Water and the Marine Strategy Framework directives, WFD and MSFD, respectively; EC, 2000; EC, 2008), and global initiatives, such as the Essential Ocean and Biodiversity Variables frameworks (EOVs and EBVs) under the Global Ocean Observing System (GOOS) and the Group on Earth Observations Biodiversity Observation Network (GEO BON), respectively (Pereira et al., 2013; Miloslavich et al., 2018). The synergistic combination of these frameworks represents an exceptional opportunity to boost marine biodiversity and ecological processes monitoring, directly funneling data and observations within decision-making processes and thoroughly depicting the status of

the aquatic environment at multiple spatial scales (Zilioli et al., 2021; Satterthwaite et al., 2021). However, the advancement and implementation of these frameworks, despite urgent, are still ongoing with some weaknesses and delays (Borja et al., 2010; Rouillard et al., 2018; Manea et al., 2021). If EU directives do not provide Member States (MSs) with clear guidelines, for instance, on baseline and threshold values against which to assess the status of the environment (Dodds et al., 2010; Fraschetti et al., 2022), leaving them free to detail how to implement their recommendations, MSs fail to establish integrated monitoring strategies transnationally to achieve directives' goals (Cavallo et al., 2019). A detailed analysis of the lists of monitoring variables indicated by these legal instruments has also highlighted their shortcomings in accounting for ecological processes and a general mismatch between them that hinders data comparison and sharing and the building up of an integrated approach to monitoring (Manea et al., 2020a). As for the EOV and EBV frameworks, these are now under development (Schmeller et al., 2017; Estes Jr et al., 2021), with some monitoring variables (i.e., the emerging ones) still to be defined. Again, these essential variables differ from those adopted by EU legislations, a fact that further limits monitoring frameworks' integration (Cavallo et al., 2019).

Despite these limitations, all these initiatives and their harmonization are strongly promising and must be supported. Being conceived for acting at different spatial scales, from regional/national (WFD and MSFD) to global (EOVs and EBVs), monitoring frameworks can provide mutual benefits to each other and support conservation at the transboundary level. EOVs and EBVs need to be built on data collected systematically and comparable at multiple temporal and spatial scales (e.g., national, regional, and global) using current technology and existing efforts (Kissling et al., 2015; Brummit et al., 2017; Bax et al., 2018; Satterthwaite et al., 2021). Any research or observing program, initiative, and infrastructure can contribute to EOV and EBV development, independently by the scale on which it acts (Kissling et al., 2018). For this reason, monitoring initiatives under EU legislation are precious to feed these global strategies. Simultaneously, EOVs and EBVs, by embedding regional/national monitoring data, can directly support the achievement of EU directives' environmental goals at the regional level.

The integration of the above-mentioned frameworks could be a concrete action to enhance marine conservation at multiple spatial scales, also in the context of protected areas. This is the case of the Natura 2000 (N2K) site network—the main conservation instrument at the EU level—that aims at providing protection to target species and habitats at both local (i.e., site level) and regional (i.e., network level) scales. The network is still under implementation (Action Plan, EC 2017) with the need to enhance its monitoring for both gaining improved knowledge on the status of its protection targets and informing conservation measures. Indeed, many coastal and marine N2K sites are still unmanaged and unmonitored, mainly due to the absence of management plans and financial shortcomings (Claudet et al., 2020). The integration of the

existing monitoring initiatives, local, national, and regional, and the transnational data sharing have been underlined as effective to fill these gaps and help N2K network enhancement at the basin scale (Orlikowska et al., 2016; Manea et al., 2020a).

This study provides an ecosystem-based approach for the selection of monitoring variables with multiple aims: (i) the incorporation of ecological processes and their combination with variables of monitoring programs in place; (ii) the advancement of the alignment and harmonization of variables included in existing monitoring frameworks—i.e., WFD, MSFD, EOV, and EBV—through a terminology matching exercise, to support their integration; and (iii) the development of guidelines for the prioritization of variables in order to facilitate the overcoming of monitoring shortcomings and simultaneously inform marine policies. Indeed, the approach is built also to incorporate socio-ecological aspects [i.e., including ecosystem services (ES)], as well as considerations on the benefits of public engagement through citizen science for policies' implementation. Finally, we present a concrete application of the proposed approach in the context of N2K sites for delivering practical insights on the advantages provided by an integrated and multiscale monitoring framework, and for guiding effective monitoring of specific N2K conservation targets, despite the existing limitations. To this purpose, we selected N2K sites in the Adriatic Sea, where several sites are unmanaged and unmonitored, but where, nonetheless, the identification and expansion of the N2K network is underway (de Francesco et al., 2020). In order to help managers and scientists set and accomplish *ad hoc* monitoring programs, we focused on two practical case studies, both exemplary for their relevance in the Adriatic N2K sites: a target species—the common bottlenose dolphin, *Tursiops truncatus*, and a target habitat—seagrass meadows.

The approach and case studies have been developed contextually to the design of the marine ecological observatory ECOAdS (Ecological Observing System of the Adriatic Sea), in the framework of the Interreg Italy-Croatia project ECOSS (ECological Observing System in the Adriatic Sea: oceanographic observations for biodiversity; <https://www.italy-croatia.eu/web/ecoss>).

Materials and methods

Ecosystem-based approach applied to monitoring variable prioritization

In this study, we use the term monitoring variables interchangeably with monitoring indicators, to refer to the measurements carried out for assessing environmental status and related changes (Hayes et al., 2015). This terminology (“indicator”) is used often in ecology and environmental planning, with many different meanings, definitions, and purposes, so that there is no

one-fits-all definition. We refer to one of the broadest and all-encompassing definitions of indicator (hereafter refer to as variable), which is “a component or a measure of environmentally relevant phenomena used to depict or evaluate environmental conditions or changes or to set environmental goals” (Heink and Kowarik, 2010). As such, monitoring variables should also be considered as instruments to be used at the science–policy interface to communicate scientific information to policymakers and non-experts, and to assess progress towards conservation goals (Heink and Kowarik, 2010; McQuatters-Gollop et al., 2019).

To drive variables’ selection and prioritization in the context of conservation management, we relied on the tenets of Ecosystem-Based Management (EBM) as defined in UNEP (2011). EBM is a dominant paradigm in ocean management, being flagged as the most appropriate approach to ensure sustainability in the use of marine resources and in conservation planning (Levin et al., 2009; Long et al., 2015). The strength of EBM derives from the application of an integrated approach that stems from recognizing the intrinsic value of ecosystems, passes through its translation into fundamental benefits for people, and finally returns to nature by considering humans as part of ecosystems, leveraging on a balance between conservation and socio-economic interests. Monitoring implementation has always been recognized as compulsory to allow effective EBM for the support of adaptive and fit-for-purpose management (Arkema et al., 2006; Leslie and McLeod, 2007), and to communicate scientific findings to policymakers (Harvey et al., 2020). We advanced the classical approach to monitoring by incorporating socio-ecological

aspects and considering the benefits of public engagement and the relevance of feeding an ES approach. The engagement of citizens in marine monitoring practices has long been explored as an approach able to provide multiple benefits by allowing the collection of extensive and reliable environmental data and favoring citizens’ sensitization towards environmental issues (Bramanti et al., 2011; Hidalgo-Ruz and Thiel, 2013; Hyder et al., 2015; Freiwald et al., 2018; Pocock et al., 2018). The ES approach has been conceived as the main means to translate the scientific knowledge on ecosystem characteristics to policymakers, thus allowing its embedding in decision-making processes (Wong et al., 2015).

We structured our approach in three steps (Figure 1), as described below.

Selection of monitoring variables

The first step foresees the establishment and selection of monitoring variables, which were divided into three categories. The first one is that of ecological variables, i.e., those specifically addressing ecological processes and that can be defined as “measurable characteristics of the structure, composition, or function of ecological systems” (NRC, 2000; Niemi and McDonald, 2004). Indeed, to promote effective conservation of habitats and species, the monitoring and conservation of ecological processes is crucially important (EPA-US, 1999; Williams et al., 2018). Monitoring practices should go beyond the mere description of species and habitat structure, and the protection of ecological processes should be systematically translated into explicit conservation actions (e.g., Klein et al.,

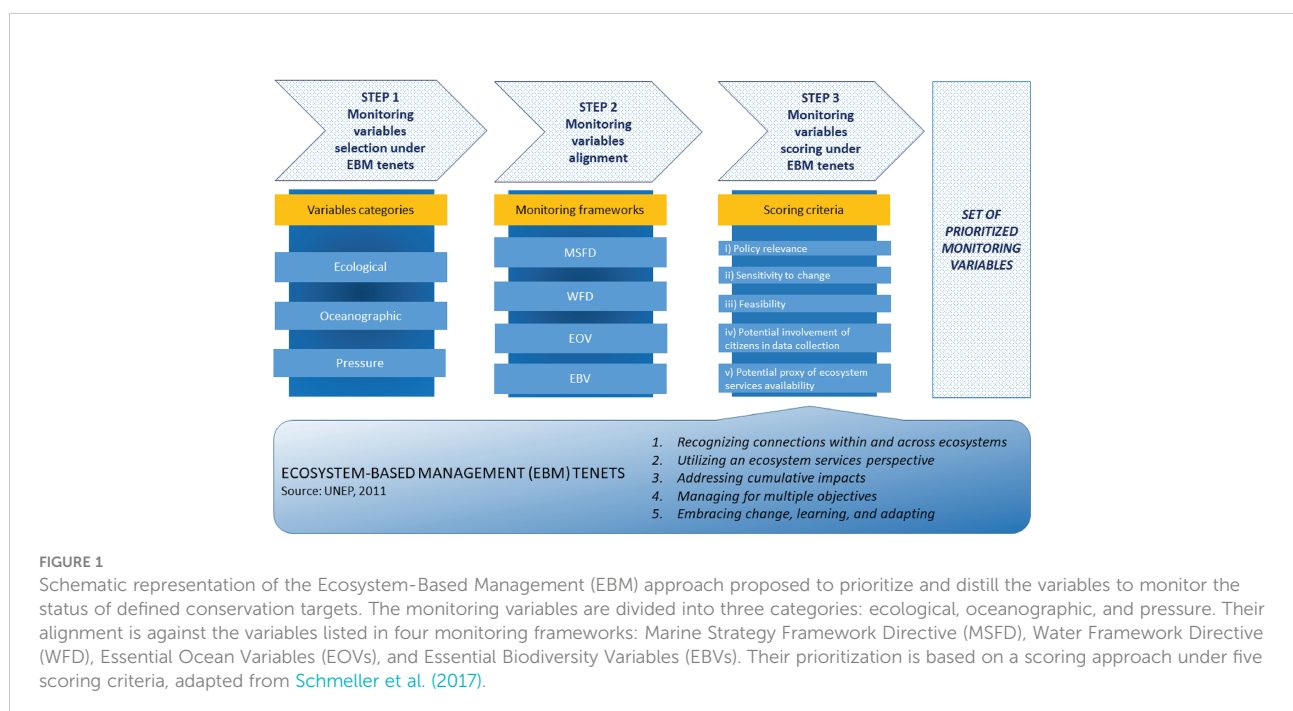


FIGURE 1

Schematic representation of the Ecosystem-Based Management (EBM) approach proposed to prioritize and distill the variables to monitor the status of defined conservation targets. The monitoring variables are divided into three categories: ecological, oceanographic, and pressure. Their alignment is against the variables listed in four monitoring frameworks: Marine Strategy Framework Directive (MSFD), Water Framework Directive (WFD), Essential Ocean Variables (EOVs), and Essential Biodiversity Variables (EBVs). Their prioritization is based on a scoring approach under five scoring criteria, adapted from Schmeller et al. (2017).

2009; Chamberlain et al., 2022). The second category concerns oceanographic variables, which depict physical oceanographic processes that regulate trend, transport, and flux of water, substances, and organisms in the marine system (such as current patterns, tidal and waves dynamics, temperature, light, and turbidity; Carr et al., 2011). The third category is represented by pressure variables, linked to any anthropogenic pressure defined as biological, chemical, or physical agent produced and/or exerted by one or more human activities that elicit an effect and impair the environmental conditions (Stelzenmüller et al., 2018). These are necessary to inform the effectiveness of existing management measures and the setting up of future ones. Indeed, monitoring variables also enable factors to individuate possible pressures acting on conservation targets and lead to any variations from their original status. In risk-based assessment procedures for management, monitoring variables should allow differentiation between natural disturbance and human-induced pressures (Stelzenmüller et al., 2018). Additionally, monitoring anthropogenic impacts has been underlined as essential to assess conservation performances also in marine protected areas (Dunham et al., 2020).

In this step, the variables must be selected to answer the need of considering ecological connectivity and the interconnections among species and between species and their environment in monitoring and conservation practices (Magris et al., 2014), thus relying on EBM principle 1 “Recognizing connections within and across ecosystems”. To guide the selection, we focused on seven key ecological processes described by Bennet et al. (2009) (Table 1): (i) climate, (ii) hydrology, (iii) interactions between organisms, (iv) movement of organisms, (v) spatial/temporal variation in primary productivity, (vi) natural disturbance regime, and (vii) formation of biophysical habitats. The selection of pressure variables must address the sources of pressure that might affect conservation targets to support EBM principles 3 “Addressing cumulative impacts” and 4 “Managing for multiple objectives”, the latter referring to trade-offs between human uses and conservation objectives.

Alignment of variables with WFD, MSFD, EOV, and EBV frameworks

The second step foresees the alignment of the variables selected in Step 1 with those listed in the WFD, MSFD, EOV, and EBV frameworks through a terminology matching exercise, to allow the definition of possible correlations among them. For both directives and EOVs, the alignment consisted in a careful match among the different frameworks’ monitoring variables. In order to respect the concept driving EBVs’ foundation, which are conceived as collectors that integrate diverse raw data (Brummit et al., 2017; Kissling et al., 2018; Zilioli et al., 2021), the alignment with EBV has been accomplished by considering the potential of a specific variable to contribute to the EBV framework, accounting for the different levels of biodiversity organization (e.g., genetic, species, community, and ecosystem).

Scoring of the selected monitoring variables

The third step consists in a variable scoring exercise based on a set of criteria, adapted by those proposed by Schmeller et al. (2017) for EBV definition, and recalling EBM principles 2 “Utilizing an ecosystem service perspective” and 5 “Embracing change, learning and adapting”. The five prioritization criteria are as follows:

i) Policy Relevance (PR) = variable that falls within the list of indicators of the WFD and MSFD directives and/or contributes to the EOV and/or EBV frameworks.

Scoring modality: 0 none of these frameworks; + at least one of the frameworks; ++ at least one directive plus EOVs and/or EBVs, or both directives; +++ both directives and EOVs and/or EBVs.

ii) Sensitivity to Change (STC) = variable able to communicate changes in time.

Scoring modality: 0 no or hardly changes can be detected; + variable that takes 10 or more years to show changes; ++ variable that reveals changes within 9 years; +++ variable detecting changes in less than 2 years.

iii) Feasibility (F) = it depends on the presence of established monitoring methods and its cost-effectiveness, i.e., the effort of time to collect samples or data and the extension of the area that can be covered by the monitoring in relation to the costs to support the activity. This criterion must be considered in the context and for the purpose of the monitoring.

Scoring modality: 0 not feasible; + there is a scientifically proven method, but it requires great effort and it is not cost-effective; ++ there is a scientifically proven method, no great effort is required, but it is not cost-effective, or the contrary; +++ there is a scientifically proven method, no great effort is required, and normal resource use (human and financial) is sufficient.

iv) Potential for Citizens Involvement in data collection (PCI) = considered as an approach able to support the collection of extensive and reliable environmental data and to enhance citizens’ engagement in monitoring and conservation issues.

Scoring modality: 0 NO; 1 YES.

v) Potential Proxy of Ecosystem Services availability (PES). This criterion was adopted only for ecological and oceanographic variables, as the pressure variables are not directly linked to ecosystem components, and therefore unsuitable to represent proxies of ES provisioning.

Scoring modality: 0 NO; 1 YES.

Application of the ecosystem-based system of variables in the Adriatic N2K sites

In this study, as exemplary cases, we considered six N2K sites of the northern Adriatic (Figure 2), which were selected within the Italy-Croatia Project ECOSS (Markov and ECOSS Partnership, 2019; Ciriaco et al., 2019; Golec and ECOSS Partnership, 2020; Miočić-Stošić et al., 2020; <https://ecoass.eu/sites/natura2000/>).

TABLE 1 Ecological processes to guide monitoring variables' selection, modified after [Bennet et al. \(2009\)](#).

Ecological process	Rationale
Climate	Climate variables directly influence several ecological processes; beyond their natural variability, they are altered by climate change that, for instance, leads to rising sea level and temperature, ocean acidification, and deoxygenation (Henson et al., 2017 ; Breitburg et al., 2018). Variables that could help to assess potential or ongoing climate-related changes include water/air temperature, pH, dissolved oxygen, frequency and amount of rainfall, mean sea level, and tidal range.
Hydrology	Hydrological variables are strictly linked to the seasonal and interannual variability in temperature, salinity, current patterns, and sediment loads coming from river runoff, which influence species presence and habitat conditions, as well as affect the primary productivity and consequently the whole trophic chain (Gillanders and Kingsford, 2002 ; Deininger and Frigstad, 2019). Among the variables useful to monitor hydrological alterations, there are dissolved oxygen, salinity, current velocity and direction, turbidity, sedimentation rate, and nutrient concentrations.
Interactions between organisms	Interactions between species (e.g., predation, herbivory, competition, parasitism, and mutualisms) alter communities' structure and dynamic, influencing other processes, such as nutrient cycling and organisms' distribution (Bennett et al., 2009). Among the variables useful to have information on organism interactions, there are cover/abundance and composition of benthic species, fish community composition and abundance, percentage cover/abundance of invasive species, behavior of species, and genetic diversity.
Movement of organisms	The dispersal of an individual has consequences not only for individual fitness, but also for population dynamics, genetics, and help explaining spatial pattern of species distribution at small and large scales (Gaines et al., 2007). Variables that can help depict this process are spatial distribution and movement of species, genetic diversity, larvae dispersal, and recruitment.
Spatial/temporal variation in primary productivity	Primary productivity influences the trophic food chain and the functioning of entire ecosystems. Alterations of primary production patterns, indeed, can dramatically affect nutrients and prey availability, and carbon sequestration processes in the water column (Roxy et al., 2016 ; Suprenand and Ainsworth, 2017). Among the variables useful to monitor primary productivity shifts, there are turbidity, dissolved oxygen, nutrient concentration in water and sediments, and chlorophyll-a.
Natural disturbance regime	Natural disturbance can affect temporally and locally species and habitats, leading also to large-scale and catastrophic impacts when linked to climate change phenomena such as storm waves, cyclones, and heat waves (Penaluna et al., 2018 and references therein). Among the variables useful to describe natural disturbance, there are temperature, dissolved oxygen, and spatial extent of the habitats that are adversely affected, through change in the biotic and abiotic structure and functions by physical disturbance, spatial distribution, and movement of species.
Formation of biophysical habitats	Both biotic and abiotic variables shape biophysical habitats affecting their quality status and their suitability for hosting species' communities. Interactions between species, bioerosion and bioconstruction processes, sediments and water chemical properties, and climate variables are among the main factors that affect this ecological process. Variables that can help depict this process are erosion-recolonization rate of species, composition of habitat-associated species, temperature, dissolved oxygen, and sedimentation rate.

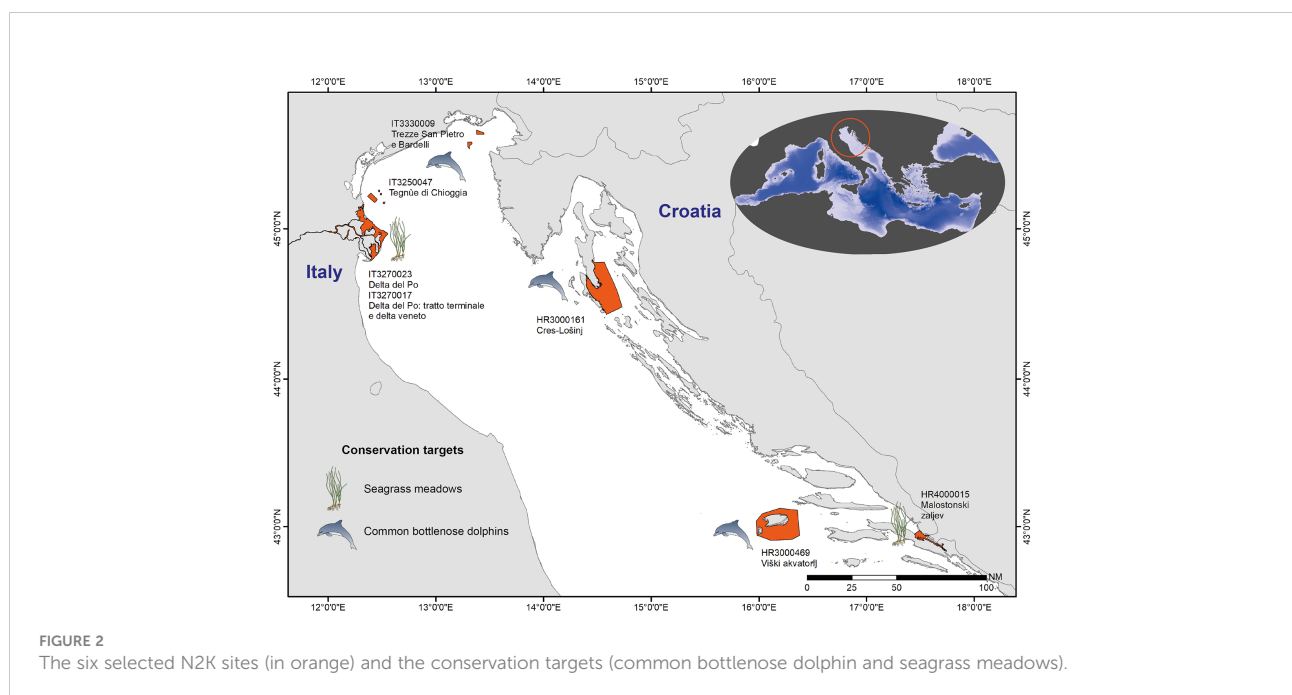


FIGURE 2 The six selected N2K sites (in orange) and the conservation targets (common bottlenose dolphin and seagrass meadows).

These sites can be considered fairly well representative of the northern Adriatic N2K network and are under the management responsibility of the project partners, who could therefore provide first-hand information. We focused on two conservation targets as exemplary case studies for the application of the variable system: (i) the common bottlenose dolphin (*Tursiops truncatus*), a species under protection in Cres-Lošinj, Viški akvatorij, San Pietro e Bardelli, and Tegnùe di Chioggia, and (ii) seagrass meadows, under protection in Malostonski zaljev and in the two Delta del Po sites. In the Delta del Po, seagrasses used to thrive, but their presence has not been observed in recent years. However, reintroduction activities are planned and seagrass monitoring will hopefully be needed again in the near future. The selection of these two case studies, as examples of monitoring targets, was primarily driven by the fact that they can be considered emblematic of transboundary contexts, such as that of the Adriatic Sea, and for the availability of local expertise and scientific knowledge, which allowed applying pragmatically the proposed variables' prioritization approach. The common bottlenose dolphin is the only cetacean species regularly inhabiting the entire Adriatic Sea. Basin-wide aerial surveys revealed the highest relative density of this species in the offshore part of the northern Adriatic (Fortuna et al., 2018), whereas boat-based studies describe their regular presence in coastal regions (Genov et al., 2008; Holcer, 2012; Pleslić et al., 2015; Rako-Gospić et al., 2017; Bonizzoni et al., 2021; Pleslić et al., 2021). Even though spatially distinct subpopulations with various levels of site fidelity have been observed, these are not isolated as some individuals were found to migrate between distant areas (Pleslić et al., 2019). The protection of this highly mobile species that moves freely across the whole northern Adriatic, regardless of geopolitical borders, has to be addressed regionally (Fortuna et al., 2018). Therefore, the monitoring strategy and the data collection to assess its

conservation status should be established and shared transnationally. The same is true for seagrass meadows, which in the area are mainly represented by *Cymodocea nodosa*, *Zostera marina*, *Zostera noltii*, and *Posidonia oceanica*, with the latter being distributed in the eastern Adriatic (Giannoulaki et al., 2013). This habitat is recognized as a key conservation target for its ecological role in supporting high biodiversity and for the many ES it provides (e.g., food, carbon sequestration; Duarte and Krause-Jensen, 2017; Unsworth et al., 2019). Its conservation should be implemented at the transboundary level to avoid a patchy distribution that would lead to an important loss of its ecological role. Additionally, connectivity among seagrass populations through fruit dispersal might be a potential reproductive strategy to favor meadows replenishment and seagrass genetic diversity (Mari et al., 2020).

Selection of monitoring variables for the Adriatic N2K conservation targets

In the case of N2K sites, conservation targets are declared in the form of species and habitats, and management levels extend over multiple spatial scales, from local (i.e., at the level of single site), to national, up to regional (i.e., at the level of the entire network). Thus, the variables' selection process started from the explicit conservation objectives defined by the considered N2K sites. In our case studies, the selection of ecological and oceanographic variables was based on the environmental characteristics of the northern Adriatic N2K sites and reflected the ecology of the two conservation targets, the common bottlenose dolphin and seagrass meadows. Additionally, we integrated the monitoring of anthropogenic impacts (Table 2). The pressure variables' selection was based on the specific management context of each N2K site depending on the present human activities and related pressures. The all selection step passed through a participative process with N2K sites' managers and experts involved in

TABLE 2 Anthropogenic activities and related pressures in N2K sites.

N2K sites	Anthropogenic activities	Anthropogenic pressures
Cres-Lošinj, Viški akvatorij, Malostonski zaljev	-nautical tourism -aquaculture -commercial fishing -spearfishing -scuba-diving -land-based activities and coastal development	-noise, physical disturbance, and pollution -chemical and biological pollution -physical disturbance, overfishing, and noise -physical disturbance - chemical pollution and physical disturbance -marine debris
Tegnùe di Chioggia and Trezze San Pietro e Bardelli	-commercial fishing -scuba-diving - recreational fishing - aquaculture -land-based activities	-physical disturbance, overfishing, and noise -physical disturbance -pollution - marine debris
Delta del Po: tratto terminale e delta Veneto and Delta del Po	-maintenance works in channels -aquaculture -commercial fishing -recreational fishing -tourism -land-based activities and coastal development	-changes in hydrological conditions, pollution -chemical and biological pollution -physical disturbance, overfishing, and noise -physical and chemical disturbance, trampling -chemical pollution, physical disturbance -marine debris

monitoring activities, and was further fed by an *ad hoc* literature review. Indeed, when available, studies focused on the two specific conservation targets in the area were used.

Alignment of variables with the WFD, MSFD, EOV, and EBV frameworks

The selected variables were aligned with those listed in official documents and technical reports of the different monitoring frameworks (WFD [Common Implementation Strategy, 2003-2004](#); EC, 2019; EOVs list within the available technical reports at https://www.goosocean.org/index.php?option=com_content&view=article&id=170&Itemid=114; EBVs list at <https://geobon.org/ebvs/what-are-ebvs/>). For the WFD and MSFD, monitoring variables were aligned starting from the harmonization carried out in [Manea et al. \(2021\)](#) as a first contribution of ECOAdS to an integrated and transboundary monitoring framework.

Scoring of monitoring variables

The scoring exercise was carried out based on the available information on N2K sites' monitoring activity collected through the participative process with N2K sites' managers and experts, and on an *ad hoc* literature review of studies reporting empirical results coming from both experimental and monitoring activities, and eventually from descriptions of monitoring approaches and data collection. To complete the whole approach, we finally verified which of the variables that should be specifically monitored by N2K managers, according to each site-specific conservation objectives, are actually monitored.

Results

The resulting lists of the selected ecological, oceanographic, and pressure variables for the common bottlenose dolphins and seagrass meadows in the northern Adriatic N2K sites are reported in [Tables 3](#) and [Table 4](#). The complete lists of references that support the variables' selection are reported in the [Supplementary Material](#).

Monitoring variables' alignment and scoring

Monitoring variables' alignment among MSFD, WFD, and EVs for both common bottlenose dolphin and seagrass meadows, and the scoring results are reported in [Figures 3–5](#), respectively. The complete terms of the aligned variables are reported in [Tables S1](#) and [S2](#), related to [Figures 3](#) and [Figure 4](#), respectively. The complete lists of references used to support variables' selection and scoring are reported in the [Supplementary Material](#). [Tables S3](#) and [S4](#) report the information on which variables are actually

monitored in the selected N2K sites, where the target species and habitat are present.

Common bottlenose dolphin

Around 56% of ecological, 40% of oceanographic, and 70% of pressure variables were not shared between EU directives and EV frameworks, and only three variables did not match any monitoring framework. Among the ecological variables, only “abundance”, “dispersal”, “emigration rate”, and “immigration rate” matched all monitoring frameworks with the exception of the WFD that does not focus on pelagic species living offshore, i.e., outside WFD range of action. Regarding the oceanographic variables, four out of the six listed matched one or both directives and EOVs (exceptions were “pH” and “transparency”, which were shared only between MSFD and WFD). EBVs do not consider oceanographic variables, as the framework is strictly focused on the biological ones. Almost none of the pressure variables matched the WFD and EV frameworks, while good matching was found between most of them and the MSFD.

For what concerns the ranking, among the ecological variables, “density”, “abundance”, and “spatial distribution” were those with the highest scores. Their feasibility score was based on the monitoring approaches adopted in the area, i.e., aerial and boat-based surveys ([Fortuna et al., 2018](#); [Bearzi et al., 2021](#)). Furthermore, these variables might be monitored also by citizens ([Embling et al., 2015](#); [Giovos et al., 2016](#)), as already happens in certain Mediterranean areas ([Ricci et al., 2018](#); [Alessi et al., 2019](#)). “Spatial distribution” was also found to be one of the most sensitive variables to changes, together with “dolphin behavior metrics”, potentially representing appropriate early-warning signals of the status of the species. Indeed, common bottlenose dolphins behave differently depending on the characteristics and geography of the area, the presence of human activities, the trophic niche occupied, and the season, being highly adaptable and opportunistic ([Bearzi et al., 2009](#)). Although “sex” and “age” fall in the list of both the MSFD and the EV framework and are monitored in Croatian N2K sites, their scores were low due to the difficulty in detecting changes with time, and because they cannot be easily tracked by citizens and are poorly suitable to ES assessment analyses. For the same reasons, “genetic diversity” has a low score, being also considered only by EBVs. Also, “prey abundance” and “prey distribution” obtained low scores; they are absent from both directives and their monitoring is not advantageous in terms of cost–benefit ratio, although better information on the bottlenose dolphins' diet is necessary ([Ricci et al., 2021](#)). Furthermore, both these variables cannot be monitored by citizens, or used for ES assessment. All these low score variables are not monitored in Croatian N2K sites.

The oceanographic variables all scored high because of the matching among monitoring frameworks, the high sensitivity to changes, and the monitoring feasibility, mainly thanks to the real-time data collection from the fixed observing systems present in the area of study ([Ravaioli et al., 2016](#); [Manea et al., 2020a](#)) and to

TABLE 3 List of monitoring variables for common bottlenose dolphin—*Tursiops truncatus* (Montagu, 1821), species under protection in Cres-Lošinj, Viški akvatorij, Trezze San Pietro e Bardelli, and Tegnùe di Chioggia N2K sites.

Ecological variables	density	(Genov et al., 2008)
	abundance	(Genov et al., 2008; Pleslić et al., 2015; Fortuna, 2006; Holcer, 2012; Pleslić et al., 2021)
	sex	(Genov et al., 2019; Fortuna, 2006)
	age	(Herrman et al., 2020 and references therein)
	recruitment rate	(Currey et al., 2009; Currey et al., 2011)
	spatial distribution	(Genov et al., 2008; Holcer, 2012; Rako-Gospić et al., 2017; Fortuna et al., 2018; Pleslić et al., 2019)
	dispersal	(Natoli et al., 2005; Nykänen et al., 2018; Pleslić et al., 2019; Genov et al., 2008)
	emigration rate	(Wells and Scott, 1990)
	immigration rate	(Wells and Scott, 1990)
	genetic diversity	(Natoli et al., 2005; Gaspari et al., 2013; Gaspari et al., 2015)
	prey abundance	(Bearzi et al., 2004; Bearzi et al., 2005 and references therein; McCluskey et al., 2016)
	prey distribution	(Notarbartolo di Sciara et al., 2002; Bearzi et al., 2004 and references therein; McCluskey et al., 2016)
	population size	(Genov et al., 2008; Fortuna, 2006; Pleslić et al., 2015)
	dolphin behavior metrics	(Fortuna et al., 1996; Bearzi and Notarbartolo di Sciara, 1999; Bearzi 2005)
	birth growth and mortality rate/mortality rate from incidental by-catch or incidents with boats	(Read et al., 1993; Haase et al., 2001; Fruet et al., 2012; xref Venn-Watson et al., 2015)
biometric measures	(Félix et al., 2018; Barratclough et al., 2019 and references therein)	
Oceanographic variables	temperature	(Bearzi et al., 2004; Carmichael et al., 2012; Taylor et al., 2016; Wild et al., 2019; Fandel et al., 2020)
	Water quality (dissolved oxygen, chlorophyll a, transparency, and pH) salinity	(Taylor et al., 2016) (Pitchford et al., 2016; Taylor et al., 2016; Booth and Tomas, 2021)
Pressure variables	interaction with fishing activities and fish farms (site fidelity, group dynamics, and seasonal and yearly occurrence)	(López 2012; Genov et al., 2019; Fortuna et al., 1996; Rako-Gospić et al., 2017)
	contaminant concentration in water	(Allan et al., 2006; Brack et al., 2017)
	contaminant concentration in tissues	(Barratclough et al., 2019 and references therein)
	spatial extent and duration of significant acute pollution events	(from MSFD; Allan et al., 2006; Brack et al., 2017)
	effects of significant acute pollution events on the health of individuals and the condition of habitats	(from MSFD; Barratclough et al., 2019 and references therein)
	type, number, and proximity of vessels to dolphins	(Baş et al., 2015; Rako et al., 2013)
	spatial distribution, temporal extent, and levels of noise pollution by traffic boats	(Rako et al., 2013; Rako et al., 2013a; Rako et al., 2013b)
	the amount, type, weight, and spatial distribution of litter and micro-litter in the water column and on the bottom	(from MSFD; Bergmann et al., 2015)
	the amount, weight, and type of litter and micro-litter ingested, the number of individuals that are adversely affected due to litter	(from MSFD; Poeta et al., 2017; Battaglia et al., 2020)
birth growth and mortality rate/mortality rate from incidental by-catch or incidents with boats	(Read et al., 1993; Haase et al., 2001; Fruet et al., 2012; Venn-Watson et al., 2015)	

The reference list is reported also in [Supplementary Material](#). The target species and N2K sites are directly linked to the EUNIS web portal (<https://eunis.eea.europa.eu/>), while variables are linked to the ECOSSE monitoring variables thesaurus (http://rdfdata.get-it.it/ecoss/ecoss_Variable).

satellite observations (Groom et al., 2019; Medina-Lopez and Ureña-Fuentes, 2019).

The pressure variables found a good match only with the MSFD. Contaminants' concentration and marine litter amount in environmental matrices were the ones with the highest scores

as these can change even in a short time and are feasible to monitor through agreed and widespread methodologies and protocols (EC report, 2013). Marine litter together with dolphin proximity to vessels are variables that can be monitored also by engaging citizens. On the contrary, the

TABLE 4 List of monitoring variables for seagrass meadows, in particular of *Cymodocea nodosa* (Ucria) Asch., *Posidonia oceanica* (L.) Delile, *Zostera noltii* Hornem., *Zostera marina* L., habitat under protection in Malostonski zaljev and Delta del Po: tratto terminale e delta Veneto sites.

Ecological variables	biomass	(Pérez and Romero, 1994)
	cover	(Marbà et al., 2014)
	growth rate	(Pérez and Romero, 1994; Marba and Duarte, 2010)
	leaf elongation rate	(Pérez and Romero, 1994)
	net primary productivity	(Koopmans et al., 2020)
	erosion-recolonization rate	(Duarte and Jensen, 1990; Bonamano et al., 2021)
	spatial distribution	(Tragonos and Reinartz, 2018)
	patch size	(Duarte and Jensen, 1990)
	biometric measures	(Cox et al., 2016)
	phenological measures	(Buia and Mazzella, 1991)
	genetic diversity	(Procaccini et al., 2001)
	habitat characterization	(Letourneur et al., 2003; Brown et al., 2011; Innangi et al., 2022)
	density of herbivores	(Méndez et al., 2017)
	abundance of herbivores	(Tomas et al., 2005)
	biomass of epiphytes	(Nesti et al., 2009)
	density of reproductive shoots	(Balestri and Cinelli, 2003)
	biomass of reproductive shoots	(Balestri et al., 2006)
	reproductive rate	(Balestri and Cinelli, 2003)
	flowering frequency	(Buia and Mazzella, 1991)
	shoot density	(Marba and Duarte, 2010)
	number of leaves per shoot	(Pérez and Romero, 1994)
	composition and abundance of associated organisms	(Como et al., 2008; Mascart et al., 2013)
presence/abundance of invasive species	(Piazzi and Balata, 2009)	
percentage cover of invasive species	(Piazzi and Balata, 2009)	
Oceanographic variables	temperature	(Buia and Mazzella, 1991; Marba and Duarte, 2010)
	salinity	(Sanchez Lizaso et al., 2008)
	PAR	(González-Correa et al., 2005)
	wave exposure	(Tuya et al., 2014)
	depth	(Marba and Duarte, 2010)
	current velocity	(Binzer et al., 2005)
	current direction	(Tuya et al., 2014)
	sediment type	(González-Correa et al., 2005)
	sedimentation rate	(Cabaco et al., 2008)
	nutrient concentration in water	(Burkholder et al., 2007)
	nutrient concentration in sediments	(Burkholder et al., 2007; Boscutti et al., 2015)
	organic matter in sediments	(González-Correa et al., 2005)
	chlorophyll a	(Apostolaki et al., 2007)
	dissolved oxygen	(Binzer et al., 2005)
	transparency	(González-Correa et al., 2005)
	pH	(Boscutti et al., 2015)
	redox potential of sediments	(Boscutti et al., 2015)
Pressure variables	oxygen concentration in sediments	(Koch 2001 and references therein)
	contaminant concentration in water	(Bonanno and Orlando-Bonaca, 2017)
	contaminant concentration in sediments	(Bonanno and Orlando-Bonaca, 2017)
	area cover destructed by anchoring-trawling	(Francour et al., 1999; González-Correa et al., 2005)

(Continued)

TABLE 4 Continued

intensity and spatial and temporal variation of physical disturbance	(From MSFD; Boström and Bonsdorff, 2000; Bourque et al., 2015)
spatial extent of the suitable habitat that is adversely affected through change in its biotic and abiotic structure and its functions by physical disturbance	(From MSFD; Boström and Bonsdorff, 2000; Bourque et al., 2015)
spatial and temporal variation of hydrographical conditions	(From MSFD; Pérez-Ruzafa et al., 2012)
spatial extent of each habitat type adversely affected due to alteration of hydrographical conditions	(From MSFD; Pérez-Ruzafa et al., 2012)
spatial extent and duration of significant acute pollution events	(From MSFD; Roca et al., 2017)
effects of significant acute pollution events on the health of individuals and the condition of habitats	(From MSFD; Roca et al., 2017)
heavy metal concentration in tissues	(Bonanno and Orlando-Bonaca, 2017)
organic pollutant concentration in tissues	(Haynes et al., 2000)
presence/abundance of invasive species	(Piazzi and Balata, 2009)
percentage cover of invasive species	(Piazzi and Balata, 2009)

The reference list is reported also in [Supplementary Material](#). The target species and N2K sites are directly linked to the EUNIS web portal (<https://eunis.eea.europa.eu/>), while variables are linked to the ECOSS monitoring variables thesaurus (http://rdfdata.get-it.it/ecoss/ecoss_Variable).

monitoring of the concentrations of plastic and contaminants in tissues and organs is difficult because it can only be carried out on stranded or captured animals; thus, these analyses cannot be planned in advance or carried out systematically. Although the ecological and pressure variable “birth growth and mortality rate/mortality rate from incidental by-catch or incidents with boats” matches the MSFD, it had the lowest scores mainly because carcasses usually sink and are not visible and by-catch is difficult to estimate from dead and stranded individuals (Bearzi et al., 2009). The variables “Interaction with fishing activities and fish farms” and “proximity to vessels” are monitored in Cres-Lošinj and Tegnù di Chioggia and could be monitored with the help of citizens, for instance, fishermen and fish farmers, as well as recreational boaters. Noise pollution and its effect on common bottlenose dolphins emerged as one of the most sensitive variables, since it is directly linked to the level of vessel traffic. As far as we know, this variable is monitored only in the N2K site Cres-Lošinj.

Seagrass meadows

We found that ca. 21% and 22% of selected seagrass ecological and oceanographic variables, respectively, did not match any of the considered monitoring frameworks. Among the ecological and oceanographic variables, ca. 67% and 44%, respectively, did not contemporarily match directives and EVs. Only one pressure variable did not match that of the MSFD, while almost all did not match that of the WFD and EVs.

The ecological variables aligned with the directives were “biomass”, “cover”, “abundance of herbivores”, and “composition and abundance of associated organisms”. The first two were scored high for their high sensitivity to changes, monitoring feasibility, and suitability for ES studies. According to Boudouresque et al. (2009) and Nordlund et al. (2018), different seagrass species present diverse morphological and physiological traits and can answer differently to the same stressor; nonetheless,

we found that more than half of the ecological variables can be uniformly considered potential early-warning signals. For instance, a 3-month experiment of temperature variations to test for warming effects on *P. oceanica* and *C. nodosa* was enough to appreciate changes in growth rates, leaf formation, and elongation rates and biomass (Olsen et al., 2012), and 6 weeks were enough to induce *P. oceanica* flowering (Ruiz et al., 2018). Variation in seagrass recruitment rates can be detected within 18 months, which include the period that falls between seed germination and successful seedling establishment (Pereda-Briones et al., 2020). Spatial distribution and especially patches’ size, depending on their extent, can vary appreciably even yearly. Shoot density was found to be a generalized variable for monitoring a wide range of stressors (Roca et al., 2016). However, among these variables, only “cover” is regularly monitored in Malostonski zaljev. Epiphyte biomass is regulated by a multiplicity of factors—their diversity, interactions with the environment, larvae and propagule availability, and the lifetime of the colonized seagrass leaf (Borowitzka et al., 2007). For this reason, estimating the sensitivity of this monitoring variable is difficult. This is also valid for the species associated with seagrass meadows, whether they are herbivores, invasive, or others.

Measurement of seagrass ecological variables at the scale of the N2K site is mainly carried out through SCUBA dive surveys and underwater videos, which are the most effective approaches for their accuracy, even if they can hardly be applied on a large scale. The monitoring feasibility of most of the variables was scored high because we considered the potential of adopting remote sensing techniques, which are reliable approaches to collect information on seagrass meadows (e.g., biomass, cover, spatial distribution, patch size, and habitat characterization), and complementary with *in situ* data collection (Paul et al., 2011; Duffy et al., 2019).

We found more than half of ecological variables being useful for seagrass ES assessment (e.g., biomass, cover, and shoot density; Ruiz-Frau et al., 2017; Hossain and Hashim, 2019; de

A



B

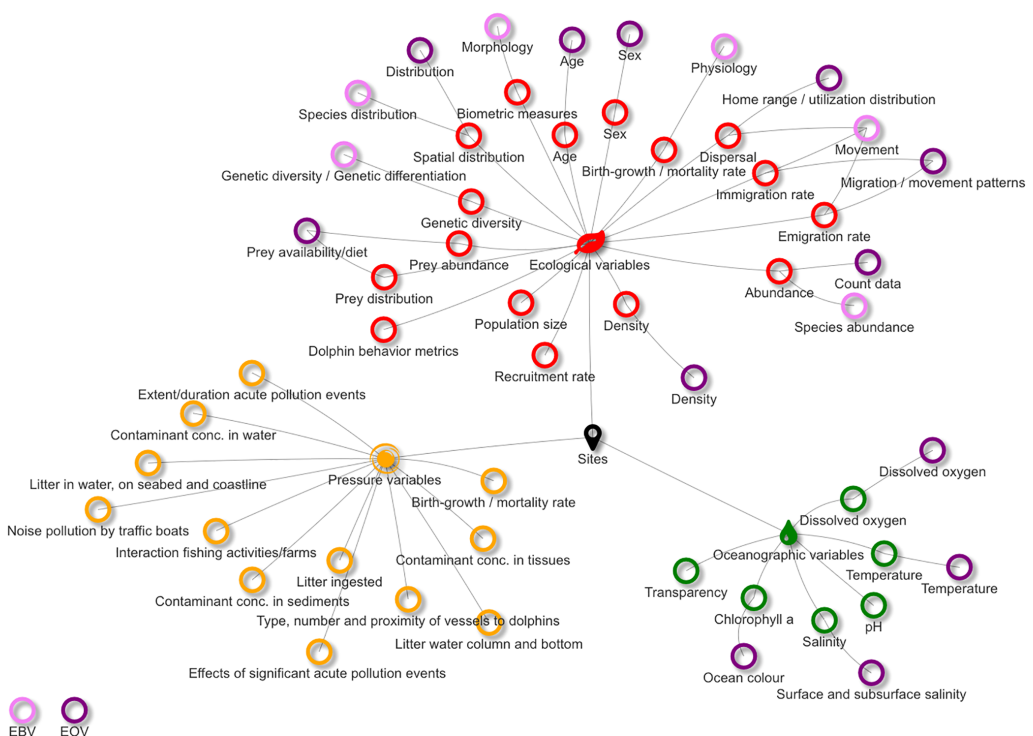


FIGURE 3 Alignment between ecological, oceanographic, and pressure variables to monitor the common bottlenose dolphin with Water Framework Directive (WFD) and Marine Strategy Framework Directive (MSFD) variables (A), and Essential Ocean Variables (EOVs) and Essential Biodiversity Variables (EBVs) (B).

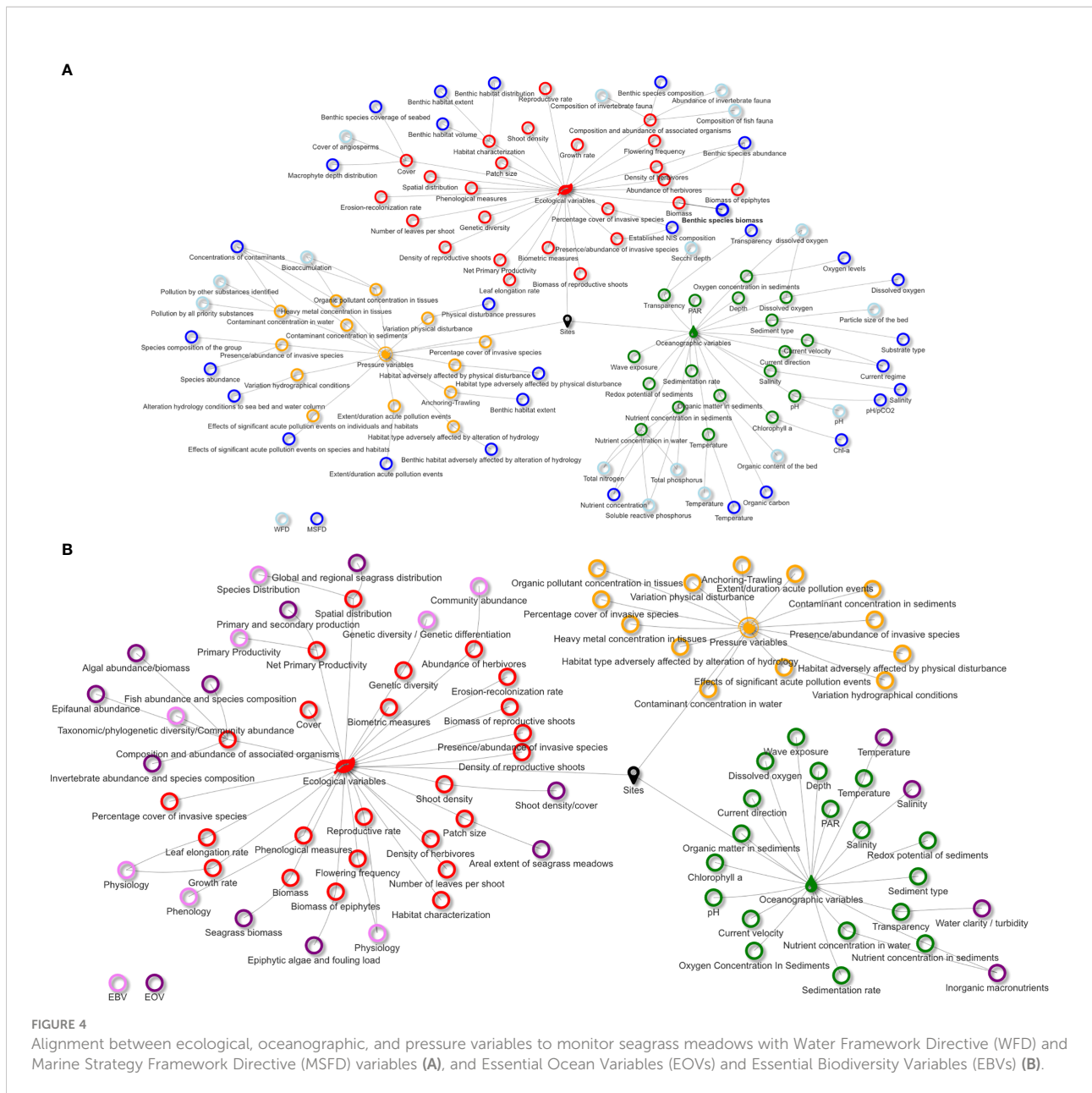


FIGURE 4 Alignment between ecological, oceanographic, and pressure variables to monitor seagrass meadows with Water Framework Directive (WFD) and Marine Strategy Framework Directive (MSFD) variables (A), and Essential Ocean Variables (EOVs) and Essential Biodiversity Variables (EBVs) (B).

los Santos et al., 2020), and also potentially measurable by citizens (Jones et al., 2018; Mannino and Balistreri, 2018; Smale et al., 2019). An example is the Community Seagrass Initiative (CSI), a citizen science project carried out by the National Marine Aquarium in Plymouth (UK), during which citizens were involved in data collection to assess the distribution and status of *Z. marina* (Smale et al., 2019). In relation to invasive species monitoring, an important citizen science contribution has been reported in the marine protected area of Egadi Islands (Mannino and Balistreri, 2018).

Oceanographic variables, as previously reported for the common bottlenose dolphin, were scored high also for seagrass because they matched diverse monitoring frameworks,

and presented high sensitivity to changes and monitoring feasibility. The monitoring feasibility of hydrographic conditions scored high thanks to the presence of fixed buoys or platforms in the area for routine studies and real-time collection of oceanographic parameters. These systems largely contribute to detect any hydrographical variations at large scale that can affect N2K sites.

Pressure variables showed quite similar scores. Contaminant and pollutant concentrations in seagrass tissues and sediments were the only ones matching both the MSFD and the WFD variables. In Malostonski zaljev, only biological and physical/mechanical disturbances are monitored, while pollutants and contamination events are not.



FIGURE 5 Scores assigned to the ecological, oceanographic, and pressure variables to monitor the health and conservation status of (A) the common bottlenose dolphin, *Tursiops truncatus*, in Cres-Lošinj, Viški akvatorij, San Pietro e Bardelli, and Tegnue di Chioggia N2K sites, and (B) seagrass meadows in Malostonski zaljev and Delta del Po N2K sites. PR = Policy Relevance, STC = Sensitivity to Change, F = Feasibility, PCI = Potential for Citizens Involvement, PES = Proxy for Ecosystem Services assessment, n.a. = information not available/sufficient.

Discussion

Our ecosystem-based system of monitoring variables has been conceived as a tool that can favor the setting of integrated and harmonized local strategic monitoring plans, track the status of habitats and species under protection, by considering driving ecological processes, and contribute effectively to large-scale monitoring. We explored the potential of an integrated approach, which combines diverse monitoring frameworks (i.e., MSFD, WFD, EOV, and EBV) for selected variables and can be able to deliver information needed to boost marine conservation at multiple spatial scales. This could help to define appropriate, focused, and feasible monitoring efforts by converging on a limited number of variables and containing the financial costs, without hindering the achievement of monitoring and conservation objectives. Additionally, it could favor the harmonization and integration of monitoring practices,

remediating the current fragmentation of existing programs (Zampoukas et al., 2013).

We tested this approach to support N2K sites and their networking, one of the main European missions to contribute to global conservation needs (EC, 2017). We focused on the northern Adriatic Sea, specifically in the area under the jurisdiction of Italy and Croatia, this work being one of the outcomes of the Interreg-Italy-Croatia project “ECOSS” (<https://www.italy-croatia.eu/web/ecoss>), and on two significant conservation targets, the species *T. truncatus* (the common bottlenose dolphin), and the habitat of seagrass meadows (mainly dominated by *C. nodosa*, *Z. noltii*, and *P. oceanica*) as exemplary case studies of selected Adriatic N2K sites. Although our study is based on test conservation targets and selected north Adriatic N2K sites (therefore cannot be considered exhaustive for the whole Adriatic basin), the proposed integrated and multi-scale approach might potentially help to set up frameworks of variable

selection in the wider Adriatic macroregion, and in other marine areas of the Mediterranean Sea and beyond. Actually, the approach can be tested and applied to guide the monitoring of other conservation tools, both legally binding and not, such as Large Scale Marine Protected Areas (LSMPAs), Specially Protected Areas of Mediterranean Importance (SPAMI), Ecologically and Biologically Significant Marine Areas (EBSAs), Important Marine Mammal Areas (IMMAs), and Cetacean Critical Habitats (CCHs) specifically for cetaceans (Carlucci et al., 2021). Indeed, it can be of particular relevance for these conservation tools with large spatial footprints, with no clear national commitments if they fall in international waters or are shared between different countries, thus making their monitoring really challenging (O'Leary et al., 2018; Costello and Molina, 2021).

In the proposed three-step approach, we defined three categories of variables, i.e., ecological, oceanographic, and pressure, selecting those that might better depict the complexity of ecological processes (Bennet et al., 2009) and track local pressures and climate change when combined to guide management decisions. Interdisciplinarity in monitoring has been highlighted as crucial to ensure comprehensive observations and understanding of environmental patterns and trends at multiple spatial scales (Benedetti-Cecchi et al., 2018). We support that combining information on biotic, abiotic, and physical elements with those on pressures and their sources helps identify ecosystems' emerging properties and their possible shifts. Thus, the first step of our approach can be applied to orient the establishment of a first set of variables, among the many, that account for a multiplicity of factors that influence the status of species and habitats.

This preliminary selection might as well inspire an update of the lists of monitoring variables considered in the existing monitoring frameworks. Indeed, the alignment of the selected variables with those required and indicated by the MSFD, the WFD, and the EV frameworks delivered, first of all, insights into the divergences among monitoring frameworks. Main divergences were observed between EU directives and EV frameworks when looking at ecological and pressure variables. In particular, some ecological variables related to the trophic ecology of the common bottlenose dolphin and some related to the physiology and phenology of seagrasses (e.g., growth and leaf elongation rates, and reproduction) matched with EVs, but were neglected by both directives despite being critical for assessing the conservation status of these two targets. The distribution and abundance of common bottlenose dolphins' prey might not be seen as relevant to affect the distribution and health of this species, which is considered a non-selective feeder, i.e., capable of shifting prey depending on their availability (Holcer, 2012; Gaspari et al., 2015). Instead, monitoring the prey is crucial, since general prey depletion has been recently recognized as a main threat for these animals (Carlucci et al., 2021), especially in the area of study, where an excessive fishing pressure is causing it

(Bonizzoni et al., 2021). As for the seagrasses, these have been used for decades as indicators of good environmental status (Lopez y Royo et al., 2010), and decadal data of cover and biomass across the entire Mediterranean recently allowed the assessment of their status and trend at the basin scale (de los Santos et al., 2019); therefore, great merit must be given to the EU legislation that has imposed this kind of monitoring. Nonetheless, in the current context of biodiversity loss, due to rapid climate change and unpredictable effects coming from multi-stressor combinations (Henson et al., 2017; Gissi et al., 2021), anticipatory signals, such as those related to the physiological and phenological status of seagrasses, mostly neglected by the directives, should be prioritized in monitoring practices, to anticipate possible negative shifts of habitats' conditions. Looking at the pressure variables, they matched almost only the MSFD ones. Monitoring pressures is fundamental for effective conservation planning and management (Dunham et al., 2020), particularly in N2K sites, whose management plans entail socio-economic objectives together with those of conservation (Kati et al., 2015). In general, ecological variables best inform about pressure effects on species and habitats, but they can often be measured once the impact has already occurred. Thus, only waiting for related signals might be insufficient on the temporal scale for taking decisions on the application of mitigation or adaptation measures. Instead, the adoption of a set of composite indicators, as the one we proposed, which considers oceanographic and pressure variables together with the ecological ones, would be most effective to correlate diverse measurements (Schmeller et al., 2017), enabling one to detect impacts earlier and inform anticipatory conservation actions.

Despite these drawbacks, we evidenced that the majority of the variables matched at least one monitoring framework among directives and EVs, bringing out the potential of their integration. This implies that part of them is currently or might be monitored through EU mandatory programs at the local and national level, as well as in N2K sites. This will be fully achievable if coordinated efforts are put in place to arrange and activate joint monitoring programs that will also include N2K sites, currently limited in terms of conservation planning and dedicated resources (Claudet et al., 2020). Simultaneously, the variables shared among directives and EVs could converge to feed the global strategies, while those not yet monitored under national law could be integrated, both to make them most effective and to further support the EVs.

The prioritization exercise allowed us to reduce the number of variables by distilling the ones that emerged as priority to be able to better respond to the ecosystem-based criteria on which our approach is based. These criteria respond to the need to both describe ecological processes and communicate the information acquired through monitoring toward management policies that are directly linked to the directives and regional strategies, or that are appropriate for ES assessments. Furthermore, the

application of an EBM approach for the prioritization of the variables helped to define possible advantages and disadvantages in their monitoring.

The concrete application of the proposed approach through case studies allowed us to provide insights and suggestions to guide variable selection based on the context and monitoring objectives of the selected N2K sites, and on the knowledge provided by the local experts. The latter was an indispensable component in the implementation and success of our exercise, and we emphasize the importance of engaging the local experts in each monitoring and management plan. Their contribution allowed us to create a narrower variables' set of potential priority to facilitate overcoming difficulties and limitations in their choice (Hayes et al., 2015) and data collection. For instance, we found the ecological "abundance and distribution" metrics to be the ones with the highest priority for monitoring the common bottlenose dolphin. Related data have been collected for some decades in the whole study area and at the level of N2K sites to predict critical zones for the conservation of the species (Pleslić et al., 2015; Fortuna et al., 2018; Pleslić et al., 2019; Farella et al., 2020; Bonizzoni et al., 2021; Pleslić et al., 2021) and to inform the recent designation of a new N2K site (IT3270025 "Adriatico Settentrionale Veneto-Delta del Po"). These monitoring efforts are carried out by local associations and institutions and, for their fundamental value, should be long-lasting and supported by constant and appropriate funding mechanisms, which at the moment are lacking. Despite being identified as more difficult to monitor, we recommend adding to the future monitoring plans some variables that could give important indications about ecological connectivity, i.e., dispersal, migration patterns, and genetic diversity. Indeed, distinct subpopulations of common bottlenose dolphin have been detected to inhabit the Adriatic Sea, and this is relevant to guide management actions aimed at avoiding the genetic erosion of this species (Gaspari et al., 2015). Furthermore, the monitoring of these variables would feed the EV frameworks.

Regarding seagrass meadows, we found that *in situ* data collection of ecological variables is the most reliable strategy, but it is time-consuming and with limited potential to be upscaled also at the level of the entire N2K site. However, new technologies and approaches are advancing, becoming powerful tools to extend the monitoring of biological and ecological metrics, which is a necessity for effective ocean observation (Benedetti-Cecchi et al., 2018). Opportunities to rely on remote data collection with good resolution combined with field data to monitor seagrasses have been described along with useful recommendations to harmonize approaches at large scales (Duffy et al., 2019). These might be considered at the scale of the N2K network and of the whole Adriatic Sea, to extend the monitoring range and avoid further loss of this habitat.

Among the pressure variables, we recommend the monitoring of pollution and contamination events, since habitat deterioration due to urbanization and agricultural activities is one of the main causes of biodiversity loss in coastal areas (Todd et al., 2019).

However, land-based sources of pollution potentially able to impair the status of marine species and habitats under protection are many and can act both locally and at a distance from the conserved area, impacting even offshore and remote zones (Kidd et al., 2019; Manea et al., 2020b). In such a context, monitoring should be used as an instrument of support for preventive and integrated coastal management, considering the land–sea continuum (Eger et al., 2021). Finally, we assessed the monitoring of oceanographic variables to be highly feasible. Indeed, the considered sites fall within a marine area that is constellated by multiple fixed-point observing systems that provide real-time data of diverse oceanographic parameters in both coastal and off-shore areas, which should be shared and integrated also at the transnational level (Ravaoli et al., 2016; Manea et al., 2020a). Additionally, the area is covered by monitoring initiatives beyond the ones mandated by law, such as the Italian Long-Term Ecological Research network (LTER-Italy), which works as a collector of long-time series of a variety of ecological data (Pugnetti et al., 2013; Zilioli et al., 2019; Capotondi et al., 2021) that are not provided by N2K monitoring. The integration of these extensive datasets, in both time and space, with those collected by the local agencies under national mandate, and their consideration by N2K sites managers, is advisable and represents an incredible opportunity to benefit from already consolidated monitoring systems able to provide information on both past and present environmental status. Contemporarily, the data already collected in N2K sites should be conveyed together with these datasets to feed the EV frameworks. The concrete application of our approach for the setting up of an ecosystem-based system of variables in the context of N2K sites, therefore, revealed the mutual benefits that can be provided if multilevel monitoring frameworks would be integrated and exploited synergistically by N2K managers. An integrated system would become an available source for N2K site monitoring and contextually local monitoring projects would provide updated data to large-scale monitoring frameworks.

In addition, our framework included the citizen science approach as a possible way to extend data collection of many ecological and some pressure variables in N2K sites. Although a main concern of citizen science studies is the level of reliability of data collection, which requires clear protocols, training of volunteers, and a quality check by professional scientists, this approach has been confirmed as useful in past experiences (Hidalgo-Ruz and Thiel, 2013; Matear et al., 2019). Actually, citizen science programs have contributed to collect information on population dynamics, health and distribution of marine organisms, and marine litter, and have also supported long-term monitoring programs of MPAs (Garcia-Soto et al., 2021 and reference therein). We believe that it can be beneficial to engage citizens, sharing visions and research questions with them in a reciprocal knowledge exchange, and involving them in the observations as a further support for large-scale and cost-effective monitoring initiatives (Couvet et al., 2008; Jones et al., 2018). We finally indicated as priority those variables that can feed ES

assessment as well. Recently, the Essential Ecosystem Service Variables (EESVs) have been proposed, delivering a first set of variable classes (Balvanera et al., 2022). This new framework aims precisely at orienting and organizing the collection of harmonized and interoperable data suitable for such assessment, which is necessary to trail progress towards sustainability and conservation goals. Therefore, monitoring certain ecological parameters even with this intent in mind is highly recommended, because it will support an approach that could better address accounting for the benefits that nature provides to humans within decision-making processes.

This three-step EBM approach to monitoring variable prioritization stems from the broad and holistic framework of ECOAdS, the Ecological Observing System of the Adriatic Sea (Pugnetti et al., 2022; <https://ecoads.eu/>). ECOAdS represents a first step towards the upscaling of coordinated monitoring efforts through shared approach and vision at both N2K sites (the local) and N2K network (the regional) scales in the Adriatic. The EBM approach to monitoring proposed here can be transferred to other contexts and scales to help build a common knowledge and monitoring framework. This is fully in line with the holistic ECOAdS vision, which aims at a common goal of nature conservation by combining multiple disciplines, capitalizing and integrating existing monitoring frameworks through a tiered approach, and recognizing the power of engaging the multitude of stakeholders who benefit from nature (Pugnetti et al., 2020; Boemare et al., 2022).

With this study and our tested approach, we aimed at underlining the need to harmonize and integrate the existing monitoring frameworks in the broadest marine context and at multiple spatial scales. Adopting an EBM and integrated approach to monitoring would deliver concrete benefits to conservation and management strategies, saving costs by relying on available resources and on consolidated and long-lasting approaches that might converge towards global initiatives for the common goal of conserving our marine environment.

Data availability statement

The original contributions presented in the study are included in the article/[Supplementary Material](#). Further inquiries can be directed to the corresponding author.

Author contributions

EM, CB, AP, LB, and AO conceptualized and proposed the idea. FG carried out the literature review on monitoring

variables. EM, CB, and AO built the alignment scheme of the variables with the different frameworks (directives and EVs). EM carried out the variable scoring exercise and wrote the first draft of the paper. GP provided knowledge support on the ecology and monitoring of the bottlenose dolphin. 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.

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fmars.2022.920366/full#supplementary-material>

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