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Are we overlooking Natura 2000 sites? Lessons learned from a transnational project in the Adriatic Sea

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Since the adoption of the Habitats and Birds Directives by EU governments, marine Natura 2000 (N2K) sites have been established in the European Mediterranean Sea, creating one of the largest international networks of protected areas. Nevertheless, to date, marine N2K sites are generally scarcely implemented, studied and monitored, and thus their management effectiveness is weak, and their environmental status is often unknown. The Interreg Italy-Croatia ECOSS project aimed at establishing the ECOlogical observing system of the Adriatic Sea (ECOAdS), to integrate the existing research and monitoring activities in the area, and to promote data sharing at international level, for enhancing monitoring and conservation in Adriatic N2K network. In the framework of ECOSS, a conceptual model was developed and applied to selected N2K sites, to review the existing knowledge, assess site effectiveness, and suggest possible improvements in their monitoring and management based on the contribution that ECOAdS can provide to their implementation. Information on social, ecological, and oceanographic elements related to the conservation and management of these case studies was gathered by consulting the project partners involved in the management and monitoring of the sites and through a literature review. The results of this study revealed a discouraging condition with no management plan in most of the sites, while regulatory measures are generally in place but without surveillance. Monitoring activities are performed occasionally, and information on presence and status of protected species is often lacking or outdated. Although the N2K network provides a unique opportunity to advance marine conservation and achieve the 30% conservation target by 2030, the biggest challenge ahead is the proper management and monitoring of N2K sites. The proposed conceptual model may be taken as a framework to properly set up ecological observing systems in the N2K network and help overcome current limitations, integrating scientific research within the N2K conservation strategies.

KEYWORDS

marine conservation, monitoring, Natura 2000 sites, European directives, Adriatic

1 Introduction

Healthy ecosystems are critical for providing goods and services to human well-being. However, multiple stressors are leading to widespread changes in marine habitat structure and ecosystem functioning at all latitudes (Claudet and Fraschetti, 2010; Halpern et al., 2015; Zunino et al., 2017; Breitburg et al., 2018; Bucci et al., 2020).

Since the '70s, the European Union has demanded common policies to halt further biodiversity decline and protect the environment. In line with the provisions of the Convention on Biological Diversity (CBD) at the 1992 Rio Earth Summit, the Habitats Directive (HD; EC, 1992) and the Birds Directive (BD; EC, 2009) were among the first directives set off to ensure the conservation of a wide range of rare, threatened, or endemic flora and fauna. The HD and BD established, also thanks to the help of the funds provided by the LIFE Programme, a system of protected areas across Europe known as Natura 2000 (N2K), forming a transnational network (Evans, 2012). Currently, the N2K network includes more than 3000 marine sites and covers almost 9% of European seas (EEA, 2021). Their number is steadily growing (EC, 2017a), also to meet the requests of the latest environmental conservation policies and initiatives which include Agenda 30 (UN, 2015), the EU Biodiversity Strategy for 2030 (EC, 2020), and the 30 by 30 target (CBD, 2021). Such a vast network adds to other types of protected areas under national legislation and in the framework of different international legal instruments (e.g., Barcelona, Bern, Helsinki, OSPAR conventions).

As demonstrated by some decades of studies, when marine protected areas are well managed and adequately enforced, biodiversity and ecosystem functions can be preserved, in particular from fishing pressure (García-Rubies and Zabala, 1990; Marbà et al., 2002; Sala et al., 2012; Edgar et al., 2014; Zupan et al., 2018; Fraschetti et al., 2022). Fish are not the only organisms that can benefit from protection; other species, such as marine mammals, birds, and macrophytes can be safeguarded if their habitats are preserved (Ronconi et al., 2012; Filby et al., 2017; Tursi et al., 2022). The effects of protection measures in the ecosystems may then lead to the preservation of numerous ecosystem services needed to support both small and large-scale economies (e.g., increase in catches, income from other resources), and determine an improvement of human well-being and the social relevance of protected areas (Mascia et al., 2010; Ban et al., 2019).

To guarantee successful, well-managed protected areas and a possible return in benefits for local communities, all related socio-economic, governance, and ecological elements and their relationships need to be identified and taken into consideration (Cicin-Sain and Belfiore, 2005; Charles and Wilson, 2009). These elements are critical factors because they determine people's willingness to set and pursue conservation objectives, thus dramatically affecting the outcome of protected areas' implementation (Charles and Wilson, 2009; Di Franco et al., 2016; Giakoumi et al., 2018; Ban et al., 2019). Similarly, information on the status of species and habitats targeted for protection and the oceanographic processes affecting them is important to facilitate predictions of how marine environments will respond to anthropogenic alterations and assess if conservation objectives are achieved in the long term. In this context, integrated oceanographic and ecological observing systems, defined as networks of monitoring facilities and infrastructures collecting physicochemical and ecological data, may be the key to identify changes in ecosystems at multiple spatial and temporal scales (see Carr et al., 2011; Benedetti-Cecchi et al., 2018; Crise et al., 2018; Manea et al., 2020; Manea et al., 2021; Manea et al., 2022). Protected areas may, then, benefit from incorporating integrated observing systems into monitoring, as already demonstrated by several examples worldwide (e.g., Carr et al., 2011; Miranda et al., 2020; Perera-Valderrama et al., 2020). Indeed, through collection of ecological and oceanographic data and assessment of indicators by monitoring programs, the achievement of management goals and objectives can be tested and, if needed, additional regulatory actions implemented (Pomeroy et al., 2004; Cicin-Sain and Belfiore, 2005; Pomeroy et al., 2005). This approach is particularly useful for N2K sites, which represents an extraordinary tool for achieving international conservation targets. Nevertheless, marine N2K sites have been often overlooked with respect to terrestrial and freshwater N2K sites (e.g., Kati et al., 2015; Meinesz and Blanfuné, 2015; Orlikowska et al., 2016; Guidetti et al., 2019; Schéré et al., 2020), probably because the formers have been implemented more recently than the latter ones (Evans, 2012; Sundseth, 2013; EEA, 2021). Therefore, the greatest challenge that still lies ahead is the appropriate management and monitoring of marine N2K sites.

The Interreg Italy-Croatia project ECOSS[1] aimed to contribute filling these gaps through the establishment of the ECOlogical observing system in the Adriatic Sea (ECOAdS)[2] (Manea et al., 2021; Pugnetti et al., 2022). The scope behind this project was to connect tightly different actors through the science-society-policy interface at an international level, through a permanent and stable partnership between Italy and Croatia. ECOAdS is constituted by the facilities, infrastructures, and long-term ecological monitoring programs that already exist in the Adriatic Sea and that are managed by different research institutes, universities, and organizations. Data on ecological and oceanographic processes and variables collected in ECOAdS at local, national, and regional scales, can be used to get information on the status of target species and habitats, and assess the conservation effectiveness of N2K sites in the project area (Manea et al., 2022). The integration of marine ecological

1 www.italy-croatia.eu/web/ecoss

observing systems would also provide a valuable tool for the implementation of EU Environmental Directives, for instance for defining Good Environmental Status (GES) under the Marine Strategy Framework Directive (MSFD; EC, 2008), and for achieving the objectives of the EUSAIR Action Plan (Manea et al., 2020; Solly and Berisha, 2021; Pugnetti et al., 2022).

In the framework of this project, a conceptual model was developed and applied to some selected N2K sites with the aim to review the existing information, assess the management and monitoring effectiveness, suggest possible improvements and highlight the contribution of ECOAdS in this context. In particular, for each case study, we identified social, ecological, and oceanographic elements, displayed and discussed the relationships among them, and highlighted possible pressures and gaps that management authorities should address to enhance the conservation of N2K sites. ECOAdS was connected to the management goals and target species of each N2K case study. Ecological and oceanographic variables and indicators that ECOAdS should monitor to assess the status of the conservation targets were also outlined.

The results of this study will inform the management of N2K sites and provide a baseline of knowledge to support the implementation of the ecological observing system in the Adriatic Sea. In addition, the conceptual model proposed here could be applied in other protected areas. Finally, since data on N2K sites is often difficult to gather, scattered, or not available, the information provided in this work can be useful to future studies aiming to investigate N2K management.

2 Materials and methods

2.1 Setting up of the conceptual model

The conceptual model was created using Cmaps v.6.04 free software[3], which allows constructing, sharing, and modifying online knowledge models represented as concept maps (Cañas et al., 2005). Specifically, the conceptual model consists of a schematic box-arrow model and was formulated following a stepwise process, as described in Grant et al. (1997). Firstly, the model required a deep understanding of all the key elements related to the management of protected areas. Social, ecological, and oceanographic elements of the N2K management were identified based on literature review on the subject (e.g., Pomeroy et al., 2004; Carr et al., 2011) and our own experience, represented graphically by boxes, and linked to one another according to their relationships. Efforts were done to keep the model as simple as possible, by avoiding an overcrowded scheme. Thus, only the most important elements and relationships were shown (Figure 1). The color of the box defines the typology of the element related to the N2K management, while the size is not relevant. Social elements (yellow boxes) are characterized by all those elements concerning the governance of N2K sites: EU Directives targeted by ECOSS (i.e., HD, BD, Water Framework Directive (WFD; EC, 2000), MSFD), the management authority, the management goal and objectives, the conservation measures, the stakeholders and the human activities. The identified ecological elements (green boxes) include the target species for which N2K sites were designated, the ecosystem services, the ecological monitoring programs, and the ecological variables measured. Oceanographic elements (blue boxes) include global changes, ocean processes, the oceanographic observing system, and the monitored oceanographic variables. Performance indicators used to assess environmental conditions or changes and to set environmental goals, constitute a cross-cutting element (orange box) since they can be obtained from a single ecological or oceanographic variable, or from multiple combinations of them. The monitoring programs, the variables, and the performance indicators were all included in the ECOAdS (red) box. A complete definition of the elements used in the conceptual model is provided in the Table S1.

The spatial arrangement of the boxes in the model follows a hierarchical organization: boxes at the top and bottom of the model refer to global aspects such as EU Directives, wide-scale monitoring programs, and ecosystem services, while in the center of the model, the elements are related to local aspects of the N2K sites, such as the goal, objectives, and target species. The ECOAdS box occupies a preeminent position in the conceptual model to make clear how ECOAdS can be integrated into the management workflow of the N2K sites. All the elements are strictly connected and the change of one determines changes in others. Arrows indicate the relationships among the elements. They can go in one direction from one box to another or can be bi-directional in case elements are expected to influence each other. Dotted lines indicate data flow, while continuous lines indicate a causal relationship between two boxes based on the direction of the arrow (Figure 1).

Starting from the top of the model, we outlined that the EU Environmental Directives ask management bodies to define the conservation measures and management goal of N2K sites. At the same time, the EU Directives also demand the effectiveness of these measures be assessed and this can be done by adopting performance indicators. The goal can be then split into more management objectives that in turn influence the choice of conservation measures. Management bodies generally engage stakeholders to discuss the limitation of the activities in the N2K sites and agree on the conservation measures. In fact, human activities in the N2K sites can directly affect species targeted for conservation, as well as functions and services provided by

2 https://ecoads.eu/

3 cmap.ihmc.us

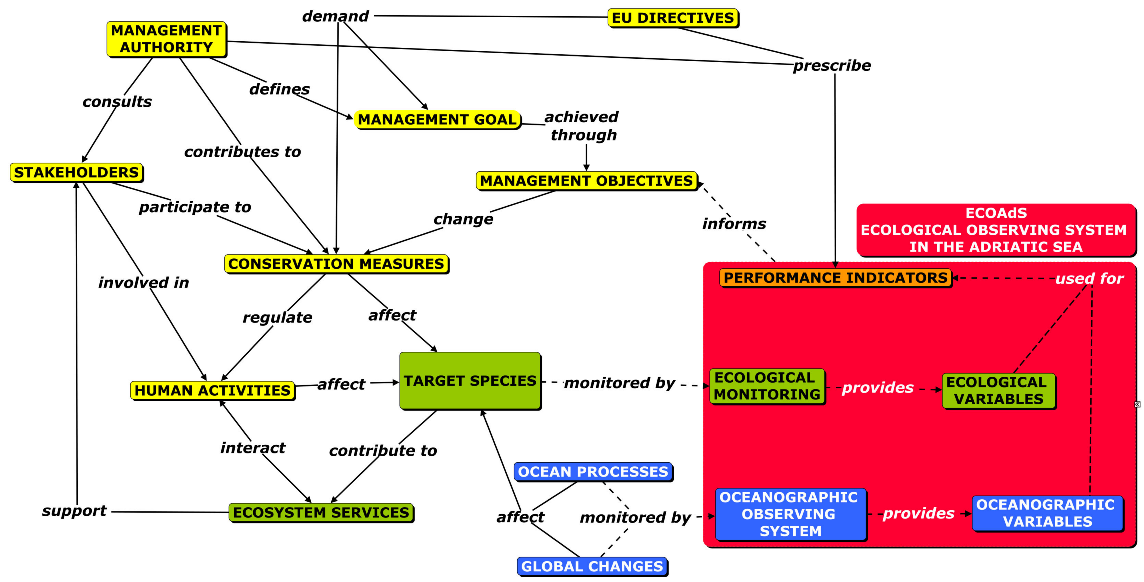

FIGURE 1
Generic conceptual model linking ECOAdS with N2K management and EU Directives. Dotted lines: data flow; continuous lines: causal relationship.

ecosystems. Natural processes and events can also affect target species. For instance, global changes, in particular those related to anthropogenically-driven climate alterations, and ocean processes are two of the main drivers of change for species and communities. Through ecological and oceanographic monitoring programs, ECOAdS collects data on environmental variables related to target species and both ecological and ocean processes. The variables, which depict the status of the system, are then used to obtain performance indicators that, in the end, track the progress towards objectives and evaluate the effects of management actions.

While the conceptual model was built around the need to manage N2K sites, i.e., with the 'Management Goal' box as an entry point, different users may start from different entry points according to their needs. For instance, an agency involved in monitoring activities may enter at the 'Ecological monitoring' box, while a public authority at the 'Management authority' box. In case, management objectives or conservation measures should be revised, the entry point could be based on these boxes.

2.2 Application of the model

The conceptual model was applied to seven Adriatic N2K sites (Figure 2) identified within the ECOSS project. These sites can be considered representative of the N2K network of the area since they include different typologies of habitats and environmental features. In addition, they are managed by the project partners, who therefore could provide information on the status of the target species and management activities. However, since some of these sites share similar ecological and geographical features, they were treated together and thus a total of four case studies were analyzed:

Case study 1: N2K sites Cres-Lošinj (HR3000161) and Viški akvatorij (HR3000469).

Case study 2: N2K site Malostonski zaljev (HR4000015).

Case study 3: N2K sites Trezze San Pietro e Bardelli (IT3330009) and Tegnùe di Chioggia (IT3250047).

Case study 4: N2K sites Delta del Po: tratto terminale e delta veneto (IT3270017) and Delta del Po (IT3270023).

Information to feed the application models was derived from questionnaires provided to the partners aimed to report the ecological monitoring programs they carry out (Vilibić and ECOSS Partnership, 2019), from technical tables at the project meetings, from the Standard Data Form (SDF) of the N2K sites[4], and from the project deliverables (Cataletto et al., 2019; Ciriaco et al., 2019; Markov and ECOSS Partnership, 2019; Golec and ECOSS Partnership, 2020; Miočić-Stošić et al., 2020; Pranovi et al., 2020). The management plan of the Delta del Po N2K site was also consulted to derive elements for this case study, even if it has not yet been approved (Ente Regionale Parco Delta del Po Veneto, 2010). When information was not available, elements were derived from literature review and knowledge available through our own experience. This was especially necessary for

4 natura2000.eea.europa.eu

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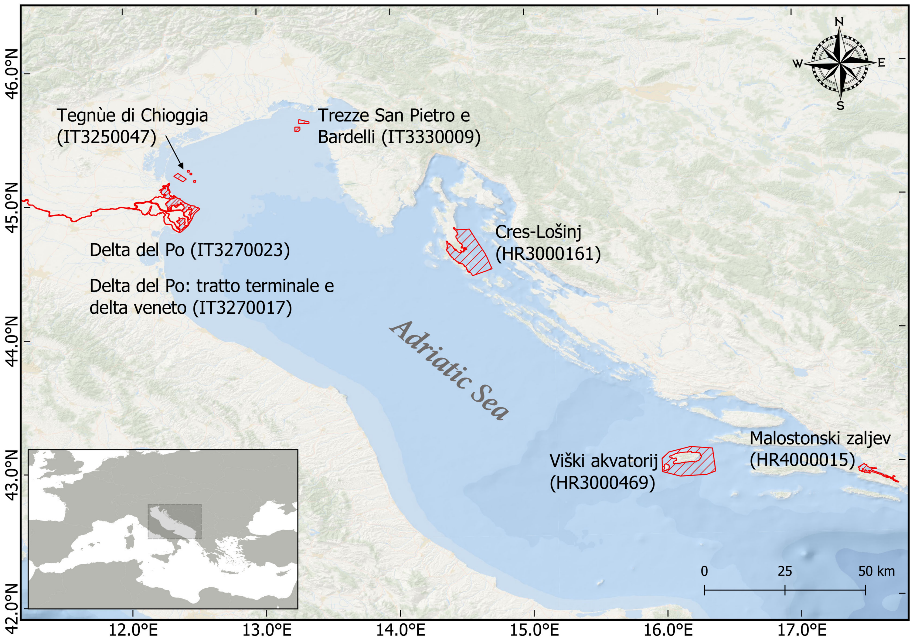

FIGURE 2
Map of the N2K sites considered as case studies in the ECOSS project. The two sites of Delta del Po are partially overlapping.

the management goals, objectives, conservation measures, monitoring variables and performance indicators that were missing in most cases. Criteria and requirements of the HD, BD, WFD (Annex V), and MSFD (Zampoukas et al., 2012; EC, 2017b) were also considered to identify such elements.

In particular, once target species, stakeholders, and human activities were identified, the management goals were outlined for N2K case studies reflecting the general objective of the HD and BD that aim at conserving the species and habitats of protection in a favorable status. To achieve these goals, specific management objectives and conservation measures were defined on the base of the target species of the case studies, and the human activities that may affect them. In the case pressures in N2K sites are expected to affect only one species, the management objectives were specifically focused on that species, otherwise, they were stated in a more general form, considering communities or ecosystems.

Ecological and oceanographic variables and performance indicators suitable to describe the status of the conservation targets and N2K effectiveness were also outlined based on the specific features of the target species and human activities, the identified management objectives, and the characteristics of the N2K case studies (Markov and ECOSS Partnership, 2019; Miočić-Stošić et al., 2020). Both state and pressure monitoring variables were considered, since they may also allow the detection of possible impacts acting on conservation targets and triggering changes in their original status. To keep the number of variables as low as possible and optimize efforts and costs for management authorities, they were also defined based on the general criteria of non-redundancy, sensitivity to change, feasibility, relevance for the N2K site, and cost-effectiveness (Pomeroy et al., 2004; Bundy et al., 2019). Even if none of the HD, BD, WFD, and MSFD specifically refer to performance indicators, the indicators here proposed are particularly in agreement with the eleven qualitative descriptors of the MSFD aimed to determine the GES. For instance, Descriptor 1, focused on biodiversity, can be investigated by different performance indicators such as change in species population demography, genetic diversity, and change in species home range and behavior. HD and BD also find correspondence in this descriptor since they do aim at conserving the species and habitats of protection in a favorable status. Descriptor 2, focused on non-indigenous species, can be monitored by analyzing trends in cover and density of invasive species. Descriptors 5 (eutrophication) and 8 (contaminants), also related to the requirements of the WFD, can be monitored by water quality indices.

To be in line with the aim of the ECOSS project, only management goals, objectives, conservation measures, variables, and indicators related to the biophysical-conservation aspects were considered (e.g., habitat quality, biological diversity, human activity regulation), while those related to socio-economic aspects (e.g., non-monetary benefits, food security, resource use conflicts) were not included.

3 Results

3.1 Case study 1: Viški akvatorij and Cres – Lošinj

3.1.1 Management aspects and target species

The N2K sites of Viški akvatorij and Cres – Lošinj in Croatia are managed by the Public Institution 'Sea and Karst' and Public Institution 'Priroda', respectively (Figure 3 and Tables S2, S3). These are two of the most important feeding and breeding areas for the common bottlenose dolphin (*Tursiops truncatus*, Montagu, 1821) in the Eastern Adriatic Sea (the only species listed in their respective SDF), so their main management goal is the preservation of the natural habitat of this species in a favorable status (Figure 3 and Tables S2, S3). However, to date, there is still no management plan, nor management objectives and other conservation measures in charge to effectively protect the target species (Markov and ECOSS Partnership, 2019). Management objectives necessary to achieve the N2K sites' goal should consider, for instance, the preservation and increase of *T. truncatus* population and its genetic connectivity with other populations, the preservation of dolphin prey species populations, the decrease of human-derived pressures, the preservation of a good seawater quality, and the mitigation of climate change and diseases impacts (Figure 3 and Tables S2, S3).

Different stakeholders act in this area including fishers, fish farmers, and, most of all, tourism companies due to the high touristic value of the area (Figure 3 and Tables S2, S3). Thus, fishing, aquaculture, tourism, and nautical sports including boating, are the main human activities in the N2K sites potentially causing dolphin bycatch (López, 2012), collision with boats, noise and water pollution (Rako-Gospić et al., 2013), change in dolphin habitat use (Pleslić et al., 2015), and marine debris pollution (Stagličić et al., 2021). Conservation measures that could effectively reduce such threats should be primarily focused on regulating all human activities, raising awareness of the local community, and increasing surveillance (Figure 3 and Tables S2, S3). In addition, the expansion of the size of the N2K site and protected area network beyond Cres-Lošinj and Viški akvatorij would guarantee the preservation of a larger portion of the home range of this highly mobile species (Pleslić et al., 2015; Fortuna et al., 2018), enhance genetic exchange between populations (Gaspari et al., 2015), and allow a better management of the source of threats that may be located outside the current borders of the N2K sites (Fortuna et al., 2018). The implementation of these measures would favor the resilience of the species to the effects of climate change (Wild et al., 2019; van Weelden et al., 2021).

3.1.2 ECOAdS and monitoring aspects

The Blue World Institute (BWI) conducts monitoring activities to assess the status of the bottlenose dolphin in the two studied sites. In addition, a considerable body of literature on the target species biology and ecology is available, especially for Cres-Lošinj (e.g., Bearzi et al., 2009; Genov et al., 2009; Rako-Gospić et al., 2013; Pleslić et al., 2015; Rako-Gospić et al., 2017; Pleslić et al., 2019). Based on the monitoring results, the dolphin populations in the two sites can be considered stable (Golec and ECOSS Partnership, 2020). Nevertheless, the main deficiency in the existing monitoring programs is that they are not conducted on a regular basis, because of the lack of resources (experts of marine mammals and funds) (Golec and ECOSS Partnership, 2020).

The effectiveness of the proposed conservation measures and the achievement of the management objectives can be assessed by some performance indicators, such as changes in dolphin population demography and behavior, genetic diversity, water quality indices, and trend in the amount of marine litter (Galgani et al., 2013; Jaiteh et al., 2013; Gaspari et al., 2015; Pavlidou et al., 2015; Pleslić et al., 2015; Fandel et al., 2020) (Figure 3 and Tables S2, S3). As an example of application of the conceptual model, the success of the regulatory actions aimed to reduce the impact of the marine traffic in the protected sites could be assessed by estimating the trend in the number of vessels inside the N2K sites and changes in dolphin home ranges or vocalizations. These performance indicators can be then calculated by collecting number, type and distribution of vessels, sound levels in water, the occurrence rate of dolphins in different areas and the characteristics of their vocalizations (Rako-Gospić et al., 2013; Pleslić et al., 2015; Fouda et al., 2018) (Figure 3 and Tables S2, S3).

Other useful monitoring variables could be, for instance, those related to the interaction of the species with fishing activities, as suggested by the project partners: signs of injuries in dolphins, number of interactions of dolphins with fishing gears or fish farms and, if possible, an estimate of the number of deaths due to bycatch (Jaiteh et al., 2013; Revuelta et al., 2018; Leone et al., 2019). These variables can be used to derive performance indicators such as the proportion of injured individuals, the interaction rate with fishing activities, and change in population demography (Figure 3 and Tables S2, S3). In addition, BWI recommended biopsy sampling for genetic and contamination analyses to better understand processes affecting the well-being of the local dolphin population (Gaspari et al., 2015; Zanuttini et al., 2019).

In relation to climate change, variables that may indicate an impact of extreme events on the species or alteration of oceanographic conditions may include the survival of dolphin offspring, dolphin prey population structure, spatial distributions of dolphins and their prey, time spent foraging by the target species per encounter, and frequency, duration, intensity of the heatwaves (Figure 3 and Tables S2, S3). In fact, different studies demonstrated that a catastrophic alteration of

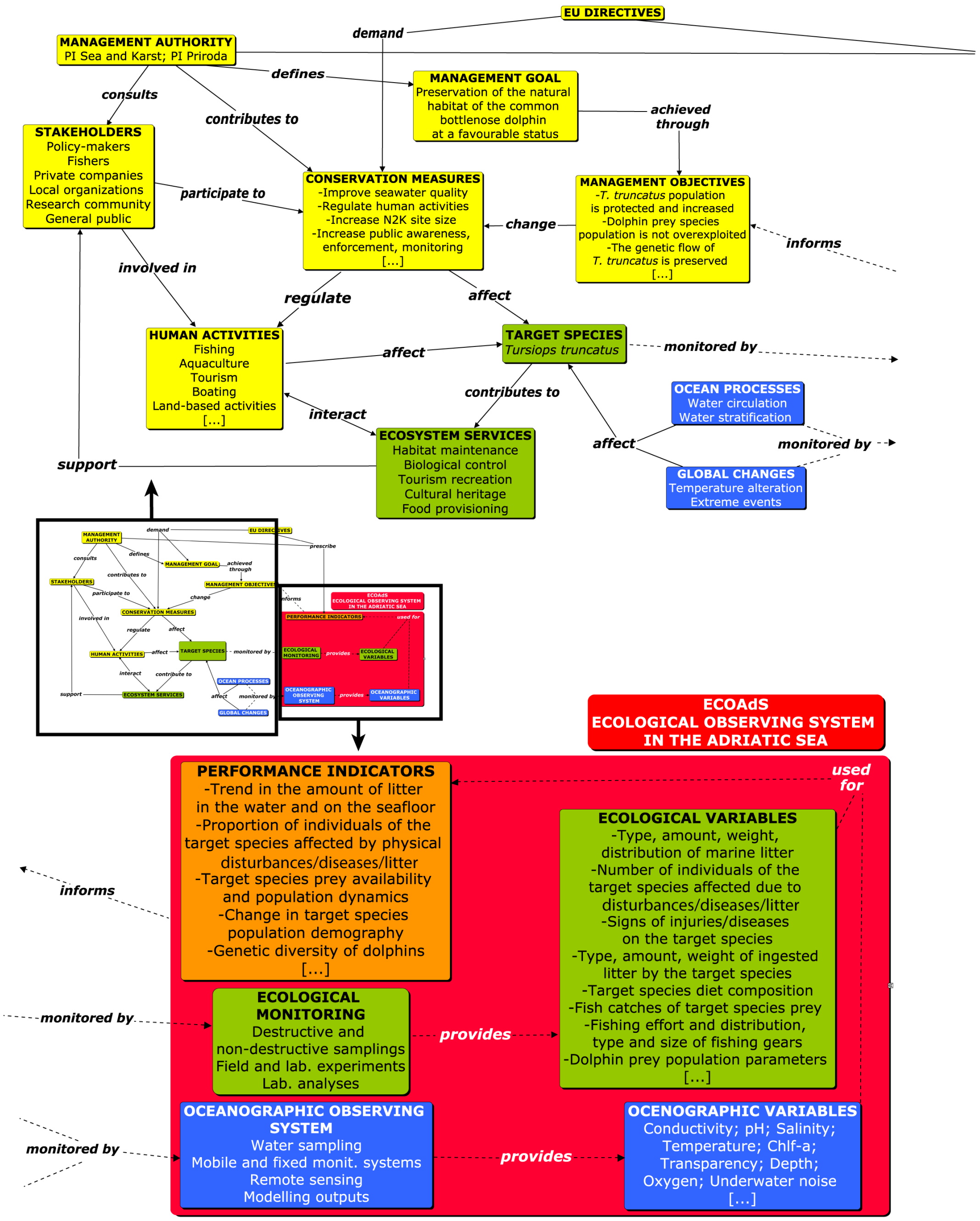

FIGURE 3
Application model of Cres-Lošinj and Viški akvatorij N2K sites for the target species *Tursiops truncatus*. For additional information see Tables S2, S3.

habitats, following marine heatwaves, caused a decline in reproductive success and survival of offspring (Wild et al., 2019); while alteration of distribution and behavior of dolphin prey species due to intense storm events, also induces a change in dolphin distribution and foraging behavior (Fandel et al., 2020).

Some of the variables proposed here are already collected in the two sites, and these include dolphin population demography, habitat use, spatial-temporal distribution, and underwater noise. The Croatian Institute of Oceanography and Fisheries (IZOR) also collects a wide range of data on physicochemical parameters, biological quality elements of the WFD, hydromorphological alterations, specific pollutants, benthic invertebrate fauna, macro-algae, and phytoplankton community (Ciriaco et al., 2019; Vilibić and ECOSS Partnership, 2019; Golec and ECOSS Partnership, 2020).

3.2 Case study 2: Malostonski zaljev

3.2.1 Management aspects and target species

The management body of Malostonski zaljev N2K site in Croatia is the Public Institution for the Management of Protected Natural Areas of Dubrovnik-Neretva County (PIDNIC), but a management plan has not been implemented yet, neither management objectives nor regulatory measures are officially defined (Markov and ECOSS Partnership, 2019). The N2K site protects two target habitats listed in the Annex I of the HD: 'Reefs' (1170) and 'Large shallow inlets and bays' (1160). This area is also under the significant influence of freshwater and characterized by the cultivation of the European flat oyster, a traditional, protected activity. Since there are no target species listed in the SDF, with the help of the project deliverables and partners, some relevant species deserving protection on the site were identified: seagrasses, the large brown algae *Fucus virsoides* J. Agardh, the noble pen shell *Pinna nobilis* (Linnaeus, 1758), the twaite shad *Alosa fallax* (Lacépède, 1803), and species forming coralligenous assemblages on the rocky substratum due to the presence of the 'Reefs' Habitat. Thus, the main management goal for this protected area could be the preservation of the target habitats ('Reefs' and 'Large shallow inlets and bays'), and the identified target species in a favorable status (Figure S1 and Tables S4, S5).

Management objectives necessary to achieve such goal should consider, for instance, the preservation of the target habitats and species in a good status, the preservation of the reef community diversity and gene pool, the decrease of human-derived pressures, the preservation of a good seawater quality and the mitigation of climate change, diseases, and the spread of invasive species impacts (Figure S1 and Tables S4, S5). As a primary conservation measure, PIDNIC suggested preserving the traditional shellfish cultivation together with natural habitats. To make this possible, it is necessary to actively support sustainable bivalve shellfish farming as part of cultural heritage and traditional value, and, at the same time, do an inventory of the biodiversity components, and monitor periodically the status of the marine environment (Golec and ECOSS Partnership, 2020). Indeed, aquaculture may impact the benthic habitats by increasing biodeposition to the seafloor (by mussel feces and pseudofeces) and induce variation in nutrient loading and fluxes, anaerobic metabolism in sediments and change in benthic community structure and functioning (Lacoste et al., 2020). In addition, the ecosystem in Malostonski zaljev N2K site is under the influence of the mainland, thus the surrounding land-based activities must be regulated to reduce water pollution and physical destruction of habitats due to urbanization. Other conservation measures that should be implemented are those aimed to limit several direct human pressures that may cause possible impact on target species, such as trampling on *F. virsoides*, anchoring and trawling on the seagrass *Cymodocea nodosa* (Ucria) (Asch. 1870) and *P. nobilis* (Francour et al., 1999; Vázquez-Luis et al., 2015), and poaching of the date mussel *Lithophaga lithophaga* (Linnaeus 1758) (Colletti et al., 2020). Installation of mooring buoys, a better surveillance, as well as the setting up of new regulations on the number of visitors, could be potential solutions to halt such threats. Regular monitoring activities in the area are required also to constantly assess the status of the target species and habitats (Figure S1 and Tables S4, S5).

3.2.2 ECOAdS and monitoring aspects

Currently, monitoring activities in the area are performed by IZOR and the University of Dubrovnik for the assessment of water quality and the status of MSFD descriptors. The activity includes the collection of physicochemical and biological parameters (e.g., chlorophyll-a, temperature, nutrients, pollutants, phytoplankton composition and abundance, sedimentation) (Vilibić and ECOSS Partnership, 2019; Golec and ECOSS Partnership, 2020). The variables collected by these monitoring activities may be particularly useful in the N2K site to assess the potential impact of the aquaculture (Ninčević-Gladan et al., 2015). The surface area devoted to aquaculture and abundance and biomass of benthic organisms, may also give us an indication of the impact of this activity in the bay (see for instance Borja et al., 2009; Valenti et al., 2018). At present, for most of the identified target species there is no adequate information (Markov and ECOSS Partnership, 2019), therefore, it is strictly urgent to create a knowledge base of their overall ecological status that would make a foundation for a management plan of the area. However, according to Miočić-Stošić et al. (2020), *C. nodosa* meadows seem to be stable, while *P. nobilis* is critically endangered due to a disease at regional scale (Carella et al., 2019; Šarić et al., 2020).

Other ecological and oceanographic variables that could be collected in the area to assess the efficacy of protection together with the corresponding performance indicators are listed in the Tables S4, S5 and in Figure S1. In particular, regarding *F. virsoides*, some monitoring variables that can give an indication of possible changes occurring to this species include, for example, spatial distribution, genetic information, individual size, biomass, adult and recruit density, mortality, and fertility rates. These variables should be then associated with data on temperature, nutrient concentration, and frequency, duration, and severity of sea storms and heatwaves. Indeed, *F. virsoides*, endemic to the Adriatic Sea, has faced an extensive regression in the last years (Battelli, 2016), probably due to the changes in the trophic status of this basin (Grilli et al., 2020) and climate change effects that seem to induce a shift in reproductive timing of this species (authors' personal observation), but further research is needed to clarify this aspect. Special attention should be also paid to other potential threats to this species, such as chemical pollutants (Falace et al., 2018) and intense herbivory (Battelli, 2016). Monitoring of contaminant concentration in *F. virsoides* tissues, as well as an assessment of the herbivore density is, hence, strictly recommended to implement adequate conservation actions (Figure S1 and Tables S4, S5).

Another destructive activity that has been reported in Mali Ston Bay is the date mussel poaching (Miočić-Stošić et al., 2020). This illegal practice often causes extensive and lasting reduction of the benthic habitat diversity with a shift from highly complex to structurally simplified habitats (i.e., biological deserts dominated by sea urchins) (Colletti et al., 2020). Efficacy of protection measures can be assessed by measuring percent cover of benthic habitat destructed by poaching and spatial and temporal extent of the disturbance (Figure S1 and Tables S4, S5). Useful information for managers may also infer from data on the number of reported offences in a year or kilograms of confiscated date mussels.

3.3 Case study 3: Trezze San Pietro e Bardelli and Tegnùe di Chioggia

3.3.1 Management aspects and target species

The Veneto Region is the main management authority of the Tegnùe di Chioggia N2K site, while the management authority of Trezze San Pietro e Bardelli N2K site is the Friuli Venezia Giulia Region, Italy (Figure S2 and Tables S6, S7). Both sites have been established to protect the mesophotic biogenic reefs of the Northern Adriatic Sea. They also share the same ecological and oceanographic processes and are subject to the same pressures. The loggerhead sea turtle *Caretta caretta* (Linnaeus, 1758) and *T. truncatus* are listed as target species in the SDFs of both sites, while *A. fallax*, and seabirds (the Mediterraneean gull *Ichthyaetus melanocephalus* (Temminck, 1820), the common shag *Phalacrocorax aristotelis desmarestii* (Payraudeau, 1826), and the yelkouan shearwater *Puffinus yelkouan* (Acerbi, 1827)) only for Trezze San Pietro e Bardelli N2K site. Many benthic species, such as the cushion coral *Cladocora caespitosa* (Linnaeus, 1758) and the stony cup coral *Astroides calycularis* (Pallas, 1766), are additionally listed in the SDFs and were here considered as relevant target species grouped under the name 'Coralligenous community', since most of them contribute to form coralligenous-like habitats with high biodiversity (Ponti et al., 2011; Falace et al., 2015). *P. nobilis* was also identified as a target species of these sites for its protected status under the HD and the recent threats it is facing (Carella et al., 2019) (Figure S2 and Tables S6, S7).

The management goal of these sites is the protection of the habitats and species identified in the N2K SDFs, and thus the conservation of all reef communities at a favorable status should be considered as the main management goal (Figure S2 and Tables S6, S7). Management plans have not been implemented for these sites. Management objectives should aim to maintain or restore a good status of the target species and their genetic diversity, minimize the effects of water pollution, the impact of invasive species, of the human activities and the effects of extreme events also linked to the climate change (Figure S2 and Tables S6, S7). Some conservation measures were issued by the management authorities including the prohibition of anchoring, professional and recreational fishing, organism collection, and the regulation of diving activities (Tables S6, S7). However, to date, the observance of the conservation measures is not guaranteed since surveillance and effective management of the sites is still lacking (S. Ciriaco personal observation). As additional conservation measures, it is advisable to remove marine litter that generally accumulates on these sites (e.g., Moschino et al., 2019) and install buoys signaling the N2K site boundaries for improving compliance with the current regulations. One of the main conservation strategies that should be put in place is increasing the protected area size and the creation of a network of mutually connected and protected sites in the Northern Adriatic Sea. Indeed, different studies have highlighted the high heterogeneity of these reefs and the importance to preserve more sites that are not currently protected, to guarantee connectivity through dispersal of the associated populations (Ponti et al., 2011; Falace et al., 2015; Fortuna et al., 2018; Bandelj et al., 2020). Joint management strategies, including offshore and terrestrial areas, with the adoption of ecosystem-based solutions are then necessary to avoid that high nutrient and sediment loads from rivers and the coast can affect the biogenic reef communities of these protected sites (Curiel et al., 2012; Falace et al., 2015) (Figure S2 and Tables S6, S7).

3.3.2 ECOAdS and monitoring aspects

Monitoring is performed only occasionally. There is no long, regular, and consistent data on species and oceanographic conditions, which is one of the main shortcomings in the management process, as highlighted by the project partners. Physicochemical or biological data can be partially derived from monitoring facilities in the proximity (e.g., buoys), or from remote sensing (e.g., chlorophyll-a from satellite), or modeling outputs (sea-current field components). This is not true for ecological data (e.g., community structure and composition) that were collected only during some projects (e.g., Interreg ITA-SLO TRECORALA, Italian PRIN ReefReseArcH) by different research institutions and companies investigating the diversity and connectivity of the mesophotic biogenic reefs (Vilibić and ECOSS Partnership, 2019; Golec and ECOSS Partnership, 2020).

Even less information is available on the spatial and temporal density and distribution of *T. truncatus, C. caretta*, *A. fallax* and seabirds in the N2K sites, and further monitoring programs should be carried out on these species (see La Mesa et al., 2015; Fortuna et al., 2018; Bearzi et al., 2021).

Taking as an example the application of the model for the 'coralligenous community', the effectiveness of the conservation measures aimed to reduce direct physical damages to the benthic organisms due to anchoring, scuba divers, or fishing can be assessed by different performance indicators, such as the proportion of injured organisms and changes in population demography. These indicators can be estimated by collecting data on population cover or density, signs of injuries on the target species, and number or cover of dead and injured organisms (e.g., Ferrigno et al., 2018) (Figure S2 and Tables S6, S7).

Particularly important for the benthic community is the early assessment of the presence, distribution, cover or density of invasive species to assess the potential risk posed by them (Figure S2 and Tables S6, S7). Similarly, the assessment of the amount, type, and weight of litter on the seafloor, as well as the number or cover of individuals adversely affected by litter is necessary to quantify the impact of such threat over time (Galgani et al., 2013) (Figure S2 and Tables S6, S7). The setting up of regular monitoring programs is, in these cases, an important strategy to report the spread of allochthonous species at their first stage or the presence of marine debris and to organize eradication and cleaning campaigns.

Alterations in pH and seawater temperature are the main consequences of climate change that interfere with the growth, body size, stress, reproductive success, and survival of many benthic species (Garrabou et al., 2009; Asnaghi et al., 2013; Zunino et al., 2017 and references therein). In addition, both processes have synergistic effects on species (Pörtner et al., 2014). To monitor such threats, it is advisable collecting data on the time of reproduction to assess potential phenological shifts, cover or density of organisms, presence of necrotic tissues, and growth, as well as data on oceanographic variables: temperature, number of extreme events (i.e., heatwaves), pH, and dissolved oxygen (Figure S2 and Tables S6, S7).

3.4 Case study 4: Delta del Po and Delta del Po: Tratto terminale e delta veneto

3.4.1 Management aspects and target species

The two Delta del Po N2K sites geographically overlap and compose a single delta system with shared habitats and species. The management body of both N2K sites is the Po Delta Veneto Regional Park Authority (Figure S3 and Tables S8, S9). A management plan was drafted for the Delta del Po N2K site (IT3270023), but to date, it has not been formally approved, even if it is used as a management tool for both sites (Ente Regionale Parco Delta del Po Veneto, 2010; Markov and ECOSS Partnership, 2019). Most of the species are exclusively related to freshwater and terrestrial habitats. For the aim of the ECOSS project, only those species strongly dependent on the marine environment were selected from the list of species under protection in these sites. These include different migratory and sedentary seabirds (the little tern *Sternula albifrons* (Pallas, 1764), the common tern *Sterna hirundo* (Linnaeus, 1758), the sandwich tern *Thalasseus sandvicensis* (Latham, 1787), the gull-billed tern *Gelochelidon nilotica* (Gmelin, 1789), the Caspian tern *Hydroprogne caspia* (Pallas 1770), the black-headed gull *Chroicocephalus ridibundus* (Linneus, 1766), the slender-billed gull *Chroicocephalus genei* (Breme, 1839), *I. melanocephalus*, and *P. aristotelis desmarestii*), all listed in the Annexes I and II of the BD. Some anadromous fish are also present (*A. fallax*, the Adriatic sturgeon *Acipenser naccarii* (Bonaparte, 1836), and the great sea lamprey *Petromyzon marinus* (Linnaeus, 1758)) that migrate from the sea to the upper part of the rivers for reproduction and listed in Annex II of the HD. Seagrasses used to thrive in the past in the Po Delta but they have not been recorded in recent years. However, since restoration activities are planned, and monitoring will be necessary for the next future, seagrasses were also considered as target species (Figure S3 and Tables S8, S9). The main management goal of these sites should include, therefore, the conservation of all these target species and their habitats (Figure S3 and Tables S8, S9).

Since both N2K sites extend on a vast terrestrial area characterized by numerous villages, human uses and pressures on target species are many and diffuse. Rivers, canals, and banks are modified by maintenance works, dike and barrier construction, soil erosion, rising of the salt wedge, and water level changes; all inducing alteration of sedimentation rate and water circulation. Recreational and commercial fishing, aquaculture and agriculture are also widely practiced in the area and are particularly important for the local economy; however, they contribute to cause changes in target species population and water quality, together with habitat fragmentation (Ente Regionale Parco Delta del Po Veneto, 2010). Finally, the river system is frequently visited by tourists as it is an attractive area for many outdoor activities (birdwatching, swimming, boating, trekking, etc.), but regulation measures should be improved since this sector represents another source of disturbance for the target species (Ente Regionale Parco Delta del Po Veneto, 2010; Verza and Cattozzo, 2015) (Figure S3 and Tables S8, S9).

Many management objectives and regulatory measures are reported in the management plan of the N2K to address the reported issues. They are mainly aimed to increase water circulation and passages for migratory fish, restore the Adriatic sturgeon population and the suitable habitats for seabirds, regulate human activities and predators' abundance to avoid impacts on target species and in particular on nesting seabirds, monitor target species status, assess pollution and improve water quality (Ente Regionale Parco Delta del Po Veneto, 2010; Markov and ECOSS Partnership, 2019) (Figure S3 and Tables S8, S9). In addition, one of the main objectives that should be considered is the implementation of integrated management strategies with other protected areas and in particular with a recent established N2K site offshore the Po River estuary (IT3270025 'Adriatico Settentrionale Veneto – Delta del Po') to enhance protection of target species whose home range includes also the marine realm. Major benefits for a more successful conservation, may also derive from involving stakeholders in the decision process and developing educational programs that could foster long-term interest and personal engagement in the management of ecosystems and natural resources (Giakoumi et al., 2018; Golec and ECOSS Partnership, 2020) (Figure S3 and Tables S8, S9).

3.4.2 ECOAdS and monitoring aspects

The Regional Agency for Environmental Protection and Prevention of the Veneto and the Institute of Marine Sciences – National Research Council perform monitoring activities in these N2K sites, assessing different physicochemical variables (e.g., temperature, salinity, current direction and velocity, organic matter, nutrients, and contaminants) and ecological variables (e.g., species composition, diversity, and abundance of phytoplankton, benthic macroinvertebrates, and macrophytes) (Vilibić and ECOSS Partnership, 2019; Golec and ECOSS Partnership, 2020). Occasionally, the management authority also monitors the spatial distribution of species, density, coverage, species richness, and community structure (Markov and ECOSS Partnership, 2019). Data on the status and distribution of *P. marinus*, *A. fallax*, and seagrasses are deficient, while much more information is available for the identified target seabirds (Ente Regionale Parco Delta del Po Veneto, 2010; Verza et al., 2011; Bon et al., 2013; Scarton et al., 2013; Verza, 2015; Scarton et al., 2018; Valle and Scarton, 2018; Miočić-Stošić et al., 2020; Scarton and Valle, 2020; Valle and Verza, 2020; Scarton, 2022). However, regular monitoring, necessary to detect population trends of these species and guide the adoption of adequate measure, is still lacking (Markov and ECOSS Partnership, 2019; Golec and ECOSS Partnership, 2020). Regarding, *A. naccarii*, this is an emblematic species of the Po River, endemic in the Adriatic Sea (Caramori et al., 2007; Arlati and Poliakova, 2009), and a priority species for conservation since its natural population has drastically decreased (Bronzi et al., 2011; Meadows and Coll, 2013). For this reason, the Adriatic sturgeon has been object of different reintroduction projects in the last decade (e.g., Life03nat/it/000113; Life04NAT/IT/000126; Life15 NAT/IT/0000989).

Conservation measures that can enhance restoration of the Adriatic sturgeon should include the improvement of river connectivity and water quality, control of illegal fishing, removal of invasive species, conservation and restoration of the spawning and foraging areas for *A. naccarii*, increase species abundance, and increase public awareness on the endangered status of this species (Caramori et al., 2007) (Figure S3 and Tables S8, S9). The effectiveness of such measures can be assessed by different performance indicators. For instance, the improvement of water circulation can be assessed by measuring some indicators of hydrological alteration (e.g., monthly magnitude of stream flow; magnitude, timing and duration of annual extreme stream flow; frequency and duration of flood and drought events) and their change over time (Richter et al., 1996; Lee et al., 2014) (Figure S3, Tables S8 and S9). To assess if the actions put in place to improve water quality are working, change in turbidity, water quality indices, the proportion of sick organisms and related contaminant level could be measured. These indicators are fed by several variables, some of which are already collected by local monitoring agencies, for instance, physicochemical water parameters, chlorophyll-a, nutrients and contaminants, and number of sick or dead organisms (Figure S3 and Tables S8, S9).

Special attention should be also given to monitoring the increase of the salinity in the delta system. Indeed, due to climate change, water extraction and alteration of river flow, salt-wedge intrusions into coastal zones are becoming more frequent and progressing upstream to the river, affecting numerous freshwater ecological processes, the migration of some target species, and the possibility to use water for drinking and soil irrigation (Simeoni and Corbau, 2009; Bellafiore et al., 2021). It is strictly urgent to adopt measures that regulate water extraction for different uses at the basin scale, creating phytodepuration basins, promoting the cultivation of plants that are more resistant to higher levels of salinity, and reducing those works that alter hydrological conditions (Zuazo and Pleguezuelo, 2009). Among the possible variables that can be monitored to detect environmental alterations are temperature, salinity, seawater level, water flow rate, amount of extracted water, number and frequency of heatwaves, amount of precipitation, population size of target species, number of dead or sick individuals, and species fertility (Figure S3 and Tables S8, S9).

4 Discussion

The application of the generic conceptual model to the four case studies selected in the ECOSS project, allowed to identify and analyze the main socio-ecological elements related to the management of these N2K sites, with the aim to understand the status of knowledge concerning such elements and the potential effectiveness of the existing management.

Overall, the management authorities were easily identified in our analysis since they have been already named locally or are represented by a regional or national institution, even if an effective management is still not in place. Also, the goal of the N2K sites can be considered well-defined since it follows the main objective of the HD and BD, which is maintaining and restoring the habitat types and species of community interest at a favorable conservation status. Human activities, and the relative stakeholders, were in part already available from the SDFs of the sites and from the questionnaires provided to the project partners (Vilibić and ECOSS Partnership, 2019). On the contrary, a general gap of information emerged regarding the management objectives and conservation measures, as well as a paucity of monitoring activities. This leads to a general lack of knowledge on the conservation status of target species in most of the considered N2K sites. In the two N2K sites protecting the mesophotic biogenic reefs of the Northern Adriatic Sea ('Trezze S. Pietro e Bardelli' and 'Tegnùe di Chioggia'), highly mobile species are listed in the SDFs as priorities for conservation, but very little information is available on their status (La Mesa et al., 2015; Fortuna et al., 2018; Bearzi et al., 2021), and they were observed only sporadically in the area. Hence they might be considered only occasional visitors. Much more information is available on the coralligenous communities present in these sites (e.g., Ponti et al., 2011; Falace et al., 2015; Nesto et al., 2020), but they are not monitored regularly. In the Malostonski zaljev N2K site, target species were not even identified and only two priority habitats were listed in the SDFs. The N2K sites where more efforts are invested in monitoring target species are Cres – Lošinj, Viški akvatorij, and Po Delta.

The lack of management plans and a concrete management process in these sites is the main reason for such data-deficiency. Even if management plans are not mandatory for N2K sites, as specified in the Article six of the HD, they may represent important tools for enhancing environmental conservation in N2K sites respect to the establishment of few regulatory measures. Indeed, in the absence of specific requirements from a management plan, objectives and conservation measures are often not defined, and monitoring activities are not performed or are often restricted to the time frame of specific research projects focusing on few processes or habitats (Golec and ECOSS Partnership, 2020). This also hampers the possibility to follow ecological trends and detect changes in population dynamics (White, 2019). The multiple human activities and pressures and the absence of surveillance are further constraints that limit the effectiveness of these protected areas.

In the light of these results, we tried to propose management objectives and conservation measures taking into consideration the target species, the human activities and their relationship, in order to address the potential sources of impact. The definition of clearly stated objectives is the primary step to specify the most appropriate performance indicators and variables to assess the achievement of the desired short-term management outcomes in the protected areas (Thomas and Middleton, 2003; Pomeroy et al., 2004). The variables and performance indicators linked to the expected objectives, target species and human pressures were identified here starting from the parameters that are already collected in the monitoring activities inside the N2K sites or in their proximity (Ciriaco et al., 2019). However, many other variables and indicators were suggested to be collected through ECOAdS, as the current monitoring is not sufficient to assess the status of the different target species and the impact of the many threats documented in the N2K sites. At this point, it is important to precise that the list of management objectives, performance indicators, and variables outlined for each N2K site are not intended to be used prescriptively but represent a starting point for effective management and appropriate monitoring programs in the N2K sites. In absence of specific and detailed information on the occurring species and their actual status, the definition of the elements to monitor is a difficult task. Future management authorities should adapt monitoring programs accordingly to the characteristics of the site, the available knowledge, the objectives, and the available human, technical and financial resources (Pomeroy et al., 2005). In the present study, only ecological indicators were considered within the ECOSS project. Other specific indicators for the assessment of stakeholder engagement, the role of leadership, the capacity of enforcement and compliance with protected areas' objectives need to be considered. Indeed, public support, and in particular strong commitment, education and participation of local stakeholders, has been found to be crucial for the long-term success of N2K management (Morris et al., 2014; Kati et al., 2015).

Our results particularly agree with those obtained by other authors that have investigated the N2K system in the last decade. Although this has an enormous potential to create a consistent network of interconnected protected areas, such a network does not still exist, and its implementation progress is considered slow in most Member States (MS). Mazaris et al. (2017) reported that the N2K system presently fails to meet several CBD targets (CBD, 2021): the relative percentage of protected marine surface area is variable among MS, offshore marine ecosystems are not well-represented, and ecological connectivity is not guaranteed. Moreover, less than 40% of the marine N2K sites have management plans, indicating limited or absent management activities in most cases (Mazaris et al., 2017). The effectiveness of the N2K network is even difficult to measure because the paucity of data due to sparse monitoring (Morris et al., 2014; Mazaris and Katsanevakis, 2018) and the absence of information on spatial distribution of threats, as in our cases (Mazaris and Katsanevakis, 2018; Mazaris et al., 2019). Our results also agree with a recent study that assessed the representativeness of the Adriatic N2K sites for the bottlenose dolphin and the loggerhead turtle (Fortuna et al., 2018). Authors found that, at present, site-based conservation tools are unlikely to be sufficient to protect a significant proportion (i.e., 60%) of both species, unless very large protected areas are designated and wide-scale mitigation measures of the threats are implemented (Fortuna et al., 2018).

Management bodies, governments and funding agencies are increasingly demanding information on management effectiveness of protected areas to assess whether results are in line with policy and management goals, and commensurate with efforts and resources (Roberts et al., 2018; Dunham et al., 2020). The conceptual model developed in this study can provide useful insights in protected areas' management and the proposed approach could be also extended to other N2K sites. Indeed, by summarizing the different components of N2K management, the model can help identify them and assess their relationship, highlight potential knowledge gaps, and provide a base for developing management plans. In addition, through the ecological observing system box, the model may help to develop adequate monitoring programs that collect data on ecological-oceanographic variables and performance indicators. Performance indicators then help to evaluate the effectiveness of conservation actions in each N2K site and revise related objectives, plans, and results. For example, if a performance indicator shows that a management objective is not being met, it may be necessary to modify or strengthen conservation measures; these will then regulate human activities and enable the conservation of target species. Vice versa, the model also allows detecting new human pressures that can act on the protected site or a new species that deserves protection, thus conservation measures or the variables necessary to monitor may require revision. Such a cyclic process follows an adaptive management approach, where the expectations of the set actions are systematically verified, and the results of such testing allow further revision and improvement of management practices (McCook et al., 2010; Nickols et al., 2019). Other types of stakeholders may also apply the model. For instance, environmental monitoring agencies may propose or change sampling techniques, variables, and performance indicators according to the target species and processes they are monitoring, and in relation to the management outcomes they are asked to verify. Thus, the observing system is not only important in the decision-making process but also in merging different fields: research, monitoring and nature management. For the aim of the ECOSS project, our conceptual model relies on ECOAdS[2], the ecological observing system in the Adriatic Sea established under the IT-HR project ECOSS[1]. However, any other observing systems or monitoring programs can be integrated in the model, according to the N2K site and local framework to which the model is applied.

To this regard, with the present study we also wanted to highlight the need to integrate existing monitoring initiatives and adopt a data sharing approach at transnational level in line with the principles of the Open Science (EC, 2018). This approach would facilitate the collection of data on ecological variables, which is generally expensive and difficult to achieve in the long-term. Ecological monitoring can be then further optimized by linking it to oceanographic monitoring, which can help predict the best timing of survey based on the ocean conditions that control the ecological process under study. For example, the optimal period for carrying out the surveys of anadromous fish populations could be derived by examining the physicochemical variables that trigger their migration (Thorstad et al., 2008). The creation of an observing system is also essential to enlarge the spatial and temporal scales of the monitoring activities and extend them outside the N2K sites, for taking into consideration different processes and species life stages (Garcìa-Charton et al., 2000; Edwards, 2004; Carr et al., 2011; Allen and Singh, 2016; Kaplan et al., 2019; Zipkin et al., 2021). While monitoring activities inside each N2K site can still be conducted by the management authority, local research institutes or private companies, large-scale data can derive only from a connected network of observing systems (Manea et al., 2022). This strategy links the potential of the protected areas to detect processes at local scales with that of the oceanographic monitoring systems at a larger scale. Thus, the response of habitats and species to both climate change and local human impacts can be revealed at multiple scales through the combination of N2K sites and observing system monitoring. Examples of extended and successful ocean monitoring systems that help to assess the effectiveness of protected area networks already exist worldwide, such as the Central and Northern California Ocean Observing System[5], and the Australia's Integrated Marine Observing System[6]. The extension and integration of the monitoring programs at different scales can also strengthen and elevate the role of the N2K sites in the Adriatic Sea: from a current condition of single isolated units to an efficient network of co-monitored and effective protected areas, as required by the CBD. This is particularly true for the N2K case studies here investigated because many of the species targeted for protection, such as seabirds, some fish, dolphins, and sea turtles, are expected to move significantly in the region (Fortuna et al., 2018). In addition, the complexity of some territories and the high number of human interests, such as in the Po Delta Park, require a broader and holistic management approach.

The results obtained in our study do not detract at all the role of N2K sites relative to the objectives for which they have been established. However, to achieve ecosystem-wide benefits, it is crucial to rethink and enlarge the aim of N2K sites. EU Member States should invest a great effort in the social and policy fields to greatly enhance N2K ability to meet its conservation targets. N2K site managers should follow an ecosystem-based approach and take into consideration the development of shared management processes between multiple N2K sites, as it is conceived in the HD (Bastmeijer, 2018). A stronger cooperation among different stakeholders is also needed to allow data and knowledge exchange (Bertzky and Stoll-Kleemann, 2009; Cvitanovic et al., 2014). In addition, to achieve broader coverage of the monitored area and focus on specific ecological factors, it may be useful to increase the

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number of sampling stations within N2K sites and standardize the variables sampled (Manea et al., 2022). In the present study, an ecological observing system (ECOAdS) for the Adriatic Sea has been described, but, also, more generally, we suggest that existing or future ecological observing systems in other areas may be a suitable tool to improve monitoring programs, to share data between different producers and users, and ultimately to support the protection of marine habitats and species (Manea et al., 2022; Pugnetti et al., 2022).

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

FG: conceptualization, data collection and review, visualization, writing of the original draft. EM, CB, LB: inputs on the methodology. BC: work package leader, supervision. AP: project leader, supervision, inputs on the methodology. GP and IV: data provisioning. VB: conceptualization, visualization, supervision. 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.2022.1070373/full#supplementary-material

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