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REGULAR PAPER

Democratizing marine restoration best practices in a digital toolbox

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Abstract
Restoration of degraded marine and coastal areas is a priority set by European policy makers, as exemplified by the recent adoption of the European Nature Restoration Law (NRL) in June 2024. This legislation-driven approach is expected to expand the European marine restoration community rapidly as the amount of funding and projects grows to meet the targets outlined by the NRL However, it is difficult to assess the success of restoration activities which is vital to ensure the viability of upscaling. Furthermore, best practices are not well established in the marine realm and scientific networks are still in their early stages of development. Here, we outline our development of a digital, online toolbox for marine restoration in collaboration with the European restoration community. The toolbox aims to go beyond simply making data FAIR (Findable, Accessible, Interoperable, and Reusable) through the creation of science-based digital services that allow for use of information for decision-making for marine restoration. The toolbox is constructed in a modular way to fulfil the needs of a diverse range of users across Europe and includes a centralized space to find methodological approaches, relevant networks, funding opportunities, and resources. The digital tools under development will be openly accessible through the Blue-Cloud 2026 platform within the thematic virtual research environment for marine restoration, which allows for the scalable use and reuse of data and code by any interested user. The toolbox aims to provide restoration community members science-based methods from which they can leverage and accelerate their restoration projects. In the pursuit to democratize access to best practices and knowledge, we go beyond providing code or data in static repositories. Based on our experience, we encourage others that are developing toolboxes or knowledge bases for diverse user groups to consider taking advantage of publicly funded infrastructure to promote their work according to open science practices.

Keywords Open science · Marine restoration · FAIR data · Decision support tools · Digitalization of restoration best practices

Lara Veylit led the writing and conceptual development of this work, all other authors reviewed and contributed inputs to the manuscript.

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1 The motivation behind developing the marine restoration toolbox

Marine ecosystems face a plethora of challenges from the triple planetary crisis of the Anthropocene (e.g. climate change, pollution, biodiversity loss), which is tightly interlinked with effects such as weather extremes, ocean acidification, pollution, the loss of habitats, extractive activities such as fisheries, and the spread of alien invasive species [1]. The loss of marine biodiversity has the potential to lead to the collapse of human coastal communities that rely on healthy marine ecosystems for their livelihoods [2, 3] both through their direct dependence on marine resources and the broader ecosystem services these environments provide, such as coastal erosion protection, cultural services, promoting biodiversity, nutrient cycling, and serving as fish nurseries. Previous human uses-oriented measures, such as those outlined by the Marine Strategy Framework Directive, together with increasing pressures led to governments failing to meet biodiversity targets set by international agreements such as the Kunming–Montreal Global Biodiversity Framework [4]. Learning from such failures, policy makers at regional, national, and international levels are now intensifying efforts towards ecological restoration activities (e.g. the United Nations Decade of Ecosystem Restoration, EU Biodiversity Strategy for 2030, EU 2030 Restoration Plan, "30 by 30", EU Nature Restoration Regulation). Ecological restoration is used by these groups as a generic term, as defined by the Society for Ecological Restoration (SER), as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" [5]. The definition of "ecological restoration" captures a continuum of actions ranging from mitigating impacts to fully restoring ecosystems. This policy evolution is particularly evident in Europe, where the EU Commission has recently adopted the European Nature Restoration Law in 2024 [6]. Despite such progress, the European restoration community remains relatively small compared to other geographic regions like North America [7] (but also see [8]). New legislation and the associated funding opportunities are expected to promote the establishment of new marine (and terrestrial) restoration communities, which presents a significant opportunity for the European restoration community to grow.

The current focus on restoration as a means to reverse biodiversity loss has raised concerns that it could be misused to justify intensifying human activities, which in turn may damage the functioning of ecosystems [5]. Furthermore, the efficacy of ecological restoration is hotly contested [7, 9, 10] due to an overall lack of long-term implementation and monitoring of restoration projects and non-standardized indicators for measuring success. Projects with the goal of increasing biodiversity often struggle to define meaningful indicators and to account for their context-specific limitations (e.g. activities that boost biodiversity via non-indigenous taxa may improve indicator scores but carry ecological risks to native biodiversity) [11, 12]. Similarly, projects targeting the restoration of species and habitats to a reference site must define what constitutes a target "healthy" status, considering shifting baselines, environmental variability, global climactic change, and the dynamic nature of ecosystems. The challenge is compounded by the fact that funding for monitoring of restoration actions is typically limited to less than ten years [13] while ecological processes often require decades to unfold [14].

Given these challenges, there is a pressing need for science-based tools rooted in best practices and standards that can help those in the restoration community develop, implement, and monitor marine restoration projects effectively. Such tools can act as a safeguard against "greenwashing"

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(where groups funding projects and practitioners exaggerate the success of projects when considering their impact on renewing nature to raise funding and/or support for their activities [15]) by disseminating best practices throughout the growing marine restoration community. As such, there is an urgent need for science-based and science-scrutinized tools that can be easily accessed and disseminated for scientists, policy-makers, restoration practitioners and other stakeholders. The digitalization of these tools is expected to democratize research developed by scientists and restoration practitioners alike. While there is a growing community of marine restoration projects and networks in Europe (e.g. the Native Oyster Restoration Alliance or NORA, the European Seagrass Restoration Alliance or ESRA, Climate Restoration Actions in Arctic and Atlantic Coastal Ecosystems or CLIMAREST), finding actionable information and navigating through project results and networks is often hindered by factors including limited data sharing, language barriers, the diversity of habitats and specialized associated knowledge, and the diversity of backgrounds that new marine restoration community members come from.

The digital marine restoration toolbox showcased in this work has been developed to combine existing resources and networks in a centralized platform with digital tools for the development, implementation, and monitoring of marine restoration projects. It incorporates exemplary cost–benefit analysis workflows which will facilitate the alignment with funding mechanisms to enhance project scalability and long-term sustainability. This toolbox facilitates the adoption of best practices for marine restoration by providing access to a comprehensive suite of tools and resources. It integrates data from various sources, supports collaboration among stakeholders, and promotes the sharing of knowledge and experiences. By standardizing methodologies and encouraging transparency, the toolbox aims to enhance the effectiveness and sustainability of restoration efforts. Additionally, it includes guidelines and tools to develop protocols that help ensure that restoration activities are scientifically sound and environmentally responsible, ultimately contributing to the long-term health of marine ecosystems. Here, we outline lessons learned in developing the marine restoration toolbox and provide a general overview of its contents.

2 Democratizing science: going beyond the FAIR principles

Following the European Commission's Open Science strategy, there is a concerted effort being made to move from a fragmented and siloed data landscape to one where data is standardized and interoperable across systems as well as easily findable through open science platforms like the European Open Science Cloud (EOSC) [16, 17]. Modern data management and stewardship practices have become more important than ever to disseminate data, information, and knowledge across scientific disciplines. In this context, repositories such as Zenodo, integrated within the OpenAIRE infrastructure, play a key role by enabling researchers to freely share datasets, publications, and software with persistent identifiers (DOIs).

However, many scientists and institutions in Europe still operate in a research model that produces closed datasets without making the data FAIR: Findable, Accessible, Interoperable and Reusable [18]. In addition, many within research are cautious about sharing data prior to publishing (particularly within ecology/biology). Furthermore, when private companies are included in projects data are usually under strict confidentiality agreements. While networks such as EMODnet [19] and Copernicus [20] facilitate the sharing of open data, many marine biologists and ecologists collecting marine biodiversity data for restoration projects are unaware of these opportunities and need guidance by experienced data managers and stewards. To be able to reuse marine biodiversity data from restoration projects for data products and tools, knowledge of ocean data best practices [21] is crucial. Communication of data management best practices, however, needs to be tailored to the audience without preconceived ideas about the experience or exposure of these communities to open data management practices. Messages such as "open as possible, as closed as necessary," represents a paradigm shift for many ecologists, biologists, practitioners, and stakeholders in general, which may not necessarily be welcomed. For example, researchers or institutions may feel a strong personal ownership over these data, partly because securing funding for such projects often requires substantial effort over many years or even decades [22]. This sense of ownership can make the transition to open data practices particularly challenging. One solution may be to incentivize scientists to share data openly following the publication of peer-reviewed work, such as through further establishing or requiring the publication of data papers.

As the number of private companies engaged in restoration projects expands, efforts will have to be made to disseminate ocean data best practices with the objective to unlock private biodiversity monitoring data. Without these efforts, data collected by private companies will likely remain inaccessible, not interoperable, and unavailable or difficult to be reused. Similarly, data generated by citizens and local communities-often through citizen science initiatives or participatory monitoring-represent a valuable and complementary source of ecological information.

Focusing on making data FAIR for the restoration community will not be sufficient to make restoration projects effective at renewing nature. The aim of the marine restoration toolbox is to make science-based tools, resources, networks, and best practices accessible to academic and nonacademic audiences alike. In addition to data, networks, projects, initiatives, and resources that are relevant to the European marine restoration community are being collected. Access to this information will be centralized through a new page in SER's restoration resources centre (see Fig. 1), with links to both external resources and the tools outlined below (the marine restoration toolbox website is accessible in the long term through SER's restoration resource centre; https://marinerestorationtoolbox.ser-rrc.org/). SER's European chapter is highlighting the marine restoration toolbox in a separate page on their website (and hence to key networks such as the Marine Restoration Working Group). This additional website in SER's resource centre centralizes access to ongoing initiatives dedicated to marine restoration. Furthermore, the website under development links to tools hosted on the Blue-Cloud 2026 platform [23–25] that combine code, data, demonstrators, and inputs from experts.

Blue-Cloud 2026 is a European open science platform that allows users to access and experiment with datasets, visualizations, and analytical tools organized in thematic Virtual Research Environments (VREs). The marine restoration VRE hosts the tools described here which are under development and provides computational resources through virtual machines in a distributed ('federated') platform. The tools added to the VRE will be available in the long term through the Blue-Cloud 2026 platform. In the case of the marine restoration toolbox, users that register for the marine restoration VRE find a catalogue of tools (i.e. collection of lightweight web applications and Jupyter notebooks). This environment allows users to import their own datasets, adapt and extend the code to specific restoration scenarios, and leverage shared computational resources for analysis and model execution. As Blue-Cloud is part of the EOSC, users are able to access data from other European data services including EUROBIS [26], SeaDataNet [27], EMODnet [19], and Copernicus [20]. Blue-Cloud's capabilities offer users openly access information and to merge critical information (i.e. physical, environmental and social data) from a variety of sources that can be of great added-value for members of the marine restoration community and to inform decision makers [28].

The digital tools in the Blue-Cloud marine restoration VRE are scalable, open, transparent, and aim to cater to a variety of users regardless of their technical background. While the approaches presented in the toolbox are not novel themselves, the aim is to reach a wider audience beyond developers and scientists. The digital toolbox showcased in this study is designed to allow users to access data and computational environments (i.e. in the VRE) alongside core information on best practices, networks, and demonstrators (in the marine restoration website). The marine restoration toolbox represents a novel approach towards "democratizing" access to marine restoration knowledge (see Fig. 1 for visual overview of the marine restoration toolbox).

3 Co-developing fit-for purpose tools for the European restoration community

Developing the digital marine restoration toolbox has been an exercise in co-design, with stakeholders involved at every stage to ensure maximum impact of the final products. To validate the relevance of each tool to user groups and to capture the heterogeneity of users, we conducted interviews with European stakeholders from a variety of organizations (e.g. from non-governmental agencies, private companies, and research institutes), roles, and different countries. These interviews particularly highlighted the need for overviews of funding (also see [29]) as a way to combat economic barriers for restoration plans. Accessible databases and compiled lists with available national and international funding sources complemented with guidelines to different application processes therefore received particular attention.

To evaluate the needs of the target users of the marine restoration toolbox (e.g. practitioners, authorities and students in marine restoration related fields) and assess how best to iteratively design tools to improve the development of marine restoration actions, the toolbox development team conducted a number of user testing sessions. These in-person or hybrid sessions have been used to inform the development of tools to (i) ensure tools address the needs of the target users of the marine restoration toolbox, (ii) collect feedback on the usability of the marine restoration website and identify kinds of content needed by users, (iii) assess the usability of tools in the marine restoration themed virtual lab by users, (iv) ensure the tools in the marine restoration themed virtual laboratory and marine restoration website will contribute to the goal of improving the outcome of marine restoration actions, and (v) explore how the toolbox can support knowledge exchange and collaboration among marine restoration stakeholders. User testing sessions were conducted in a workshop as part of the SER Europe 2024 Conference (SER2024), with European marine restoration experts engaged in European marine restoration projects, and in training sessions organized by SER Europe and at the SER Conference in 2025.

The marine restoration toolbox has a modular design and dynamic nature, with the possibility to upgrade, update and add features and tools over time (e.g. higher resolution remote sensing technologies, autonomous drones). In addition, the VRE is considered "living" and open to the addition of tools that may serve new user groups in the community.

Fig. 1 Overview of the marine restoration toolbox. The toolbox includes a website that links users to relevant resources and to the marine restoration themed virtual lab where a curated demonstration cases and tools are available with associated code, data, and computational resources

3.1 The marine restoration toolbox website

The marine restoration toolbox website is designed to be dynamic, continually expanding with new networks and resources as the community develops. SER-Europe's Marine Restoration Working Group will serve as the core group that provide feedback on the structure and content of the marine restoration toolbox website following its launch. This team of subject matter experts have provided feedback through the development of the marine restoration toolbox website to tailor the content and structure to the needs of marine restoration community (see Fig. 2. For website front page). The marine restoration toolbox website serves is the first centralized hub for information on best practices for marine restoration, including lessons learned from previous restoration projects and resources organized by the phases of restoration (as defined by SER; see [30]).

The marine restoration toolbox website includes information from case studies, (i.e. from the CLIMAREST project), in which various marine restoration interventions have been implemented in Europe. These case study descriptions also include informative videos that outline the motivation behind implementing each action and footage of implemented solutions. In addition, a road map of how to perform cost-benefit analyses for marine restoration actions is provided. This road map aims to help users evaluate the financial costs of implementing various restoration actions, and methods for evaluating benefits (economic and ecological). Users will also find information on best practices for engaging stakeholders. These best practices are tailored to marine restoration actions, due to the vital importance of community engagement for developing successful marine restoration actions. As test users highlighted the need for an overview of funding sources, the development team also compiled an overview which is available in the marine restoration website.

4 Tools in the marine restoration themed virtual lab

The tools described below are available in Blue- Cloud's marine restoration themed VRE (the EcologicalRestoration Lab on https://bluecloud.d4science.org/group/ecologicalrestorationlab). The marine restoration themed VRE serves as an environment for users to experiment with code and data in a cloud-based environment (all code is also openly available on GitLab https://gitlab.sintef.no/climarest. The marine restoration themed VRE is an innovative hub for tools that can be used through the different phases of restoration by practitioners. The VRE provides users with the ability to interact with demonstrators, adapt code for their own cases, and access information provided by subject-matter experts on demonstrators and relevant data (e.g. from EMODNet).

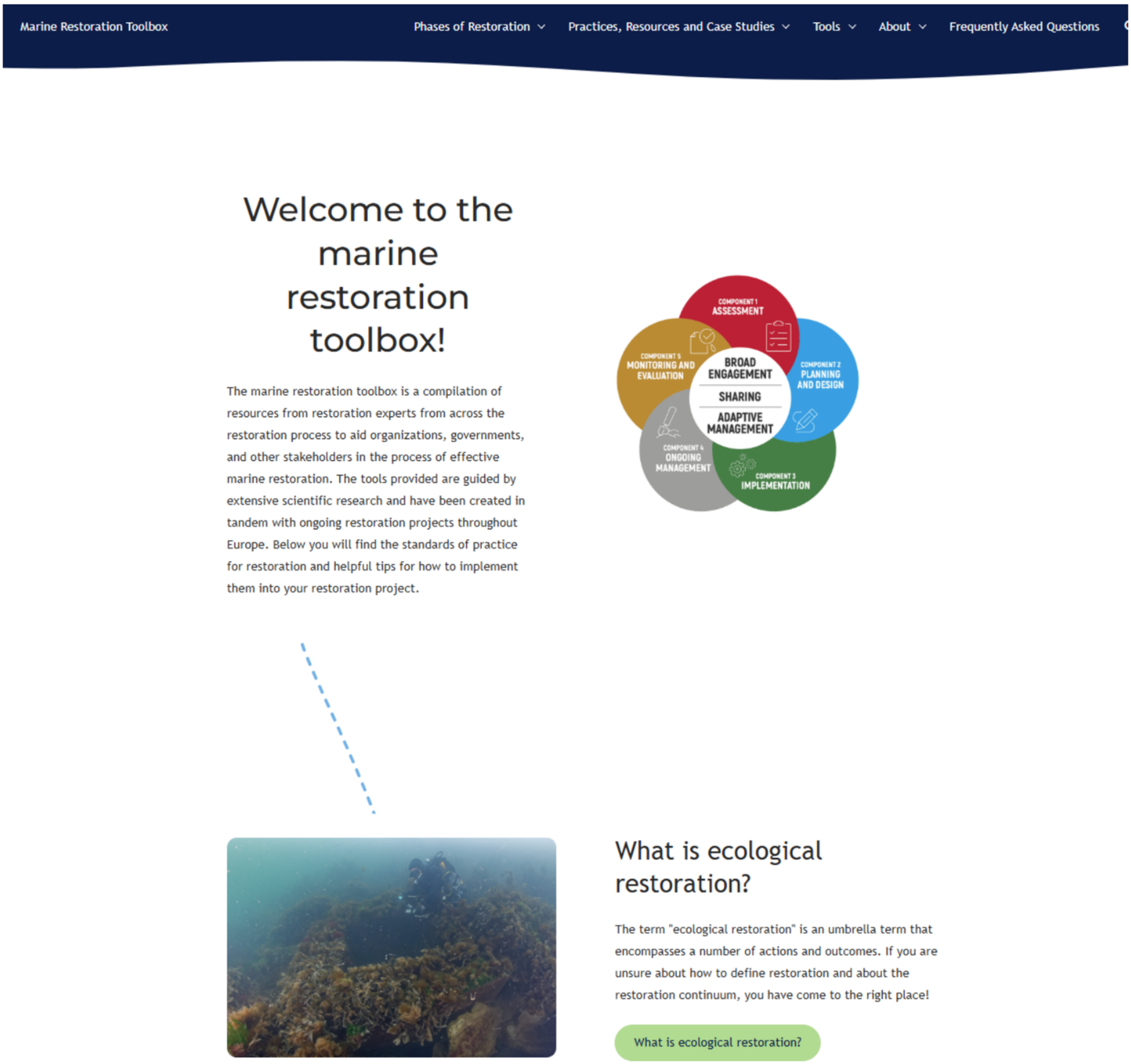

Fig. 2 Landing page of the marine restoration toolbox website. The structure and content have been co-developed by stakeholders identified by the CLIMAREST demonstration site leaders

4.1 Protocol development survey

Only recently have openly available, detailed guidelines that follow best practices been developed for restoration in the marine realm (e.g. for seagrass meadows [31], macroalgal forests [32], coral reefs [33], salt marshes [34], and oyster bed reefs [35]). Practitioners require access to high quality, science supported protocols, with detailed information and instructions, in order to enhance and ensure the success of new restoration plans that are effective at renewing nature but are also inherently context dependent. Access to protocols based on past restoration initiatives is essential to smoothen the learning curve of restoration, i.e. increase replication efficiency and up-scaling. Developing new protocols is resource-intensive, time-consuming, and entails complex decision-making across various activities. The goal is to leverage existing protocols and guidelines to reduce the risks associated with initiating new restoration actions and requires balancing of financial, social, and ecological dimensions. In addition, restoration protocols should incorporate information on socio-ecological factors (e.g. engagement of local citizen science groups for lower-cost long-term monitoring, engagement of stakeholders impacted by the restoration action) that may determine the successful outcome of a restoration project. Practitioners new to restoring a habitat (e.g. macroalgal forests) will need access to frameworks and guidelines to tailor solutions that can take advantage of existing protocols that follow best practices as they develop their own restoration actions and activities.

In the marine restoration toolbox, we developed a survey-based tool by adapting the framework proposed by Smith and colleagues [36, 37], to develop tailored protocols (Fig. 3). The tool embeds information on relevant sources of historical data (e.g. Ocean Biodiversity Observation System or OBIS), definitions (e.g. from SER), and relevant open-source publications. The survey adapted from the decision tree outlined in [36] is made available to users in a lightweight web application built using the Streamlit framework in the marine restoration virtual laboratory. Users are walked through the survey with links to relevant resources provided to support collating additional information. Once completed, the interface allows the user to download responses to survey questions in a pdf. The survey aims to provide users a self-assessment during the planning stages of a restoration action to ensure science-backed resources are shared with practitioners when developing protocols. Tailored protocol development surveys included in the VRE include for artificial reef development and deployment, native oyster restoration, seagrass restoration,European lobster reintroduction, pressure mitigation in marine coastal habitats, and macroalgal forest restoration.

4.2 Multi-criteria area selection tool for site prioritization demonstrator

One important factor that influences whether a restoration project is successful is site selection [38].To perform site selection effectively, site suitability maps can integrate spatially explicit information on relevant ecological, social, and technical criteria [39, 40] to maintain socio-ecological systems. Criteria to develop successful restoration actions are only partially similar to those used in conservation prioritization [41, 42]; criteria to consider when selecting areas to restore include connectivity between populations and habitat suitability (in cases where species will be reintroduced) but also other spatially explicit information on historical presence of the species to be restored, the presence of climate refugia, potential threats, human related pressures and existing marine spatial management and conservation policies. Connectivity between populations (i.e. facilitated by dispersion) are needed to support a stepping stones system and corridors enhancing species flow. In addition, it drives genetic heterogeneity allowing for the restoration of a healthy population structure composed of heterogeneous age and size classes. Therefore, in the context of marine restoration, metapopulation dynamics (i.e. interactions between connected local populations) are crucial to consider [43, 44].

In the marine restoration virtual laboratory, we provide a demonstrator of how multiple spatially explicit data layers can be combined to plan and prioritize restoration target areas. The decision support tool framework used in this demonstration is *restoptr* [45] for spatial combinatorial optimization of geospatial data for restoration. As a constrained optimization framework, *restoptr* for spatial combinatorial optimization of geospatial data for restoration. As a constrained optimization framework, restoptr optimizes for factors such as connectivity with other areas (e.g. Marine Protected Areas) in addition to considering constraints. The tool combines geospatial data on ecological, social and technical criteria for a given target area, namely: maritime traffic, distribution and spatial extent of invasive species and/or keystone species, coastal infrastructure, Marine Protected Areas and human population density. The tool is designed to combine selected/available spatially explicit data to suggest optimal sites for restoration. The tool will be implemented as a web application dashboard in the R Shiny framework [46] and be accessible through the marine restoration research environment on Blue-Cloud. Users can sort through geospatial layers, dynamically change what criteria are applied for constraining the site selection and adjust weighting criteria. In addition, descriptive text provides context on the demonstration case, information on the restoptr framework, how to interpret results, and documentation on data sources (including the location of open datasets used to create the demonstration case and associated documentation). While this tool aims to show the criteria that should be considered in restoration planning, we emphasize that the involvement of experts is necessary for selecting which criteria users consider for the development of locally tailored actions.

4.3 Regional digital twin demonstrators

Digital twins, defined by the Digital Twin Consortium as “a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity” are emerging as a popular concept in many areas, including within the fields of ocean science and ecology [47, 48]. Several initiatives such as the European Digital Twins of the Ocean work towards developing digital twins of marine systems and making these twins interoperable [49, 50]. In particular, these initiatives aim to leverage the possibility of using digital twins to test different hypothetical scenarios (referred to as “what-if” scenarios). Digital twins of the ocean integrate and contextualize different data streams (e.g. ocean temperature with species distribution abundance) for data-driven decision-making from different relevant “what-if” scenarios. Digital twins represent a unique opportunity within the field of marine restoration to provide decision makers (such as local public authorities) with simulated restoration scenarios under different conditions. Particularly

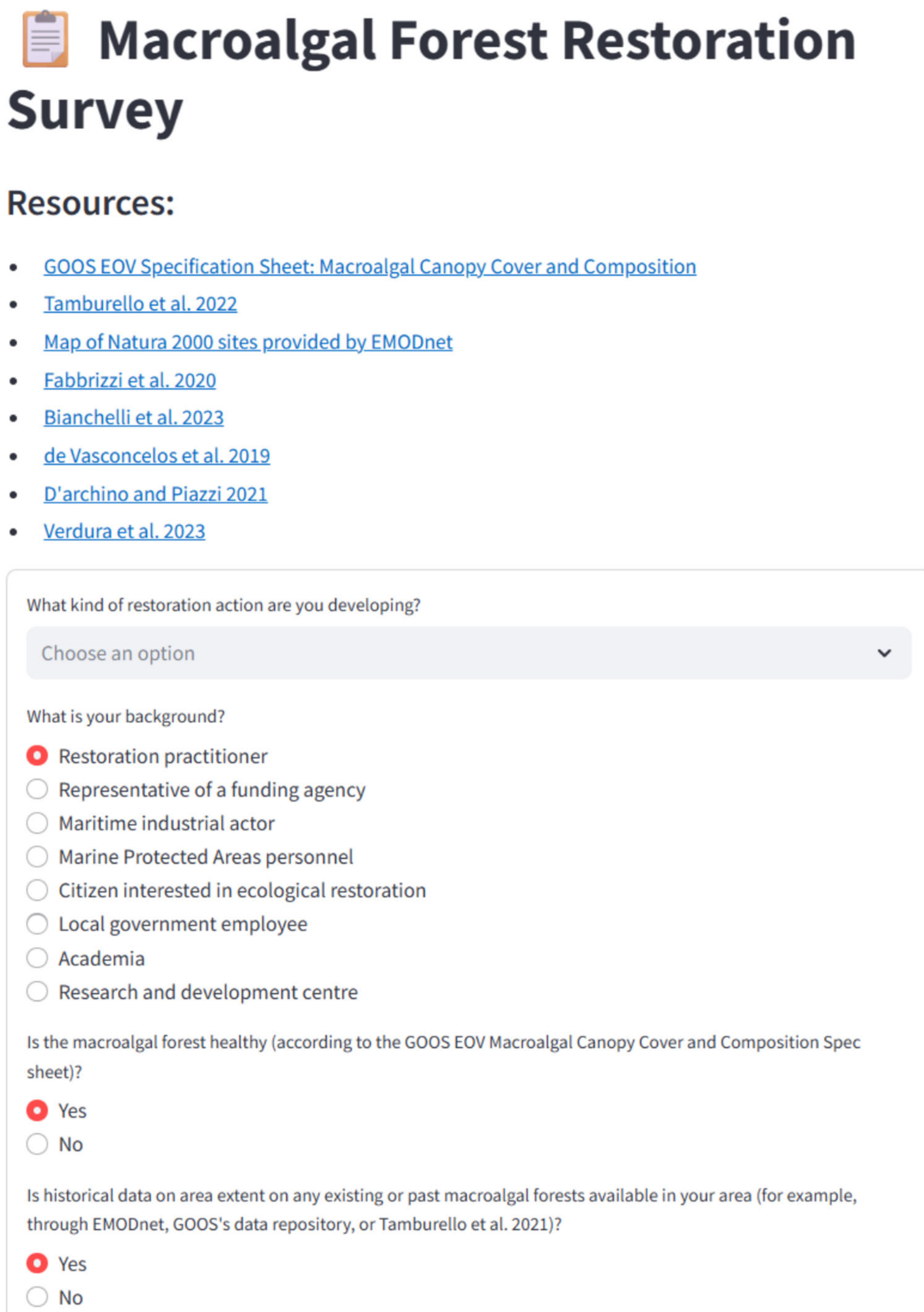

Fig. 3 Survey to guide users through developing protocols that follow best practices for macroalgal forest restoration. The tool is an interactive web application and available in the Blue-Cloud marine restoration themed virtual research environment

relevant scenarios to explore for authorities, stakeholders and practitioners to assess benefits and risks when initiating a marine restoration action in a target area include: the historical presence of the species/habitat to be restored, local human drivers responsible for habitat loss, different climate change-related scenarios (e.g. temperature, sea level), different maritime uses and restrictions (e.g. by fisheries, maritime traffic, coastal development, Marine Protected Areas), differences in species boundaries (e.g. latitudinal range expansion, non-native species introduction). As ecological digital twins require multiple data streams including fine-scale biodiversity data, the use of digital twins in decision-making could also catalyze the shift from closed to open ecological data.

In the marine restoration virtual lab, we have collected available data from several areas where restoration interventions are ongoing for the development of digital twins. The effect of different modeled climate scenarios is considered alongside data collected *in situ* and historical data from open repositories (e.g. from EMODnet, Copernicus) and combined, contextualized, and presented in Jupyter notebooks.

Data and code are available alongside natural language text written by subject matter experts about the relevance of each presented scenario and information on data made available through Blue-Cloud. By making continuous data updates and twins available, the process of working with data and code is streamlined through the provision of both computational resources and an interactive environment for testing and experimentation with what-if scenarios. Dedicated outputs like interactive visualizations can be used by decision makers (e.g. from local to governmental authorities) without specific technical expertise through their provision in the form of widgets. These visualizations and information in the digital twin demonstrators aim to serve as a framework for decision-support during the development, implementation, and monitoring phases of projects. These dedicated outputs are also presented in the form of interactive Streamlit applications in the the virtual research environment. While the development of Digital Ocean Twins marks a significant advancement in marine science and management, it is important to acknowledge the current limitations in ecological data availability. These Digital Ocean Twins rely heavily on high-resolution, comprehensive datasets to accurately simulate complex ocean dynamics and ecosystem responses. In many restoration contexts, baseline data on ecosystem conditions, species interactions, and long-term ecological trajectories may still be scarce or fragmented. Addressing these gaps progressively and with scientific rigour will be essential to ensure that Digital Ocean Twins evolve as effective and reliable tools that can meaningfully contribute to robust, adaptive, and resilient restoration planning.

4.3.1 Developing a digital twin demonstrator for seagrass restoration

One frequently cited reason for the lack of consensus on the success of projects aimed at restoring ecosystems is the absence of long-term monitoring, as well as low monitoring frequencies and limited spatial resolutions. Intertidal coastal areas are generally surveyed during low tide, when exposed and using a variety of *in situ* visual surveys, sampling and image analysis (e.g. photoquadrats). As these methods are both costly in terms of time and funding, there has been a recent increase in the use of remote sensing tools from satellite and aerial surveys, both manned and unmanned [31]. Monitoring activities in intertidal areas are, however, complicated by the fact that tidal behaviour of the ocean leads to periodic coverage of areas of interest.

In the digital twin demonstrator that has been developed for practitioners restoring seagrass meadows, we showcase a free tool for monitoring intertidal photosynthetic communities including seagrasses, microphytobenthos, and seaweeds that relies on the use of satellite imaging to measure changes to the Normalized Difference Vegetation Index (NDVI) in a selected area during low tide. Remote sensing tools such as the one outlined here can enhance both spatial extent and temporal frequency, which are necessary for high quality monitoring of any restoration effort. The tool is based on the work of Haro and colleagues [51]. The digital twin demonstrator focuses on the area where a series of interventions have taken place to establish new seagrass meadows in intertidal areas on the Irish coast. The demonstrator is available in a Jupyter notebook with the accompanying Streamlit application within the marine restoration Blue-Cloud VRE (Fig. 1).

Leveraging the feature of Jupyter notebooks to combine code and documentation in a user-friendly interactive environment, data, models, and visualizations are described alongside shortcomings for different approaches (e.g. monitoring of seagrass meadows using remote sensing) and code for reproducing analyses. Widgets allow non-technical users to navigate maps (e.g. showing NDVI for monitored areas see Fig. 4). The notebook includes an explanation of how users can access images from the Sentinel-2 satellite for their own area through the Copernicus program to experiment with the provided method. Additionally, a demonstration of the method using data from an area where a seagrass meadow restoration project has been initiated is included. It is hoped that this tool can be used for long-term monitoring of restored seagrass meadows in particular, as well as for monitoring and assessing donor meadows. Specific variables of interest (e.g. threshold cloud cover extent) are pointed out and provide users with suggested experiments that they can run using the computational resources provided by Blue-Cloud.

The digital twin demonstrator for seagrass restoration practitioners also investigates potential barriers to successful seagrass meadows establishment. In the demonstrator, information is provided on how to access openly available data on key physical, biological, and anthropogenic hindrances to the establishment of seagrass meadows. Specifically, data on sea surface height in the demonstration area (provided by CMEMs) are provided in the form of a time series alongside a list of other physical factors that can be explored (e.g. light at the seabed, ocean salinity, wave energy, sediment characteristics). Data on the locations of point sources of pollution (sewage outlets; data provided by EMODnet Human Activities) are also presented in an interactive map. This map visualization is followed with a map visualization of outputs from a global ocean model showing estimated concentration of biogeochemical variables (e.g. chlorophyll-a, nitrates, phosphate, and ammonium) that may lead to eutrophication in the waters surrounding seagrass transplants. Finally, historic sea surface temperature estimates are provided in an interactive widget alongside future scenario predictions for sea surface temperature (SST) in Ireland (see Fig. 5). These scenarios are provided to users as future-proofing restoration actions is vital to their continued success and for developing projects that impactfully improve ocean health.

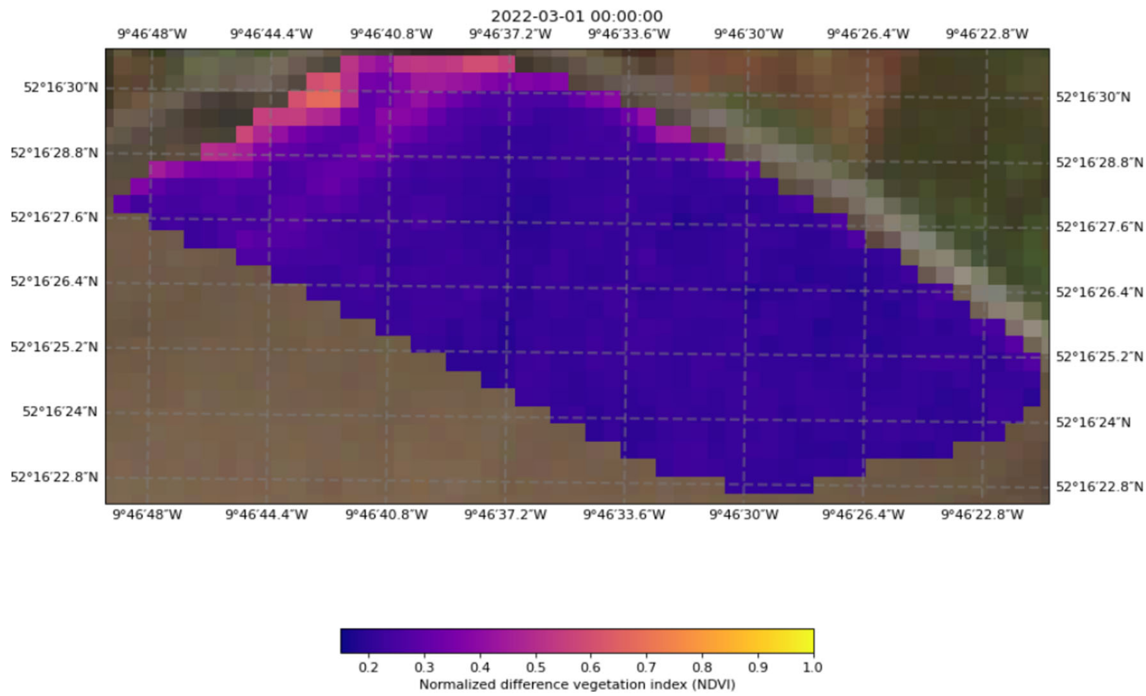

Fig. 4 An interactive visualization from the digital twin demonstrator for the restoration of seagrass meadows. A tool showcased in the demonstrator allows for monitoring of newly established seagrass meadows using remote sensing tools. Users are guided in how to access imagery from Sentinel-2 through Copernicus Marine Services and methods for estimating NDVI, one indicator that can be used to estimate the area extent of seagrass meadows

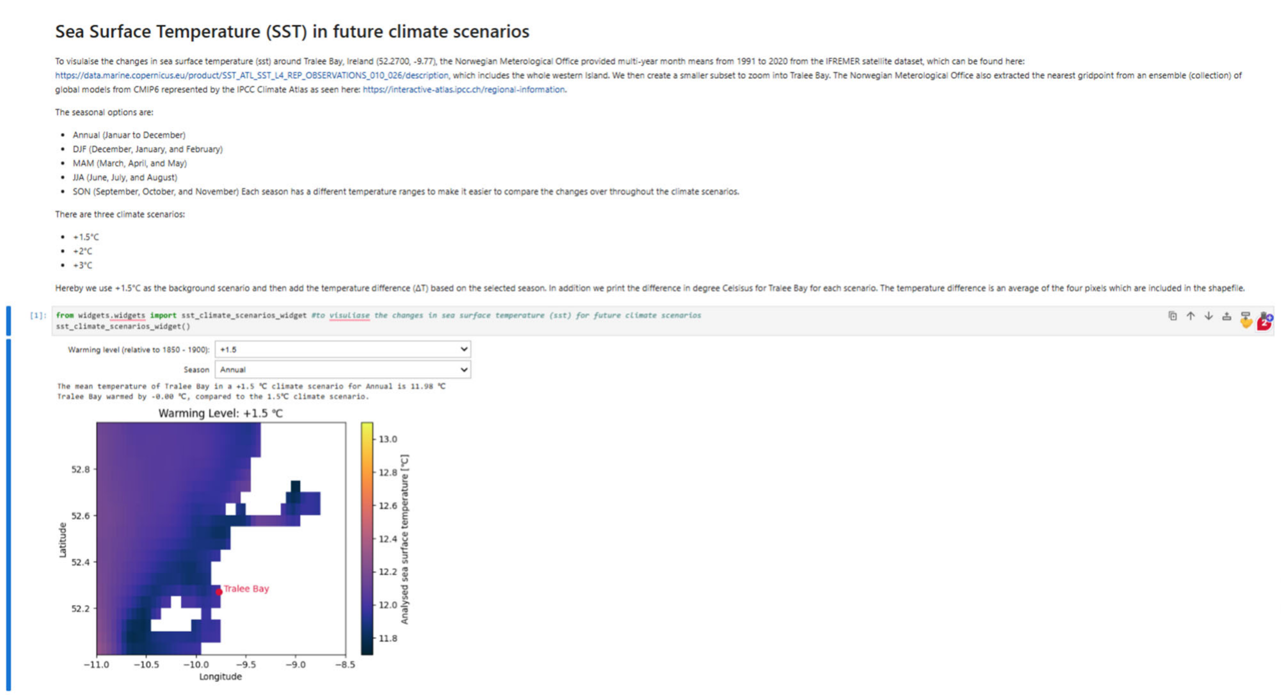

Fig. 5 A visualization from the digital twin demonstrator for the restoration of seagrass meadows showing text and an interactive visualization depicting future scenario predictions for sea surface temperature (SST) in the area surrounding the demonstration case

5 Lessons learned

As it is often the case when catering to a variety of stakeholders, challenges faced during the digital tools design and development stages are less technical but rather related to communication. The proliferation of initiatives to create openly available applications, services, and platforms for the sharing of digital products on cloud platforms may lower the threshold for even unexperienced and non-technical users to access and test open solutions. As public data infrastructure matures, projects will be able to exploit existing infrastructure such as Blue-Cloud 2026 to avoid the duplication of effort and resources when building their tools. In fields such as marine ecosystem restoration, where the community is expected to grow rapidly, access to data, as well as access to information and knowledge (i.e. best practices and low-cost methods) must be communicated appropriately and made openly accessible. With a developing community of networks across Europe and the rest of the world, there is great value in a centralized toolbox or 'one-stop-shop' for finding relevant contacts, funding opportunities, and examples of tools and methods provided by scientists. Through the design and development of digital tools, stakeholders should ideally be involved at every level of the development process from ideation, testing of prototypes, to finally giving input on the fully realized tools. Ambitious initiatives that target a variety of user groups with different backgrounds and profiles can benefit from modular frameworks to provide a variety of different tools for different purposes and users. In this context, fostering networking among stakeholders not only enhances collaboration and mutual learning but also ensures that digital solutions are better aligned with the real needs and practices of diverse communities.

Admittedly, when developing tools for users from different scientific, professional, and national backgrounds it will be impossible to develop tools that satisfy the individual needs of every possible user. Crucially, the toolbox acknowledges that restoration actions are highly context-dependent; what is appropriate in one ecological, social, or regulatory setting may not be appropriate in another. Therefore, rather than prescribing a one-size-fits-all protocol, the toolbox promotes adaptable, evidence-informed approaches tailored to specific environmental and management conditions. Inputs from stakeholders, for example, need to be considered in the best possible way and weighed against reaching the aim of stakehoders' initiative (e.g. democratizing science-based approaches to improve the development, implementation, and monitoring of marine restoration projects).

There are also several technical challenges associated with developing digital solutions and making them openly accessible. Here, we were able to take advantage of existing infrastructure for making solutions available through Blue-Cloud 2026. However, future developers of similar toolboxes may need to develop and fund infrastructure for hosting services in the absence of publicly funded infrastructure. Using existing infrastructure does potentially carry trade-offs. For example, Blue-Cloud is developed to host container-based services. Therefore, we developed all services for the marine restoration VRE to be containerized for ease of deployment as a dialogue was initiated before the development of the VRE. While Blue-Cloud 2026 and European Digital Twin Ocean (EDITO) handle any container-based solution, there are specific (i.e. Docker) image requirements in place for correct versioning of packages and to ensure services work on both platforms. Therefore, the Blue-Cloud 2026 and marine restoration toolbox VRE development teams worked together to test and deploy services both locally and on the cloud-based infrastructure provided by Blue-Cloud. This required technical expertise i.e. in the deployment of containerized services as well as resource allocation to time dedicated to making applications available through the VRE. Future developers of digital toolboxes are encouraged to identify infrastructure needs and limitations before developing services to ensure the infrastructure and services are compatible. Finally, developers may need to account for the time required to implement services on cloud-based infrastructure.

Ensuring long-term accessibility was one major challenge faced by the development team of the marine restoration toolbox. Although medium-term solutions are in place to ensure that the website (through funding provided to SER through the CLIMAREST project) and the VRE (through funding of the Blue-Cloud 2026 project) will be available beyond the lifetime of the CLIMAREST project, long-term accessibility remains a challenge. Although funding for the infrastructure behind Blue-Cloud will terminate in 2026, the European Commission is developing a long-term plan to consolidate and fund marine data infrastructure (such as EDITO and Blue-Cloud). Therefore, while the marine restoration VRE may no longer be hosted by Blue-Cloud's infrastructure following the termination of funding, the services will almost certainly continue to be available through future platforms/infrastructure. The difficulties associated with securing accessibility to the tools and services in the marine restoration toolbox highlights a serious shortcoming of the current project-based funding structure. Many services and data products are developed over the course of the lifetime of singular projects, which may result in too short a lifetime for uptake of tools and resources by growing communities. We therefore advise other initiatives to consider the time and resources needed for ensuring long-term accessibility of data products and services at the onset of projects and recommend funding bodies to provide long-term funding for data infrastructure such as EDITO and Blue-Cloud.

Based on our experiences developing the marine restoration toolbox, we advocate for an approach that is created in collaboration with end users which nevertheless is as agile as possible. Furthermore, the creation of content in accessible formats that match the diversity of users is also essential to democratize access to data, information, and knowledge.

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Declarations

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