Developing regional digital twins for marine restoration in the CLIMAREST project

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The recent passage of the Nature Restoration Law by the European Union presents an opportunity for the growth of the marine restoration community. The marine restoration toolbox developed in the Climate Restoration Actions in Arctic and Atlantic Coastal Ecosystems (CLIMAREST) project aims to bring science-backed best practices to current and future marine restoration practitioners to maximize the effectiveness of restoration actions through connecting users to established networks, experts, and tools. The toolbox provides tools to be used through the lifespan of projects (i.e., assessment, planning and design, implantation, ongoing management, and monitoring and evaluation). The toolbox is composed of two interconnected elements that will be hosted beyond the lifespan of the CLIMAREST project (ending in November 2025); (1) the toolbox website which will be included in the Society for Ecological Restoration's Restoration Resource Centre (2) the marine restoration themed virtual lab hosted by Blue-Cloud 2026. The toolbox furthers its impact through its incorporating in existing infrastructure hosted by established communities (i.e., the Society for Ecological Restoration and Blue-Cloud 2026). The virtual lab on Blue-Cloud serves as an environment for users to experiment with data, code, and demonstration cases - including regional digital twins.

In total, there will be five digital twin demonstrators in the marine restoration virtual lab matching the five demonstration areas where restoration actions are being implemented in CLIMAREST. The demonstrators cover erosion modelling and rates in the high Arctic, seagrass meadow establishment in Ireland under changing environmental conditions, macroalgal forest restoration around the island of Madeira in Portugal, oyster bed reef restoration in France, and the reintroduction of the European lobster near aquaculture in the north of Spain. Each digital twin demonstrator is structured in a story-telling format, with contextual information on the demonstration area context the regional twin is developed for (i.e., the high Arctic, the Spanish coast), data requirements for addressing the topic of the twin (e.g., erosion mitigation using Nature Based Solutions), relevant data sources (e.g., the Norwegian Polar Institute, OBIS), data collected *in situ*, open data from local (e.g., country-specific) and European repositories (i.e., Copernicus, EMODnet), and interactive model outputs (e.g., climate simulations, wave models). Subject matter experts provide text throughout each twin to contextualize the data, models, and information so users are guided in their interpretation of figures, models, and in use of provided code.

The CLIMAREST digital twin demonstrators incorporate data and information on the societal context of each area (e.g., tourism as a pressure), information on biodiversity (e.g., from historic or current sampling campaigns), and observational/model outputs describing physical characteristics (e.g., sea ice loss). Furthermore, users can simulate "what if" scenarios for each region linked to climate change. The anticipated user base of the digital twins are restoration practitioners and scientists engaging in restoration research. Thus, detailed comments on running provided python code are also provided as well as walkthroughs for use of European data infrastructure (i.e., registration for Copernicus Marine Services or CMEMS) to provide users the ability to go beyond the provided examples and apply the code and examples to their own cases. The current demonstrators are Jupyter notebooks that incorporate widgets and sliders, allowing users to interact with different scenarios more easily. These features abstract away model complexity by eliminating the need to run separate code chunks for each timestep or parameter.

To provide a more detailed outline of one of the digital twin demonstrators, we will discuss the Arctic case digital twin which is in the late stages of development. This twin is currently in the form of a Jupyter notebook currently that begins with an outline of the case, context, data requirements for erosion rate modelling and a conceptual model illustrating how these data sources can be combined for decision-making for developing a restoration action. Users are then walked through an interactive (Folium) map illustrating where the Arctic demonstration is located (i.e., on the Svalbard archipelago) followed by local drone images of areas under consideration for implementing Nature Based Solutions. Then, users are provided a time series with information on the population of Svalbard split by permanent residents and tourists (data provided by Statistics Norway and translated to English) as well as a map of settlements across the archipelago. Then users are walked through the process for accessing data through CMEMS with data and models illustrating how the Arctic is rapidly warming, and sea ice is declining. Users then can interact with a map to find the location of historic sampling campaigns via a widget and subset data to view which taxa have been observed over time (provided by the Norwegian Polar Institute). Users then can interact via sliders and drop-down menus with visualizations of a wave model created in the CLIMAREST project to look at several parameters including significant wave height, ice thickness, and ice area coverage. Finally, users can interact via sliders and drop-down menus with "what if" local climate change scenarios visualized in maps provided by the Norwegian Metrological institute.

Following data management principles (e.g., FAIR & TRUST), the CLIMAREST digital twins also serve as a method for making non-traditionally published data accessible, such as drone images. The drone images are then accessible through a user's workspace on Blue-Cloud allowing for reuse by users. The digital twins also take advantage of the progress that has been made to make data and services interoperable by, for example, providing datasets from diverse sources side by side to facilitate the data-driven storytelling approach used in each twin. Without the efforts of the wider community that have been standardizing and simplifying access to data such as satellite imagery, population statistics, and biodiversity observations the development of the digital twins in CLIMAREST would not be possible.

To make the digital twins widely available and used by our target user group, dedicated web pages will be made for each twin to be incorporated in the toolbox website on SER's RRC. To reach users from the EU DTO, the twins will also be available on Blue-Cloud 2026 and EDITO infra with listings in the Iliad marketplace. This allows for demonstrators to be easily findable. Due to the similar requirements from Blue-Cloud and EDITO (i.e., container-based applications), the replication of work is anticipated to be minimal. The replication of hosting on the Blue-Cloud and EDITO platforms further provides resilience as the current long-term plans for financing open EU data infrastructure is uncertain. Furthermore, EDITO was chosen as the second infrastructure to host the digital twins due to the positioning of EDITO as the core infrastructure for the EU DTO. However, the marine restoration themed virtual lab on Blue-Cloud also hosts tools that are not twins as well as habitat-specific protocol development surveys, and an interactive app to explore how marine spatial planning tools can be used for prioritizing sites where marine restoration actions are implemented. Thus, both Blue-Cloud and EDITO serve as important infrastructures for the CLIMAREST toolbox to reach both users today and into the future.