Spoke 1

Mapping and monitoring actions to preserve marine ecosystem biodiversity and functioning

Vision

Spoke 1 aims to establish an **integrated national system for marine biodiversity observation**, leveraging innovative approaches such as eDNA-based monitoring, remote sensing, modelling to increase our understanding about the distribution, present status and role of biodiversity in driving the ecosystem functioning at sea.

Mission

The mission of Spoke 1 relies on the following targets:

- filling gaps in current marine-coastal biodiversity knowledge (from species to ecosystems from structure to functioning);
- use the most cost/effective and develop new/emerging methodologies and technologies to monitor biodiversity changes in space and time;
- assess the effects of global and local stressors on a suite of habitats to provide mechanistic-based predictions on the future distribution of marine habitats;
- set priorities and plan new conservation/restoration scenarios to reach EU targets
- transfer the Italian monitoring and conservation best practices to innovate cross-border cooperation strategies at Mediterranean and extra Mediterranean seas;

Strategic Objectives

The primary objectives are:

- **Integrate historical and contemporary data** to provide an updated framework on the status of Italian marine ecosystems.
- **Identify biodiversity hotspots and critical areas for conservation**, utilizing advanced technologies and multidisciplinary approaches.
- **Develop standardized protocols for monitoring and assessment**, ensuring interoperable and accessible biodiversity data.
- **Analyze the impact of anthropogenic pressures** on marine biodiversity, including fisheries, aquaculture, pollution, maritime traffic, climate change and invasive species introductions.
- **Promote evidence-based ecological conservation, restoration and mitigation strategies**, including evaluating the effectiveness of current conservation actions.

Such objectives support the creation of a permanent marine biodiversity observatory, integrating data and tools to guide conservation policies and contribute to guide sustainable human uses.

State-of-art analysis

General

Marine biodiversity is facing unprecedented threats due to climate change, habitat degradation, pollution and unsustainable human activities. Understanding and monitoring biodiversity patterns and dynamics is essential for developing effective conservation strategies to expand present conservation setting to reach the 2030 targets, yet significant gaps remain in our ability to assess ecosystem health and forecast future changes.

Current Advances in SPOKE 1 Marine Biodiversity Research

In recent years, marine biodiversity research has evolved considerably, leveraging cutting-edge technologies and interdisciplinary approaches. SPOKE 1 key development include:

eDNA and molecular monitoring: environmental DNA (eDNA) techniques have revolutionized biodiversity assessments, enabling non-invasive monitoring of species presence, abundance, and distribution. These methods provide higher sensitivity and efficiency compared to traditional survey techniques.

Remote sensing and GIS applications: satellite imagery, aerial drones, and GIS-based spatial modelling now allow for large-scale biodiversity assessments, facilitating real-time monitoring of marine ecosystems.

Automated and AI-Driven biodiversity assessments: the integration of artificial intelligence and machine learning with monitoring tools (e.g., underwater cameras, passive acoustic monitoring) has enhanced species identification and habitat classification.

Long-Term ecological research and biodiversity databases: collaborative efforts have led to the development of an extensive biodiversity database, improving the capacity to track changes in space and time. All information gathered through SPOKE 1 activities and historical data are included in the Spatial Geoportal which will be one of the backbones of the Gateway.

Assessment of present conservation settings: in Italy, the protection of the territory is linked to a series of tools that international scientific literature has widely documented as potentially very effective (e.g. Protected Areas, Natura 2000 sites). These tools derive from the application

of national, international, and European directives. However, since these areas are often established without basic scientific knowledge and a systematic conservation planning approach that includes clearly stated criteria (e.g. connectivity, representativeness, efficiency), their establishment often does not correspond to evidence of effective protection. The reasons for this are not limited to design issues. Spoke 1 aims to analyze the state of marine conservation, developing new knowledge, tools and methodologies for expanding protection and restoration, evaluating biodiversity within and outside Protected Areas, and analyzing the management effectiveness of Protected Areas.

Climate change impact assessments on biodiversity and ecosystem functioning: in SPOKE 1, predictive models play a crucial role in evaluating the impacts of climate change and effects of human-driven factors across spatial scales (from local to regional) on marine biodiversity, providing insights into species distribution shifts, habitat resilience and ecosystem tipping points. Specifically:

Species Distribution Modeling (SDM): SPOKE 1 integrates both mechanistic and correlative-stochastic models to project the potential distribution of dozens of marine species under changing environmental conditions. These models help anticipate species range shifts and identify vulnerable ecosystems, supporting proactive conservation strategies.

Habitat resilience assessment: current efforts focus on developing network-based simulation approaches to assess the effects of species extinctions and habitat degradation on ecological networks. This methodology aims to predict how marine habitats respond to biodiversity loss and to guide adaptive management strategies.

Ecosystem tipping points analysis: Various modelling techniques are being developed to identify critical thresholds beyond which ecosystems undergo irreversible changes. These approaches will enhance our understanding of nonlinear ecological responses to environmental stressors, aiding in the design of early warning systems for ecosystem collapse.

Through these advancements, SPOKE 1 is pioneering new methodologies for assessing climate change impacts, providing robust, science-driven tools for biodiversity conservation and marine ecosystem management.

Knowledge gaps and opportunities

Knowledge gaps. Despite significant advancements in marine biodiversity research, several key challenges remain. However, these challenges also present unique opportunities, particularly within the framework of SPOKE 1, where interdisciplinary collaboration and large-scale coordination are fostering innovative solutions.

Fragmentation of Data. Biodiversity data have historically been fragmented, collected by multiple institutions using diverse methodologies, and often lacking interoperability. However, the development of the **Gateway Spatial Geoportal** within SPOKE 1 offers an unprecedented opportunity to centralize, standardize, and integrate biodiversity datasets. By adopting **FAIR**

principles, the geoportal will facilitate data-sharing among scientists, practitioners and policymakers, enhancing evidence-based decision-making and conservation strategies.

Lack of Standardized Monitoring Protocols. Disparities in data collection methods can limit comparability across marine ecosystems. Recognizing this, SPOKE 1 has proactively addressed this gap by establishing **standardized sampling and experimental protocols** from the very beginning of the project. This harmonized approach not only ensures data consistency but also fosters comparability across diverse marine environments, enabling more robust meta-analyses and long-term monitoring efforts.

Limited Predictive Capabilities. Predicting biodiversity responses to environmental change remains a challenge due to the complexity of species interactions and ecosystem dynamics. However, a major opportunity lies in the integration of **Joint Species Distribution Models (J-SDMs)**, a novel approach that allows researchers to model not only species distributions but also their **ecological interactions**. Within SPOKE 1, a concerted effort is being made to develop **mechanistically based J-SDMs**, which will significantly enhance predictive capacity and improve ecosystem management under future climate and anthropogenic scenarios.

Insufficient Conservation/Restoration Success Metrics, tools and methodologies. The absence of standardized metrics, **tools and methodologies** to assess present conservation settings and restoration effectiveness has historically hindered the evaluation and implementation of marine conservation efforts. However, within SPOKE 1, recent **comprehensive review efforts,** knowledge acquisition and application of new technologies have provided **a clearer framework for measuring conservation/restoration success,** further expanding present settings. By consolidating best practices and identifying key indicators, these advancements will help refine conservation/restoration strategies and improve long-term ecological outcomes.

Major opportunities

One of the greatest opportunities emerging from SPOKE 1 is the unprecedented synergy among hundreds of researchers, spanning multiple institutions and disciplines, who are working collaboratively towards shared goals. This large-scale coordination has enabled:

- the adoption of **standardized methodologies**, ensuring data consistency and comparability;
- the establishment of **large-scale biodiversity monitoring efforts**, leveraging both traditional and emerging technologies;
- the integration of **cutting-edge modelling approaches**, bridging the gap between mechanistic and empirical research;
- the enhancement of **data accessibility** through centralized platforms like the Gateway Geo-portal;
- the fostering of **policy-relevant research**, ensuring that scientific advancements directly inform conservation and management actions.

By leveraging these opportunities, **SPOKE 1 is not only addressing existing knowledge gaps with the identification of present baselines but also shaping the future of marine biodiversity science**, setting a precedent for coordinated, impactful research at a national and international scale.

Research & Innovation priorities

The research and innovation priorities of SPOKE 1 align with the overarching goals of the **National Biodiversity Future Center (NBFC)**, focusing on marine biodiversity assessment, monitoring, conservation, restoration, and sustainable management. Below, each major activity line is detailed with its **specific research and innovation priorities**. SPOKE 1 is at the forefront of **marine biodiversity research and innovation**, driving advancements in **monitoring, restoration, conservation and sustainable management**. The coordinated effort across multiple institutions is **bridging scientific knowledge with cutting-edge technology**, ensuring that biodiversity research translates into tangible conservation actions and sustainable policy development.

1. Marine Biodiversity Monitoring & Assessment

Research Priorities:

- develop and implement **standardized methodologies** for biodiversity assessment across multiple scales and marine habitats;
- enhance **long-term ecological monitoring networks** to detect biodiversity trends, including the effects of climate change and human activities;
- improve **marine biodiversity mapping** using remote sensing, **eDNA**, and **AI-driven image analysis**;
- integrate **Joint Species Distribution Models (J-SDMs)** and functional trait-based approaches to understand community dynamics;
- improve present knowledge about present conservation settings in Italy, providing insights into the current effectiveness of Italian MPAs in advancing marine biodiversity conservation while contributing to international conservation goals at national level, such as the "30×30" initiative.

Innovation Priorities:

- deploy **autonomous underwater vehicles (AUVs)** and real-time **sensor networks** also using Underwater IoT, for continuous monitoring;
- enhance interoperability of data sources through the **Gateway Geo-portal**, ensuring seamless access to biodiversity information for researchers and decision-makers;
- apply **machine learning** to analyze big data from environmental sensors and monitoring programs.

2. Ecosystem Functioning & Biodiversity Dynamics

Research Priorities:

- investigate the role of **marine biodiversity in underpinning ecosystem services** such as carbon sequestration, coastal protection, and fisheries productivity;

- improve understanding of **species interactions and trophic dynamics**, integrating functional ecology with traditional biodiversity assessment;
- evaluate the **impacts of climate change and anthropogenic pressures** on key marine species and habitats.

Innovation Priorities:

- develop **predictive ecological models** linking biodiversity to ecosystem functioning under different environmental scenarios.
- Utilize **metagenomics and microbiome research** to study biodiversity at the microbial level.
- Apply **Dynamic Energy Budget (DEB) models** to quantify energy flow across trophic levels.

3. Restoration & Conservation of Marine Habitats

Research Priorities:

- Understanding present status of marine conservation and support national process to reach CBD targets
- define **best practices for marine conservation/restoration**, focusing on key habitats such as **seagrass meadows, coralligenous reefs and soft-bottom communities**.
- Develop **genetic and functional biodiversity indicators** to measure restoration success.
- Assess the **effectiveness of active vs. passive restoration** approaches in different environmental settings.

Innovation Priorities:

- develop **bio-engineered solutions** (e.g., artificial reefs, bio-inspired substrates) to enhance natural recruitment of species.
- Integrate **remote sensing and UAV monitoring** to track the effectiveness of conservation/restoration efforts.
- Utilize **biotechnology tools** (e.g., stress-resistant strains for restoration purposes).

4. Sustainable Management of Marine Resources

Research Priorities:

- assess the impacts of **fishing, aquaculture and coastal development** on marine biodiversity.
- Explore strategies for **ecosystem-based fisheries management** (EBFM) and **sustainable mariculture**.
- Develop **spatial planning frameworks** integrating biodiversity conservation/ restoration into maritime policies.

Innovation Priorities:

- apply **blockchain technology for traceability** in sustainable seafood supply chains.
- Develop **decision-support tools** to guide policymakers in marine spatial planning.

- Utilize **bioeconomic models** to evaluate trade-offs between conservation and resource use.

5. Biodiversity Data Infrastructure & Digital Innovation

Research Priorities:

- enhance **data harmonization and integration** across national and international biodiversity databases.
- Develop **big data analytics** for marine biodiversity research.
- Standardize biodiversity assessment protocols across **national monitoring programs**.

Innovation Priorities:

- strengthen the **Gateway Geo-portal** for real-time biodiversity data access.
- Develop **AI-driven predictive models** for biodiversity forecasting.
- Implement **open science frameworks** for marine biodiversity research, ensuring transparent data sharing and collaboration.

6. Citizen Science & Public Engagement

Research Priorities:

- investigate the effectiveness of **citizen science** in biodiversity monitoring and conservation efforts.
- Assess the **socio-economic value of biodiversity conservation**, linking biodiversity to local economies.
- Develop methodologies for **integrating indigenous and local knowledge** into conservation strategies.

Innovation Priorities:

- create **mobile applications** and digital tools for citizen engagement in biodiversity monitoring.
- Develop **immersive educational programs** using VR and AR to enhance public awareness of marine ecosystems.
- Implement **gamification strategies** to increase participation in biodiversity conservation initiatives.

Some of these possible innovation priorities dealing with Citizen Science & Public Engagement will be developed inside the Biodiversity Sampling Week 2025 campaign.

Expected Impacts

The activities within SPOKE 1 are designed to generate **scientific, economic and societal impacts**, reinforcing the **importance of biodiversity monitoring, conservation and restoration** for sustainable development. Below, we outline the key expected impacts across these dimensions.

1. Scientific and Technological Impacts

Advancing Marine Biodiversity Science

- **Standardization of biodiversity monitoring**: SPOKE 1 is addressing one of the major knowledge gaps in marine biodiversity research: the lack of standardized methodologies. By developing unified monitoring protocols and innovative tools, the project will enable comparable and reproducible biodiversity assessments at national and international levels, finally improving conservation/restoration strategies.
- **Development of next-generation monitoring tools**: the creation of connected sensor networks, biomimetic sensors and high-resolution underwater multi-sensors will revolutionize how biodiversity and environmental variables are monitored, offering real-time, cost-effective solutions.
- **Pioneering ecological and predictive modelling**: the implementation of Dynamic Energy Budget (DEB)-based models, Joint Species Distribution Models (J-SDMs) and other mechanistic models will enhance our ability to predict biodiversity shifts under climate change scenarios, providing essential insights for conservation strategies.
- **Bridging science and decision-making**: the Spatial Geoportal will integrate diverse marine biodiversity datasets, making scientific information accessible to policymakers, conservationists, and researchers, thus facilitating science-based decision-making. Assess present conservation status and plan new conservation and restoration areas to reach CBD targets, evaluating biodiversity within and outside Marine Protected Areas, analyzing the management success of MPAs, considering their conservation objectives.

2. Economic Impacts

Enhancing the Blue Economy and Marine-Based Industries

- **Sustainable fisheries and aquaculture**: by providing real-time data on biodiversity and environmental conditions, the tools developed in SPOKE 1 will support sustainable fisheries management, reducing the risks of overfishing and habitat degradation.
- **Carbon sequestration and blue carbon markets**: the development of ShinyApps for ecosystem service valuation (e.g. *Posidonia oceanica* carbon sequestration models) will provide a framework for marine carbon credit markets, attracting investments in nature-based solutions for climate mitigation.
- **Marine Spatial Planning (MSP) and Coastal Zone Management**: the integration of biodiversity and environmental data into decision-making tools will support economic activities such as tourism, offshore energy development, and coastal urban planning, ensuring they are aligned with biodiversity conservation goals.
- **Creation of new marketable services**: products such as sediment core dating, marine habitat restoration techniques and bio-indicator-based monitoring systems will be commercially viable tools for environmental consultancies, regulatory bodies, and private industries.
- **Job Creation in the environmental sector**: the deployment of biodiversity monitoring technologies and restoration programs will lead to new employment opportunities in marine conservation, environmental consulting, and biotechnology, supporting the growth of green and blue economy sectors.

3. Social and Policy Impacts

Strengthening Societal Engagement and Awareness

- **Citizen science and public engagement**: by integrating citizen science initiatives into biodiversity monitoring (e.g. engaging local communities in marine species observation), SPOKE 1 fosters public participation in environmental conservation.

- **Biodiversity as a public good**: the development of biodiversity indicators and predictive models empowers communities to make informed decisions about local and regional environmental management, improving coastal resilience to climate change.
- **Improved public health through a one-health approach**: biodiversity conservation directly enhances ecosystem resilience and human well-being (i.e. thanks to the mechanistic link between biodiversity-ecosystem functioning-ecosystem services), particularly in coastal communities where marine resources are integral to local livelihoods and food security.
- **Policy alignment with European and global agendas**: the project supports EU Biodiversity Strategy 2030, the Marine Strategy Framework Directive (MSFD) and the UN Sustainable Development Goals (SDGs), ensuring that marine conservation aligns with international sustainability commitments.

By integrating cutting-edge science, innovative technology and socio-economic strategies, SPOKE 1 is setting a new paradigm for biodiversity conservation and management. Its expected impacts extend beyond academia, influencing policy-making, economic growth and societal well-being, making marine biodiversity a key asset for sustainable development.