BRIDGE-BS

ADVANCING BLACK SEA RESEARCH AND INNOVATION

FOR A SUSTAINABLE BLUE ECONOMY

BRIDGE Black Sea (BRIDGE-BS)

BRIDGE-BS was a Horizon 2020 project that advanced the Black Sea's marine research and innovation capacity in order to co-develop blue economy pathways under multiple stressors for the sustainable use of ecosystem services. It developed an ecosystem-based management framework to enable policy uptake and foster citizen engagement. The project ran from June 2021 to November 2025.

BRIDGE-BS partner organisations

The consortium consisted of 31 partners from 14 countries:

Introduction

The Black Sea is a semi-enclosed basin with 10 large, inflowing rivers. It has a maximum depth of 2,210m, and is the largest anoxic-sulfidic[1] water body on Earth. With unique habitats, abundant resources, and rich cultural heritage, the Black Sea is vital to its coastal communities, and the more than 160 million people inhabiting its watersheds. Black Sea ecosystem services[2] support a vibrant blue economy[3], with new technological innovations offering significant potential to further enhance its sustainability.

Several stressors negatively impact the Black Sea, including those relating to climate change (i.e. warming, acidification, deoxygenation), as well as eutrophication, marine litter, chemical pollution, overfishing, the introduction of invasive alien species, and war-related impacts[4]. These lead to biodiversity loss and are a threat to socio-ecological resilience[5]. Between the 1970s and the early 1990s, unsustainable levels of fishing, nutrient pollution and invasive species led to the weakening of Black Sea ecosystem resilience causing the collapse of its fisheries, widespread eutrophication and increased deoxygenation. However, the ecosystem has stabilised and partially recovered since the 2000s[6], likely due to better management, although it is still far from its previous healthier state.

Building on past and current projects and initiatives, BRIDGE Black Sea (BRIDGE-BS) developed new tools and capabilities to predict the long-term impact and emerging risks from multiple stressors. This enables the identification of a safe operating space, respecting ecosystem boundaries, within which a sustainable blue economy can flourish. It includes innovations in environmental monitoring, data integration, climate scenario modelling, analysis of the resilience of Black Sea ecosystems, their ecosystem services and tipping points[7], and risk assessments to support ecosystem-based management. Through co-development with local communities and policy makers, key management measures for a resilient and productive Black Sea were identified to ensure the long-term sustainability (to 2050 and 2100) of the Black Sea's blue economy.

1 Lacks oxygen in its bottom waters (i.e. is anoxic) and is rich in hydrogen sulfide, a toxic gas produced by microbes under anoxic conditions.

2 The benefits provided by the processes, functions and structure of the marine environment that directly or indirectly contribute to societal welfare, health and economic activities (https://www.marineboard.eu/valuing-marine-ecosystems)..

3 Well-established industries in the Black Sea include shipping, transport, port operations and logistics, shipbuilding and repair, fisheries and aquaculture, and tourism. Emerging industries include energy and offshore resources, blue biotechnology, defense and maritime security.

4 For more information on war-related pollution in the Black Sea see: https://black-sea-maritime-agenda.ec.europa.eu/safeguarding-black-sea-region-results-regional-roundtable-war-related-pollution

5 The capacity of natural and socioeconomic systems to persist, adapt or transform when faced with disturbances, whilst maintaining their essential functions (https://www.marineboard.eu/publications/building-coastal-resilience-europe p14).

6 https://pubmed.ncbi.nlm.nih.gov/27643946/

7 The critical point at which a transition to a new state is triggered, and a return to the previous state is difficult or impossible (https://www.marineboard.eu/publications/building-coastal-resilience-europe).

New knowledge and predictive tools to evaluate risks from multiple stressors

BRIDGE-BS expeditions, surveys and model results have provided updated understanding of the current status of the Black Sea and the impact of multiple stressors. Pilot sites (Figure 1) were used as focal points for research, and various offshore areas were also surveyed. In addition, harmonised marine monitoring methods were developed for implementation across the region.

Environmental assessments[8] show that:

- The Black Sea has warmed at least 2.6 °C since 1980, which is faster than the global average of 0.6 °C;
- Preliminary data from the Western Black Sea indicate that nitrate levels have declined from 8 to 5 µm between 1988 and 2022, however local eutrophication events still occur;
- The Black Sea remains oxygen poor, and future warming[9] could further shrink the upper oxygen-rich layer; and
- Toxic hydrogen sulphide is present as shallow as 80 m in central parts of the Black Sea, posing risk to blue economy sectors. However, inflow of oxygen-rich water from the Mediterranean limits its build up, and should be included in future oxygen budgets to better predict risks.

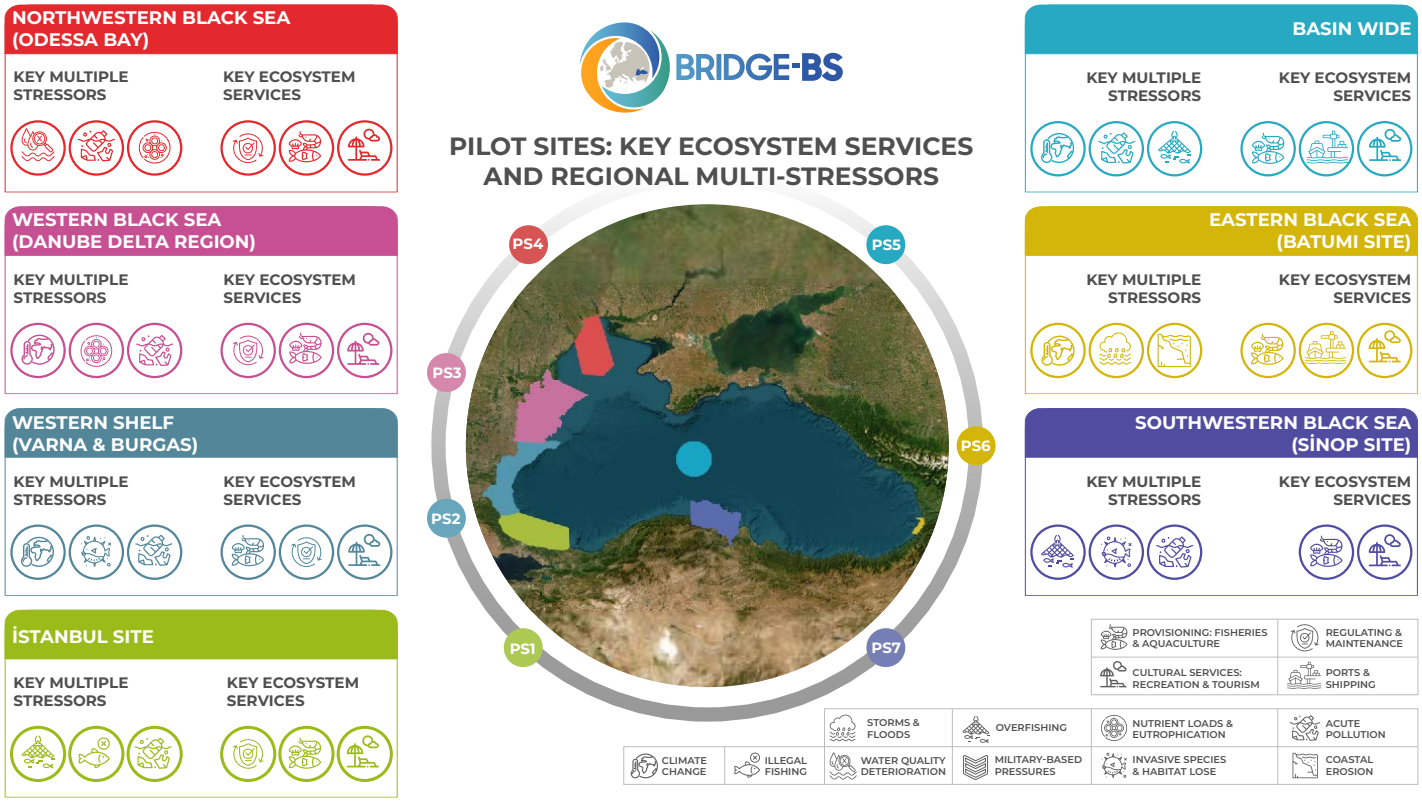

Figure 1: The pilot sites used as focal points for research, stakeholder engagement, and the development of sustainable blue economy scenarios. Each site has unique ecosystem services and stressors. Basin-wide assessments were also carried out.

[8] Deliverable 5.2: https://doi.org/10.5281/zenodo.17229148

[9] For an explanation of the link between warming and deoxygenation see p12: https://marineboard.eu/publications/ocean-oxygen

The **biotechnology potential**[10] of Black Sea marine resources has been demonstrated through the identification of thousands of industrial enzyme candidates from sediment microbes with potential use in biorefinery, bioremediation, pharmaceuticals, and food processing and processes (e.g. sulphide oxidation, denitrification).

A **basin-scale resilience assessment**[11] showed that the Black Sea ecosystem crossed a tipping point around 2005. From the late 1980s, the ecosystem was characterised by eutrophication, large numbers of jellyfish, and low numbers of zooplankton and fish. After 2005, fish stocks started to recover and phytoplankton and jellyfish numbers decreased, indicating a shift towards partial recovery, improved health and a more resilient ecosystem enabled by better management and positive changes in ecosystem structure. However, crossing future tipping points is still a possibility if temperatures continue to rise. Initial assessments using fisheries landing data show differences in tipping point dynamics between the north-western and southern Black Sea; thus resilience assessments are needed at both basin- and local- scales. This will require further research on ecosystem functioning and services at local- and regional- scales, improved local monitoring and data sharing, and better use of remote sensing and modelled data.

To move towards a cost-effective, integrated land-sea early warning system for multiple stressors, BRIDGE-BS tested and verified the use of a combination of **smart sensor technologies**[12] (Figure 2). These showed high feasibility for adoption and technological readiness up to full operational scale. A tailored approach is recommended for the integration of these methods into observation systems and national monitoring programmes. Sensors technologies tested include:

- Biogeochemical sensors for pH, carbon dioxide, and hydrogen sulphide tailored to the environmental conditions of the Black Sea. These can be used by local municipalities, national monitoring programmes, and offshore sectors to help cope with climate change risks;
- eDNA[13] as a non-invasive, rapid and cost-effective method for assessing biodiversity[14]. This can complement traditional trawling techniques as part of monitoring programmes that support conservation, sustainable fisheries management, and the identification of areas for protective measures;
- DNA metabarcoding[15] as a tool for rapidly monitoring phytoplankton biodiversity and Harmful Algal Bloom (HAB) species, with greater sensitivity in taxonomic resolution than traditional approaches using microscopy. This can enhance biodiversity assessments carried out by environmental agencies and monitoring authorities;
- A combination of underwater acoustic and aerial drone-based methodologies for rapid and non-invasive jellyfish detection, which can be applied to monitoring activities;
- Metagenomic[16] exploration of novel enzymes with biotechnological potential that can be scaled up for industrial applications; and
- Autonomous platforms such as gliders and scanfish (a towed vehicle), and fixed (benthic) platforms connected to mobile platforms with Internet of Things (IoT) technologies[17].

[10] Deliverable 5.4: https://doi.org/10.5281/zenodo.17229461
[11] Deliverable 3.2 will be available at https://zenodo.org/communities/bridge-bs/records?q=&l=list&p=1&s=10
[12] Deliverable 5.5 will be available at https://zenodo.org/communities/bridge-bs/records?q=&l=list&p=1&s=10
[13] Genetic material obtained from environmental samples such as sediment or water, without any obvious signs of biological source material. It is used as an indicator for the presence of species.
[14] Deliverable 5.3 will be available at https://zenodo.org/communities/bridge-bs/records?q=&l=list&p=1&s=10
[15] Sequencing genetic 'barcodes' to identify species from an environmental sample (e.g. water or sediment samples containing eDNA) to identify multiple species simultaneously (i.e. communities) and their abundances.
[16] The study of the structure and function of DNA from all the organisms in an environmental sample.
[17] A network of smart, interconnected underwater objects that enable monitoring of vast, unexplored areas of the Ocean.

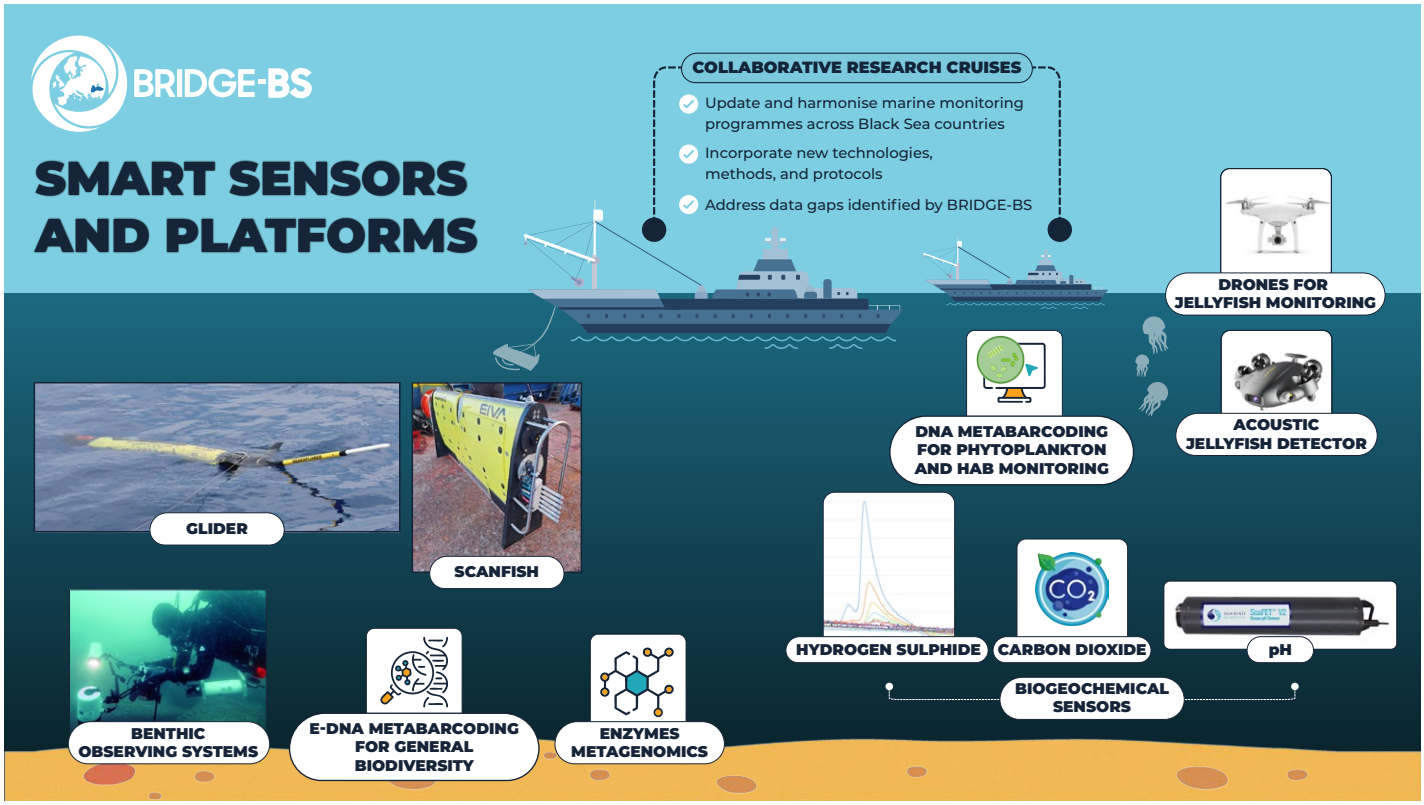

Figure 2: Overview of smart sensors and platforms tested during BRIDGE-BS collaborative research cruises.

Biological indicators have been tested as potential new **indicators of ecosystem resilience** to help assess how close the system is to a tipping point[18]. These include indicators of food web structure (trophic levels[19] of catches/populations) and the function of seafloor biological communities (bioturbation[20] and bioirrigation[21]). These can inform the development of restoration plans, including for coastal blue carbon habitats, and can be adapted for monitoring environmental status. Further testing of these indicators is required for their validation and future uptake.

The **BRIDGE-BS Digital Twin Ocean (DTO) demonstrator**[22] (Figure 3) is one of the key outputs of BRIDGE-BS, combining many of the tools developed. It aims to be a virtual representation of the Black Sea to support policy makers in informed decision making using what-if scenarios, trade-off analyses, and sectoral and stakeholder input. It integrates data from the BRIDGE-BS portal and database, high-resolution biophysical models of the Black Sea and its watershed, socio-economic scenarios, the resilience assessments, the Artificial Intelligence-based decision support tool, and the risk-based cumulative efect assessment tool (see below for individual descriptions of these). It defines current and future ecosystem status and risks, and develops risk management contexts and policy objectives for specific areas, focusing on ecosystem services and future pressure scenarios. The DTO demonstrator can be used to define ecosystem boundaries for a safe operating space for the Black Sea blue economy and to inform adaptive management.

18 Deliverable 3.1 will be available at https://zenodo.org/communities/bridge-bs/records?q=&l=list&p=1&s=10
19 Describes an organism's position in a food chain or food web based on how it obtains energy and nutrients.
20 The mixing and disturbance of sediments and soils by living organisms, such as through burrowing, feeding, and plant root activity.
21 The process by which organisms living in sediment actively exchange water and dissolved substances between the overlying water column and the sediment by burrowing, pumping, and feeding.
22 https://bridgeblacksea.org/index.php/black-sea-dto/; https://dekosim.ims.metu.edu.tr/digitaltwin/

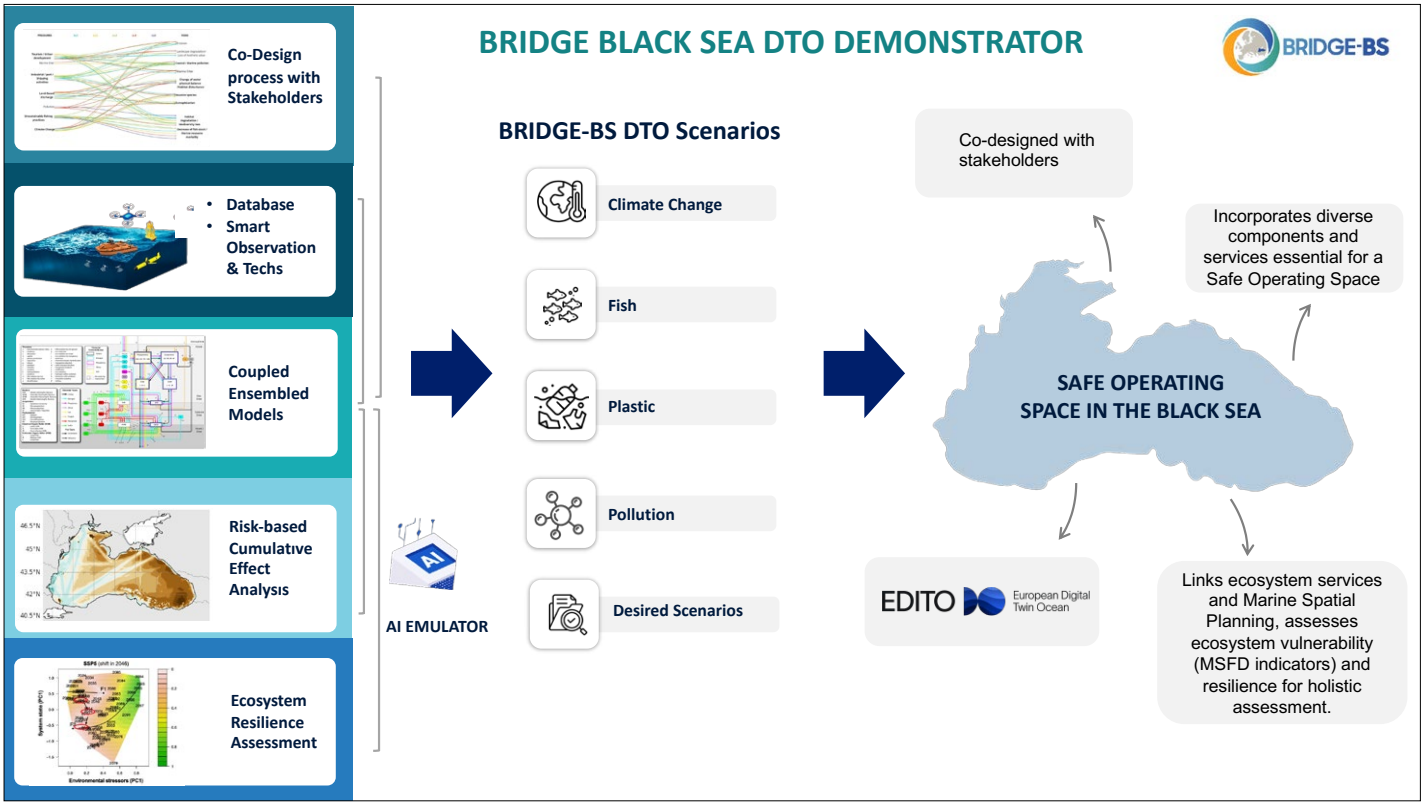

Figure 3: Overview of the BRIDGE-BS Digital Twin Ocean (DTO) demonstrator.

The **BRIDGE-BS portal and database**[23] is an interdisciplinary platform that provides public access to methodology as well as physical, chemical and biological datasets from Black Sea observations and modelling generated from BRIDGE-BS, previous projects and other regional, European and global databases (including SeaDataNet[24], EMODnet[25], Sentinel[26], and the Black Sea Water Quality Database[27]).

The Marine Ecosystem and Climate Research Center (DEKOSİM[28]) of the Middle East Technical University will maintain the BRIDGE-BS portal, database, and the DTO demonstrator. It is also leading in the integration of the DTO demonstrator into the EDITO infrastructure[29], as part of the European DTO initiative.

An **Artificial Intelligence based decision support tool**[30] uses prototype machine learning models to analyse how the Black Sea ecosystem responds to multiple pressures and to inform adaptive management. The tool provides regional and pilot site-level analysis of cause-effect relationships between environmental pressures and forecasted biological responses. It also integrates basin-scale observational and model data to investigate more complex interactions across space and time. To improve the accuracy of this tool, physical and biogeochemical data gaps need to be filled, including full spatial time series from observations and/or model outputs. In the future, this tool may be used to support scenario testing and in the development of early warning systems for HABs or fisheries collapses.

A **risk-based cumulative effects assessment decision support tool**[31] was developed for stakeholders to understand and predict spatial hotspots of environmental impacts of cumulative pressures from blue economy sectors. Impact scores from specific sectors are generated to test and assess future adaptive management strategies, which can support marine spatial planning. Further development of the tool depends on the integration of socio-economic data to link cumulative pressures to impacts on ecosystem services.

An **ensemble of Black Sea-specific high-resolution coupled models**[32] covering the full marine system can be used to assess the current and future impact of multiple stressors to help decision makers to understand current environmental status, assess trade-offs, develop management strategies, and revise regional and national maritime policies.

23 https://bridgeblacksea.org/index.php/bridge-bs-database-logged/
24 https://www.seadatanet.org/
25 https://emodnet.ec.europa.eu/en
26 https://sentinels.copernicus.eu/
27 https://blackseadb.org/
28 https://dekosim.metu.edu.tr/
29 https://edito-infra.eu/
30 Deliverable 4.3 will be available at https://zenodo.org/communities/bridge-bs/records?q=&l=list&p=1&s=10
31 Deliverable 4.4 will be available at https://zenodo.org/communities/bridge-bs/records?q=&l=list&p=1&s=10
32 Deliverable 2.3 will be available at https://zenodo.org/communities/bridge-bs/records?q=&l=list&p=1&s=10

The **blue economy observatory for the Black Sea**[33] is an online platform that provides a dashboard for monitoring the sustainable development of the Black Sea blue economy. It provides an overview of the current status of blue economy sectors in each Black Sea country, and various future scenarios developed by BRIDGE-BS. Policy makers, researchers, and businesses can gain insight to inform evidence-based decision making to support regional and national level blue economy policies. It also highlights the current regional sustainability deficiencies, data gaps, and data access issues. Data from the observatory feeds into the BRIDGE-BS DTO demonstrator and future plans are being developed for the long-term maintenance of the observatory.

The **BRIDGE-BS Black Sea accelerator**[34] operated in cooperation with the DOORS Black Sea project[35] and supported 15 startups, small to medium-sized enterprises, and researchers to scale up innovative solutions and sustainable blue economy businesses in a variety of sectors ranging from fisheries and aquaculture to maritime transport.

Two **BRIDGE-BS High Tech Summits** for the Black Sea showcased innovations to a regional audience and promoted dialogue among diverse blue economy actors. Ideas were explored for new services and products that bring value and jobs, including for plastic management, energy, sustainable local aquaculture, and algal biotechnology.

Training and capacity building activities (Figure 4) strengthened the Black Sea research community. These include the Virtual Blue Career Centre[36], the PhD programme on blue economy[37], Young Ambassadors Programme[38], Summer and Winter Schools[39], and a science-policy-technology Massive Open Online Course[40] (MOOC). Local stakeholders were engaged through living labs[41], local and regional policy makers through a series of participatory events, and the general public made aware of the importance of a healthy Black Sea and sustainable blue economy through Ocean Literacy activities, the Black Sea Ocean Literacy Network[42] and citizen science campaigns[43].

Visions for the future of the Black Sea

Key projections for the future state of the Black Sea under different climate change scenarios have been developed using coupled physical-biogeochemical models that have been downscaled to provide local-scale information. These indicate that sea surface temperature will increase between 0.9 to 3.8 °C by 2100 depending on future carbon dioxide emissions. This will impact oxygen concentration, which is expected to decrease by at least 9%. Biodiversity is predicted to decline, and ecosystem dynamics and fisheries productivity to be altered. In addition, BRIDGE-BS models have provided future projections of plastic pollution based on socio-economic scenarios with different levels of economic growth, population, and potential environmental policies affecting plastic input from rivers and coastal cities[44]. These projected increases in stressors will impact the resilience of the Black Sea, increasing the need for caution to ensure the sustainable development of blue economy activities.

Three types of scenarios (see paragraphs below) have been created to inform the development of adaptive management recommendations and future actions for blue economy sectors to align with desired sustainability objectives[45]. These scenarios are included in the Black Sea DTO demonstrator and should be used to update Black Sea sustainable blue economy strategies and policies. They can also be used by blue economy operators to make decisions on where to channel innovation and investments, and on appropriate management measures to ensure sustainability.

33 https://blackseabeo.eu
34 https://bridgeblacksea.org/index.php/black-sea-accelerator/; Deliverable 7.3 will be available at https://zenodo.org/communities/bridge-bs/records?q=&l=list&p=1&s=10
35 https://www.doorsblacksea.eu/
36 https://bridgeblacksea.org/index.php/virtual-blue-career-center/
37 https://bridgeblacksea.org/index.php/2024/10/04/bridge-bs-phd-students-are-advancing-black-sea-research/
38 https://bridgeblacksea.org/index.php/young-ambassadors/
39 Deliverable 9.5 will be available at https://zenodo.org/communities/bridge-bs/records?q=&l=list&p=1&s=10
40 https://bridgeblacksea.org/index.php/bridge-black-sea-mooc/; https://ocw.metu.edu.tr/course/view.php?id=365
41 A space where local communities, experts, and decision makers get together to develop, test and improve ideas.
42 https://bridgeblacksea.org/index.php/ocean-literacy-network/
43 Deliverable 9.6 will be available at https://zenodo.org/communities/bridge-bs/records?q=&l=list&p=1&s=10
44 Deliverable 2.4 will be available at https://zenodo.org/communities/bridge-bs/records?q=&l=list&p=1&s=10
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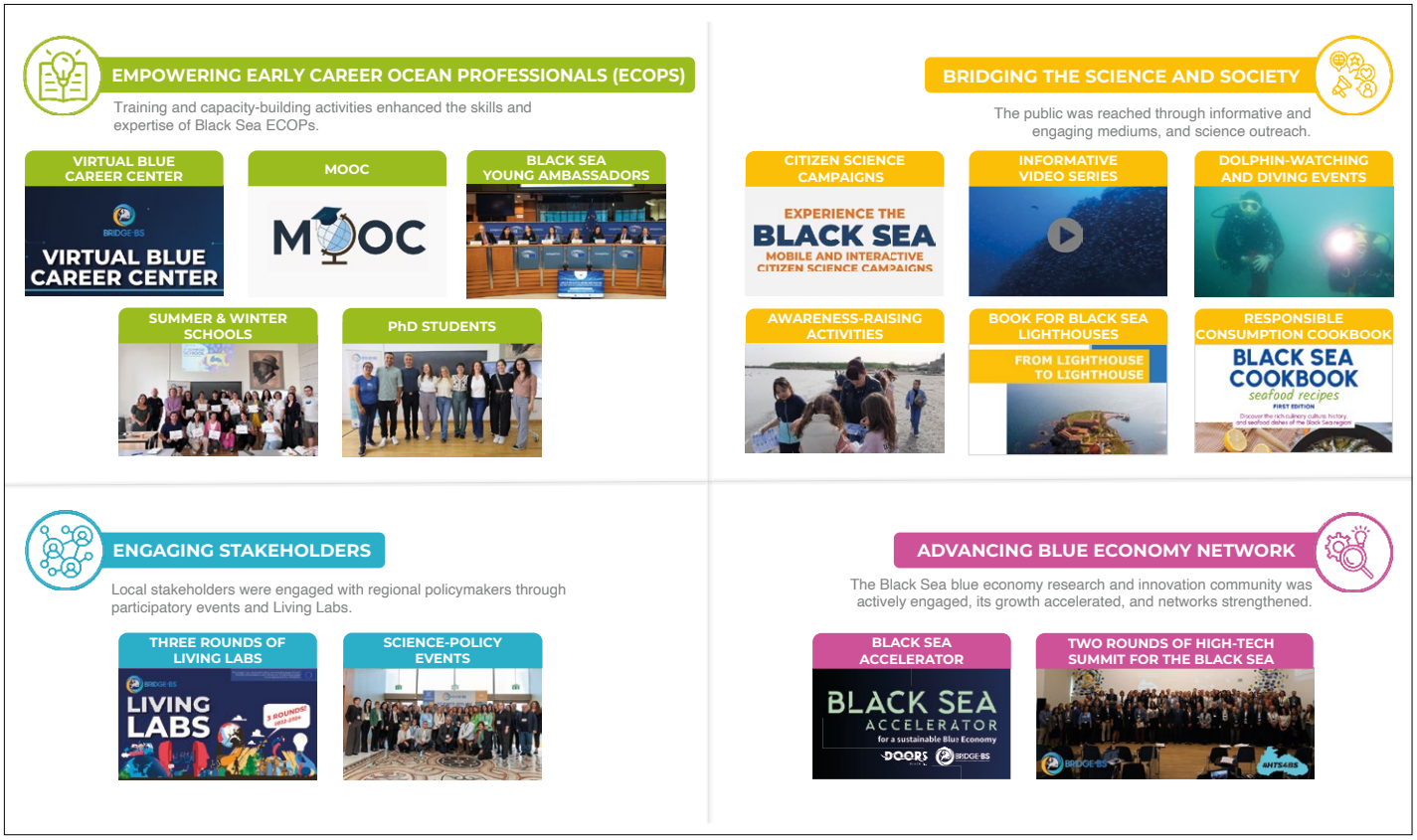

Figure 4: Overview of training and capacity building activities supported by BRIDGE-BS.

2050 sustainable blue economy imaginaries[46] offer plausible future trajectories for the Black Sea's blue economy for 2050, assuming that sustainability is achieved. They were developed at basin- and pilot site- scales, using a foresight exercise that took into account varying innovation (technological to social) and governance (sea basin to local) conditions, and local stakeholder perspectives. These imaginaries provide a way for decision makers and wider stakeholders to foster collective thinking and strategic dialogue to navigate future challenges and opportunities, and to make decisions under uncertainty. They can be used by national administrations to support the development of blue economy strategies.

Desired scenarios[47] combine the physical-biogeochemical model results, sustainable blue economy imaginaries, and perspectives from local actors gathered through the living labs. They highlight preferred and realistic scenarios for marine and terrestrial activities that influence marine ecosystems and resources, and help support the development of a sustainable blue economy taking into account climate change. The cumulative effect assessment tool was used to predict future environmental impacts of these scenarios and showed that at basin-scale fishing, maritime transport and nutrient inputs from terrestrial sources would cause the most environmental impact, while aquaculture or offshore wind energy would cause more local impacts. These scenarios should inform evidence-based policy-making, for example for marine spatial planning by national administrations.

Transformative pathways[48] for the Black Sea blue economy were co-designed by coastal community stakeholders during six participatory living labs across the pilot sites, engaging a total of 162 organisations. These pathways can lead to shifts to a more sustainable, resilient and equitable state. Stakeholders identified challenges for a sustainable blue economy, agreed on a vision for 2050, and identified actions to transform blue economy sectors to reach this vision. Sectors analysed include aquaculture, tourism, marine renewable energy, marine environmental observation and management, fisheries, and the port and shipping sectors. Key actions identified include advancing technologies, digitalisation, training, and community engagement. Although stakeholders did not identify the need for holistic systems thinking, these actions do support the social-ecological resilience of coastal communities via learning and participation (i.e. monitoring, capacity building, stakeholder engagement).

[46] https://bridgeblacksea.org/index.php/2025/03/14/bridge-bs-takes-you-to-the-future-of-the-black-sea-with-2050-sustainable-blue-economy-imaginaries-for-the-black-sea-report/

[47] Deliverable 4.4 will be available at https://zenodo.org/communities/bridge-bs/records?q=&l=list&p=1&s=10

[48] Deliverable 6.3 will be available at https://zenodo.org/communities/bridge-bs/records?q=&l=list&p=1&s=10

Future research and policy needs

To limit the impact of human activities on the health and resilience of the Black Sea, preserve core ecosystem services and provide a safe operating space for the development of a sustainable blue economy, the following actions should be achieved within the next five years.

Recommendations for policy makers

- **Develop and update blue economy strategies, regulations, and enforcement** at national and regional level to align with the adaptive management recommendations developed by BRIDGE-BS, including to: prioritise small-scale fisheries; reinforce sustainable fisheries policies and ecosystem-based fisheries management; adopt green transport solutions for vessels and port infrastructure; develop offshore wind energy and sustainable aquaculture; reduce pollution from watersheds and coastal areas; and promote innovative and sustainable tourism;
- **Further strengthen the science-policy interface and dialogue** in the Black Sea region by improving coordination between and supporting existing mechanisms e.g. the Black Sea Commission (BSC), Black Sea Economic Cooperation (BSEC), and the General Fisheries Commission for the Mediterranean and Black Sea (GFCM);
- **Implement systems and resilience thinking in the management** of the Black Sea blue economy, and integrate participatory stakeholder approaches into adaptive management strategies using BRIDGE-BS scenario development and stakeholder engagement methods;
- **Develop a dedicated financial framework for blue economy grants, financial incentives, and regional coordination** among national level financing actors, and national and regional acceleration/incubation mechanisms[49]. A long-term framework to support future editions of the Black Sea Accelerator and the High Tech Summit to consolidate its role as a reference forum for regional innovation in the Black Sea should be established;
- **Implement a consistent ecosystem-based approach to marine spatial planning** in each Black Sea country and at basin-scale using the BRIDGE-BS tools. This will strengthen and ensure effective management of the current network of marine protected areas, including the regulation of human activities (e.g. fisheries, transport, tourism) in and around MPAs;
- **Update and harmonise marine monitoring programmes** across Black Sea countries based on newly tested technologies, methods, protocols and data gaps identified within BRIDGE-BS. In addition, a regional monitoring framework should be established to harmonise socio-economic data collection and open access across Black Sea countries to feed into the blue economy observatory and link to the BRIDGE-BS DTO demonstrator; and
- **Support the continuation and expansion of capacity building activities** developed under BRIDGE-BS including the Massive Open Online Course, Black Sea Young Ambassador programme, Virtual Blue Careers Centre, and the Black Sea Ocean Literacy Network.

[49] Deliverable 7.2 will be available at https://zenodo.org/communities/bridge-bs/records?q=&l=list&p=1&s=10

Recommendations for research and operational services

- **Further develop, coordinate, and deploy smart sensor technologies,** combined with traditional observational systems;
- **Continue to develop standardised methodology** for an integrated land-sea multiple stressor early warning system to harmonise monitoring;
- **Consolidate the integration of BRIDGE-BS observation data, models, and predictive management tools into the BRIDGE-BS Digital Twin Ocean (DTO) demonstrator,** and include new scenarios, use-cases and functionalities catering to stakeholder needs. Links between the BRIDGE-BS DTO, Copernicus Marine Service, EMODnet, and the European DTO should be defined and organised;
- **Facilitate training for policy makers on the tools** developed within BRIDGE-BS;
- **Include knowledge gaps in an updated version of the Black Sea Strategic Research and Innovation Agenda (SRIA),** including: future resilience and tipping point assessments; under-monitored sources of stressors and improved links between pressures and drivers; model downscaling for higher resolution at local scale; identifying the boundaries of a safe operating space; further advancement of oxygen and hydrogen sulfide mapping; Ocean acidification assessments; Danube influence on the Black Sea; validation of the industrial potential of biomolecules; socio-ecological research using scenarios; and mitigation of war-related pollution in the Black Sea; and
- **Provide support to rebuild the research capacity of Ukraine.**

These recommendations support the implementation of policies, strategies and initiatives at a global level (e.g. the Kunming-Montreal Global Biodiversity Framework, the UN Decade of Ocean Science for Sustainable Development, the Sustainable Development Goals), EU level (e.g. EU Ocean Pact, EU Water Resilience Strategy, European Green Deal, EU Biodiversity Strategy, Marine Strategy Framework Directive, Marine Spatial Planning Directive, Nature Restoration Regulation, Birds and Habitats Directives, Mission Restore our Ocean and Waters), and regional level (e.g. Bucharest Convention, EU Black Sea Strategy, EU Danube Strategy, Black Sea Synergy, Common Maritime Agenda, Black Sea Strategic Research and Innovation Agenda and Implementation Plan). They will support the implementation and enforcement of this complex policy framework in the Black Sea region by all actors, particularly at the local level. More information on specific actions for stakeholders to implement these recommendations can be found in the '2030 Blue Roadmap for the Black Sea[50]'.

[50] Deliverable 8.4 will be available at https://zenodo.org/communities/bridge-bs/records?q=&l=list&p=1&s=10

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