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# A blueprint for integrating scientific approaches and international communities to assess basin-wide ocean ecosystem status

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Ocean ecosystems are at the forefront of the climate and biodiversity crises, yet we lack a unified approach to assess their state and inform sustainable policies. This blueprint is designed around research capabilities and cross-sectoral partnerships. We highlight priorities including integrating basin-scale observation, modelling and genomic approaches to understand Atlantic oceanography and ecosystem connectivity; improving ecosystem mapping; identifying potential tipping points in deep and open ocean ecosystems; understanding compound impacts of multiple stressors including warming, acidification and deoxygenation; enhancing spatial and temporal management and protection. We argue that these goals are best achieved through partnerships with policy-makers and community stakeholders, and promoting research groups from the South Atlantic through investment and engagement. Given the high costs of such research (€800k to €1.7M per expedition and €30–40M for a basin-scale programme), international cooperation and funding are integral to supporting science-led policies to conserve ocean ecosystems that transcend jurisdictional borders.

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Oceanic ecosystems are experiencing rapid environmental change and over the next century are likely to undergo substantial shifts and reach tipping points in the function, and thus in the services they provide to humankind. Technological innovation and changing markets have modified how we interact with the marine environment[1] leading to increased shipping traffic and vessel sizes, expansion of fisheries further offshore[2], emerging exploration for deep-sea minerals, bioprospecting, and hydrocarbon extraction[3]. Ecosystem resilience can mitigate the combined pressures from climate change and human activities but it depends on their status (e.g., isolation vs. connectivity, distribution and diversity, temporal stability, functioning), our understanding of which is rarely transdisciplinary and also hampered by the persistent strong imbalances between the global North and South. This has serious implications for effective ocean governance, particularly as climate–ocean interactions and ecosystem status should be assessed the same way across and between ocean basins. The scientific community's ability to formulate knowledge-based measures to address the climate and biodiversity crises largely rests on finding ways to tackle geographic disparities in availability and access to scientific infrastructure, data, and services[4] and on our ability to build robust human networks to bridge the geographical divide.

Here we present an 'Atlantic Science Blueprint' showing how we can change this situation. Our Blueprint emphasises the importance of developing innovative technologies, sharing human and technical capacities (including access to offshore vessels and equipment) and incorporating marine environmental and human activities data generated from diverse sources, including industry and local ecological knowledge. This is vital if we are to work effectively between nations to translate knowledge into 'actionable science' and an understanding relevant to shaping ocean policy and governance regimes at the ocean basin scale.

## The Atlantic science Blueprint

Our Blueprint is founded on whole-ocean observations implemented by (1) an autonomous floating sensor fleet with funding and participation by an international consortium (ARGO floats), (2) coordinated transatlantic oceanographic monitoring arrays, and (3) innovative cost-effective technologies and ocean models to expand the spatio-temporal scales of observations and so provide the physical oceanographic framework for ecosystem studies. To overcome disparities in research and equipment capacity, detailed research co-design between North and South Atlantic must include shared access to offshore vessels, data, training, and supporting infrastructure. It must include effective capacity building and wider engagement, and be completed in parallel with science planning. Barriers created by limitations in funding structure, travel restrictions, or more recently, pandemic-related regulations mean this remains challenging.

We advance six priorities (Fig. 1) that target fundamental gaps in our understanding of basin and regional-scale oceanography (Priority 1) and ecosystem resilience (distribution, connectivity, responses to climate change and multiple stressors; Priorities 2–4). It allows us both to deliver an integrated assessment of ecosystem status and dynamics and to understand resilience to global change in the deep and open Atlantic Ocean. We argue that these four research priorities must be grounded in close collaboration, capacity development and meaningful engagement with key stakeholders (Priority 6) to inform management priorities, aggregate, standardise and disseminate research data and products through regional and global platforms (Priority 5) and by embedding work at the science–policy interface throughout (Priority 6). Between 2019 and 2023, these six priority areas are being developed through an international research programme 'iAtlantic, an integrated assessment of Atlantic marine ecosystems in space and time' (www.iatlantic.eu).

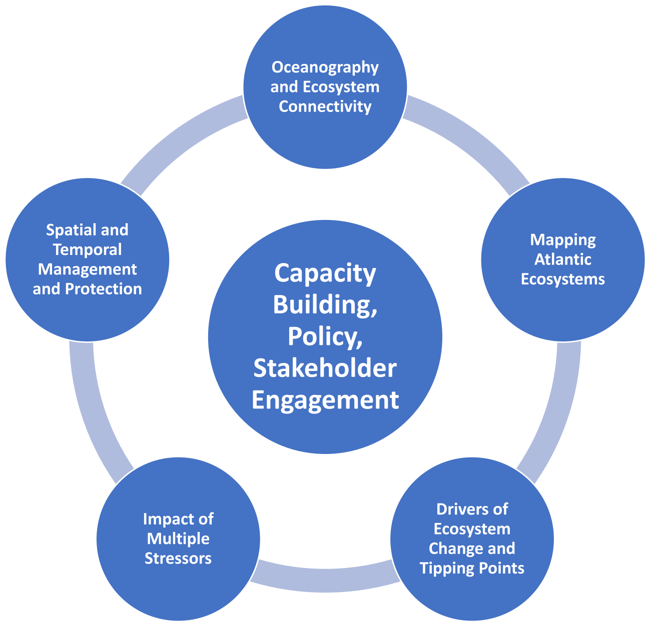


**Fig. 1 Priorities for action.** The six priorities for action to assess deep and open ocean ecosystems that will create the actionable scientific evidence needed for their long-term sustainable management.

**Priority 1—Atlantic oceanography and ecosystem connectivity**. Marine ecosystem status, dynamics and species dispersal are driven by oceanographic conditions. In the Atlantic, the largest ocean-scale features are wind-driven currents and the Atlantic Meridional Overturning Circulation (AMOC)—the overturning ocean conveyor that distributes heat and energy and regulates our climate. These currents are directly linked and controlled by basin-scale forcing and dynamics at inter-annual to decadal timescales[5]. While inter-annual variability masks a potential longer-term anthropogenic decline in the overturning strength[6], it is likely AMOC is experiencing its weakest state in the last 1600 years[7].

Understanding and predicting AMOC change requires a comprehensive observing system that needs to cover both North and South Atlantic[8]. In addition to the 20-year-long RAPID-MOCHA oceanographic sensor array in the subtropical North Atlantic, the arrays in the subpolar North Atlantic (OSNAP array[9]) and the subtropical South Atlantic (SAMOC/SAMBA arrays[10]) need upgrading to include ecosystem-relevant physical and biogeochemical measurements. Using high-resolution climate-based predictions of past and future ocean circulation, with a focus on eddy-rich resolutions to support observational records and species dispersal studies, we can simulate the past 60 years under realistic forcing[11], thus allowing very detailed comparisons with instrumental observations[5,12]. These ocean general circulation models include basin-scale configurations at 1/20° for the pan-Atlantic (VIKING20X[5]) and Agulhas Current region (INALT20[13]). The next 50 years can be forecast by coupling the model to an active atmosphere, e.g. simulating global warming scenarios[14]. To address the role that basin-wide circulation plays in the tidally driven dynamics of near-bottom currents which are the local physical environment supporting deep-sea benthos, we use the output from VIKING20X and INALT20 to drive ultra-high-resolution models, simulating regional hydrography at a 500 m pixel resolution.

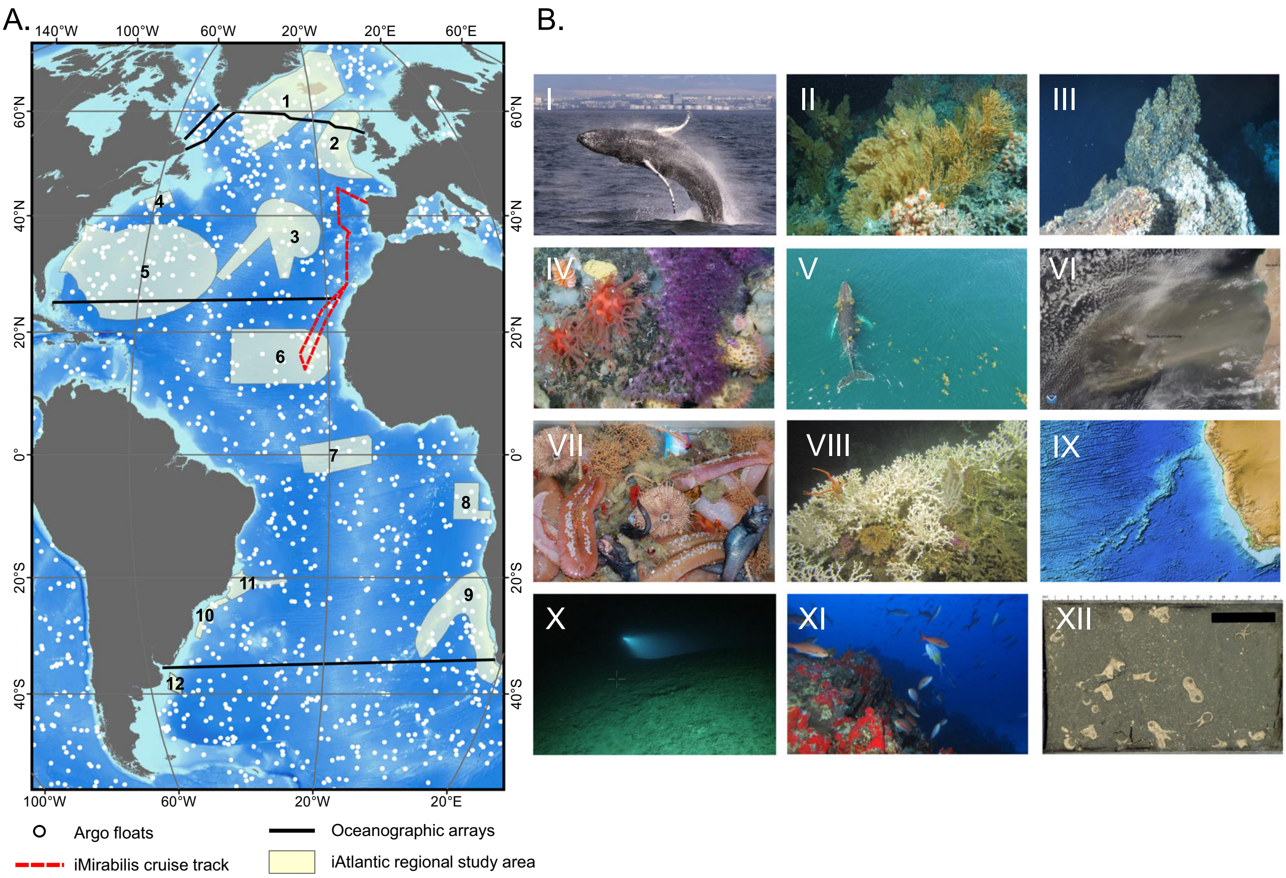


**Fig. 2 Study regions and focal species, ecosystems or key processes. A** iAtlantic study regions mapped alongside transatlantic oceanographic monitoring arrays and Argo float locations and the track of iAtlantic's 2021 "iMirabilis2" research and capacity building expedition. **B** Images illustrating focal species, ecosystems or key processes in each region: (I) Subpolar Mid-Atlantic Ridge (MAR) open ocean ecosystem off Iceland—a humpback whale breaching offshore Iceland (Image Credit: Stefán Ragnarsson, Hafrannsóknastofnun); (II) Abyssal plain, submarine canyon and cold-water coral banks from the Rockall Trough to the Porcupine Abyssal Plain—a cold-water coral reef framework on Rockall Bank (Image Credit: J Murray Roberts, University of Edinburgh, JC073); (III) Cold-water coral and hydrothermal vent ecosystems, central Mid-Atlantic Ridge—vent mussel beds at Lucky Strike, Mid-Atlantic ridge (Image Credit: Ifremer[97]; (IV) Deep-sea canyons and open-ocean ecosystems, NW Atlantic—rocky substrate of the Gully canyon supporting diverse cold-water coral and sponge epifauna (Image Credit: Fisheries and Oceans Canada); (V) Subtropical open-ocean ecosystems of the Sargasso Sea—a humpback whale migrating through clumps of *Sargassum* weed (Image Credit: Andrew Stevenson, Whales Bermuda); (VI) Eastern tropical North Atlantic, Cabo Verde—here Saharan dust blown offshore Mauritania/Senegal is deposited around Cabo Verde where it helps fuel primary productivity (NASA MODIS Rapid Response Team, M. Scott); (VII) Equatorial deep/open ocean fracture zones—catch from a scientific trawl in the Romanche Fracture Zone (Image Credit: André Barreto, University of the Itajaí Valley (UNIVALI)); (VIII) Continental slope, margin and cold seep ecosystems from Angola to the Congo Lobe—cold-water coral reef in the hypoxic waters off Angola (Image Credit: MARUM—Center for Marine Environmental Sciences, University of Bremen); (IX) Abyssal plains and deep-sea ridge ecosystems of the Benguela Current from the Walvis Ridge to South Africa—bathymetric image showing the Walvis Ridge, stretching SW from the coast of Namibia (Image Credit: NOAA); (X) Deep-sea continental slope, banks and cold seep ecosystems off Brazil—a submersible illuminates a deep pockmark in Santos Basin (Paulo Sumida, University of São Paulo); (XI) Vitória-Trindade Seamount Chain off Brazil—Creole fishes *Paranthias furcifer* and the endemic wrasse *Clepticus brasiliensis* on Vitória Bank (Image Credit: Hudson Pinheiro, California Academy of Sciences); (XII) Cold-water coral banks in the Malvinas Upwelling Current off Argentina—the cut surface of a sediment core collected off Argentina showing abundant fossil cold-water coral fragments. Scale bar 5 cm (Image Credit: MARUM—Center for Marine Environmental Sciences, University of Bremen).

Forecasts to 2070 show just how complex oceanographic changes in the Atlantic are likely to be. Most subtropical surface water masses show increases in temperature and salinity but mid-water masses may become either warmer and saltier or cooler and fresher depending on location. Critically, evidence is growing that subsurface marine heatwaves will increase in intensity and frequency, with half the regions targeted by iAtlantic (Fig. 2) likely to experience them in the next 50 years. We need to study how these anomalies evolve so we can understand their implications for ecosystem function[15].

Hindcast and forecast modelling can be used to investigate the role of ocean circulation changes on ecosystem connectivity by exploring how marine populations stay connected through the dispersal of their passively drifting pelagic larvae or juveniles. OceanPARCELS[16] combined with biologically realistic larval behaviours[17–20] can simulate the spreading of several million particles on inter-annual to decadal timescales. By further combining this modelling with genomic approaches, it is possible to quantify demographic connectivity over a species' range and identify spatial isolates[21] with particular emphasis on the vulnerability of regional connectivity to changing ocean circulation patterns[22]. In iAtlantic, this approach is applied to a subset of amphi-Atlantic species such as reef framework-forming cold-water corals, cold seep and hydrothermal vent fauna.

**Priority 2—Mapping Atlantic ecosystems**. Habitat maps, including mapping confidence, are key tools supporting marine spatial planning and ocean governance. Atlantic maps show major gaps for even basic parameters like depth, with a strong imbalance between the North and South Atlantic. This is critical, as ecological insights increase with observational resolution[23], especially for ecosystems with abrupt transitions (e.g. seabed cliffs, abyssal hills) that change biodiversity patterns[24]. Since ecological patterns and processes occur across a wide range of scales there is no single optimal scale at which ecosystems should be studied[25] and we advocate mapping geomorphology, ecology and biology at a broad range of scales to understand the status and resilience of Atlantic ecosystems. With an area of >100 million $km^2$ and an average depth of 3600 m, this is a vast challenge in the Atlantic. The solution is a combination of increased, well-designed, nested mapping efforts, the use of 'opportunity' data generated by industry, and the development of innovative technologies to increase efficiency, improve accessibility and reduce costs both in data acquisition and analysis.

We divide the mapping requirements into three groups:

*Basin-scale (>1000 km across)*: Objective approaches to marine landscape classification[26] using machine-learning algorithms or automated cluster analyses[27,28] are revealing the broad-scale patterns in seabed habitats while basin-scale species distribution modelling is producing basin-scale predictions of where vulnerable marine ecosystem (VME) indicator and commercially important taxa occur under current and future climate scenarios[29].

*Regional scale (100–1000 km across)*: Highly integrated water column and seafloor mapping operations should combine data collection across multiple technologies and platforms. Regional predictive habitat mapping models show clear improvements in species predictions when physical oceanographic variables are included[30]. Data from beyond the scientific community, notably from industry, needs to be integrated. Automated GIS techniques to discriminate geomorphological features, including cold-water coral reefs, can rapidly increase data processing rates[31] and are now being applied for the first time to datasets from the South Atlantic.

*Local-scale ecosystem structure through ultra-high-resolution mapping (<1–10 km across)*: It is now possible to conduct centimetre to metre-scale integrated mapping activities in waters >200 m deep. Acoustic surveys of seabed features, including cliffs and overhangs, carried out using ROVs and AUVs, produce 3D ultra-high-resolution bathymetric maps[32] with ecological communities assessed using visual and targeted sampling. Photogrammetry using structure-from-motion techniques is increasingly applied to create 3D models of deep ecosystems[33,34] and to study species interactions using point pattern analysis[35].

Oceanographic observations and predictive habitat modelling allow species and biodiversity observations to be extrapolated to regional and ocean basin scales. These models can help determine survey and management priorities in the deep and open ocean[36] and can be linked to the biological traits[37] of key species to understand how important ecosystem services may be distributed over space[38].

Technological solutions to ecosystem mapping can be both low- and high-tech. For example, a new low-cost camera system deployed during iAtlantic to survey benthic ecosystems down to 1000 m has conducted >400 surveys on seamounts and portions of the Mid-Atlantic Ridge around the Azores covering >200 km of seabed[39] with deployments in the South Atlantic planned for 2023. At the high-tech end, autonomous underwater vehicles (AUV) combined with new sensors can massively increase the range of co-located observations we can make. iAtlantic recently demonstrated the technology to sample environmental DNA ("eDNA", DNA traces left by organisms when cellular material is shed into their environment via skin, excrement, etc.) during acoustic habitat surveys using a novel Robotic Cartridge Sampling Instrument (RoCSI). AUV surveys can also return many thousands of photographs a day, far beyond human processing[40] requiring artificial intelligence approaches using deep learning to classify taxa during ecosystem assessments[41] with parallel computing drastically reducing the time and costs of data processing[42].

By using these innovative technologies, alongside established methods, it is possible to tackle the immense challenge of working across an ocean at basin, regional and local scales.

**Priority 3—Drivers of ecosystem change and tipping points**. By identifying place-based risks and tipping points, managers can enhance monitoring and mitigation measures as the likelihood of ecosystem change increases. This has helped drive the development of seafloor observatories (e.g. EMSO, the European Multidisciplinary Seafloor and water column Observatories[43]) which contribute to climate change assessments[44] and to monitoring ecosystem change over years-decades[45]. Ecosystem state change may be heralded by early warning signals[46] including slowed recovery time between different states, increased spatial and temporal variance, and increased genetic autocorrelation[47]. However, the lack of standardised monitoring and assessment limits our understanding of stability, resilience, and tipping points in the deep and open ocean[48,49]. We, therefore, advocate an empirical place-based approach to quantify drivers of ecosystem change and search for breaking points using diverse, less conventional time series data. When analysed using rigorous, standardised statistical approaches across these places, a set of harmonised outputs and trends can be produced to reveal important basin-scale shifts that have taken place and thus whether future tipping points may be reached.

In the Atlantic, biological time series range from datasets on bacteria and primary producers to VME indicator taxa, whales, tunas and sharks. They include fisheries records, plankton tows, repeat camera surveys and data from observatories including EMSO-Azores, Porcupine Abyssal Plain Sustained Observatory (PAP-SO), Bermuda Atlantic Time Series Study (BATS) and Cabo Verde Ocean Observatory (CVOO). There are fewer deep and open-ocean time series in the South Atlantic than in the North. As funding (see Supplementary Table 1) and human capacity to change this is limited, we argue for novel approaches to reconstruct time series in the data-poor deep and open ocean. The iAtlantic programme adopted five approaches to construct time series in places where classical ecological surveys did not exist.

(1) *Structure-from-motion (SfM) photogrammetry* to create 3D temporal reconstructions of benthic communities from repeated ROV surveys. At the Lucky Strike hydrothermal vent field on the Mid-Atlantic Ridge, geo-referenced points from images at known time points are aligned to reconstruct the whole vent edifice using SfM[33]. The evolution of complex structures and community changes can be studied at centimetre scales. Recent findings show remarkable vent community stability over 25 years[50,51], suggesting they could be more vulnerable to mining disturbances than previously thought.

(2) *Capture-recapture models* can be used to understand the population dynamics of important species that migrate across ocean basins but are only rarely observed. For example, an analysis of a citizen-science catalogue of humpback whale (*Megaptera novaeangliae*) tail fluke images standardised by survey efforts suggests that whale

abundance in Bermuda's waters increased linearly since 2011, and varied from ~790 individuals in 2016 to ~1400 in 2020[52,53]. This confirms Bermuda's importance for migrating humpbacks and may partly reflect the International Whaling Commission's (IWC) ban on commercial whaling in 1986. This ban likely also explains the increased marine mammal sightings off Iceland and Nova Scotia. The local ecological knowledge (LEK) from Bermuda also led to work characterising whale songs and acoustic presence in Bermuda[54] stimulating discussion on cetacean conservation in Bermudian waters, including area-based management tools (ABMTs). Integrating LEK has great potential to be upscaled and used in poorly monitored open-ocean areas including the South Atlantic.

(3) *Water column hydroacoustics* derived from Acoustic Doppler Current Profilers (ADCPs) are primarily used to gather water column current data. But their acoustic backscatter records can also be used to derive proxies of plankton biomass through time[55]. ADCPs should be routinely deployed on marine infrastructure, opening the possibility of further industry collaborations to scale up such time series in deep and open ocean areas.

(4) *Geochemical and palaeo proxies* are important tools to reconstruct drivers of ecosystem change beyond ecological observational periods. Using fossil cold-water corals, Portilho-Ramos et al.[56], for example, were able to demonstrate the importance of changes in food flux for the rise and fall of these ecosystems in the Atlantic. O'Brien et al.[57] used benthic foraminifera from mid-latitude and subpolar North Atlantic sediment cores to show strong shifts in benthic ecosystems over the last ~150 years, with peak responses occurring in areas that experienced large changes in surface circulation, temperature, and/or productivity.

(5) *Ancient environmental DNA (aDNA)* uses eDNA methods and metabarcoding on sediment cores to reproduce temporal changes in pelagic plankton. Using cores from five sites in the North Atlantic, Selway et al.[58] presented clear evidence of aDNA from the ubiquitous coccolithophore *Emiliania huxleyi*, demonstrating the potential of this technique but also highlighting the importance of minimising contamination during sample collection and storage.

As more deep and open ocean ecological time series datasets are examined, one driver of change dominates: temperature. Rising temperatures are, for example, driving northward expansion of capelin spawning habitat around Iceland, increasing connectivity to Greenland (Kristinn Guðnason, unpubl.), while zooplankton species with warm water affinities now characterise the community over the Scotian Slope in eastern Canada[59]. These trends show a clear transition in the late 1990s and early 2000s corresponding to strong changes in basin-scale oceanographic processes (i.e. AMOC, Atlantic multi-decadal oscillation and subpolar gyre dynamics[60,61]. Such changes may trigger oscillations such as those seen in the biologically diverse communities associated with cold-water corals off western Scotland, which switch between cooler and warmer water affinities according to the state of the North Atlantic Oscillation[62]. In the South Atlantic, widespread declines in catches of cooler water species of groundfish on the Brazilian Meridional Margin[63] and cooler water species of large migratory pelagics throughout the South Atlantic may also be related to positive thermal anomalies, although the effects of fisheries pressure cannot be discounted and may be synergistic.

**Priority 4—Impact of multiple stressors**. In addition to ocean warming, acidification and, in some regions, reductions in oxygen levels, changes in salinity, food quality and supply to the ocean's interior, many benthic and pelagic ecosystems are impacted by increasing fishing pressure and face the prospect of deep-sea mining distributing sediment plumes, which are highly toxic[64], over vast areas[65,66].

Our understanding of the effects of these multiple stressors on ecosystem functions, such as nutrient remineralisation, carbon cycling, and precipitation of minerals, in the deep and open ocean, is limited and largely restricted to the NE Atlantic, mostly from seamounts and canyons, or from single stressor experiments on cold-water corals. Studies of synergistic effects or investigations from deep and open-ocean pelagic ecosystems are rare[67]. Very little is known about the impacts on larval stages of keystone or VME indicator species, yet maintaining larval connectivity is vital to marine ecosystem longevity and restoration[68]. This prevents robust ecosystem-based management since organisms in the deep and open Atlantic Ocean, such as cold-water corals, are amongst the most vulnerable to climate change and resource exploitation[69].

We argue for both in situ and ex situ approaches to examine the effects of different climate and anthropogenic stressors on key deep pelagic and benthic species. We will need to study larval, juvenile and adult stages to understand how multiple stressors could impact ecosystem functions and services. We will need to study experimental organisms from a wide range of depths including the mesopelagic to hadopelagic zones and in many cases wide geographic distributions, allowing us to extrapolate results to equivalent regions. In this Blueprint we propose four in situ and ex situ approaches spanning North and South Atlantic.

(1) *In situ regional ecosystem studies across natural gradients*: Natural environmental gradients provide proxies for variations in stressors under climate change[70]. Both pelagic and benthic ecosystem functions must be compared across latitudinal gradients and across eutrophic to oligotrophic systems. As climate change reduces nutrient input to the upper ocean, phytoplankton assemblages should shift from fast-sinking diatoms to slow-sinking picoplankton[71,72], metabolism in the water column should increase leading to reductions in both quantity and quality of organic matter arriving at the seafloor[71,73]. This will significantly impact the benthic community composition, structure and ecosystem function. Given natural variability in pelagic productivity and POC flux across the Atlantic, and the strong relationship between ecosystem processes and POC flux[74], we expect that deep-sea assemblages will be impacted differently in oligotrophic and eutrophic deep-sea basins. It will be important to assess how potential regime shifts in upper ocean ecosystems caused by global warming and overfishing (e.g. shifts from fish to squid-dominated ecosystems) are likely to alter the flux of fish vs. squid carrion to the seafloor and the response of benthic and demersal scavenger communities.
At bathyal depths, cold-water corals create important biogenic habitats throughout the Atlantic where a deep aragonite saturation horizon (ASH) allows the dead skeletal frameworks of scleractinian corals to persist for millennia[75,76]. As ocean acidification causes the ASH to shoal, vast areas of deep-sea reef habitat will be exposed to waters corrosive to these skeletons and the reefs they form[77,78]. Thus, as well as addressing the implications of multiple stressors on living corals and their larvae, we argue it is also essential to assess their implications on the biogenic structures these corals form[79,80]—here inter-basin comparisons between coral mineralogy in the Pacific, with

its naturally shallow ASH, and Atlantic integrated with ex situ multiple stressor studies are required.

(2) *Ex situ studies to assess multiple stressor effects on hard-bottom species (adult and pelagic larval life stages)*: Studies tackling the effects of particulate plumes (from both seafloor mining and fishing) in combination with climate change stressors are urgently needed. The first modelling studies suggest that plumes from polymetallic seafloor massive sulfide mining around the Azores would persist for up to 6 months, disperse up to 20 km through 800 m of the water column and cover up to 150 $km^2$, reaching many areas that support VMEs and fishing activities[66]. Studies to examine the impacts on cold-water corals, sponges, vent mussels and their pelagic larvae need to expand and build upon early results that show how exposure to mining waste has severe toxic effects leading to significant mortality in deep-sea habitat-forming octocorals[64]. For such experiments, it is essential to share expertise in maintaining these organisms and their larvae in research aquaria.

(3) *Ex situ studies to assess multiple stressor effects on soft-sediment ecosystems*: Although the soft sediment ecosystems of the abyssal ocean cover ~60% Earth's surface we understand little of their vulnerability to changing ocean conditions. The single and cumulative impacts of increased temperature and organic matter quality on soft sediment ecosystems need to be assessed using incubation experiments in eutrophic and oligotrophic ecosystems. By adding isotopically labelled diatoms of different labilities (e.g. fresh vs. degraded) to sediments, changes in carbon mineralisation and the incorporation of plankton carbon into different benthic size classes (microbes, macrofauna) can be measured to see how these stressors will affect carbon mineralisation, sequestration, and food-web dynamics. Benthic lander experiments to measure background respiration and nutrient flux rates can then be used to ground-truth background organic matter mineralisation rates.

(4) *Ex situ studies assessing effects of multiple stressors on deep open-ocean pelagic ecosystems*: The biology of the deep pelagic remains poorly studied, yet these organisms play critical roles in open-ocean ecosystem functioning. It is now possible to carefully sample from the deep pelagic and use mesocosms to maintain mesopelagic organisms during ecophysiological measurements. It will be particularly important to study the combined effects of climate change and sediment plume loading and take advantage of easily-accessible deep pelagic species (e.g. the jellyfish *Periphylla periphylla*) in fjordic environments to conduct experiments.

**Priority 5—Spatial and temporal management and protection**. The ecosystem impacts of climate change and human activities are not evenly distributed across marine space, so management approaches must be tailored to suit spatially explicit situations and scenarios[81,82], i.e. area-based management. Area-based management tools (ABMT) include marine spatial planning (MSP), marine protected areas (MPAs), including networks, dynamic management measures, locally managed marine areas including indigenous, community and privately managed areas and sectoral tools such as closure of certain vulnerable areas to fishing, shipping or mining. Depending on the ecological, socioeconomic or cultural management objectives, different types of ABMT and stringency of regulation may be employed. For example, MPAs may range from strictly protected marine reserves to areas where uses compatible with the MPA objectives are allowed.

In addition to appropriate baseline information, the successful implementation of an ABMT depends on the correct identification and understanding of different stakeholders, their practices, expectations and interests[83]. The ABMT must be developed with full and open involvement of all stakeholders including local communities, applying appropriate techniques for multi-actor group coordination and collaboration[84,85].

Systematic conservation planning (SCP), or similar processes, are frequently used to support transparent, data-driven development of ABMTs. SCP gives a framework to help meet societal values and to support effective stakeholder co-creation[86]. Previous efforts using SCP have demonstrated the benefit of a systematic approach to cross-sectoral planning and management[87–89]. Ban et al.[90] describe the key benefits of systematic planning relative to sector-specific or ad hoc approaches, including transparency, inclusiveness, integration, and efficiency. Recently Combes et al.[91] used this approach to identify potential priority areas for protection across the North Atlantic and van Denderen et al.[92] developed a data-driven approach to provide management options to protect VMEs.

SCP requires management and conservation goals and objectives to be identified alongside environmental and human activity data. Advanced web-based Geographic Information System (GIS) tools, (e.g. GeoNode) can support this process, allowing data from regions of interest, including conservation zones and areas that may in the future be commercially exploited, to be stored and visualised. The iAtlantic project developed an Atlantic GeoNode (www.geonode.iatlantic.eu) and launched an All-Atlantic Ocean Data Community site on the GEOSS Portal (www.geoportal.org). GeoNode offers all stakeholders an interface to explore and view geospatial data, without requiring technical expertise or providing full access to the original data, facilitating data sharing and communication of management options whilst respecting commercial sensitivities or academic embargos. The ultimate goal is to produce transparent ocean basin scale management scenarios for the whole Atlantic based on FAIR (Findable, Accessible, Interoperable, Reusable) and Open Data practices. Robust data sharing and dissemination channels, such as the GEOSS portal, connect local, regional and global data infrastructures and services e.g. the South African Environmental Observation Network (SAEON[93]), PANGAEA, and the European Marine Observation and Data network (EMODnet[94]), aligning Northern and Southern data providers and services along mutually agreed standards.

**Priority 6—Capacity building, policy, stakeholder engagement and outreach**. There are many international initiatives, directives and agreements to tackle issues threatening the health of ocean ecosystems (see Supplementary Note 1). Here we summarise the relevance of our Blueprint to the UN Sustainable Development Goals notably SDG14—Life Below Water—which aims to "conserve and sustainably use the oceans, seas and marine resources", and SDG17 to "strengthen the means of implementation and revitalise the Global Partnership for Sustainable Development". SDG14 calls for an increase in scientific knowledge, research capacity and marine technology transfer to improve ocean health and to enhance the contribution of marine biodiversity to economic development, particularly in developing nations. Our Blueprint is centred around international partnership, recognising that sharing knowledge, expertise, technology and funding while encouraging and promoting public, public–private and civil society partnerships is vital. In particular such partnerships must leverage data collection and acquisition in the South Atlantic, supported and enabled by appropriate capacity development and research infrastructure investment for local science communities and networks[95].

Thus it is essential to prioritise human and technical capacity development. Capacity building and technology transfer are key pillars of the UN Biodiversity Beyond National Jurisdiction treaty negotiations and are an integral part of the SDGs. Regional and sectoral bodies urgently need access to new information generated by scientific research programmes in order to better manage their respective activities and fulfil their mandates. This is especially important given that the Atlantic is a rapidly changing and dynamic ocean. Capacity building is also implicit in both the Belém Statement on Atlantic Ocean Research and Innovation Cooperation and the South-South Framework for Scientific and Technical Cooperation in the South and Tropical Atlantic and Southern Oceans[96]. Through this 'All Atlantic' mandate, research funding from the EU can pay for work in the South Atlantic, helping address the inequities that otherwise impede meaningful partnerships between workers in the global North and South. This is particularly important given the substantial financial costs of working in the deep and open ocean (Supplementary Table 1) where a 30-day expedition and subsequent work totals between €800k and €1.7M and a 4-year programme like iAtlantic costs €30–40M including all offshore expedition costs. These costs must be considered when science-led policy plans to manage biodiversity in areas beyond national jurisdiction are being developed.

## Outlook

Unprecedented rates of global change and rapid growth of human activities are changing ocean ecosystems, which transcend jurisdictional borders and vary in complex ways across both space and time. The challenges of sustainable management at the ocean basin scale are vast and are impeded by the unequal distribution of human and technical capacities between the global North and South.

We are entering an era when international science and policy communities can build the strong, practical collaborations needed to tackle these challenges. We have outlined priority areas to help improve our understanding of oceanography and ecosystem status in the deep and open ocean and demonstrate how empowering local communities bordering the Atlantic through sharing human and technical capacities can help develop this approach globally. Developing cost-effective technologies and building trusted relationships with industry partners can help democratise marine data acquisition and access. Similarly, recent advances in computing and data analytics allow us to develop crucial time series and allow us to explore drivers of ecosystem change and tipping points.

Throughout, our Blueprint emphasises the importance of high-quality, open-source, interoperable data in supporting systematic conservation planning and spatial management at the ocean basin scale. In particular, we call for targeted capacity and network building to support inclusive, interdisciplinary and internationally collaborative research. Finally, we argue that the Atlantic Ocean and its science–policy community provide the ideal test bed for international cooperation that moves beyond generalities to the specific actions we need to achieve sustainable development in the deep and open ocean.

## Data availability

iAtlantic project data referred to in this perspective paper are primarily available in PANGAEA (https://www.pangaea.de/?f.project=iAtlantic) and through the FAIR archiving services on SAENOE (https://www.seanoe.org), BODC (https://www.bodc.ac.uk), and GEOMAR (https://data.geomar.de).

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## Author contributions

J.M.R. and L.-A.H. conceived the paper; J.M.R. assembled the authors, developed the structure and produced the first draft. A.B. and D.J. drafted text for Priority 1. C.W.D. and V.A.I.H. drafted text for Priority 2. L.-A.H., M.M. and J.M.R. drafted text for Priority 3. A.S., M.C.-S. and J.M.R. drafted text for Priority 4. T.M., T.D., K.L. and M.S.N. drafted text for Priority 5. V.G., D.E.J., S.U. and B.B. drafted text for Priority 6. All authors including B.D., E.K., C.O., J.A.A.P., S.A.R. and A.J.S. contributed to create the concept advanced in this paper and edited the manuscript. J.M.R. and C.W.D. developed the costing estimates and completed final edits to the MS.

## Competing interests

The authors declare no competing interests.

## Additional information

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