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Science challenges and solutions to support implementation of the Biodiversity Beyond National Jurisdiction Agreement

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The Biodiversity Beyond National Jurisdiction (BBNJ) Agreement provides a new opportunity to consolidate and achieve global marine environmental goals. Here we focus on how science and technology will support its implementation. We provide an overview of existing scientific knowledge and methods that are scalable to Areas Beyond National Jurisdiction (ABNJ). Reviewing data gaps, challenges and opportunities, we outline solutions and a roadmap focused on enhancing resources and capacity.

The United Nations Agreement on the Conservation and Sustainable use of Marine Biological Diversity of Areas Beyond National Jurisdiction (ABNJ)—the Biodiversity Beyond National Jurisdiction (BBNJ) Agreement (also referred to as the 'High Seas' Treaty) was adopted in June 2023 in a landmark victory for global ocean conservation, and in promoting equity and fairness in the use of ocean resources. It reached 60 ratifications in September 2025 and entered into force on 17th January 2026. The overarching objective of the Agreement is to deliver sustainable use and conservation of marine biodiversity in ABNJ. This is ~61% of the open ocean[1] that falls outside the remit of individual coastal nations' Exclusive Economic Zones (EEZs). The assessment and monitoring of marine health in ABNJ brings many challenges. Tools, methods and technologies used in coastal and shelf environments will need to be revised to become applicable to ABNJ; data gaps from the surface to the seafloor must be addressed. Novel technologies are also needed to deliver the pace of scientific advancements required to successfully implement treaty objectives. In addition, the significant challenges facing the marine environment, including climate change (Fig. 1), pollution, and emerging pressures from commercial exploitation of marine resources, mean that work to support implementation of the Agreement must begin in earnest[2]. Many of the knowledge gaps for ABNJ have been identified[3], the need now is to assess the magnitude of these knowledge gaps and propose ways to address them.

Context

There is an increasing interest in how science is used in international conventions, including the participation of scientific bodies at the multilateral treaty-making stage[6]. As with other UN conventions, science will be included through the establishment of a Scientific and Technical Body (STB) and other independent bodies. For example, the Intergovernmental Panel on Climate Change (IPCC) provides scientific information and technical guidance to the United Nations Framework Convention on Climate Change (UNFCCC), whilst the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) is a major provider of information for the Convention on Biological Diversity (CBD). The challenges with establishing similar mechanisms for the BBNJ Agreement and using 'best available science' include the fact that the ABNJ is one of the least known ecosystems on earth. Only 27.1% of the deep sea has been mapped to modern standards according to the Seabed 2030 project, and it is estimated that ~90% of marine species are yet to be discovered[7]. It is vital that the new STB for the BBNJ Agreement establishes mechanisms for engaging with these other bodies providing scientific evidence, particularly IPBES due to close interlinkages between the CBD and BBNJ Agreement. There is a growing body of literature on ensuring better interlinkages between agreements and ensuring that the science-evidence pathways are fit for purpose[8,9].

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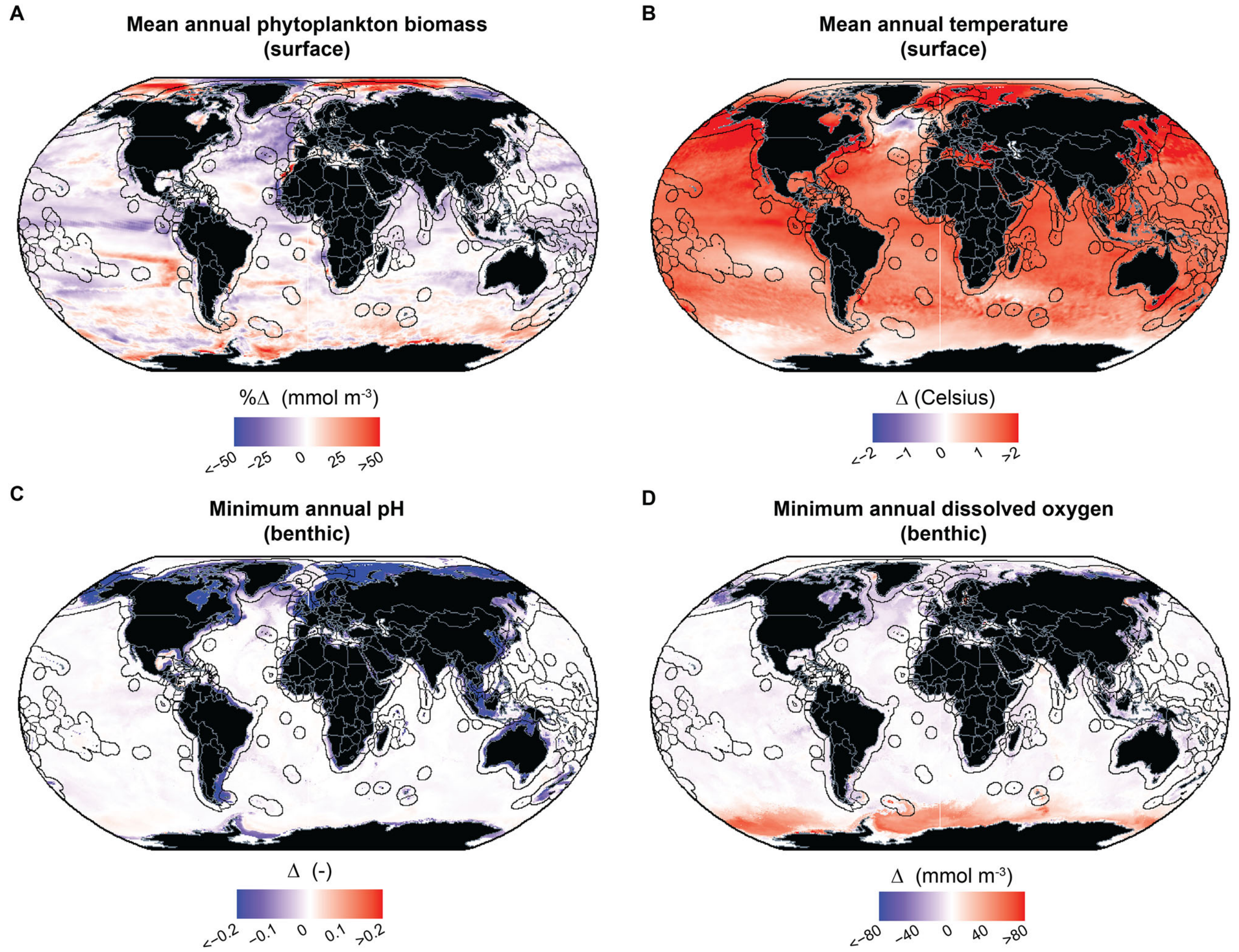

Fig. 1 | Projected marine environmental anomalies under SSP 5-8.5. Spatial distribution of projected changes in oceanographic variables by 2050-2060 relative to a baseline period of 2000–2010, under the IPCC Shared Socioeconomic Pathway 5-8.5 (high emissions scenario). Exclusive Economic Zone boundaries marked in black. Panels show: **A** percentage change in mean surface total phytoplankton concentration; **B** absolute change in mean sea surface temperature (°C); **C** absolute change in minimum benthic pH; **D** absolute change in minimum benthic dissolved oxygen concentration (mmol m^{-3}). Data were accessed from Bio-ORACLE V3[4,5], where projections are derived from a suite of Earth System Models used in CMIP6. Data available from: https://bio-oracle.org [data accessed: 16 December 2024].

Aims and objectives

The BBNJ Agreement includes four pillars by which to set and achieve goals: (1) Marine Genetic Resources (MGR), (2) Area-based Management Tools (ABMTs), (3) Environmental Impact Assessments (EIAs) and (4) Capacity Building and Transfer of Marine Technology (CBTMT). In this article, we take each of these pillars in turn and: (a) explore current knowledge, including methods and solutions that can be used to achieve the science objectives of the BBNJ Agreement, (b) identify where technologies can be adapted or require further development and investment, (c) showcase examples of relevant science and lessons-learned on solutions; and (d) present a road-map to deliver the science required to fulfil the BBNJ Agreement objectives, and ensure the Agreement can be delivered as an effective, global effort to protect marine biodiversity in ABNJ.

There are two important caveats to be made: (i) The BBNJ Agreement is a catalyst for the need to address many of the scientific challenges in ABNJ but is not the sole driver—the proposed roadmap therefore, although focused on the specifics of the BBNJ Agreement, contains solutions that can be applied generally for a better understanding and management of ABNJ; (ii) Although BBNJ ratification and implementation is highly contingent on political will and outcomes, the objectives of the BBNJ are still fundamental for good scientifically informed governance of ABNJ. We do not, therefore, provide a detailed political analysis here but focus on science and solutions.

Pillar 1: Marine Genetic Resources (MGR)

Context and current understanding

Protection and monitoring of biodiversity relies on robust baseline data, coupled with time series to detect natural variation and longer-term change. However, data on marine biodiversity are scarce in the remote ABNJ[10]. Traditional taxonomic data, alongside time series from earth observation, provide the backbone of our present understanding of how life in the ocean is structured and responding to change[11]. However, we are undergoing a technological revolution in ocean observation, in terms of platforms, sensors and sample analysis methods. An upsurge in molecular approaches, which can be used to study the taxonomy, ecosystem role, and connectivity of organisms, can provide greater knowledge of the biota, its distributions and its interactions[12].

The BBNJ Agreement covers the digital sequencing of MGR, and the equitable sharing of information and benefits arising from the use of MGR and Digital Sequence Information (DSI). The aim is to enhance scientific collaboration and capacity building, while improving transparency and traceability of MGR and increasing fair and equitable data sharing. In addition to its value for understanding the oceans, the material originating from biota contains a multitude of known and undiscovered biotechnology applications[13], which can potentially be used to generate profits, as is envisioned under the Agreement. Given the potential of products arising from the utilisation of DSI from both ABNJ and EEZs, there is a risk of obligation

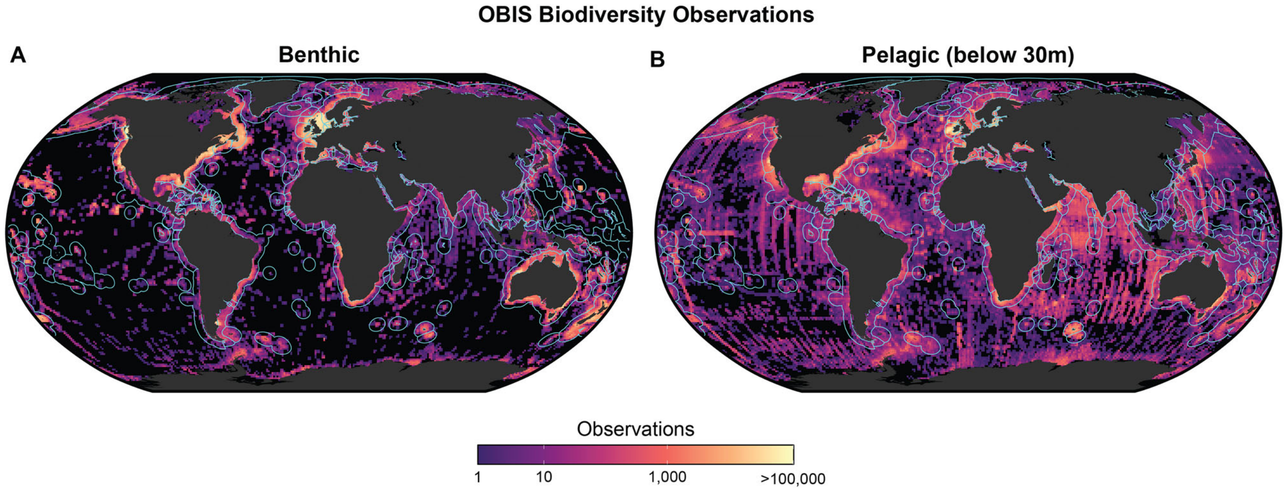

Fig. 2 | Global spatial distribution of offshore marine biodiversity records. Density of Animalia observation records extracted from the Ocean Biodiversity Information System[27] and aggregated onto a 1° × 1° grid. Data were filtered for depths >30 m and classified as benthic or pelagic using an automated pipeline that stratifies OBIS record depth against GEBCO bathymetry; see ref. 25. Exclusive Economic Zone boundaries marked in blue. Panels show: **A** distribution of benthic observations ($n \approx 12.7$ million), where less than 4% of observations are in Area Beyond National Jurisdiction (ABNJ); **B** distribution of pelagic observations ($n \approx 6.2$ million), where less than 18% of observations are in ABNJ. Data were derived from ref. 25 [data accessed: 15 December 2025], and calculations were based on grid cell EEZ classifications provided in ref. 28 [data accessed: 12 August 2024].

stacking for users; they would be required to pay into both the BBNJ fund and the CBD's CALI Fund[14]. This problem is compounded by the absence of an agreed definition of DSI under either agreement.

Equally important are the provisions for information-sharing regarding MGR. The BBNJ Agreement establishes a requirement for notifications of novel collections (including a data management plan), where MGR will be deposited, and which databases will hold any DSI. Notably, neither the BBNJ Agreement nor the CBD have defined what is meant by DSI, leaving countries to define it independently. For MGR and DSI, there will be a unique 'batch identifier' (to be developed) that must be included with metadata.

The Agreement also specifies open access and use of FAIR data principles[15], and the tagging of data originating from the BBNJ Agreement. These principles should be considered for the recent CBD COP decision on DSI[16], which makes several requirements of public databases that hold MGR data, or align with databases that do. Sharing of data in all formats (i.e. from raw sequence to fully processed data, including analysis pipelines) with full transparency on the details of data-handling should be encouraged, to ensure both experts and non-experts are able to benefit from new knowledge gained (i.e. CARE principles; ref. 17). The International Nucleotide Sequence Database Collaboration (INSDC) database, already synchronises data from across the globe daily, but georeferencing could be improved. A harmonisation of approach across conventions, and conformity of approach by researchers and database managers in this respect, would be valuable[18].

Gaps in knowledge

Limited time series coverage (Gap 1a). Long-term time series provide statistical power to determine how sensitive or resilient ecosystems are to past changes and perturbations, provide a testbed for models to project the future, and are key to understanding ecological change for management decisions. However, for ABNJ this presents three key challenges: (i) Capacity issues: funding for long term research is in serious decline worldwide[19], (ii) there is a decreasing number of taxonomic experts[20] and (iii) inadequate data coverage; oceanic regions (in ABNJ) are poorly served with long time series with a couple of exceptions (e.g. Continuous Plankton Recorder[21]; Atlantic Meridional Transect (AMT)[22]). These have included ad-hoc molecular sampling, although for AMT this is now being consolidated and made available through involvement in the UN Ocean Biomolecular Observing Network project[23]. There are a few deep-sea monitoring programmes, with exceptions such as the European Multidisciplinary Seafloor and water column Observatory network, Ocean Network Canada, Monterey Bay Aquarium Research Institute station M, Long-Term Ecological Research Hausgarten and the Deep Ocean Observing Strategy. Efforts are being made to consolidate existing genetic data from the deep sea into global repositories (e.g. the International Seabed Authority Deep-Sea Biobank Initiative). High latitudes are poorly covered even with satellite data, and some fast-warming areas such as the Indian Ocean are particularly data poor[11].

Baseline data gaps (Gap 1b). As with the availability of time series data for ABNJ, accessible baseline biodiversity data are also spatially unbalanced (Fig. 2). Most benthic and pelagic data are from the northern hemisphere and temperate latitudes[24,25]. Data availability declines with depth and is particularly deficient below 2000 m. The Global Ocean Gene Catalog reveals significant differences in benthic and pelagic functioning, and pelagic data dominate the database (95.9% of samples) compared to benthic data (4.2%), with just 7.2% of mesopelagic samples (200–1000 m) and 10.2% from depths below 1000 m. This indicates vast communities and depths that remain largely underexplored, with minimal sampling in the polar oceans[13]. Even the most frequently sampled regions still have incomplete taxonomic databases[26]. In addition, available data are taxonomically biased with a strong emphasis on fish, with data largely derived from fisheries monitoring[25]. Issues with incomplete reference DNA libraries continue to hamper efforts to link DNA sequences with taxa present for most other groups.

Knowledge gaps in molecular science (Gap 1c). Accessing, analysing, and interpreting data derived from MGR rely on specialist molecular techniques and bioinformatic knowledge. Molecular data often require advanced sequencing technologies and computation pipelines to generate meaningful insights, such as identifying species, functional genes, or ecological patterns. Without expertise in these areas, countries, particularly those with fewer resources, may struggle to fully access benefits. This gap could create inequities in access to resources and slow down efforts to protect marine biodiversity globally.

Solutions

Despite artificial intelligence (AI), big data, and supercomputers, there is still no substitute for a direct, continuing pulse-check of how our planet is reacting to anthropogenic stresses. Long-term monitoring of the 'vital organ' function of big ecosystems is expensive. Therefore, in remote oceanic areas beyond national boundaries, we need creative solutions, melding information from a suite of methods to fill sampling and time-series data gaps.

Satellite time series are now long enough to assess changes in phytoplankton in response to climate change[29,30] (Gap 1a). Such satellite data provide unprecedented spatial and temporal resolution with improving discrimination of phytoplankton taxa and size classes. The taxonomic differentiation of phytoplankton groups from satellite has been improved through the combination with metagenomic data[31]. Mapping zooplankton swarms[32] and even large higher predators[33] is being achieved thanks to the ever greater spectral and spatial resolutions of radiometry-based satellites (Gap 1b). Satellite products are also applied as inputs to species distribution models[34]. However, coverage of higher trophic level taxa, deeper layers of the ocean, and of higher latitudes will still need to be filled from other sources. For example, global databases of biodiversity observations such as OBIS have improved greatly in recent decades [ref. 35; Fig. 2] (Gap 1b). Developments in the application of analysis techniques such as clustering algorithms (which are used to group similar data points into clusters) can also help robustly combine spatially sparse observational data for comparison with model products[36]. Further ground-truthing of modelled data would strengthen the confidence of our analysis of global biodiversity and resource patterns under future climate change and allow for a more informed and climate-smart approach to EIA within the BBNJ Agreement (Gap 1a and Pillar 3).

Increasing availability of MGR data can provide an essential baseline on biodiversity in remote oceans, and new technologies have potential for filling sampling gaps from ocean depths and at wide geographic scales, but bring their own challenges. The ease of eDNA sample collection alongside autonomous sample collection offers great potential, but data sharing must be transparent and accessible to ensure traceability and interoperability. Mechanisms for depositing in open-access platforms are essential (Gap 1c). Methods such as eDNA, automated imaging and AI-based analyses[37] often generate data that are not easily translated for use in Earth System Models, and there have been calls to remedy this for molecular data[38] (Gap 1b).

Models have also been used to fill gaps in data, but this can introduce circularity, and this approach is critically reliant on the suitability of the models themselves. As one solution, ensemble approaches (that combine multiple simulations to provide a range of possible outcomes) from Earth System Models (Fig. 1) are considered more reliable for ABNJ than for the detail of shelf dynamics, and these tend to agree very broadly on the general direction of change, at least for the lower latitudes and within lower trophic levels such as phytoplankton [ref. 39; Fig. 1A] (Gap 1b). However, for projecting properties such as higher trophic level biomass with marine ecosystem models such as those in the FishMIP ensemble, there is a far greater uncertainty[40,41]. These stem from a suite of factors, including a fundamental lack of understanding of key processes such as temperature responses and food web interactions[40,42]. Modellers and empiricists have joined forces to better understand how ecosystems work, resulting in achievable action plans[43].

Large-scale coverage and extended time-series of key variables will enable good spatial management, with a question-driven approach. This should be coupled with greater collaboration that will facilitate the development of central products such as the KAUST Metagenome Analysis Platform Global Ocean Gene Catalog 1.0, which is the largest open access resource available and matches class with gene function, geographic location and ecosystem type[13] (Gap 1c). Likewise, large and valuable fisheries operate in these remote ocean areas, and these are generally covered at present outside of the BBJ Agreement framework, through a series of Regional Fisheries Management Organizations. Fisheries data, while valuable, are often extremely hard to access, so integrating these data remains a challenge. Some success stories in engaging with the fishing industry provide grounds for optimism, one notable example being the Antarctic krill fishery. This not only enables access to data directly derived from the fishery[44], but some vessels provide a platform for scientific research, and members of the krill fishing industry co-fund ecosystem research[45].

Beyond the science needs, adequate funding mechanisms will allow us to address the computational costs of processing the voluminous data they produce; the need for high-quality, open-access molecular data-sets, including reference libraries; best practice protocols and standard procedures[46], and including expensive set-up and analysis costs[47,48]. However, the environmental costs of high computational capacity and optimisation of resources also need to be considered (including better sharing of training data for AI models).

Also required are investments in capacity building and technology transfer. This could include training programmes to develop skills in the handling and interpretation of data, or the creation of regional centres with shared facilities, providing open-access tools. Collaborative research networks under the BBNJ framework could play a key role in knowledge exchange (Gap 1c).

In summary, a wide suite of methods together provides MGR data coverage of remote oceans, in dimensions of space, time and depth. These include earth observation, models, databases, classical data from research ships, ships of opportunity, fishing vessels, through to autonomous floats and moorings and eDNA. All have substantial strengths and weaknesses, but with new capabilities of extracting and combining information from many large and diverse data sources, the strengths of each complementary approach can be maximised. However, a recent study of global zooplankton time series[11], found that only a minority had their data openly available, with these stored across a diversity of repositories. With fisheries-related data also voluminous but often even harder to obtain, there is clearly much potential for improved data networking under the BBNJ Agreement.

Pillar 2: Area-based Management Tools (ABMT)

Context and current understanding

ABMTs are the foundation of modern marine conservation and key to achieving marine biodiversity conservation goals and sustainable use of marine resources. Article 1 of the BBNJ agreement is important in being clear that the intention of AMBT in the BBNJ agreement is to 'manage sectors or activities' to achieve conservation *and* sustainable use objectives, so comments on conservation measures below need to be considered in that context.

There are five major anthropogenic threats to marine biodiversity in ABNJ: fishing (Fig. 3), climate change (Fig. 1), pollution, shipping and mining[1]. These are currently managed through a range of ABMT such as: sectoral fishing closures, including closures to bottom trawl fisheries to protect Vulnerable Marine Ecosystems (VMEs), Areas of Particular Environmental Interest (APEIs) to protect from deep-sea mining activities, Voluntary Benthic Protected Areas in the south Indian Ocean[49], and Marine Protected Areas (MPAs).

In terms of the conservation aspect of ABMTs, MPAs are designed to protect, preserve, restore and maintain biological diversity and ecosystems, in order to improve resilience to stressors such as climate change and marine pollution. At present, just 1.44% of ABNJ is protected by MPAs[50] compared to 18.7% within EEZs. Whilst short of the global target of protecting 30% of the ocean by 2030, many of the designated sites are seen as 'paper parks', providing little protection for species and ecosystems within[51,52], and at present, MPAs exist in a fragmented governance system. Much more work is thus needed to ensure MPAs and other ABMTs are 'fit for purpose' to deliver the objectives of the BBNJ Agreement, which provides a global and cross-sectoral mechanism by which to establish new ABMTs for ABNJ.

In Antarctic waters, MPAs have been identified through the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) Agreement. In the North-East Atlantic, there are also MPAs in ABNJ identified under the Oslo-Paris (OSPAR) Regional Seas Convention.

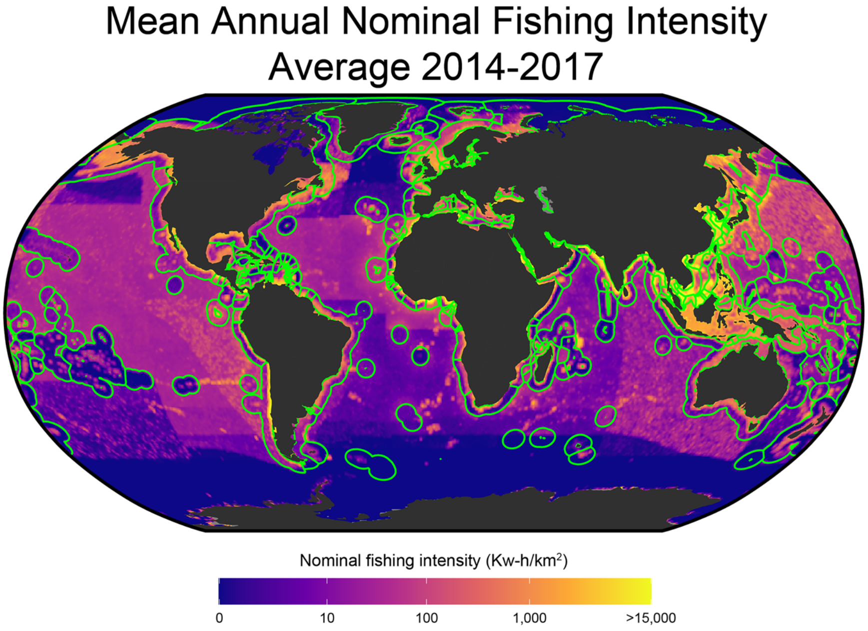

Fig. 3 | Global distribution of annual nominal fishing intensity (2014–2017). Spatial distribution of mean annual nominal fishing effort intensity (kWh km^{-2}) derived from ref. 28. Exclusive Economic Zone boundaries are shown in green. Data represent the aggregated effort of all fishing sectors targeting pelagic and demersal functional groups across all size classes (<30 cm, 30–90 cm, ≥90 cm). The map shows the mean intensity calculated over the period 2014-2017. Both fishing effort data and grid cell surface areas were accessed from ref. 28 [data accessed: 12 August 2024].

Indicative criteria for the identification of individual MPAs, and considerations for networks of MPAs, vary depending on the policy concerned, but all have elements in common. Nine of the indicative criteria for ABMT in the BBNJ Agreement match the criteria used in the identification of Ecologically and Biologically Significant Marine Areas (EBSA) under the CBD. Thus, there will be lessons to be learned from the CBD EBSA process, as well as from CCAMLR and OSPAR. Additional work in assessing important areas has been carried out by NGOs, such as foundational work to identify important bird areas, Important Marine Mammal Areas[53], Important Marine Turtle Areas, important Shark & Ray areas, and key migration routes for large pelagic species such as tuna and billfish in ABNJ.

The concepts of seascapes, bioregions, habitat mapping and biogeography can provide insights into MPA network representativeness. By classifying the physical environment into environmental envelopes sharing a similar suite of environmental conditions, these can serve as a proxy for distinct assemblages of organisms. This enables the assessment of what is represented in an MPA network, and what is rare or unique for the region of interest[54,55]. In ABNJ, this has been applied in the identification of Areas of Particular Scientific Interest (APEI) in the Clarion Clipperton Fracture Zone (NE Pacific), to determine the original APEI network design[56] and additions to the network based on an assessment of representativeness[57]. This type of approach may also be useful in understanding migrations or 'habitat corridors' for migratory species[58].

With respect to uniqueness and representativeness, sea-surface temperature gradients, or ocean fronts, are widely regarded as ecological hotspots, associated with higher diversity and biomass across many trophic levels[59], often starting with diatom growth driven by increased nutrient availability[60]. Front distributions derived from satellite remote sensing data have been used as a proxy for increased biodiversity to guide the delineation of MPAs[61,62] and EBSAs such as the North Atlantic Current and Evlanov Seamount[63,64]. Frontal regions also provide evidence of climate-forced changes in front formation or location to help establish longer-term priority areas, as species and habitats shift in response to climate change[65,66].

While seascape-type approaches provide a broad-scale understanding and assessment of representativeness, rarity and uniqueness, the criteria for selection of MPAs or other ABMT often demand a finer-scale understanding of the distribution of ecosystems. For the protection of VMEs or functionally significant habitats, environmental niche modelling (also known as habitat suitability modelling and species distribution modelling) provides a means to fill data gaps. For example, modelling the distribution of framework-forming cold water corals[67] and deep-sea sponge aggregations[68]; although these models tend to err on the side of false positives, which brings conundrums when seeking to protect a proportion of them.

Gaps in knowledge

Gaps in vertical and horizontal spatial baseline data (Gap 2a). As discussed in section 1a above, gaps in spatial coverage and baseline data from the surface to the ocean floor are key issues, as such data are a prerequisite for effective MPA design and management. Most marine biodiversity records come from surface waters or the seabed, regardless of ocean depth, and deep-pelagic biodiversity is vastly under-represented[25,69].

The importance of benthic habitats and species in providing key ecosystem services in nutrient cycling, bioprospecting, and climate regulation is recognised[70]. However, data on the functional significance of habitat, beyond habitat provision, are sparse for the deep sea; therefore, increased visual exploration is needed.

Gaps in connectivity data (Gap 2b). Connectivity of sessile organisms is principally by means of larval dispersal, and biophysical models inform us on how well connected MPAs are[71]. The challenge then is obtaining data on larval ecology and particularly planktonic larval duration for deep-sea species[72]. Consideration of functionally important areas and connectivity for other pelagic species is challenging, and this is significantly magnified for mesopelagic species, for which there is a vast data gap. Population genetic studies provide a complementary means to assess connectivity, and scales of dispersal and connectivity in the deep sea might be comparable to or slightly larger than those in shallow water[73].

Climate change considerations (Gap 2c). Another clear gap is that science is urgently needed to support the implementation of ABMT in light of the ongoing impacts of climate change. The BBNJ Agreement recognises climate change as a key driver of biodiversity loss and degradation of marine ecosystems and, therefore, by design, is a major stimulus for ocean-based climate-smart conservation[74,75]. Thus, improving ecosystem resilience to climate change (i.e. adaptation) and recognising the vital role the ocean plays in global carbon cycling and in regulating the global climate system (i.e. mitigation) are key objectives of the Agreement. When designed with consideration for necessary evidence, and when well-managed, MPAs and ABMT have the potential to deliver on both climate change adaptation and mitigation[65,76]. However, more often than not, implementation on the ground lags behind scientific evidence[77] within national contexts, requiring solutions to accelerate momentum and coordination in ABNJ.

'Sustainable use' assessment (Gap 2d). In order to inform the management of ABMTs, there will also need to be information on pressures linked to socio-economic activities and on marine ecosystem valuation (e.g. Natural Capital). This is crucial so conservation measures are considered alongside the need to support food security and other socio-economic objectives[78].

Solutions

There is a clear role for remote sensing from satellites in the large-scale mapping of biodiversity indicators and ecosystem function[79], which can be significantly enhanced by increasing the spatial resolution and quality of data[80] (Gap 2a). An established remotely sensed indicator for the pelagic environment is primary production[81,82]. However, it is important to ground-truth data with in-situ observations[83]. Incorporation of ocean colour with frontal information allows for identification of seascapes that can be used to define different strategies for ABNJ when combined with species distribution modelling[58]. Metrics like this can be used to define protected areas in the open ocean, by measures of connectivity, representativeness, vulnerability and function from the individual to the ecosystem level (Gap 2a, b). Where empirical larval connectivity data is not available, mapping the modelled distribution of key habitats and species can thus facilitate a spatial understanding of ecosystem function and enable this to be more fully considered in MPA site selection (Gap 2b). Satellite monitoring can also be used to identify illegal or harmful activities by fishing vessels[84] that could undermine the intended benefits of High-Seas MPAs.

In relation to the conservation of valuable species, efforts for monitoring and protection of mobile species will require re-analysis of existing tracks of tagged mobile animals. Connectedness of megafauna among MPAs can be investigated using telemetry and tracker data, which provide datasets on migrations and movement[85]. In addition to proximal observations tracked by satellite, measures of connectedness can be obtained, indirectly, from the combination of remote sensing data, circulation models and genetic data; demonstrated for coral spawn connectivity in the Red Sea[86] (Gap 2b).

Delivering a climate-smart approach to the implementation of the BBNJ Agreement objectives will require broad, coordinated mechanisms. At present, MPAs and other area-based conservation measures are most often static, while species and habitats redistribute in response to changing ocean conditions[87]. Two scientific approaches currently help meet this target[88]. This includes siting ABMTs in areas harbouring important species and habitats at present, whichalso exhibit some degree of resistance to climate change, or where habitat conditions will improve in future (climate change refugia and bright spots, i.e. anticipatory planning; refs. 65,66) (Gap 2c). In these areas, and without the expectation of climate-driven adaptation, species are expected to remain within their physiological limits and may survive despite larger environmental challenges elsewhere. Some authors argue that designating sites across the full spectrum of climate change sensitivity provides better opportunities for wildlife, as it may limit other pressures on species and promote their ability to cope with climate change in more affected regions (e.g. climate change hotspots), e.g. through Other Effective area-based Conservation Measures (OECMs)[89]. However, once physiological limits are surpassed locally through climate change, there is little that protection from other stressors may do to support species. Alternatively, ABMT can be managed dynamically, allowing for boundaries to shift, in space and time, as species distributions move in response to climate change (i.e. dynamic ocean planning, ref. 90). Dynamic MPAs raise challenges in implementation and enforcement[91], but without such approaches to the design of ABMT, there is a risk that species used as 'designating features' move, and these sites' ability to fulfil their conservation goals weakens, reducing overall effectiveness (Gap 2c). These strategies also involve considering the horizontal as well as the vertical extent of habitats, to support species moving into deeper waters, as they track the deepening of suitable habitat[92].

Information on the location of biologically meaningful climate change refugia and bright spots (i.e. areas remaining stable or improving, regardless of climate change) are being considered in the design of MPAs in the UK, the Mediterranean and other regions (Fig. 4). There is also growing momentum to ensure areas sequestering carbon, beyond the coast, are included within protected area networks and other spatial management mechanisms[93,94]. As the evidence base grows, and associated decision support tools become more commonplace, dedicated resources are now needed to ensure those designing and managing ABMTs have access to the skills and engagement necessary to make best use of them and thus ensure that the climate-related targets of the Agreement can be delivered (Gap 2c).

In terms of the sustainable use aspect, there is a need to build on research undertaken on marine ecosystem valuation in the deep sea and ABNJ[95] as valuations of deep-sea ecosystems are still sparse[96]. In addition, better integrating BBNJ Agreement objectives with other regimes dealing more specifically with economic activity (e.g. fisheries and shipping) is also important; better links with the International Maritime Organization (IMO), ISA International Seabed Authority (ISA), Food and Agriculture Organization of the United Nations (FAO)[97]; and closer working with industries to share information and data (Gap 2d).

Pillar 3: Environmental Impact Assessments (EIAs)

Context and understanding

An EIA will be required for planned activities in ABNJ that may cause substantial pollution of, or harmful changes to, the marine environment (e.g. deep-sea mining or cable laying, marine carbon dioxide removal, or activities not otherwise assessed by another relevant body that have equivalent standards), and may be required for activities within national jurisdiction that may result in adverse impacts on ABNJ. Common requirements for both are sharing the EIA report through the Clearing House Mechanism, and for continued monitoring and review. However, the knowledge gaps discussed in previous sections may impede evidence-based impact assessment or management[98].

The BBNJ Agreement requires that frameworks, processes, thresholds and factors/metrics be defined for conducting and reporting EIAs[99]. To define acceptable thresholds for activity, baseline conditions must be defined and agreed upon. Ecologically 'good' states need to be defined in a meaningful way, either quantitatively using available data or through more subjective assessments of 'good' or 'degraded' state. For example, maintaining the state of an ecosystem within the range of natural variation when undisturbed is an objective way of achieving conservation of communities and habitats (e.g. between 54 and 79% for marine seabed community biomass; ref. 100). Where activities are deemed necessary, science must provide solutions for the prevention and mitigation of adverse effects.

Regarding future conditions, tipping points for global climate and biodiversity are already being observed, which creates a new array of challenges for the BBNJ Agreement[101]. An altered climate system is projected for decades to come, even under strong emissions curbs[102]. These changes are deeply affecting ocean biodiversity patterns[87], with further impacts on people and ecosystems[103] leading to conflict in the use of ocean resources[104]. The BBNJ Agreement is focussed on the need to 'protect, preserve, restore and maintain biological diversity and ecosystems,…to strengthen resilience to stressors, including those related to climate change'. Thus, climate change evidence must become an integral part of the associated EIA process.

Gaps in knowledge

Broad-scale and cumulative impacts (Gap 3a). The current global frameworks for EIAs are sector- or region-specific and do not address cumulative impacts[105]. Cumulative impact assessments are much more challenging and require greater understanding to keep pace with a global increase in the use of marine space[106]. The expectation of EIAs to address cumulative impacts as well as climate change cements the need for

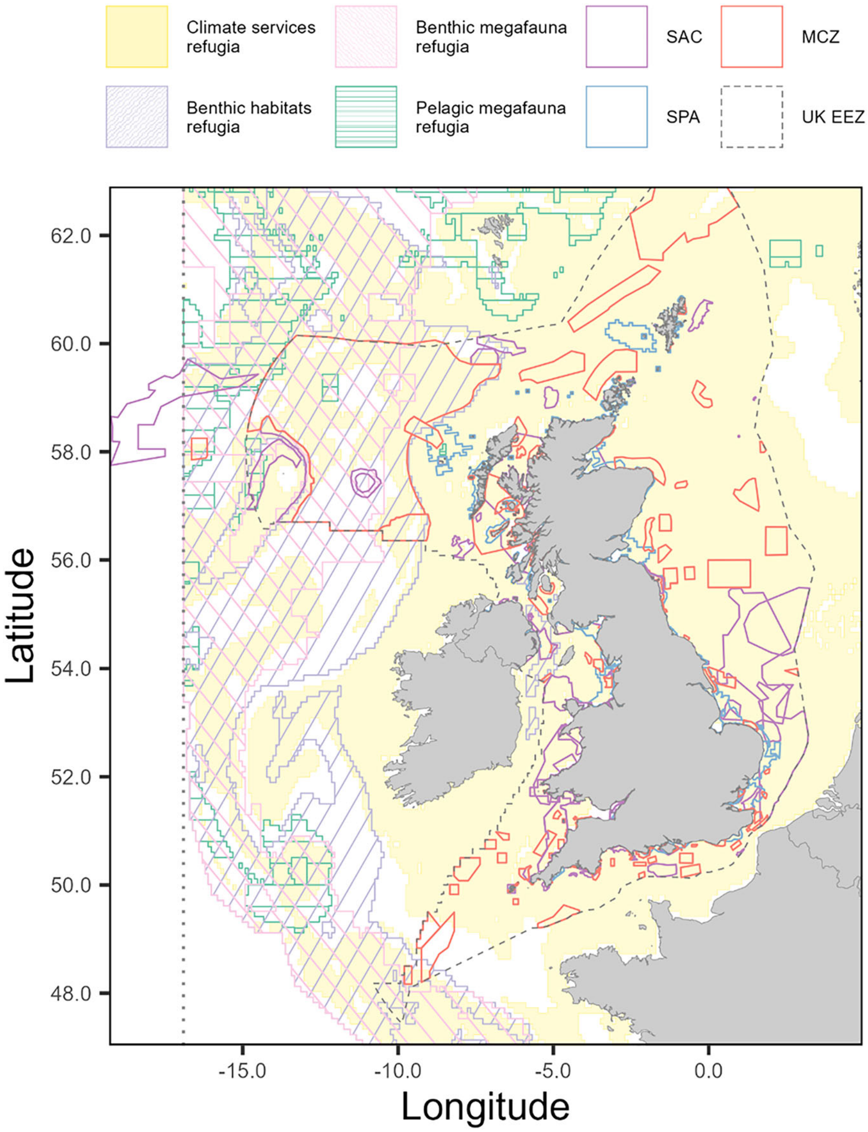

Fig. 4 | Locations of long-term (2026–2069) climate change refugia for benthic species and habitats within the United Kingdom Exclusive Economic Zone (NE Atlantic) relative to the location of the current MPA network, and the adjacent ABNJ region where two OSPAR MPAs are located and managed (the Hatton Bank candidate Special Area of Conservation and the Hatton-Rockall Basin MPA). Climate change refugia emerge in both emissions trajectories, RCP4.5 and RCP8.5 (high confidence). Refugia were identified using a decision support tool which itself uses biogeochemical and species distribution models to assess the effects of climate change on the marine environment. Such tools could be applied under EIAs of ABNJ in order to inform climate-smart spatial management under the BBNJ Agreement (Gap 3c). Figure adapted with permission from ref. 94.

proactive and strategic assessments (rather than traditionally reactive; ref. 107) to better understand risks and cumulative impacts on unmapped biodiversity and resources in ABNJ. This would then facilitate EIAs for planned projects and activities in the context of the outcomes of Strategic Environmental Assessment (SEA), which is a systematic process for evaluating public plans, processes and strategies early in their development (Article 39.2 of the BBNJ Agreement).

Accessibility of data and tools (Gap 3b). Unprocessed output from earth-system- and similar large-scale numerical models is large, complex and often inaccessible to non-expert users. Promoting access to, and the usability of, ocean climate modelling data by diverse users involved in ocean spatial management is thus key to uptake of such evidence in policy design[65,76].

Inclusion of climate data (Gap 3c). The uptake of climate evidence in the delivery of the CBD has been slow; therefore, this gap can be filled by incorporating climate change evidence (of current and potential future impacts on biodiversity) as a fundamental step of EIA by design.

Solutions

SEAs are used to assess current and potential future impacts of planned activities. This provides a benchmark against which new EIAs can be considered, consistent with BBNJ Agreement objectives (Gap 3a). Assessment of cumulative impacts will enable more effective implementation of all other elements of the BBNJ Agreement and contribute to climate change mitigation. In turn, SEAs can be complemented with regional-scale SEAs conducted by the COP. This will help ensure that marine biodiversity data and management are relevant at ecologically meaningful scales[98] and can be useful to identify knowledge gaps and opportunities for collaboration, helping to effectively consider cumulative impacts in EIA. For example, Regional Environmental Assessments have been undertaken in the deep-seabed mining sector through a process to develop a Regional Environmental Management Plan for the northern Mid-Atlantic Ridge[108] (Gap 3a).

A key opportunity in the BBNJ Agreement will be to improve baseline-setting at a regional level and ensure comparable regional-level data are gathered to inform environmental management in the vast ABNJ. This can be achieved through developing a uniform framework for regional co-development of data collection and research, ensuring data can be pooled and benefit regional management through improved understanding of ecological connectivity (e.g. Ocean Census) (Gap 3b).

Numerical modelling tools have increasingly been used as the basis for decision support tools to enable impact assessment and help identify solutions for climate-adaptive spatial management [refs. 65,66, Fig. 4]. Available tools include ecosystem models, species distribution models and food web models. These include the global Climate Model Intercomparison Project (CMIP—https://wcrp-cmip.org/, for ocean exposure to climate change), the Fisheries and Ecosystem Model Intercomparison Project (FishMIP—https://fishmip.org/), as well as AquaMaps (a global resource for projected marine species distributions). There are also global climate risk tools focussed on natural systems[109] that can be applied. Such models can be used to estimate where the global ocean species and habitats of conservation and commercial value are more sensitive or resilient to climate change[110]. Through numerical modelling, we can estimate the potential effect of different futures on the marine environment, including pressures driven by climate change and human activity[111]. This can enable an assessment of potential trade-offs required to inform stakeholder consultations and EIA, fundamental to spatial management of the ocean[112] (Gap 3b).

Applications at the scale of individual MPAs, however, often require the regional downscaling of such information or the use of regionally parameterised ecosystem models and species distribution models, which are rare in the ABNJ. Modelling data then needs to be translated into a format that is usable by practitioners[65] (Gap 3b, c). Users also request uncertainty information when using this type of model data, and efforts are underway to provide this.

There is growing momentum within national and regional jurisdictions to create better integration between National Adaptation policies and spatial management policies for the marine environment—including through climate-smart conservation and planning mechanisms[113,114]. Now, those approaches can be used and refined in the BBNJ Agreement, drawing on available tools and evidence to deliver a climate-resilient approach to spatial management in ABNJ (Gap 3c).

Pillar 4: Capacity Building and Transfer of Marine Technology (CBTMT)

This pillar straddles Pillars 1–3, because if the scientific solutions proposed in this paper are to be effective, then they need not just to be applied at scale but in a way that allows nations to contribute regardless of economic status. Ensuring adequate financial mechanisms are in place is clearly a prerequisite for the delivery of this pillar. Support for international cooperation in marine scientific research and transfer of technology are legal obligations under Article 8.3 on International Cooperation, and also involves politics, which is not discussed further here. Key considerations for successful implementation of CBTMT include: (a) having systems for the transfer of marine technology, (b) making use of existing capacity to address a lack of infrastructure and or capacity, and (c) developing human knowledge networks and expertise. Critical investment and long-term government funding are also needed to support SIDS in developing critical research infrastructure and resources.

In terms of systems for transfer of technology, the immediate challenge is that Developing States, and some Small Island Developing/Large Ocean States, often lack infrastructure, such as research vessels, but also data processing facilities, and in some cases, reliable internet. Capacity can be developed by taking advantage of new, low-cost technologies, e.g. the Maka Niu imaging system[115], as well as opportunistic use of available infrastructure, such as joining other sea-going efforts (Gap 4a, b).

Science solutions will benefit by being promoted and deployed across global networks, thus enabling 'capacity-sharing'[116] (Gap 4b). One way this capacity sharing can be improved is by building networks of researchers, such as the African Network of Deep-water research[117] (Gap 4c). Making better use of existing capacity also involves better integration with programmes such as the UN Ocean Decade and the Challenger150 programme, which are enhancing efforts to coordinate and standardise data collection across the five ocean basins (Gap 4b). Global networks can also be used to share expertise and equipment, spread awareness of funding or fieldwork opportunities, and to support the development of early career researchers, who are key to building and maintaining strong scientific capabilities into the future (Gap 4c).

International cooperation, coordination and knowledge-sharing will be essential for enabling the effective implementation of BBNJ Agreement activities[118], and this must be done in a way to make better use of existing capacity, not adding burdens onto already resource-constrained parties. For example, the CBD and the UNFCCC provide lessons learned and opportunities for greater international cooperation and collaboration in relation to implementation, and there is increasing emphasis on the importance of alignment of effort across conventions[119], which will now need to include the BBNJ Agreement and its associated scientific and technical bodies (Gap 4a). The BBNJ Agreement, therefore, provides an opportunity to review how the gathering of biodiversity and climate data for oceans across the different reporting mechanisms can be better aligned. Also, lessons from national implementation of the CBD can often apply to the BBNJ Agreement in an international context and global collectives such as the Sustainable Oceans Initiative (SOI), linked to the CBD, provide a strategic framework through which to catalyse partnerships and facilitate improved coordination in ABNJ (Gap 4a).

We have outlined above the background and major gaps and solutions for each of the four BBNJ pillars and summarised these in Table 1.

Roadmap to enhance data resources within ABNJ

From our analysis of the BBNJ Agreement objectives above, and to address the gaps and solutions identified (Table 1), we provide a distilled roadmap of actions to guide science and policy communities to support a science-based implementation of the Agreement (Fig. 5).

Action 1: embrace technological advancements

While maintaining existing time series and traditional taxonomic expertise is imperative, technological advances are necessary for improved data collection in remote ocean locations. Marine sampling is undergoing a technological revolution, including acoustic, imaging and molecular approaches[47] and autonomous data collection, for example, using underwater cameras to monitor plankton communities[37]. Digital cameras can monitor micro- to macro-scale species[120], and machine learning can provide rapid, automatic recognition of these images[121]. Identifications from genomic data can help with training automated imaging systems[122] and support cross-comparison with taxonomic data. As such systems become miniaturised and automated, there is potential to deploy them on the same platforms (e.g. gliders, floats, moorings and ships-of-opportunity) that are collecting environmental data, greatly increasing the number and geographical extent of observations.

Action 2: upscale spatial-temporal coverage and sharing of data

Pelagic and benthic sampling of remote ocean areas often occurs within national programmes, and there is much scope for improved data-sharing, or hosting coordinated networks of sampling and data, e.g. the COPEPOD global plankton database. Other initiatives that bring multiple observational datasets together are the Global Biodiversity Information Facility (GBIF), INSDC Ocean Biodiversity Information System (OBIS) (Fig. 2), or in key regional areas (e.g. SOOSmap, SCAR-MarBIN, and KRILLBASE in the Southern Ocean). Likewise, there are freely accessible data analysis tools, e.g. ECOTAXA[47]. To facilitate these types of databases for use in sustainable management of ABNJ, improvement in the pipeline from data-to-tools is required, including greater interoperability between databases and maintaining common metadata standards. Information obtainable from sampling infrastructure should be maximised, using platforms with the capability to collect biodiversity data alongside monitoring of physical and biogeochemical conditions.

Action 3: novel funding sources and data collection platforms

The inaccessibility of ABNJ, coupled with a challenging funding climate, requires enterprising approaches to data collection, such as utilising fishing vessels as research platforms. In the Southern Ocean, krill fishing vessels are involved in a co-funding model with NGOs (Antarctic Wildlife Research Fund, antarcticfund.org), and feeding into an ecosystem approach to management. 'Ship-of-opportunity' exemplar programmes such as the AMT (https://amt-uk.org/) also help maximise sampling opportunities (e.g.

Table 1 | Summary of major gaps and solutions for each of the four BBNJ pillars

BBNJ Pillar	Gaps	Solutions
Pillar 1: Marine Genetic Resources (MGR)	Limited time-series coverage Baseline data gaps Knowledge gaps in molecular science	Use of satellite data; increased ground-truthing of modelled data; global biodiversity databases Increased development of methods such as eDNA; image analysis with Artificial Intelligence and machine-learning; ensemble approaches from Earth System Models; global open-access databases. Transparent data sharing on central open-access platforms; traceable & interoperable data; optimisation of computational resources and investment.
Pillar 2: Area-based Management Tools (ABMT)	Gaps in vertical and horizontal spatial baseline data Gaps in connectivity data Climate change considerations 'Sustainable use' assessment	Use of satellite data in large-scale mapping of biodiversity indicators, ocean colour and seascapes Species distribution models; telemetry and tracking data for mobile species Siting MPAs in climate change refugia; dynamic MPAs or OECMs; decision support tools for climate-resilient MPAs Information on pressures from socio-economic activities; Natural Capital evaluation; integration with international bodies governing ocean resources.
Pillar 3: Environmental Impact Assessment (EIA)	Broad-scale and cumulative impacts Accessibility of data and tools Inclusion of climate data	Strategic Environmental Assessment, undertaken at a regional scale A framework for regional co-development of baseline data collection and research; pooling of data Decision support tools based on numerical modelling data; assessment of potential trade-offs; integration of national adaptation and spatial management policies.
Pillar 4: Capacity Building and Transfer of Marine Technologies (CBTMT)	Systems for transfer of marine technology Lack of infrastructure and/or data processing facilities Developing human knowledge networks and expertise	International cooperation; investment in SIDS, knowledge-sharing and networks; Alignment of effort across conventions. Opportunistic use of available infrastructure; utilise novel, low-cost technologies; promote capacity-sharing Global science networks; support development of Early Career Researchers.

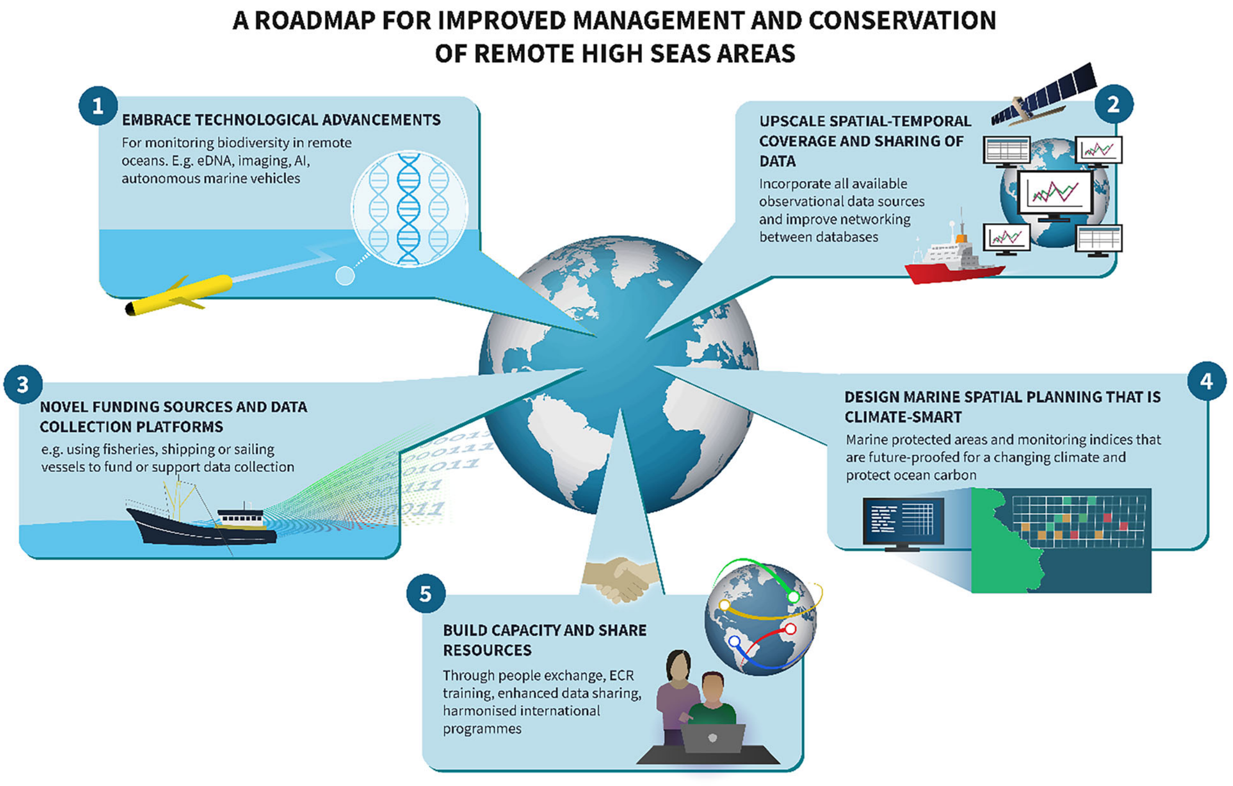

Fig. 5 | A roadmap of actions required for management and conservation of ABNJ to support the successful implementation of the UN BBNJ Agreement. See detail for each action in the text.

supporting a standardised biological sampling like BIO-GO-SHIP, ref. 123). Alternative platforms, such as moorings and commercial and recreational shipping, can be used[48], e.g. the Continuous Plankton Recorder (CPR) survey (https://www.cprsurvey.org/), and the ARGO network of autonomous observing floats[124]. This activity can be supported through outreach and providing co-benefits to stakeholders or industry.

Action 4: design marine spatial planning that is climate-smart

Adaptive, climate-smart approaches for ABMTs (e.g. MSPACE, https://www.smmr.org.uk/funded-projects/marine-spatial-planning-addressing-climate-effects/outputs/) need to remain effective as species ranges shift under changing ocean conditions, and protect high carbon areas of the seafloor, using conservation to deliver mitigation. This can be implemented through (i) Anticipatory Planning: Establishing ABMTs in current biodiversity hotspots that exhibit resistance to climate change, or are predicted to improve as climate refugia or 'bright spots', (ii) Dynamic Ocean Planning: Allowing ABMT boundaries to shift in response to species redistributions, accounting for horizontal and vertical habitat changes, such as species moving into deeper waters, or (iii) siting MPAs across a range of climate futures using OECMs.

Action 5: build capacity and share resources

Effective implementation of BBNJ Agreement activities requires international collaboration, supported by alignment of effort across conventions. This can be achieved through international working groups and data-sharing agreements that are facilitated through networking and cross-national scientific collaborations, training (including support for early career researchers), and financial support for SIDS. Utilising low-cost technologies is therefore key to bridge gaps between wealthy and poorer scientific communities. Initiatives such as the High Seas Alliance (highseasalliance.org), the Deep Ocean Stewardship Initiative (https://www.dosi-project.org/), and the Tara Ocean Foundation (https://fondationtaraocean.org/en/home/) bring together scientists and policymakers in a combined effort to inform and expedite action towards implementing governance in ABNJ.

Discussion

There is a growing body of literature in relation to governance and the political and legal aspects of the BBNJ Agreement, but less on how it will be implemented from a scientific and technological perspective. This analysis of the status of the science for ABNJ demonstrates considerable challenges, ranging from the lack of basic biodiversity monitoring and long-term time series, through to the understanding of processes in ABNJ, such as connectivity between areas at large scales or depths.

However, the analysis also shows how major scientific and technical developments in recent years can be utilised to address these challenges and gaps, and provides a roadmap towards the operationalisation of solutions. This supports prioritisation of effort and resource mobilisation so that solutions can be applied at scale and in an equitable manner.

Although the focus of this paper has been on how science and technology can support implementation, and the status of different science areas in relation to this, there is also the important issue of the mechanisms for how science is integrated into processes effectively and makes best use of resources. For example, we are lacking a central governance body to draw together and harmonise multilateral rules for access and benefit sharing (ABS) between nations to ensure accessibility of data, interoperability and enhanced outcomes for ABS, resulting in recent calls for policy-makers to come together with other relevant stakeholders to standardise rules across UN Fora[18].

The proposed solutions roadmap offers a way forward to address key knowledge gaps and enable solutions to meet the urgency of the challenge for BBNJ Agreement implementation, and provide wider benefits for the ocean and society. It is important to note, however, that the readiness and availability of technology, scientific data and expertise vary enormously among countries, so the roadmap will only succeed if capacity building and technology transfer are progressed with urgency.

The challenges are numerous: the lack of integrated observing methods, increased global collaboration, the requirement for long-term government funding rather than reliance on time-limited research grants, and greater accessibility and standardisation of data. All of this needs to occur with mechanisms that can be transferred at a global scale, not just at the national level, where the cost of ratification could be a limiting factor for developing countries[125].

Data availability

No datasets were generated or analysed during the current study.

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References

1. O'Leary, B. C. et al. Options for managing human threats to high seas biodiversity. *Ocean Coast. Manag.* **187**, 105110 (2020).
2. Blasiak, R. & Jouffray, J.-B. When will the BBNJ Agreement deliver results. *Ocean Sustain.* **3**, 21 (2024).
3. Jarvis, R. M. & Young, T. Pressing questions for science, policy, and governance in the high seas. *Environ. Sci. Policy* **139**, 177–184 (2023).
4. Tyberghein, L. et al. Bio-ORACLE: a global environmental dataset for marine species distribution modelling. *Glob. Ecol. Biogeogr.* **21**, 272–281 (2012).
5. Assis, J. et al. Bio-ORACLE v3.0. Pushing marine data layers to the CMIP6 Earth system models of climate change research. *Glob. Ecol. Biogeogr.* https://doi.org/10.1111/geb.13813 (2024).
6. Gaebel, C., Novo, P., Johnson, D. E. & Roberts, J. M. Institutionalising science and knowledge under the agreement for the conservation and sustainable use of marine Biodiversity of Areas Beyond National Jurisdiction (BBNJ): stakeholder perspectives on a fit-for-purpose Scientific and Technical Body. *Mar. Policy*. **161**, 105998 (2024).
7. Ocean Census. https://oceancensus.org/how-the-census-works/the-mission/. Accessed 4 December 2025.
8. Friedman, S. The interaction of the BBNJ Agreement and the legal regime of the area, and its influence on the implementation of the BBNJ Agreement. *Mar. Policy* **167**, 106235 (2024).
9. Carlson, C. J. et al. Pathways to an intergovernmental panel on pandemics: lessons from the IPSS and IPBES. *Lancet* **6**, 101178 (2025).
10. Chapman et al. Biodiversity monitoring for a just planetary future. *Science*. **383**, 34–36 (2024).
11. Ratnarajah, L. et al. Monitoring and modelling marine zooplankton in a changing climate. *Nat. Commun.* **14**, 564 (2023).
12. Lindeque, P. K., Parry, H. E., Harmer, R. A., Somerfield, P. J. & Atkinson, A. Next generation sequencing reveals the hidden diversity of zooplankton assemblages. *PLoS ONE*. **8**, e81327 (2013).
13. Laiolo, E. et al. Metagenomic probing toward an atlas of the taxonomic and metabolic foundations of the global ocean genome. *Front. Mar. Sci.* **1**, 1038696 (2024).
14. CBD. *Guide to the Cali Fund: Sharing the Benefits of Genetic Data from Nature* 9 (2025).
15. Wilkinson, M. et al. The FAIR Guiding Principles for scientific data management and stewardship. *Sci. Data* **3**, 160018 (2016).
16. SCBD. Decision adopted by the Conference of the Parties to the Convention on Biological Diversity on 1 November. 16/2 Digital sequence information on genetic resources. https://www.cbd.int/meetings/COP-16 (2024).
17. Carroll, S. R. et al. The CARE Principles for Indigenous Data Governance. *Data Sci. J.* **19**, 43 (2020). pp. 1-12.
18. Sett, S. et al. Harmonize rules for digital sequence information benefit-sharing across UN frameworks. *Nat. Commun.* **15**, 8745 (2024).
19. Vucetich, J. A., Nelson, M. P. & Bruskotter, J. T. What drives declining support for long-term ecological research? *BioScience* **70**, 168–173 (2020).
20. McQuatters-Gollop, A. et al. From microscope to management: the critical value of plankton taxonomy to marine policy and biodiversity conservation. *Mar. Policy*. **83**, 1–10 (2017).
21. Reid, P. C., Colebrook, J. M., Matthews, J. B. L. & Aiken, J. The Continuous Plankton Recorder: concepts and history, from Plankton Indicator to undulating recorders. *Prog. Oceanogr.* **58**, 117–173 (2003).

22. Rees, A. P., Smyth, T. J. & Brotas, V. The Atlantic Meridional Transect Programme (1995-2023). *Front. Mar. Sci.* https://doi.org/10.3389/fmars.2024.1358174 (2024).
23. Chavez, L. einanM. et al. A. The Ocean Biomolecular Observing Network (OBON). *Mar. Technol. Soc. J.* **56**, 106–107 (2022).
24. Howell, K. L. et al. A blueprint for an inclusive, global deep-sea ocean decade field program. *Front. Mar. Sci.* **7**, 584861 (2020).
25. Bridges, A. E. H. & Howell, K. L. Prioritisation of ocean biodiversity data collection to deliver a sustainable ocean. *Commun. Earth Environ.* **6**, 473 (2025).
26. Hestetun, J. T. et al. Significant taxon sampling gaps in DNA databases limit the operational use of marine macrofauna metabarcoding. *Mar. Biodivers.* **50**, 70 (2020).
27. OBIS. Ocean Biodiversity Information System. Intergovernmental Oceanographic Commission of UNESCO. Available at: https://obis.org/ (2025).
28. Rousseau, Y., Watson, R. A., Blanchard, J. L. & Fulton, E. A. Evolution of global marine fishing fleets and the response of fished resources. *Proc. Natl. Acad. Sci. USA* **116**, 12238–12243 (2019).
29. Thomalla, S. J., Nicholson, S.-A., Ryan-Keogh, T. J. & Smith, M. E. Widespread changes in Southern Ocean phytoplankton blooms linked to climate drivers. *Nat. Clim. Change* **13**, 975–984 (2023).
30. Ferreira, A. et al. Climate change is associated with higher phytoplankton biomass and longer blooms in the West Antarctic Peninsula. *Nat. Commun.* **15**, 6536 (2024).
31. El Hourany, R. et al. Linking satellites to genes with machine learning to estimate phytoplankton community structure from space. *Ocean Sci.* **20**, 217–239 (2024).
32. Basedow, S. L. et al. Remote sensing of zooplankton swarms. *Sci. Rep.* **9**, 686 (2019).
33. Rodofili, E. N., Lecours, V. & LaRue, M. Remote sensing techniques for automated marine mammals detection: a review of methods and current challenges. *PeerJ* **10**, e13540 (2022).
34. Klaassen, M., Marques, T. A., Alves, F. & Fernandez, M. Trends in marine species distribution models: a review of methodological advances and future challenges. *Ecography* e07702 (2025).
35. Rabone, M. et al. Access to Marine Genetic Resources (MGR): raising awareness of best-practice through a new agreement for Biodiversity Beyond National Jurisdiction (BBNJ). *Front. Mar. Sci.* **6**, 520 (2019).
36. McGinty, N., Irwin, A. J., Finkel, Z. V. & Dutkiewicz, S. Using ecological partitions to assess zooplankton biogeography and seasonality. *Front. Mar. Sci.* **10**, https://doi.org/10.3389/fmars.2023.989770 (2023).
37. Clark, J. R., Fileman, E. S., Fishwick, J., Ruhl, S. & Widdicombe, C. E. The Western Channel Observatory Automated Plankton Imaging and Classification System. *Oceanography* **38**, 29–31 (2025).
38. Mock, T. et al. Bridging the gap between omics and earth system science to better understand how environmental change impacts marine microbes. *Glob. Change Biol.* **22**, 61–75 (2016).
39. Tittensor, D. P. et al. Next-generation ensemble projections reveal higher climate risks for marine ecosystems. *Nat. Clim. Change* **11**, 973–981 (2021).
40. Heneghan, R. F. et al. Disentangling diverse responses to climate change among global marine ecosystem models. *Prog. Oceanogr.* **193**, 102560 (2021).
41. Eddy, T. D. et al. Global and regional marine ecosystem models reveal key uncertainties in climate change projections. *Earth's Future* **13**, e2024EF005537 (2025).
42. Atkinson, A. et al. Steeper size spectra with decreasing phytoplankton biomass indicate strong trophic amplification and future fish declines. *Nat. Commun.* **15**, 381 (2024).
43. Flynn, K. J. et al. More realistic plankton simulation models will improve projections of ocean ecosystem responses to global change. *Nat. Ecol. Evol.* **9**, 1562–1570 (2025).
44. Hill, S. L. et al. Observing change in pelagic animals as sampling methods shift: the case of Antarctic krill. *Front. Mar. Sci.* **11**, 1307402 (2024).
45. Meyer, B. et al. Adjusting the management of the Antarctic krill fishery to meet the challenges of the 21st century. *Proc. Natl. Acad. Sci. USA* **122**, e2412624122 (2025).
46. van der Loos, L. M. & Nijland, R. Biases in bulk: DNA metabarcoding of marine communities and the methodology involved. *Mol. Ecol.* **30**, 3270–3288 (2021).
47. Lombard, F. et al. Globally consistent quantitative observations of Planktonic ecosystems. *Front. Mar. Sci.* **6**, 196 (2019).
48. de Vargas, C. et al. Plankton Planet: a frugal, cooperative measure of aquatic life at the planetary scale. *Front. Mar. Sci.* **9**, 936972 (2022).
49. Crespo, G. O. et al. Beyond static spatial management: Scientific and legal considerations for dynamic management in the high seas. *Mar. Policy*. **122**, 104102 (2020).
50. Protected planet. Accessed at: https://www.protectedplanet.net/en (2024).
51. Grorud-Colvert, K. et al. The MPA Guide: a framework to achieve global goals for the ocean. *Science* **373**, 6560 (2021).
52. Pike, E. P. et al. L. Ocean protection quality is lagging behind quantity: applying a scientific framework to assess real marine protected area progress against the 30 by 30 target. *Conserv. Lett.* **17**, e13020 (2024).
53. IMMA Secretariat. *Important Marine Mammal Area regional Workshop for the North West Atlantic Ocean and Wider Caribbean* 75 (IMMA Secretariat, IUCN SSC-WCPA Marine Mammal Protected Areas Task Force, 2024).
54. Howell, K. L. A benthic classification system to aid in the implementation of marine protected area networks in the deep/high seas of the NE Atlantic. *Biol. Conserv.* **143**, 1041–1056 (2010).
55. Evans, J. L., Peckett, F. & Howell, K. L. Combined application of biophysical habitat mapping and systematic conservation planning to assess efficiency and representativeness of the existing High Seas MPA network in the Northeast Atlantic. *ICES J. Mar. Sci.* **72**, 1483–1497 (2015).
56. Smith, C. R. et al. Preservation reference areas for nodule mining in the Clarion-Clipperton Zone: rationale and recommendations to the International Seabed Authority. In *Proc. Pew Workshop on Design of Marine Protected Areas for Seamounts and the Abyssal Nodule Province in Pacific High Seas, Oct 23-26, 2007* (University of Hawaii at Manoa, 2008).
57. McQuaid, K. A. et al. Using habitat classification to assess representativity of a protected area network in a large, data-poor area targeted for deep-sea mining. *Front. Mar. Sci.* **7**, 558860 (2020).
58. Anabitarte, A. et al. The use of Atlantic seascapes for marine protected areas planning in the context of the marine biological diversity of Areas Beyond National Jurisdiction Agreement. *Mar. Pollut. Bull.* **214**, 117776 (2025).
59. Acha, E. M., Piola, A., Iribarne, O. & Mianzan, H. *Ecological Processes at Marine Fronts: Oases in the Ocean* 68 (Springer, 2015).
60. Mangolte, I., Lévy, M., Haëck, C. & Ohman, M. D. Sub-frontal niches of plankton communities driven by transport and trophic interactions at ocean fronts. *Biogeosciences* **20**, 3273–3299 (2023).
61. Miller, P. I. & Christodoulou, S. Frequent locations of oceanic fronts as an indicator of pelagic diversity: application to marine protected areas and renewables. *Mar. Policy* **45**, 318–329 (2014).
62. Miller, P. I., Weidong, X. & Carruthers, M. Seasonal shelf-sea front mapping using satellite ocean colour and temperature to support development of a marine protected area network. *Deep Sea Res. Part II Top. Stud. Oceanogr.* **119**, 3–19 (2015).
63. Davies, T. E. et al. Multispecies tracking reveals a major seabird hotspot in the North Atlantic. *Conserv. Lett.* **14**, e12824 (2021).

64. Wakefield, E. D. et al. The summer distribution, habitat associations and abundance of seabirds in the sub-polar frontal zone of the Northwest Atlantic. *Prog. Oceanogr.* **198**, 102657 (2021).
65. Queirós, A. M. et al. Bright spots as climate-smart marine spatial planning tools for conservation and blue growth. *Glob. Change Biol.* **27**, 5514–5531 (2021).
66. Queirós, A. M. et al. *Early-warning System: Climate-smart Spatial Management of UK Fisheries, Aquaculture and Conservation. A Report of the NERC/ESRC Marine Spatial Planning Addressing Climate Effects Project*. https://doi.org/10.14465/2023.msp02.tec (2024).
67. Davies, A. J. & Guinotte, J. M. Global habitat suitability for framework-forming cold-water corals. *PLoS ONE* **6**, e18483 (2011).
68. Howell, K. L., Piechaud, N., Downie, A. L. & Kenny, A. The distribution of deep-sea sponge aggregations in the North Atlantic and implications for their effective spatial management. *Deep Sea Res. Part I Oceanogr. Res. Pap.* **115**, 309–320 (2016).
69. Webb, T. J., Vanden Berghe, E. & O'Dor, R. Biodiversity's Big Wet Secret: the global distribution of marine biological records reveals chronic under-exploration of the deep pelagic ocean. *PLoS ONE* **5**, e10223 (2010).
70. La Bianca, G. et al. A standardised ecosystem services framework for the deep sea. *Front. Mar. Sci.* **10**, 1176230 (2023).
71. Ross, R. E., Nimmo-Smith, W. A. M. & Howell, K. L. Towards 'ecological coherence': assessing larval dispersal within a network of existing Marine Protected Areas. *Deep Sea Res. Part I Oceanogr. Res. Pap.* **126**, 128–138 (2017).
72. Hilário, A. et al. Estimating dispersal distance in the deep sea: challenges and applications to marine reserves. *Front. Mar. Sci.* **2**, 6 (2015).
73. Baco, A. R. et al. A synthesis of genetic connectivity in deep-sea fauna and implications for marine reserve design. *Mol. Ecol.* **25**, 3276–3298 (2016).
74. SBSTTA. In *Proc. SBSTTA Twenty-sixth Meeting, Nairobi, 13-18 May, 2024: Potential Options for Modalities for Collaboration and Cooperation with Relevant Global and Regional Organizations in the Context of the Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction* (SBSTTA, 2024).
75. BBNJ. Agreement on Biodiversity Beyond National Jurisdiction, U.N. Treaty Series No. 1234, 4th March 2023. https://www.un.org/bbnj (2023).
76. Queirós, A. M. et al. *Early Warning System: Climate-smart Spatial Management of UK Fisheries, Aquaculture and Conservation. A Report of the NERC/ESRC Marine Spatial Planning Addressing Climate Effects Project* (Marine Climate Change Impacts Partnership, 2023).
77. Wilson, K. L., Tittensor, D. P., Worm, B. & Lotze, H. K. Incorporating climate change adaptation into marine protected area planning. *Glob. Change Biol.* **26**, 3251–3267 (2020).
78. United Nations. BBNJ Agreement Factsheet 3 ABMTs. 5 (2024).
79. Skidmore, A. K. et al. Priority list of biodiversity metrics to observe from space. *Nat. Ecol. Evol.* **5**, 896–906 (2021).
80. Pettorelli, N. et al. Satellite remote sensing of ecosystem functions: opportunities, challenges and way forward. *Remote Sens. Ecol. Conserv.* **4**, 71–93 (2017).
81. Kulk, G. et al. Primary production, an index of climate change in the ocean: satellite-based estimates over two decades. *Remote Sens.* **12**, 826 (2020).
82. Sathyendranath, S. et al. Ocean biology studied from space. *Surv. Geophys.* **44**, 1287–1308 (2023).
83. Cavender-Bares, J. et al. Integrating remote sensing with ecology and evolution to advance biodiversity conservation. *Nat. Ecol. Evol.* **6**, 506–519 (2022).
84. Paolo, F. S. et al. Satellite mapping reveals extensive industrial activity at sea. *Nature* **625**, 85–91 (2024).
85. Möller, L. M. et al. Movements and behaviour of blue whales satellite tagged in an Australian upwelling system. *Sci. Rep.* **10**, 21165 (2020).
86. Raitsos, D. E. et al. Sensing coral reef connectivity pathways from space. *Sci. Rep.* **7**, 9338 (2017).
87. Molinos, J. G. et al. Climate velocity and the future global redistribution of marine biodiversity. *Nat. Clim. Change* **6**, 83–88 (2015).
88. Whitney, C. K., Cheung, W. W. L. & Ban, N. C. Considering the implications of climate-induced species range shifts in marine protected areas planning. *FACETS* **8**, 1–10 (2023).
89. Lezama-Ochoa, N. et al. Identifying climate refugia and bright spots for highly mobile species. *npj Ocean Sustain.* **4**, 35 (2025).
90. Maxwell, S. M. et al. Dynamic ocean management: defining and conceptualizing real-time management of the ocean. *Mar. Policy* **58**, 42–50 (2015).
91. Hazen, E. L. et al. A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. *Sci. Adv.* **4**, eaar3001 (2018).
92. Doxa, A. et al. 4D marine conservation networks: combining 3D prioritization of present and future biodiversity with climatic refugia. *Glob. Change Biol.* **28**, 4577–4588 (2022).
93. Project Ireland 2040: National Marine Planning Framework. Department of Housing, Local Government and Heritage. Government of Ireland, 210p (2022).
94. Queirós, A. M. et al. Identifying and protecting macroalgae detritus sinks toward climate change mitigation. *Ecol. Appl.* **33**, e2798 (2023).
95. Ottaviani, D. *Economic Value of Ecosystem Services from the Deep Seas and the Areas Beyond National Jurisdiction* 135 (Food and Agriculture Organization, 2020).
96. Lopez-Rivas, J. D. & Cardenas, J. C. What is the economic value of coastal and marine ecosystem services? A systematic literature review. *Mar. Policy* **161**, 106033 (2024).
97. Wang, J. & Zhang, Y. The area-based management tools coordination between IMO and BBNJ agreement regimes and its implications on vessel pollution control. *Front. Mar. Sci.* **11**, https://doi.org/10.3389/fmars.2024.1341222 (2024).
98. McQuaid, K. et al. The need for Strategic Environmental Assessments and Regional Environmental Assessment in ABNJ for ecologically meaningful management. One Ocean Hub Policy Brief. 9 (2022).
99. Hitchin, B. et al. Thresholds in deep-seabed mining: a primer for their development. *Mar. Policy* **149**, 105505 (2023).
100. Hiddink, J. G. et al. Quantifying the carbon benefits of ending bottom trawling. *Nature* **617**, E1–E2 (2023).
101. Lenton, T. M. et al. (eds). *The Global Tipping Points Report 2023* (University of Exeter, 2023).
102. IPCC. Summary for policymakers. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC, 2021).
103. Pecl, G. T. et al. Biodiversity redistribution under climate change: Impacts on ecosystems and human well-being. *Science* **355**, 6332 (2017).
104. Scheffers, B. R., Oliviera, B. F., Lamb, I. & Edwards, D. P. Global wildlife trade across the tree of life. *Science*. **366**, 6461 (2019).
105. Druel, E. Environmental Impact Assessments in Areas Beyond National Jurisdiction. IDDRI, Studies, No. 01, 42 (2013).
106. Willsteed, E. A., Jude, S., Gill, A. B. & Birchenough, S. N. R. Obligations and aspirations: a critical evaluation of offshore wind farm cumulative impact assessments. *Renew. Sustain. Energy Rev.* **82**, 2332–2345 (2018).

107. Hassanali, K. & Mahon, R. Encouraging proactive governance of marine biological diversity of Areas Beyond National Jurisdiction through Strategic Environmental Assessment (SEA). *Mar. Policy* **136**, 104932 (2022).
108. Weaver, P. P. E. et al. *Regional environmental assessment of the Northern Mid-Atlantic Ridge*. 229 (2019).
109. Boyce, D. G. et al. A climate risk index for marine life. *Nat. Clim. Change* **12**, 854–862 (2022).
110. Cheung, W. W. L., Palacios-Abrantes, J. & Roberts, S. M. Projecting contributions of marine protected areas to rebuild fish stocks under climate change. *npj Ocean Sustain.* **3**, 11 (2024).
111. Olsen, E. et al. Testing management scenarios for the North Sea ecosystem using qualitative and quantitative models. *ICES J. Mar. Sci.* **80**, 218–234 (2023).
112. Frazao-Santos, C. et al. E. Key components of sustainable climate-smart ocean planning. *Ocean Sustain.* **3**, 10 (2024).
113. Tittensor, D. P. et al. Integrating climate adaptation and biodiversity conservation in the global ocean. *Sci. Adv.* **5**, eaay9969 (2019).
114. Wåhlstrom, I. et al. *Bringing Climate Change into Ecosystem Based Management of the Sea: Data and Methods for the Symphony Framework: Symphony—A Cumulative Assessment Tool Developed for Swedish Marine Spatial Planning.* (Swedish Meteorological and Hydrological Institute, Norrköping, Sweden, 2020).
115. Novy, D. et al. Maka Niu: a low-cost, modular imaging and sensor platform to increase observation capabilities of the deep ocean. *Front Mar. Sci.* **9**, 986237 (2022).
116. Lezak, S. From capacity building to capacity sharing. *Nat. Sustain.* **7**, 1–3 (2024).
117. McQuaid, K. A. et al. Practical actions to strengthen capacity for deep-water research in Africa. Available at: https://doi.org/10.24382/gxbv-sp22 (2024).
118. Harden-Davies, H. et al. M. First to finish, what comes next? Putting capacity building and the transfer of marine technology under the BBNJ Agreement into practice. *Ocean Sustain.* **3**, 3 (2024).
119. Gupta, H. & Singh, N. K. Climate change and biodiversity synergies: a Scientometric analysis in the context of UNFCCC and CBD. *Anthr. Sci.* **2**, 5–18 (2023).
120. Bicknell, A. W. J., Godley, B. J., Sheehan, E. V., Votier, S. C. & Witt, M. J. Camera technology for monitoring marine biodiversity and human impact. *Front. Ecol. Evol.* **14**, 424–432 (2016).
121. Irisson, J.-O., Ayata, S.-D., Lindsay, D. J., Karp-Boss, L. & Stemmann, L. Machine learning for the study of plankton and marine snow from images. *Annu. Rev. Mar. Sci.* **14**, 277–301 (2022).
122. Pierella Karlusich, J. J., Lombard, F., Irisson, J.-O., Bowler, C. & Foster, R. A. Coupling imaging and omics in plankton surveys: state-of-the-art, challenges, and future directions. *Front. Mar. Sci.* **9**, https://doi.org/10.3389/fmars.2022.878803 (2022).
123. Clayton, S. et al. Bio-GO-SHIP: the time is right to establish global repeat sections of ocean biology. *Front. Mar. Sci.* **8**, https://doi.org/10.3389/fmars.2021.767443 (2022).
124. Claustre, H., Johnson, K. S. & Takeshita, Y. Observing the global ocean with Biogeochemical-Argo. *Ann. Rev. Mar. Sci.* **12**, 23–48 (2020).
125. Tiller, R. & Mendenhall, E. And so it begins—the adoptions of the 'Biodiversity Beyond National Jurisdiction' treaty. *Mar. Policy* **157**, 105836 (2023).

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Competing interests

The authors declare no competing interests.

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