Accelerating Ocean Species Discovery and Laying the Foundations for the Future of Marine Biodiversity Research and Monitoring

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Abstract

Ocean Census is a new Large-Scale Strategic Science Mission aimed at accelerating the discovery and description of marine species. This mission addresses the knowledge gap of the diversity and distribution of marine life whereby as few as ten percent of the ocean's predicted 2.2 million species have been described to date. Without improved knowledge of marine biodiversity, tackling the decline and eventual extinction of many marine species will not be possible. Marine biota has evolved over nearly 4 billion years and includes many branches of the tree of life that do not exist on land or in freshwater. This biota provides numerous benefits to humankind, many of which remain unknown, and governs large-scale biogeochemical processes in the ocean and wider Earth system. Understanding what is in the ocean and where it can be found is fundamental science, which is required to understand how the ocean works, the direct and indirect benefits it provides to society and how human impacts can be reduced and managed to ensure marine ecosystems remain healthy.

Here, we describe a strategy to accelerate the rate of ocean species discovery and description by: 1) employing consistent standards for the digitisation of species data to broaden access to biodiversity knowledge and enabling cybertaxonomy; 2) establishing new working practices and adopting advanced technologies to accelerate taxonomy (e.g. third-generation sequencing, 3D high-resolution imagery, new sampling technologies and artificial intelligence); 3) building the capacity of stakeholders to undertake taxonomic and biodiversity related research and development, especially targeted at low- and middle-income countries (LMICs) so that they can better assess and manage life in their waters and contribute to global biodiversity knowledge; and 4) increasing observational coverage on dedicated expeditions. A new programme, Ocean Census, is conceived as an open network of scientists anchored by Biodiversity Centres with a global distribution in developed countries and LMICs. Through a collaborative approach, including co-production of science with teams from LMICs, and by working with funding partners, Ocean Census will focus and grow current efforts to discover ocean life globally, and permanently transform our ability to document, describe and safeguard marine species. Capacity development, co-production of science and the development of a comprehensive digitisation strategy will help to democratise biodiversity science and empower all people including indigenous communities to document, monitor and manage our ocean species.

Introduction

Ocean Life and the Biodiversity Crisis

The ocean comprises the greatest area of wilderness on Earth (Jones et al., 2018 compared to land in Watson et al., 2016) and is Earth's largest ecosystem, comprising 1.3 billion km^3 of water covering 71% of the surface of our planet. It harbours an astonishing diversity of species especially at a deep phylogenetic level. For example, regarding Metazoans, at the phylum level, which differentiates the major transitions in animal body plans, physiology, and molecular evolution, 15 of 33 accepted animal phyla (WoRMS, 2023) are comprised exclusively of marine species, an additional 8 are dominated by marine species while only one has currently no known marine members (May, 1994, Rogers et al., 2022a; see Table 1). The ocean is home to some of the largest and smallest organisms ever to have existed on earth. Indeed, the smallest organisms may constitute the greatest potential for taxonomic discovery, accounting for the largest proportion of marine diversity and biomass (Bar-On et al., 2018). Life is found everywhere in the ocean and has adapted to the most extreme marine environments including the deepest trenches (e.g. Challenger Deep in the Marianas Trench; Jamieson, 2015, Jamieson et al., 2023), anoxic hypersaline basins (Danovaro et al., 2010), and high temperature deep-sea hydrothermal vents (Van Dover, 2000). Ocean life has evolved over nearly 4 billion years (e.g. Tashiro et al., 2017) and its diversity provides numerous benefits to humankind (e.g. Worm et al., 2006; Barbier, 2017; Lotze, 2021), many of which we are only just uncovering (e.g. marine genetic resources; Blasiak et al., 2020). Yet, compared to terrestrial systems, we still only have a basic understanding of how life is distributed in the ocean (e.g. Gagné et al., 2020), how it contributes to the functioning of marine ecosystems (Gamfeldt et al., 2014; Thurber et al., 2014) as part of the Earth's life-support systems, and how it underpins human society and the well-being of its citizens. Nearly ninety percent of an estimated 2 million species of marine life remain undescribed, and many geographic regions and ecosystems remain poorly explored (Webb et al., 2010; Mora et al., 2011; Ramirez-Llodra et al., 2011; Bouchet et al., 2023). As a result, human society cannot fully comprehend the vital importance of a healthy ocean and the indispensability of Earth's marine life in supporting human well-being.

Insert Table 1

Global economic prosperity and long-lasting economic growth has been a relatively recent achievement but it has come at the expense of society (Moranta et al., 2022), climate stability and biodiversity which has declined by an estimated 40% (Dasgupta, 2021). In the ocean, defaunation may have started later than on land and there are fewer recorded extinctions, but evidence suggests that there has been a significant loss of biodiversity with cascading ecological changes across food webs, altering the function of marine ecosystems (McCauley et al., 2015; Cowie et al., 2022; Edgar et al., 2023) and their capacity to provide goods and services to millions of people in the world (Smale et al., 2019; Isbell et al., 2023). Assessment of the IUCN Red List of species, a metric that quantitatively estimates extinction risk in organisms (IUCN, 2017), suggests that the proportion of marine species threatened with extinction is 11-46% and spans the range for species from terrestrial groups (20-25%; Webb and Mindel, 2015; Rogers et al., 2020). It is likely that the poor level of observation and monitoring of ocean species and, more fundamentally, less taxonomic knowledge compared to terrestrial ecosystems means that many extinctions and declines have not been recorded (e.g. Webb and Mindel, 2015, Rogers et al., 2020; Cowie et al., 2022). The ocean biodiversity crisis is driven both by the decline of species (e.g. more than three quarters of oceanic sharks and rays are threatened with extinction; Pacoureau et al., 2021) and the degradation and collapse of ecosystems (e.g. tropical reefs have lost half of their coral cover since the 1870s; Wilkinson et al., 2016a; IPCC, 2019).

Why Invest in Accelerating Species Discovery in the Ocean?

Societal Well-Being and Management of the Ocean

Human society is founded on the ecosystem services provided by biodiversity. Biodiversity contributes to human health and well-being by providing food, underpinning livelihoods, producing oxygen, regulating climate, protecting millions of communities from extreme weather events, remediating pollution, supporting mental health and cultural practices, and providing novel metabolites that form a significant proportion of the pharmaceuticals we use to fight disease (Dasgupta, 2021). It has been estimated that benefits to society from the natural world are equal to or greater than global domestic product (OECD, 2019). The annual value of industries that are highly dependent on biodiversity, such as construction and agriculture, is estimated at $13 trillion with a further $31 trillion added by industries moderately dependent on ecosystem services (OECD, 2019). Estimates of the contribution of ocean ecosystems to people have varied widely, with estimates of "gross marine product" of at least $2.5 trillion and a total asset base of the ocean being $24 trillion (Hoegh-Guldberg et al., 2015) while another study has appraised the value of ocean ecosystem services at $49.7 trillion per annum (out of a total of $124.8 trillion; Costanza et al., 2014; based on 2011 figures of ecosystem area and value per hectare). These figures are, however, contested and also hide the societal value of the oceans in terms of wider benefits to people. For example, global marine capture fisheries landed about 78.8 million tonnes (MT) of fish in 2020 with a further 8.3MT coming from mariculture (FAO, 2022). The value of marine fisheries has been estimated at around $100 billion per annum, with marine fisheries supporting about 260 million livelihoods and providing about 2.9 billion people with 20% of their protein needs as well as being a critical source of micronutrients (Lam et al., 2016; Selig et al., 2018). Coastal and marine tourism depend on healthy marine ecosystems and constitute approximately 50 percent of all global tourism, equal to US$4.6 trillion or 5.2 percent of global gross domestic product (Northrop et al., 2022). Income from tourism is particularly important for small island developing states (SIDs) and coastal communities (Northrop et al., 2022). It has been estimated that over 775 million people globally are highly dependent on marine ecosystems for nutrition, employment and coastal protection (Selig et al., 2018).

Alongside cultural, educational and historic knowledge and perceptions, understanding the variety and distribution of life on Earth is fundamental to appreciate its importance to human well-being and strengthening our connection with nature. It is also critical to manage which human activities take place, where and when, in order to ensure biodiversity is maintained for present and future generations. Increased knowledge of the diversity and distribution of life in the ocean can lead to improved conservation and ocean management outcomes at local, national, regional and international levels (Rabone et al., 2019). Networks of Marine Protected Areas (MPAs) are an obvious example, where knowledge of the diversity and distribution of species is critical to the effective application of conservation. This is particularly the case for threatened species (IUCN Red List species), although very few marine species are red listed and with increasing depth in the ocean even less, despite that red listing can protect deep-sea species (Sigwart et al., 2019). If MPAs are to protect a representative proportion of biodiversity, protection should include consideration of habitat, species and genetic diversity. *Ad hoc* designation of MPAs leads to poor conservation outcomes for biodiversity and threatened species (e.g. Klein et al., 2015; Asaad et al., 2018) and can have implications for social equity and community livelihoods and long-term well-being (Gill et al., 2019). Even where systematic planning is undertaken to inform the designation of MPAs, it often uses proxies such as terrain or habitat to infer "importance", can be subject to compromise resulting from negotiations during the MPA designation processes by some stakeholders with specific economic or political interests (e.g. fisheries, tourism, oil extraction; Edgar et al., 2008; Stevenson et al., 2019) and rarely considers genetic interconnectedness among regions. The discovery of new habitats and biodiversity, including novel species, have informed the placement of MPAs and other conservation measures. An example is the recent discovery of mesophotic reef ecosystems on the Philippine Rise in 2014 (Nacorda et al., 2017), which led to the designation of a fully protected MPA and a wider area of controlled management for fisheries by the government of the Philippines in 2018. Similarly, efforts are underway to restore degraded sites in Sundarbans, the world's largest contiguous mangrove wetland which is an UNESCO World Heritage Site and a RAMSAR site. These efforts are based on the findings from robust coastal biodiversity mapping exercises that have also integrated state-of-art approaches including use of environmental DNA (Chatterjee et al., 2019; Ghosh et al., 2022).

Sustainable management of marine living resources requires, first of all, knowledge of the species occurring in a certain area (Glover et al 2018) and the carrying capacity of target populations of species to fishing mortality or other forms of harvesting (e.g. Jennings et al., 2008; Glover et al 2018). Responses to management can be influenced by diverse aspects of species ecology, including population size, distribution, age structure, connectivity, life history and interactions with other species (Jennings et al., 2008; Ovenden et al., 2015). Many of these responses can be specific to genetically distinct stocks or populations of a species, so a knowledge of intraspecific genetic and biological variation is important (e.g. Ovenden et al., 2015). An understanding of the wider impacts of exploitation on the ecosystems that harbour target species, as well as the effects on non-target species, is also critically important to conserve biodiversity (e.g. Crowder et al., 2008; Ovenden et al., 2015; Clark et al., 2016). This is because exploitation methods, such as bottom trawling or long-lining, can cause significant mortality of non-target species through bycatch and habitat destruction. These impacts can be so severe that they lead to increased risk of species extinctions (e.g. seabirds such as albatrosses and petrels and pelagic sharks; e.g. Anderson et al., 2011; Pacoureau et al., 2021). Data on the distribution of species and habitats in the ocean supports sustainable management of living marine resources and the habitats and other non-target species associated with them. This includes data on species presence, abundance, health, size distributions, diets, life-history traits, cellular and molecular responses to changing geochemical gradients, and other aspects of biology important to sustainable management.

The ocean is playing an increasing role in the direct economic activities of coastal States. An example of this is the rapid increase in ocean renewable energy installations in regions such as European waters (e.g. UK Government, 2021). Ideally, such development should conform to the principles of a blue economy, whereby they are economically viable, environmentally sustainable, and equitable to society (Bramley et al., 2021). Environmental sustainability means that blue economic activities should be at least neutral to biodiversity but, ideally, should be regenerative or restorative to marine species, habitats and ecosystems (Sala et al., 2013; Bramley et al., 2021). Knowledge of biodiversity is critical for the spatial management of human activities in the ocean to avoid harm to natural ecosystems. Moreover, such knowledge can be pivotal in removing bankability barriers that influence blue financing globally.

The conservation and sustainable use of marine biodiversity is integral to international treaty obligations under the United Nations Convention of the Law of the Sea (UNCLOS), the Convention on Biological Diversity and a range of other conventions, treaties and agreements (see Rogers et al., 2020) including the provisionally agreed international legally binding instrument under UNCLOS on the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction. At present, the ability of many States, especially low-income States, to meet their national, regional and international policy commitments is hindered by insufficient knowledge and institutional capacity to document and obtain information on the biodiversity in their own waters and in areas beyond national jurisdiction, (e.g. Rogers et al., 2020, 2021a).

The current gaps in knowledge create challenges in setting baselines, monitoring how biodiversity is responding to changes in human activities and climate change (e.g. Edgar et al., 2023) and in evaluating if the policies and management plans implemented are proving effective. At present, we are effectively blind to how life in the ocean is responding to our intentional and unintentional actions and to rapidly changing environmental conditions. New molecular approaches, including environmental DNA (eDNA), environmental metabarcoding and environmental metagenomics, offer powerful technologies that will greatly assist in monitoring biodiversity (Cordier et al. 2022; reviewed in Rogers et al., 2022a). However, for these technologies to be effective, DNA libraries that connect sequences to accurate species identifications with archived, vouchered and openly accessible materials are required. At present, existing quality-controlled barcoding libraries are insufficiently populated to be of general use in monitoring biodiversity using DNA sequencing approaches (Hestetun et al 2020; Rogers et al., 2022a). In addition, the accuracy of species identifications submitted to databases can also be questionable, an extreme example being where 100% of the sequences on GenBank were assigned to not only the wrong species of narcomedusae but to an organism in a completely different family (Lindsay et al., 2017). Moreover, there are instances where many of the taxonomically intractable groups (free-living marine nematodes and members of Nemertea), which are widespread in many environments are rarely represented in available sequence databases limiting acceleration and quantification of the true extent of ocean biodiversity (e.g. Bhadury and Austen 2010; Kumar et al., 2015).

Scientific Endeavour

Life began in the ocean and much of the legacy of nearly four billion years of evolution is recorded in the DNA of marine species. The discovery of extremophiles and chemosynthetic communities at deep-sea hydrothermal vents on the Galapagos Rift in 1977 changed humanity's perceptions of where life may be found elsewhere in the solar system and the universe beyond (Cable et al., 2021). The taxonomy and systematics of marine species is fundamental science. The ocean already presents some of the best-known examples of the links between environment and evolution at the genomic level (e.g. the evolution of antifreeze proteins in polar marine fish and other adaptations to extreme environments; Rogers, 2012). Sampling across the tree of life has been important in understanding how key genes involved in development and diversification of body plans, known as Homeobox genes, have evolved and function in invertebrates, fish and humans (e.g. Holland, 2013; Ferrier, 2016; Brauchle et al., 2018). A broader sampling of life in the ocean is critical to understanding the laws that drive evolutionary processes and how genomes can change across generations from simple nucleotide substitutions to changes at the level of chromosomes and in the expression (the switching on and off) of genes (Lewin et al., 2018). At a time when climate destabilisation is forcing rapid alterations in the Earth system, biodiversity science is key to resolving how marine ecosystems are responding to multiple stressors and assessing how genetic variation in marine life could support climate adaptation.

Marine Genetic Resources

Marine genetic resources are present in all marine life, including the physical genes and genomes (DNA and RNA), the information they encode (i.e., digital sequence information), and the products of these genes, including a wide range of molecules (e.g., enzymes, structural proteins, peptides and secondary metabolites), their derivatives, the biological processes they are a part of (e.g., biosynthetic pathways), and the physical structures they form that offer actual or potential value to humanity (Saha et al., 2018; Rabone et al., 2019; Rogers et al., 2021a). Marine genetic resources have been a source of pharmaceuticals, nutraceuticals, personal care products, research tools (e.g. green fluorescent protein), industrial enzymes, aquaculture species and functional food products and can be applied in the management and conservation of marine species (Blasiak et al., 2020; Rogers et al., 2021a). For example, to date, 17 pharmaceutical drugs derived from marine organisms have been clinically approved, including treatments for cancer and drug resistant cancer cells, nosocomial infections, neuropathic pain, hypertriglyceridemia and viral agents such as *Herpes simplex* (www.marineparmacology.org; Blasiak et al., 2020; Midwestern University, 2020). Another 24 marine-derived products are in clinical trials and a further 250 in preclinical investigations (Blasiak et al., 2020; Midwestern University, 2020). The anticancer drug Aplidin has also been found to be effective against the SARs Covid-2 virus (Taglialatela-Scafati, 2021). Most of the approved pharmaceuticals have been derived from compounds extracted from marine invertebrates, many of which are derived from bacterial associates, with sponges being a particularly rich source (Blasiak et al., 2020), potentially partly because of their endosymbionts. Another example is Dolastatin-10, a key drug scaffold which originates from the tropical marine mollusc *Dolabella auricularia* (Gao et al 2021) and which has been found to have its origin through complex interactions between the mollusc and a cyanobacterium. The genetic basis of these interactions and geographic distribution of Dolastatin-10 are now being investigated from shallow tropical coastal biotopes of South Asia (Bhadury, 2023). Most importantly, genomic resources store biological information in a remarkably compact form that can be safely and inexpensively preserved for future analysis. Securely archiving genetic resources provides insurance globally against the irretrievable loss of data that might otherwise result from biodiversity loss and extinction. We have only just begun to explore the enormous potential of marine genetic resources and a large portion of these lie in the undescribed biodiversity of the ocean. These genetic resources could also pave the way to using synthetic biology approaches to address long-term societal needs.

Accelerating the Discovery of Species to Halt the Ocean Biodiversity Crisis and Meet Societal Needs for Sustainable Development

An important key to halting the biodiversity crisis, sustainably managing human activities in the ocean and protecting nature's contributions to society is transforming our understanding of the diversity and distribution of life in the ocean. This transformation is not currently proceeding at sufficient speed because taxonomy has largely been reliant on methods first developed in the 18th and 19th Centuries (Rogers et al., 2022a). Even though this process is now assisted by DNA sequencing, it is still very slow and often requires examination of the original samples on which previous species descriptions were based (type specimens). Limited capacity in terms of numbers of taxonomists across all groups of marine organisms is also a key challenge (Engel, 2021, Mammola, 2023). As a result of this, the rate of description of new species has barely changed since the 1840s (see Figure 1; Rogers et al., 2022a; Bouchet et al., 2023). On average, the length of time to describe a species from when it is first collected from the ocean has been estimated at 13.5 years (Bouchet et al., 2023). Because taxonomic studies are intrinsically time consuming and processed slowly, robust systematic frameworks that build upon an accurate taxonomy are limiting factors negatively affecting our ability to address many big questions in marine and broader biological sciences including an understanding of global patterns and processes, as well as in ocean management for which a knowledge of species diversity is crucial (e.g. Godfray, 2002; Godfrey & Knapp, 2004; Godfrey, 2007; Rogers et al., 2022a). As a result, marine taxonomy has fallen out of favour with scientific journals and funding agencies (e.g. Hamilton et al., 2021; Pinto et al., 2021), leading to a decline in taxonomic science and the current taxonomic crisis (Godfray, 2002). This decline is particularly visible in some regions such as Africa, South and South-east Asia, where the flow of funding support for taxonomy-related research has fallen dramatically over the years. Unfortunately, this has coincided with the global biodiversity crisis, when knowledge on the diversity of marine species and where they live is urgently required to inform efforts to conserve, restore or sustainably manage them (Knapp & Boxshall, 2010; Britz et al., 2020) or, in the event they become extinct in the near future, preserve the knowledge of them, including their genomic data (Dubois et al., 2021; Engel et al., 2021; Cowie et al., 2022). This lends a new urgency to accelerate collection, documentation and description of ocean life (e.g. Maddison et al., 2012; Dubois et al., 2021).

Insert Figure 1

To resolve the taxonomic crisis as it manifests for ocean species, The Nippon Foundation (https://www.nippon-foundation.or.jp/en) and the Nekton Foundation (https://nektonmission.org/) assembled four international Expert Working Groups on: Marine Taxonomy and Species Discovery; Digitisation; Public Engagement; and Capacity Development & Legacy. These Working Groups collectively developed a strategy to accelerate the rate of ocean species discovery and description, the goal being to assist in addressing the biodiversity crisis in an inclusive, diverse and equitable manner, and by managing, storing, sharing and curating this new knowledge so that it is accessible to all stakeholders. This strategy involves solving both technical and social challenges as well as adopting already proven approaches to accelerate species discovery, the accessibility of taxonomic data and its application to current societal needs. It will form the basis of a new programme to accelerate the discovery and description of marine species: Ocean Census.

A New Approach to Accelerating Ocean Species Discovery

Methods

A literature review was undertaken to understand the current state of marine taxonomy and biodiversity research, its historical development, and potential new approaches to accelerating species discovery and description (Rogers et al., 2022a). This review formed an initial document for subsequent deliberations by the four working groups. Expert Working Groups were drawn globally to try and ensure representation from both high income and low- and middle-income countries (LMICs), as well as equal representation in terms of gender and experience i.e. to include both early career and more senior researchers. Two virtual workshops were undertaken, resulting in the development of two Interim Reports (Rogers et al., 2021b,c) and a Feasibility Report (Rogers et al., 2022b). These reports were reviewed and commented upon by a team of Senior Experts (see Acknowledgements) and finalised following revision. The present paper summarises the findings of the Interim Reports and Feasibility Report prepared by the Expert Working Groups and provides a holistic view of how to accelerate species discovery in the ocean, how to translate biodiversity data to knowledge that can be applied in decision making with respect to human activities in the ocean, and how to expedite future biodiversity monitoring in the ocean.

The Concept

Solving the current taxonomy crisis has been subject to wide discussion and controversy in the literature (e.g. Godfrey, 2002, 2007; Godfrey & Knapp, 2004; Ebach et al., 2011; Dupérré et al., 2020; Dubois et al., 2021; Engel et al., 2021). In particular, there has been polarisation between those wanting to maintain traditional approaches to species description versus those advocating methods based solely or largely on DNA sequencing and/or the use of high-resolution videos or photographs, the latter in cases where preservation largely destroys the appearance and characteristics of the organism (e.g. Ebach and Holdrege, 2005; Gutiérrez & Pine, 2017; Dupérré 2020; Engel et al., 2021). We suspect that part of this dispute has resulted from a natural polarisation in taxonomy between research focused on understanding evolution in species at a range of scales from deep phylogeny in the tree of life to mechanisms of speciation and radiation (evolutionary taxonomists) versus that focused on trying to understand recent diversity and distribution of life and its drivers, both natural and anthropogenic (eco-taxonomists; see Figure 2 for explanation). Evolutionary taxonomists tend to require highly detailed integrative phylogenetic descriptions with a large number of characters and as much genomic information as feasible whereas eco-taxonomists tend to require the minimum number of morphological characters and genetic information possible in order to define and identify species.

Insert Figure 2

Here we favour an integrated approach to accelerating taxonomy whereby conventional species description is improved, guided and accelerated using modern technologies (e.g. high-resolution digital imaging and DNA sequencing; e.g. Wheeler 2018; Rogers et al., 2022a), albeit with an additional step of rigorous standardised approaches to digitisation and by minimising the number of characters needed for species descriptions. We also recognise that, whilst specialist taxonomists may be needed for final species descriptions (e.g. Britz et al., 2020), many aspects of morphological description comprise time-consuming but non-specialist genetic sequencing, imaging and specimen vouchering, tasks which can be adequately carried out by skilled scientists, technicians, curators or research students (Vences, 2020). Likewise, field samples can be sorted into recognisable groups by parataxonomists, i.e. non-scientists or technicians trained to sort biodiversity samples into putative taxa, also known as informal names or morphospecies (e.g. Krell, 2004). Sequencing barcode genes also provides in-depth data that allows for sorting specimens into evolutionary significant units that can then be studied more formally. This frees up taxonomists to devote their time to the hypothesis-driven science of taxonomy, as well as associated phylogenetic and other analyses to address wider questions regarding evolution, biogeography and biodiversity. Most importantly, this integrative approach may accelerate ocean biodiversity-related research and renewed funding support in the LMICs where many habitats, including shallow coastal biotopes are yet to be fully explored.

We identify four key areas which, together, will assist in accelerating the discovery of species. These are:

- Digitisation
    - Digitisation of all data associated with specimen collection
    - Generation of a Digital Life Form (DLF)
    - Development of an integrative cyber-biodiversity system for dissemination of data that uses and builds on existing infrastructures (WoRMS, OBIS, GBIF)
- Adoption of new technologies
    - Technologies that accelerate the identification and description of new species
    - Technologies that enable cybertaxonomy
    - Technologies that enable subsequent biodiversity monitoring
- Capacity development
    - Training and employment of more taxonomists and support specialists, especially from LMICs, to increase the rates of species discovery and description
    - Creation of a global open network of taxonomists working towards species discovery and description in the ocean
    - Funding and support to develop taxonomic institutions in LMICs

    - Promote and subsidise access to specialist equipment/facilities/ knowledge at established institutions to support knowledge transfer
- Expeditions targeting poorly studied parts of the ocean with respect to biodiversity
    - Expeditions targeting poorly sampled regions of the global ocean from the intertidal zone to deep-ocean trenches
    - Continued effort to describe species in existing collections from past expeditions

Digitisation

Digital Life Forms

Core to the concept that has been developed is the initial creation of a Digital Life Form (DLF) in the field or in the laboratory which is associated with a collected sample/specimen (Figure 3). We use the term DLF as it has no taxonomic connotations, although the specimen to which it pertains is identified as far as possible using a standardised Open Nomenclature (ON) method (based on Sigovini et al., 2016; Horton et al., 2021). Additionally, a specimen is assigned a Globally Unique Identifier (GUID) which in the case of Ocean Census will usually refer to an expedition, sampling event and identification number (Rabone et al., 2019; Horton et al., 2021) and, where appropriate, a parent identification (many species are found living in or on other species, in which case the latter is the parent). As well as the specimen information, a rigorous standardised approach to the digitisation of all information related to the collection of a specimen in the field is adopted to record sampling location and date, environmental conditions, images of the habitat where the organism lives and any other relevant information which may support better understanding of its biology and ecology. This will include use of the Taxonomic Databases Working Group (TDWG) standards and vocabularies embodied in the Access to Biological Collection Data (ABCD) and Darwin Core (DwC) aimed to support the interoperability of collection and observation data from physical to digital (Berendsohn et al., 2011; Wieczorek et al., 2012). Usage of these community-led, globally accepted data standards is critical to making data Findable, Accessible, Interoperable and Reusable (FAIR; Wilkinson et al., 2016b), and therefore to incorporation into environmental policy and widespread public use downstream (see Rabone et al., 2023 for discussion). Further digital information will be acquired whilst a specimen is processed from a collection in a museum or other institution. Data should include:

- A Globally Unique Identifier (GUID) for the specimen or sample (e.g. Rabone et al., 2019; Horton et al., 2021)
- Date and location of collection including precise day, time, latitude, longitude, and depth
- Maps or bathymetric charts of sampling location and habitat description (e.g., Gerovasileiou et al., 2019; Mayer et al., 2018)
- Measurements of essential biodiversity and ocean variables (e.g. physics, biogeochemistry, biology and ecosystems; Pereira et al., 2013; Constable et al., 2016; Muller-Karger et al., 2018; Sloyan et al., 2018; Woodall et al., 2018; Centurioni et al., 2019; Jetz et al., 2019; Levin et al., 2019; Estes et al., 2021; Global Ocean Observing System, 2022)
- High-resolution stills and video imagery of the specimen (preferably living and in an anaesthetised, 'relaxed' state where good photos cannot be obtained from living animals), the sampling locality and, where appropriate, the sampling event itself (e.g., Katija et al., 2022).
- DNA sequence data for universal barcoding genes (as minimum)

- Specimen characterization such as biomass, dimensions, colour, state of health, maturity
- Details of parent sample and sub-sampling of specimen (e.g. tissue subsamples for DNA sequencing, see Rabone et al., 2019)
- Details of sample processing, preservation, and final repository (institution, registration number)
- Policy-relevant information (e.g. number of the permit for collection, number of CITES export/import permits, jurisdiction where sampling took place)
- Culturally relevant information (indigenous or local name for organism; indigenous and local knowledge and uses for organism; e.g. Sigwart et al., 2021)

Insert Figure 3

The DLF created is maintained indefinitely and enables the addition of a full species description in the future and subsequent updating of information on distribution and other aspects of ecology and taxonomy (e.g. morphological variability). In this respect, this concept bears some similarities to the idea of quantum taxonomy (Maddison et al., 2012) and is also analogous to the Digital Extended Specimen concept described by Hardisty et al. (2022). Data collected with specimens are uploaded to appropriate global databases as soon as possible following collection (e.g. species occurrence records to the Ocean Biodiversity Information System (OBIS); genetic data to the International Nucleotide Sequence Database Collaboration, taxonomic data to the World Register of Marine Species, genomic sample availability to the Global Genome Biodiversity Network). Where such databases are not available (e.g. for image data), data incubators will be developed to hold and allow access to data while the community of scientists who specialise in the data type can develop standards for data acquisition, metadata, storage and access. This should build towards obtaining the funds for a new global database.

Our suggested approach to marine species discovery is an example of integrated taxonomy which introduces an intermediate step between the sampling process and final species description. The introduction of the DLF enables ecological and other studies to be undertaken on consistently identified organisms prior to formal description. A proof of concept of this approach has been demonstrated through the Moorea Biocode Project (see Box 1), whereby an effort was made to produce both genetic (DNA) and morphological barcodes (digital keys), dynamically linked to images and other data to create a model system for biodiversity science (Meyer et al., 2006). Using these data, ecological studies, such as on food webs, have been possible in the absence of described species but by using consistent identification based on DNA barcodes (e.g. Leray et al., 2012, 2015). A similar initiative for wholly image-based workflows is the SMarTaR-ID marine taxon reference image database (Howell et al., 2019).

Box 1: The Moorea Biodiversity Project

The Moorea Biocode Project was initiated in 2006 with objectives to DNA-barcode the first entire tropical ecosystem including terrestrial and marine environments (Meyer et al., 2006). Alongside the barcodes, an additional objective was to create digital keys (morphological barcodes) dynamically linked to images and genetic data to enable the identification of individual species (Meyer et al., 2006). The aim of this was to create a unique model system for biodiversity science (Meyer, 2006) whereby it is possible to link the genomic information on biodiversity to physico-chemical, ecological, and socioeconomic data (Davies et al., 2014). Ultimately the intention was to be able to model the impacts of anthropogenic changes to ecosystems and ecosystem services through the creation of an Island Digital Ecosystem Avatar (IDEA; Davies et al., 2014; Cressey, 2015). The Moorea Biocode Project is set within the Genomic Observatories Network, itself part of the Genomic Standards Consortium and the Group on Earth Observations (GEO) through its Biodiversity Observation Network (GEO-BON).

The Moorea Biocode Project and the wider Genomic Observatories Network has adopted a number of standardised approaches to ensure that environmental data are linked to both DNA barcode and other genomic data as well as to voucher specimens of the species that have been sequenced (Davies et al., 2014; Deck et al., 2017). It is important for the purposes of ecology and other areas of science to link physical samples and their associated genetic data with biological and ecological data at the point of collection (Deck et al., 2017). Whilst the standard genetic databases which are part of the International Nucleotide Sequence Database Collaboration (INSDC; https://www.insdc.org/) encourage the submission of environmental metadata, this is not a requirement. To overcome this situation the Genomic Observatories Metadatabase (GeOMe, http://www.geome-db.org/) was established to link sequence data to organisms, their sampling localities and habitat (Deck et al., 2017). GeOMe follows a set of customisable rules that ensure terminology is compliant to Darwin Core and MIxS standards (Yilmaz et al., 2011; Wieczorek et al., 2012; Deck et al., 2017). Each record is also assigned a unique identifier so it can be traced across multiple databases (Deck et al., 2017). Environmental samples and specimens of organisms are deposited at natural history museums, repositories and bio-banks to act as reference material for taxonomy and also as sources for future genome sequencing studies (Davies et al., 2014).

The systematic approach used by the Moorea Biocode Project has enabled a range of studies to be undertaken on biological communities prior to description and naming of taxa. An example has been food web studies undertaken on reef hawk fish and squirrel fish species through DNA barcode analysis of gut contents (Leray et al., 2012, 2015). Almost all (94%) of the prey found in the guts of these predatory fish had barcodes with >98% similarity to Biocode reference sequences and revealed new information on resource partitioning, feeding behaviours and the broader ecological consequences of feeding strategies (Leray et al., 2012, 2015).

DLFs will be useful for short-term and finer-scale ecological studies, but crucially we see the digitisation and accessibility of species data as a tool to assist taxonomists in the ultimate aim of naming and describing species. Naming species with reference to related species will reconcile provisional species discoveries with the knowledge built over the last 250 years using morphological characters. This final step is important to provide knowledge of biodiversity over large spatial and temporal scales. Since Linnaeus first devised a system and language to describe biodiversity, taxonomists have named, defined and refined an inventory of life on Earth, including more than 240,000 marine species (WoRMS, 2023) and counting. Most of these species do not have DNA sequences (Aylagas et al., 2016, Hestetun, 2020), and thus an integrated approach using both DNA and morphology is essential to build on our existing knowledge of biodiversity. Both DNA and morphological data on species are useful, DNA sequences allow for a statistically rigorous method for species delimitation and evolutionary relationships, while morphological data can provide information on ecosystem function, ecology and anatomy.

Fundamental to this concept is that data are, where feasible, interoperable across institutional, national, regional and global databases, and that they are quality assured and traceable. This is essential to ensure that they are viewed by all stakeholders as trustworthy for application to science, ocean conservation and management. Accessibility of taxonomic and biodiversity data to end users is key to resolving the current taxonomy crisis and to ensuring long-term security for taxonomists and their institutions (Ebach et al., 2011; Saunders, 2020). It is also important that digitisation is aligned with international principles such as the FAIR (Findability, Accessibility, Interoperability, and Reusability; Wilkinson et al., 2016b), CARE (Collective Benefit, Authority to Control, Responsibility, and Ethics; Carroll et al., 2022) and FPIC (Free, Prior and Informed Consent; Perrault, 2004) principles to guide data collection and sharing practices in a way that is ethical, equitable and respectful of communities' and data providers' rights. This approach therefore requires the infrastructure, tools and capacity for near-real-time recording of the discovery of ocean life worldwide, with the 'digital fingerprint' necessary to improve data quality, interoperability, accessibility and more equitable and fairer use by communities including indigenous and local communities, scientists, and policy- and decision-makers.

The Cyber-Biodiversity System

Ocean Census will develop a Cyber-Biodiversity System providing the technological infrastructure, including the workflows and tools, required to ensure that all Ocean Census data are transparently and efficiently managed. The system will utilise existing data workflows and technologies (e.g WoRMS, OBIS, GBIF and DarwinCore vocabulary) and integrate them. The Ocean Census Cyber-Biodiversity System will be cloud-based, providing on-demand access to data and digital services for digitising, processing, storing and sharing marine biodiversity data, information and knowledge using standard operating procedures. This system will be built in close consultation with Ocean Census partners and will closely support delivery of the discovery and capacity development objectives of the programme by co-designing the workflows and tools necessary to enable more effective collection, curation, and translation of data on ocean life for scientists and other users from all countries. A modular approach will be used to develop the Cyber-Biodiversity System (Figure 4).

Insert Figure 4

A Digitisation and Data Staging Module will provide a secure and high-performance space to gather, clean, quality control, and standardise all Ocean Census data and information before it is distributed for processing or archiving. The digital output of each Ocean Census expedition will be formidable: images, acoustics, video recordings, gene and genome sequences, sensor readings, and written observations are just a handful of the (meta)data types that Ocean Census will generate and synthesise. Rapidly 'staging' or hosting, cleaning, and organising data so they can be efficiently processed, combined with other data, and delivered to users or long-term archives will be essential to the efficient discovery of new biodiversity as well as the digital legacy of the Ocean Census programme. The Digitisation and Data Staging Module will use cloud-based services to securely host the data generated and needed by the "scientific" community and other users in a 'Data as a Service' (DaaS) model (see below).

All partners, including those who do not have capacity to host and mobilise large data collections locally, will have the capacity to analyse data as it streams in from global expeditions and integration activities. Importantly, this module does not seek to be a long-term archive itself, but a working space to promote standardised data handling to speed discovery and transparency. For data types with matching global long-term archives/databases (e.g. INSDC for sequence data, or OBIS for occurrence data), this module provides a local, shared storage solution to prepare Ocean Census data products for submission. For data types without a long-term, multinational archive, this module will provide mid-term storage and preservation of data for the Ocean Census Digital Incubator until viable long-term options are available (see below).

The Data Processing Module will host the software and services to analyse data from Ocean Census, its partners and/or external sources before these data are distributed to partners, decision-makers and the public. The Data Processing Module will contain collections of software and tools for Ocean Census personnel and collaborators to transform, integrate, analyse, visualise, and communicate the results of the programme's digitisation efforts and it will be combined with data imported through the Cyber-Biodiversity System. It will rely on standardised data in the Digitisation and Data Staging Module and the standard operating procedures developed in the early stages of the programme.

This module will offer 'software as a service' (SaaS) via the cloud and will ensure that consistent, traceable, and reproducible methods are used on data and information in the Ocean Census Cyber-Biodiversity System. For partners without local computing capacity, the Data Processing Module will provide a shared processing facility, while also providing tools that can be used in others' systems to achieve the same Ocean Census-grade standardisation, quality assurance, and interoperability with external systems. We view this as essential in the democratisation of species discovery for the global marine taxonomy community.

Building on the two prior modules, the Digital Exchange Module will facilitate access to and the delivery of Ocean Census data between all partners to online repositories and platforms. The Digital Exchange Module will be designed to facilitate delivery of 'gold standard' marine biodiversity data, as well as to ensure that the programme's digital reach and impact are tracked.

The Ocean Census Digital Incubator will support communities with developing and adopting new technologies to transform how they digitally capture and communicate data on ocean life. While some biodiversity data are well-managed globally (e.g. sequence information), other data types have no internationally agreed archives, governance, or standards (e.g. image data). Acquisition of ocean life data often uses time-consuming manual methods that depend on individual's activities and expertise, slowing down data sharing. Thus, data are often underutilised or lost after projects conclude. Moreover, limited human, technological or financial capacity can limit adoption of promising technological solutions in local, national or regional contexts.

The aim of this activity is primarily to help 'level the playing field' in the application of data management and science in marine biodiversity research, and to address known gaps in knowledge transfer—both in terms of data types (e.g. large-scale storage, automation and application of machine learning to imagery data; see below) and country- or region-specific capacity development to adopt or integrate data management and science into workflows, supported by the Ocean Census network of institutions and researchers.

We recognise that other cyber-taxonomy platforms exist (e.g. the European Distributed Institute of Taxonomy [EDIT] Platform for Cybertaxonomy; Berendsohn et al., 2011) and, following the philosophy to make use of what has already been developed rather than repeat work, we will integrate the Ocean Census Cyber-Biodiversity System with these or at the very least ensure it is interoperable with them. We also note that the Ocean Census Cyber-Biodiversity System will be developed through extensive consultation on all aspects of the platform to ensure the system meets the needs of scientists, ocean managers, industry and policymakers. Once the system is established, applications can be further developed to meet the needs of these user communities. Options may include enhancing use of Ocean Census data in leading decision-support tools and platforms, tailored to public or private sector decision-making needs, or harnessing citizen science initiatives to generate data on ocean life in collaboration with indigenous and local communities. These pathways could be established by strengthening the ocean knowledge base of existing policy- and decision-support platforms, such as the Exploring Natural Capital Opportunities, Risks and Exposure (ENCORE) or the UN Biodiversity Lab, among many others.

This will require deeper curation and processing of decision-grade derivative products from Ocean Census data (e.g., species occurrence records, abundance, biomass, etc.) to provide applicable indicators for the diverse range of users (e.g., ecosystem service indicators, biodiversity seascape maps for marine spatial planning, species, populations or stocks). For example, based on the knowledge generated through Ocean Census, platforms such as Ocean+ Habitats could be enhanced through near-real-time connections with OBIS for taxonomic coverage, transparently visualising the 'known unknowns'—i.e. locations that have not been surveyed for species or habitats —by country or region. This application could help to guide targeting of Ocean Census expeditions to focus sampling activities, support governments in identifying which areas of marine biodiversity importance require protection or restoration or will be able to direct overseas development aid to the locations that need it most. Solutions will also be co-developed in community-based or low-income contexts. For example, by coordinating Ocean Census with community science initiatives and other discovery activities with indigenous peoples and local communities, this activity could support integration of community insights and local or traditional knowledge into policy processes and indicators for biodiversity and ecosystem conservation and sustainable management. This approach could also pave the way towards developing blended blue financing schemes in order to support blue economy initiatives, in particular for coastal countries representing LMICs.

New Technologies

A variety of technologies have been developed or are in development which increase the quality of species descriptions and can potentially accelerate taxonomy over the longer term through their applications to cybertaxonomy (defined in Rajmohana and Bijoy, 2012; see also Berendsohn et al., 2011). These technologies are reviewed in Rogers et al. (2022a) and include advanced, high-resolution 2D and 3D imaging, DNA sequencing including the use of 3rd generation sequencing technologies in the field and artificial intelligence / machine learning.

High resolution digital 3D imaging techniques such as photogrammetry, confocal laser scanning microscopy, optical projection tomography, magnetic resonance imaging and micro-computed tomography (micro-CT), can rapidly create high-resolution morphological and anatomical data in 3D (e.g. Boistel et al., 2011; Faulwetter et al., 2013a,b; Nguyen et al., 2014; Medina et al., 2020). Multispectral imaging has also been used to produce high resolution images of the colours and shapes of organisms (e.g. Chan et al., 2022). 3D and multispectral images can be used to produce virtual type specimens from original type material. This is a major enabler of cybertaxonomy, allowing taxonomists to examine a specimen via the web for comparative purposes without access to the actual specimen, thus saving time and cost and avoiding risk in sending specimens from museums or negating the need for researchers to travel to where a sample is stored. Whilst some argue that such technologies do not yet have the resolution to produce virtual types (Dupérré 2020) or that some information is not stored by these methods (e.g. CT or SEM scans do not record colour), technology is improving rapidly.

Molecular data can assist in the identification and classification of new taxa (Rogers et al., 2022a). The simplest approaches are based on a single or a few barcoding genes (e.g. Hebert et al., 2003a,b). However, 3rd generation high-throughput sequencing technologies enable a larger portion of the genome to be analysed for taxonomic purposes (Rogers et al., 2022a). Low coverage genome sequencing followed by analysis of a number of taxonomically informative nuclear, mitochondrial and chloroplast genes can provide a large amount of data for phylogenetic analysis and diagnosis of new taxa (genome skimming; Krehenwinkel et al., 2019). DNA metabarcoding approaches have been applied by terrestrial taxonomists on large numbers of specimens with clustering of sequence data being used to focus the work of taxonomists (e.g. Riedel and Narakusumo, 2019; Srivathsan et al., 2019; Garces et al., 2020). These technologies are now highly portable, making them amenable to undertaking sequencing studies in the field and, furthermore training researchers in metabarcoding or metagenomic approaches in the field (Krehenwinkel et al., 2019; Watsa et al., 2020; Ames et al., 2021). This can be especially useful in low and middle-income countries where fully equipped molecular biology laboratories may not be available to local scientists.

New technologies can also allow sampling of organisms that are highly fragile, and which are destroyed by more traditional sampling methods such as trawls. A good example of this are gelatinous zooplankton, especially groups such as physonect siphonophores, lobate ctenophores and larvaceans (Robison et al., 2017; Hetherington et al. 2022). Remotely operated vehicles (ROVs) or submersibles have been equipped with detritus samplers (D-samplers) which consist of an open tube which can be manoeuvred to enclose an organism then closed at the top and bottom (Robison et al., 2017; Teoh et al., 2018). More recently, a rotary actuated dodecahedron made of polymer has been developed which can also be employed by an ROV or submersible to enclose small to medium-sized gelatinous organisms (Teoh et al., 2018). Even when these organisms are sampled intact, the process of preservation can destroy them through fragmentation/disintegration or damage delicate structures and modify colouring which are important characters for taxonomy (e.g. the external feeding filters of larvaceans; Robison et al., 2017). For such organisms, in-situ photographs/video of the animal of sufficient resolution to image taxonomically important morphological characteristics are important (Matsumoto et al., 2003; Robison et al., 2017). Large gelatinous organisms remain a significant problem for sampling and in the future a combination of a tissue sample, DNA sequence data and high resolution in-situ 3D imaging may be a useful approach for taxonomy (Vences, 2020). Because of the morphological plasticity in some gelatinous taxa, cases have been uncovered where species identification is only possible through including DNA sequence data and species diagnoses have been modified to include such sequence data (Lawley et al., 2022; Montenegro et al., 2023). Ecological studies of zooplankton are now often carried out using imaging combined with machine learning to identify taxa (reviewed in Irisson et al., 2022; Rogers et al., 2022a).

Artificial intelligence (AI) approaches, inclusive of both machine learning and deep-learning methods, such as artificial neural networks, are being widely applied to the identification of taxa from images as well as from active acoustic (biological echosounder) and passive acoustic data (reviewed in Rogers et al., 2022a). To date, these approaches have generally been applied to specific identification projects or tasks (e.g. identification of fish or plankton from image data or whales from acoustic monitoring data; Goodwin et al., 2022; Katija et al., 2022). There are developing initiatives to generate global databases for some organisms, including plankton and benthic organisms (Goodwin et al., 2022; Irisson et al., 2022). However, the development of ever more powerful computing capacity, new approaches to pattern recognition and larger collections of images / videos could enable AI to play a greater role in species identification (e.g. MacCleod et al., 2010) if taxonomist-curated images were available in the large quantities necessary for producing robust training data. To address this bottleneck problem of labelled high quality training data, the machine learning community has proposed new learning algorithms such as self-supervised learning that can make use of non-annotated data for improving the performance (for instance in plankton image analysis (Midtvedt et al., 2022). Access to data on the web via web scraping technologies have made large quantities of identified and unidentified images of marine organisms available for deep-learning approaches to species identification (e.g. Jarić et al., 2020; Stringham et al., 2020, Langenkämper et al. 2017), especially if unsupervised clustering techniques are employed (Schroeder et al., 2020). Coupled with large-scale citizen science projects dedicated to collecting such imagery, specifically for biodiversity documentation such as iNaturalist, these technologies could offer a powerful approach to identification of species, especially megafauna and macroalgae. This could include documentation of unidentified or undescribed species which could help to target future sample collecting efforts.

Capacity Development

More than two-thirds of countries surveyed by the International Oceanographic Commission of UNESCO have a national strategy in place to achieve the UN Agenda 2030 for Sustainable Development, but only a fifth have a specific strategy for Sustainable Development Goal 14 (Life Below Water) (IOC-UNESCO, 2020). Ocean research capacity, researchers and infrastructure, are disproportionately concentrated in the global north and within the hands of men (IOC-UNESCO, 2020) illustrating inequalities in the capacity to understand, manage and sustainably use our connected ocean (e.g. Rogers et al., 2021a). On the other hand, many threats to the ocean and its biodiversity including warming, acidification, pollution, fishing and invasive species are global issues affecting all marine ecosystems. Addressing such imbalances in scientific capacity and access to the global ocean will be a fundamental component in improving the governance and ultimately the health of the ocean (Hornidge et al., 2023).

Increasing capacity for marine species discovery and taxonomy is required to meet the current deficit in our knowledge of ocean biodiversity (e.g. Ebach et al., 2011; Fontaine et al., 2012; Baldini et al., 2021; Engel et al., 2021). This is not just human capacity but also institutional capacity to process samples and to store, maintain and curate specimen collections, including, for example, cryogenic storage of tissues for genomic DNA extraction (e.g. Paknia et al., 2015; Baldini et al., 2021) and associated images. For example, there are limited efforts underway to develop DNA tissue banks regionally in the Bay of Bengal of the Northern Indian Ocean and the Ocean Census can help accelerate such initiatives over the long term. Capacity development activities must be fully inclusive and equitable, with a particular focus on biodiversity rich LMICs (e.g. Barber et al., 2014; Paknia et al., 2015; Titley et al., 2017; Britz et al. 2020; Prathapan & Rajan, 2020). Such countries should be able to advance the development of science and knowledge through the employment, training and development of local experienced taxonomists and support staff through professional valorisation and stability within their respective countries. This will enable species discovery and biodiversity monitoring to be led locally to meet specific economic needs as well as contributing to international commitments under treaties such as the Convention for Biological Diversity and the new treaty on Biodiversity Beyond National Jurisdiction (Prathapan & Rajan, 2020; Saunders, 2020). Our approach in Ocean Census is to foster co-production of taxonomy and biodiversity research between scientists and to assist in developing the research infrastructure for species discovery, the housing of collections of biological material (Barber et al., 2014; Paknia et al., 2015; Tolochko and Vadrot, 2021; Woodall et al., 2021; see below) and the management of a correlated curated image repository accessible to all stakeholders. Ocean Census also recognises the need to strengthen international networks of taxonomists for purposes of knowledge exchange, making decisions on standardisation of methods and for pooling of resources and effort to achieve ambitious goals for species discovery targeting regions and ecosystems that have been poorly sampled (Bax et al., 2018; Tolochko and Vadrot, 2021; Woodall et al., 2021). Such networks are also important in maintaining dialogue and engagement with scientists from LMICs to ensure that capacity development activities have a long-lasting legacy (Bax et al., 2018). Building expertise across LMICs may also help to reduce the need for transboundary movement of specimens and therefore any impact of the permitting processes under the Nagoya Protocol, aimed at combating biopiracy, but which have seriously impacted international biodiversity science (e.g. Ebach et al., 2011; Prathapan & Rajan, 2020).

An overriding goal in developing global capacity in marine taxonomy and biodiversity science will be to maximise the opportunities for scientists trained in this program to remain employed in marine science and biodiversity discovery and its conservation beyond the duration of the program. It can be challenging for expert taxonomists without additional areas of expertise to remain employed. Therefore, we propose to build capacity across the biodiversity value chain from foundational research to knowledge products and policy advice. This approach will improve uptake of research and the retention and employability of those whose capacity has been developed and self-sufficiency for countries to lead, from the collection, identification and processing of samples to the translation of science into decision-making processes. Explicit requirements and opportunities in all elements of this program for training and development are essential to ensure appropriate capacity in marine biodiversity discovery, data science and communication is achieved and is done so within the specific context of the partner institutions and countries.

Through building capacity across the biodiversity value chain, we will also provide individual countries with the capability and opportunity to lead surveys in their own waters (providing tailored support as needed) including, for example, for biodiversity discovery and environmental assessment and enhance their capability to engage in management and policy activities. Skills development will be tailored to meet the needs and aspirations of the individuals. Such skills development will likely consist of a mix of hands-on training held during expeditions, general training at national and regional centres, and more specific skills training at the Ocean Census Biodiversity Centres. Technical skills training (e.g. sample processing, database management, communication) will be extended to participants at national and regional centres, while specific specialist training at the Biodiversity Centres will develop specific skills and knowledge (potentially as part of a higher degree).

Monitoring, evaluating and learning processes will be an essential component of capacity development under Ocean Census and should help identify, in conjunction with the registries of practices in the literature, needs and opportunities to be further explored by Ocean Census and its funders. As a starting point, there will be an annual review of progress against the Ocean Census Equity Principles (see Box 2) as well as against KPIs to be developed. At the end of Year 3 there will be a more extensive review of the progress of Ocean Census and further development of a capacity development component more strategically aligned with needs and expectations captured.

Box 2. Ocean Census Equity Principles

1. *Ocean Census* will be undertaken for the purposes of the discovery of ocean species and providing data for sustainable ecosystem-based ocean management and conservation for the benefit of biodiversity, ecosystems and humankind.

2. *Ocean Census,* its participants and activities will not discriminate on the grounds of age, disability, gender reassignment, marriage and civil partnership, pregnancy and maternity, race, religion or belief, sex or sexual orientation.

3. *Ocean Census* will work to level knowledge and develop capacity amongst all coastal states to undertake marine species discovery, biodiversity science and the management of their ocean biodiversity.

4. *Ocean Census* will be planned so that science is co-produced in full consultation with the relevant government, government departments and institutions of low- and middle-income countries and small-island nations, intergovernmental organisations, academic institutions and civil society including non-governmental organisations and indigenous communities local to the expedition.

5. *Ocean Census* will operate under the FAIR (data are Findable, Accessible, Interoperable and Reusable) and CARE principles (Collective benefit, Authority to Control, Responsibility and Ethics) for

the production and subsequent use of data related to all aspects of its scientific work whilst respecting the rights of sovereign states in terms of authority and control of data originating from national waters and the species sampled therein.

6. Data collected as part of *Ocean Census* will be released according to FAIR principles as soon as is practically feasible and usually within 12 months of collection. Exceptionally, data can be released up to 24 months following its collection (e.g. if the data are important to the completion of a Ph.D. thesis). The only exceptions to this are if the release of data would endanger species or contravene the security of states or indigenous people. In line with Provision 4 states and indigenous people have authority and control over data collected in national waters.

7. *Ocean Census* and its participants will be compliant with international and national laws with respect to conservation, sampling, and transport of samples of species and all biological material associated with them including genetic materials. Examples of international treaties in respect of this provision include the Nagoya Protocol of the Convention on Biological Diversity and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES).

8. *Ocean Census* and all participants have a duty to ensure that all biological material, especially type material is archived in a secure manner indefinitely which also ensures its accessibility for future scientific research. It is acknowledged that some types of material may be destroyed during research (e.g. tissue subsamples, DNA) but this should not harm future prospects for scientific research on a species (e.g. samples are held in replicate). It is also recognised that some states may not have the facilities for secure storage of materials in which case an agreement (e.g. a Materials Transfer Agreement or MTA) on loan of material to a suitable institution in another country may be made on the understanding that once facilities are available in the country of origin they are returned.

9. Ocean Census will develop through an open network anchored through the *Ocean Census Biodiversity Centres* as well as the *Ocean Census Virtual Taxonomy Networks* (see below). Through these networks, knowledge, training and technology will be shared for furthering the purposes of species discovery and biodiversity monitoring globally.

10. *Ocean Census* will work to build the value-chain for marine biodiversity globally with an aim to a long-term transformation of ocean biodiversity science and monitoring ensuring a permanent legacy to the programme.

Expeditions

The urgency that the decline of biodiversity places on species discovery means that a significant effort in field collection of organisms is required (e.g. Dubois et al., 2021; Cowie et al., 2022). Many parts of the ocean remain poorly sampled, either because they lie in or adjacent to the waters of LMICs, they are inaccessible (e.g. the high seas) or lie in extreme environments (e.g. the deep sea; Glover et al., 2018; Hughes et al., 2021; or polar marine ecosystems; e.g. Brandt et al., 2007; Verhaegen et al., 2021; Ramirez-Llodra et al., 2022). Only small fractions of many deep-sea ecosystems have been explored by biologists (Rogers et al., 2015; Ramirez-Llodra et al., 2011) with the deep pelagic being a particular challenge (Webb et al., 2010) because of its size, remoteness and the fragile nature of the organisms that inhabit it making them difficult to sample (e.g. Raskoff et al., 2003). As well as geographic biases in collections of taxa, there are also taxonomic biases in the effort on their taxonomy (e.g. Troudet et al., 2017; Hughes et al., 2021; reviewed in Rogers et al., 2021a). Groups such as vertebrates are well sampled (Appletans et al., 2012; Scheffers et al., 2012), whereas for some groups of marine invertebrates it is estimated that less than 20% have been described (generally small organisms; Appeltans et al., 2012). In these cases, tens of thousands or even more than a hundred thousand species may remain unsampled and/or undescribed (e.g. Nematoda, Gastropoda, Peracarida; Appeltans et al., 2012; Bouchet et al., 2016). More complete sampling of taxa is also important in testing taxonomic hypotheses and identifying global patterns and processes and lack of adequate coverage of taxa could potentially lead to erroneous conclusions which impact on our understanding of the evolution and biogeography of the marine realm (see Dubois et al., 2021 for examples from recent amphibians; Sands et al., 2021 for an example on Antarctic ophiuroids). Description of species from single individual specimens (singletons) is also problematic, as the range of morphological and genetic variation cannot be documented (e.g. Fontaine et al., 2012). This can lead to mis-informed and unstable species descriptions (e.g. *Hippocampus guttulatus;* Vasil'Eva, 2007*)*, although such specimens are key targets for further investigation and study. More field collections can help to address many of these issues.

We also identified that repeat sampling of stations from some of the global and regional expeditions of European and US vessels in the 19th and 20th centuries (e.g. the Challenger Expedition) would be worthwhile to obtain fresh specimens of species that they described, especially where those descriptions were incomplete. A particular priority will be to collect genetic data from type-localities from original descriptions. This is because inadequate descriptions from these expeditions acts as a significant constraint on efforts to describe new species, often requiring the study of museum types with all that implies in terms of travel, costs and time (Riedel et al., 2013). Even where such material still exists in museums, particularly for deep-sea species, it is often a single, damaged specimen that was not live collected (e.g. Williams et al., 2020) and is unlikely to be amenable to modern integrated taxonomic approaches, limiting its use. It may also provide samples to study change in some of these sampling localities following severe impacts on the ocean from industrialisation, including pollution, overfishing and climate disruption such as changing carbonate chemistry (ocean acidification). Such repeat sampling will enable LMICs to "reclaim" their biodiversity through co-produced expeditions. There is a growing fleet of Ocean-Class research vessels with mechanisms to enable participation or leadership of cruises by scientists from LMICs, including privately owned platforms (Rogers et al., 2021a).

Expeditions will be undertaken to discover marine species from the intertidal zone, coastal subtidal environments, and the deep sea, including the hadal zone, from polar regions to the tropics, and will incorporate both benthic and pelagic ecosystems. These expeditions will deploy appropriate sampling technologies and infrastructure to these different ecosystems with implications for expedition organisations and logistics as well as costs (the further from shore and the deeper the ecosystem the larger the cost).

Finally, we also recognise that large collections of undescribed and in many cases uninvestigated samples from past expeditions exist in museums and other institutions. Ocean Census will also include these specimens in efforts to describe marine species. Priority will have to be based on condition of samples, documentation of their collection and subsequent curation as well as on geographic regions which are poorly sampled.

Ocean Census Structure

Ocean Census has been initially funded by The Nippon Fountation, an organisation that funds global projects in the areas of social innovation including ocean sciences (e.g. The Nippon Foundation-GEBCO Seabed 2030; Mayer et al., 2018; https://seabed2030.org/). The project will be administered by the Nekton Foundation who were initially tasked with developing the scientific approach to the programme. A wide network of partners are being engaged with the programme with collaborations including: the provision of seagoing infrastructure (e.g. research vessels, deep-submergence platforms, other equipment), co-production of science (e.g. Museums, other biodiversity institutions, sequencing centres), development of cyber-infrastructure (e.g. UNEP World Conservation Monitoring Centre), provision of other forms of technical assistance and training (e.g. industry partners) and other forms of direct and indirect funding or support. Partnerships will also be established with governments, governmental institutions, academic institutions, non-governmental institutions and civil society, including indigenous communities within countries in whose waters Ocean Census will operate.

Ocean Census will be organised as an open network with the aim to promote inclusivity and equity across the global community of marine taxonomists, taxonomy support specialists and trainee or early career researchers (Figure 5). The programme will initially be established at Biodiversity Centres, the first of which will be located at the Oxford University Museum of Natural History (https://www.oumnh.ox.ac.uk/). Initially, Biodiversity Centres will be located at national natural history museums or other institutions undertaking marine species discovery and description activities and able to arrange national and international loans of material. These institutions have established collections of ocean species and significant infrastructure for taxonomic studies including imaging, sequencing and other advanced technologies discussed above. Their primary activities will include:

- Sorting and digitisation of samples collected during Ocean Census Expeditions including identification of known species.
- DNA sequencing of species collected during Ocean Census Expeditions.
- High resolution 2D and 3D imaging of specimens collected during Ocean Census Expeditions including through application of advanced imaging technologies such as microcomputed tomography (micro-CT).
- Description of new species collected during Ocean Census Expeditions.
- Undertake training and capacity development activities.
- To act as resource centres for use of advanced facilities for Ocean Census where they may not be generally available for the global marine taxonomy community (e.g. high-throughput DNA sequencing, micro-CT).

Insert Figure 5

As the programme develops, Biodiversity Centres will be identified in regions where such institutions have historically been under-supported, usually in LMICs. Assistance will be provided to these institutions to develop a business plan for each potential centre, to contribute to species discovery within the Ocean Census programme as well as providing facilities for capacity development as laid out above. All Biodiversity Centres will be encouraged to develop complementary skills across the biodiversity value chain to ensure longevity of these institutions and their personnel once the funded Ocean Census programme has been completed. The Biodiversity Centres will together form the Ocean Census Global Marine Biodiversity Network.

The marine species discovery pipeline will be considerably enhanced by the coordination of taxon-specific expertise at a global scale. An accelerated and scaled species discovery process will need to draw upon all available expertise, including expertise that resides outside the Ocean Census Biodiversity Centres, in universities, regional museums, government research organisations, non-government research organisations, and the general community (citizen scientists). The Ocean Census solution is to create a series of taxon-specific virtual networks that will act as a bastion of knowledge for species identification, species descriptions, and support the Biodiversity Centres with taxonomic training and mentorship. We envisage ten or more such networks that could grow from informal taxonomy guilds that already exist for organism groups such as isopods, bivalves, sea urchins, worms, red algae etc. This has proven the most effective way of harnessing taxonomic expertise for projects such as the WoRMS database.

An experienced taxonomist within each network will be resourced to organise discussion groups, identification/training workshops (based on specimens from Ocean Census Expeditions), mentorship of emerging experts such as early career researchers, establishment of minimum standards of species description and publication, validation of new species discoveries and descriptions generated by Ocean Census, validation of sequence and distribution records in global databases, preparation of biogeographic datasets, and to organise the sequencing or imaging of pivotal specimens (e.g. type/topo-types) in museum collections.

These networks will be funded either directly from the program or via the Ocean Census Biodiversity Centres. Annual re-funding will be contingent on meeting key performance indicators set for the previous year.

Essential Ocean Variables and Molecular Biodiversity Monitoring

The global ocean observing community is providing guidance and incentives for researchers to standardise and share their measurements. The Framework for Ocean Observing published in 2012 (Lindstrom et al., 2012) outlines a series of standards, and a process through which Essential Ocean Variables (EOVs) can be identified and progressed from conceptual through prototype to a mature level where they support global observation and reporting (Constable et al., 2016). Alongside collection of specimens, Ocean Census will collect as many EOVs as feasible within the limitations of specific expeditions. This will range from measurements of temperature using instrumentation carried by SCUBA divers (e.g. from dive computer data) to a full range of physical measurements achievable on an Ocean Class research vessel capable of deploying a CTD and water sampling rosette, mapping the seafloor using multibeam bathymetry and undertaking *in-situ* measurements using submersibles, remotely operated vehicles or autonomous platforms. Such data will add to global data archives on EOVs but will also enable the modelling of the distribution of species and whole communities to better understand current distribution and the future effects of climate change.

The usefulness of the Ocean Biodiversity Information System as a general repository for marine biodiversity data is being substantially upgraded (e.g. De Pooter et al., 2017). Collaboration with the Marine Biodiversity Observation Network and the Smithsonian's MarineGEO observatory (Duffy et al., 2013; Muller-Karger et al., 2014) is helping to develop an integrated and practical pathway toward a Global Ocean Observing System (GOOS) that includes biological measurements supported by existing physical and biogeochemical EOVs. Environmental DNA (eDNA) is already forming an important tool to assess the relative levels of biodiversity in different localities (reviewed in Rogers et al., 2022a). However, this approach is limited by the lack of sequences that are attributable to known species (Rogers et al., 2022a). Because of the integrated approach used by Ocean Census in terms of collection of sequence data alongside species, the programme will greatly assist in populating the reference sequence libraries within the Barcode of Life Data System (BOLD; https://www.boldsystems.org/) and global DNA databases (INSDC). This will enhance the use of eDNA approaches for assessment of species diversity and how it changes over time as a result of global or local anthropogenic stressors or as a result of management interventions. eDNA is increasingly being used as a biomonitoring tool, enabling the identification and quantification of species within different marine ecosystems (e.g. Thomsen et al., 2016; Hunter et al., 2018; Shelton et al., 2019; Sanchez et al., 2022) and the assessment of water quality (Apotheloz-Perret-Gentil et al., 2017; Yang and Zhang, 2020). Deployment of well-designed eDNA surveys will be more cost effective than large-scale field sampling surveys using morphological identification (Apotheloz-Perret-Gentil et al., 2017; Gold et al., 2021; Jo et al., 2021) potentially enabling LMICs to undertake biodiversity assessment and monitoring where at present they are unable because of limited human capacity and other resources. Ocean Census will include such molecular tools in its capacity development activities with a particular focus on low-cost portable sequencing technologies (Rogers et al., 2022a).

Ocean Census will enhance data collection of EOVs and molecular data through the deployment of a "Tool Kit" deployable through a containerised laboratory that can be transported to coastal localities or onto large research vessels. This will include equipment for sample sorting and preservation as well as measurement of environmental parameters and for DNA sequencing.

Ocean Literacy

There is a major deficit in people's awareness of ocean life and its importance in supporting human society. Ocean Census therefore aims to raise and inspire public and partner awareness of ocean life and the programme to accelerate its discovery. Highlighting the critical nature of the biodiversity crisis and why it is important to all eight billion people needs a carefully crafted communications strategy which does not hide from the reality of how hard it is to gain media coverage, policymaker, existing regional frameworks and public attention. The thesis is simple - widespread attention leads to knowledgeable support at scale and that, in turn, triggers global action and positive change. Such a communications campaign can take a long time to bear fruit as has been illustrated by the length of time it has taken to create public awareness and increasingly gain broad, if largely passive, public support over the climate crisis.

The recent June 2022 survey by The Nippon Foundation of 10,000 Japanese people's relationship with the ocean provides an excellent barometer of the need to pull every media lever possible to maintain an emotional connection with the ocean (Nippon Foundation, 2022). In the wake of the COVID pandemic, the survey showed 45% of respondents had not physically been to the ocean in the past year - and as a result their *'connection'* and *'affection'* for the ocean declined and fewer of those people felt '*that the ocean is important'*. The good news in the survey was that overall awareness of ocean issues and participation in activities to protect it had risen since 2019. It is reasonable to conclude that if the ocean issue and the importance of biodiversity within it can be kept in the public eye we can, in the words of The Nippon Foundation Chairman Mr Yohei Sasakawa, help young people *'feel affection toward the ocean and understand the role that the bounty of the ocean plays in their daily lives'.*

To gain an audience, to inform, educate and entertain that audience, and to build its trust and loyalty can only be done through establishing a constant emotional connection. Maintaining audience attention in such a ferociously fought battle for our precious time, when fewer people are experiencing the ocean first hand, means serving a constant diet of stories that appeals to their taste for facts and quenches their thirst for knowledge. To succeed in this strategy Ocean Census aims to simultaneously address policymakers and vast numbers of people right from the start by:

- Creating a constant flow of entertaining and informative content.
- Harnessing a cost-effective and proven global distribution partnership with paid distribution through trusted news sources and a paid social media amplification partner.

Content will be created for Ocean Census outreach activities in the following ways:

- **Nautilus Expedition content:** providing the main pillars for content creation, public and partner engagement throughout the year.
- **People at the centre:** Put the voices of real people who others can relate to at the centre of the storytelling - creating an emotional connection with the audience and thereby gain attention in a "shared" media economy that will accelerate our ability to build awareness and ultimately garner active support to encourage and enact change.
- **Different content for difference audiences**: Content will be created / repackaged for different audiences on different platforms – i.e. content for news media distribution is very different to social media
- **Innovative ocean storytelling**: the greatest area of opportunity for innovation – which will be a key aspect of the strategy – will be achieved during Ocean Census expeditions, utilising new technologies and live broadcast links.
- **Community generated content**: harvest and repackage content about life from the scientific, civil society, public, indigenous and local communities as well as citizen science communities for distribution through the news and digital media.
- **Partnership**: harness the investment and story-telling skills of the story-telling industry to tell the story of ocean life and Ocean Census (e.g. broadcaster commissions a series / documentary about Ocean Census rather than Ocean Census trying to produce and distribute its own content).

Ocean Census will focus these activities through an Ocean Life Media Centre that will be the core of engagement activities with the following objectives and activities:

- **To create content:** anchored from Ocean Census Expeditions and from community generated content.
- **To create awareness of Ocean Census and** raise public awareness of the startling diversity of ocean life through:
  - Distribution of news content via partnership and paid distribution.
  - To build an online community: through distribution of social media content amplified eovby paid promotions.
- **To engage key partners to collaborate with Ocean Census:** through successful launch and direct marketing and engagement of key stakeholder groups (scientific, expedition, technology, civil society etc).
- **To participate on the global policy stage:** through Ocean Census leadership (Science Director, Digitisation Lead, Director and Media and Expedition Director) participating at high profile international ocean events as keynote speakers (e.g. UN Oceans, Economist World Ocean Summit).
- **To build partnerships with the story-telling industry:** to harness their skills, resources and investment to tell the story of Ocean Census and ocean life (e.g. broadcast series, immersive installations).
- **To innovate ocean story telling** during Ocean Census diver-based expeditions.

- **To inspire and engage young people:** initially with live educational events from Ocean Census Expeditions and, as the programme develops, with the production of new ocean life educational resources, freely available for schools, teachers and students with partnerships with professional education companies.
- **To operationalise and coordinate communications activities across all of Ocean Census** – by maximising media and public engagement from visuals and data harvested on Expeditions and developing frictionless, cost-effective workflows, both on expeditions and onshore, with science and data teams.

The content generation strategy builds on the experience of the Nekton Foundation with science expeditions in the western Indian Ocean co-produced with in-country scientists and policymakers. An important element of the outreach for these expeditions has been the participation and story-telling of local scientists, policymakers and members of civil society (see for the Maldives Expedition, 2022: https://nektonmission.org/missions/maldives/the-voice-of-the-maldives).

How Will Ocean Census Be Funded?

In 2010, Wheeler asked the intriguing question of what NASA would do if it encountered a planet where only 2 million out of 10 million species were known, and a large number of these species were facing extinction. He concluded that NASA would design a mission to learn as much as possible about life on this hypothetical planet including prioritization of scientific questions, clarifying the goals of the mission and detailing what infrastructure was needed to achieve it, using this as a basis to seek funding (Wheeler, 2010). Proportionately we know less about the species in the ocean but it is widely accepted that they are under threat from both local and global anthropogenic stressors (Rogers et al., 2022a). What we have proposed here is the equivalent of a NASA Large Strategic Science Mission (Cangi et al., 2019). These missions typically cost between $1.3 billion (Earth Science Aqua) to $9.2 billion (Hubble Space Telescope; Cangi et al., 2019). Smaller projects in the Discovery and New Frontiers programmes are capped at $450 million and $850 million respectively but these costs exclude launch and post-launch costs (Cangi et al., 2019).

The largest programme to date aiming to document marine biodiversity was the Census of Marine Life (CoML) which ran from 2000 to 2010. CoML was initiated by the Alfred P Sloan Foundation with a grant that amounted to $78 million by the end of the project (https://sloan.org/programs/completed-programs/census-of-marine-life). However, with in kind and other cash contributions from governments, international organisations and maritime industries, the total funding for the programme amounted to approximately $650 million (http://www.coml.org/about-census/). Fourteen Field Projects catalogued about 30 million species distribution records and by the end of the programme 1,200 new species were discovered with a further estimated 5,000 still to be described (http://www.coml.org/about-census/). Whilst this number seems small given the size of the programme it should be considered that CoML was focused on documenting ecosystems and communities as well as their ecology and led to more than 2,600 scientific papers by its completion and also founded OBIS (http://www.coml.org/about-census/).

As with the Census of Marine Life, Ocean Census has been initiated with a multi-year core grant, in this case from The Nippon Foundation. We expect that partner contributions will significantly boost this funding through the provision of infrastructure, equipment and consumables for the programme. Sea time is especially expensive with research vessels costing between $25,000 to $87,500 a day or more excluding fuel costs (Rogers et al., 2021a). Contributions of places on existing research vessels or donation of dedicated vessel time for Ocean Census is therefore a particularly valuable source of funding for the programme. As Ocean Census continues, we anticipate contributions from many partners including governments, foundations, industry, academic institutions and from civil society. However, we regard Ocean Census as a Large-Scale Strategic Science Mission, the largest ever to be undertaken on ocean biodiversity, and as such it is anticipated funding from all sources, including cash and in-kind support will exceed $1 billion. Furthermore, Ocean Census has deliberately been designed to continue beyond the 10 years of planned programme to deliver a permanent legacy in terms of approaches, infrastructure and human capacity to discover, describe and monitor the biodiversity of our largest ecosystem, the ocean.

Summary

Ocean Census will become the single largest global programme in history to discover and document ocean life and fulfil a major role in the great scientific challenge to describe and sequence all life on Earth, playing a key role in the protection of the ocean, and thus the Earth and human society that relies on it. Ocean Census will transform our understanding of the diversity and distribution of life in the ocean by accelerating species discovery through four main strategies:

- Digitisation of all data associated with the collection of marine species to promote the use of cybertaxonomy including the development of an intermediate step between specimen collection and description of species termed here the Digital Life Form. The Ocean Census Cyber-Biodiversity System will be an integral part of this digitisation strategy collecting, storing and disseminating species data to appropriate existing global databases, archiving data for which such databases do not exist and converting data to knowledge useful to specific user communities (e.g. scientists, ocean managers, policymakers, industry and civil society).
- The adoption of new technologies and working practices that accelerate the process of species description. This will involve the development of large teams of taxonomists and support specialists (e.g. molecular biologists, imaging specialists) at Biodiversity Centres. Also, the development of networks of taxonomists including both academic institutions and citizen scientists globally working towards the same goal of species discovery and description.
- Increase the global human capacity and infrastructure to discover and protect marine life including through Ocean Census Expeditions and specific training activities.
- Conduct Ocean Census Expeditions targeted at collecting biological specimens (and when feasible related physical and biochemical) measurements from poorly investigated regions (e.g. areas beyond national jurisdiction, the deep sea) thereby contributing to increased coverage of Essential Ocean Variables, and global biodiversity monitoring efforts.
- Raise and inspire public and partner awareness of ocean life and the programme to accelerate its discovery and Ocean Literacy.

Ocean Census will be organised as an open network of scientists and other specialists focused on the discovery and description of species in the ocean. This will be anchored by Biodiversity Centres and will be accompanied by Virtual Taxonomic Networks which focus on specific taxonomic groups to fulfil the Ocean Census mission. This open network approach will be central to democratisation of marine taxonomy / biodiversity research globally and is supported by the digitisation and data policies and capacity-building activities through Expeditions and Biodiversity Centres. Together these initiatives are essential to maximise human effort on species discovery.

Ocean Census also comprises a major public outreach and education element with story-telling on the ocean focused on scientists, policymakers and citizens living in coastal countries hosting

Expeditions. Outreach will be managed by professional communicators and will be distributed through partner and paid organisations to ensure maximum reach and impact amongst audiences at local to global levels.

Initial funding for Ocean Census has been granted by The Nippon Foundation and will be supplemented directly and in-kind through a network of partners. It is a Large-Scale Strategic Science Mission that has been planned for delivery over 10 years but which is also designed to live beyond this time providing a permanent legacy in acceleration of marine species discovery and biodiversity monitoring. Over the decade of Ocean Census it is our intention to accelerate species discovery 10-fold and deliver fundamental scientific understanding of the distribution of life in the ocean. This will provide the science required to understand how the ocean is changing and how it can be better managed as a place of importance to the planet and wonder to humans.

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Table Captions

Table 1. Number of animal species distributed across phyla in the ocean and on land. These are accepted species names. Data from the WORMs Register of Marine Species (https://www.marinespecies.org/index.php), accessed 20/4/2023. Data for Onycophora come from Baker et al. (2021).

Tables

Table 1

Taxon	Number of marine species	Number of non-marine species
Animalia		
Acanthocephala	514	9
Annelida	13,797	1,029
Arthropoda	58,302	29,710
Brachiopoda	412	0
Bryozoa	6,449	106
Chaetognatha	132	0
Chordata	23,950	17,301
Cnidaria	11,997	28
Ctenophora	205	0
Cycliophora	2	0
Dycemida	122	0
Echinodermata	7,530	0
Entoprocta	198	2
Gastrotricha	518	355
Gnathifera	0	1
Gnathostomulida	100	0
Hemichordata	133	0
Kinorhyncha	341	0
Loricifera	45	0
Mollusca	50,856	34,140
Nematoda	6,583	6,797

Nematomorpha	5	0
Nemertea	1,334	13
Onycophora	0	187
Orthonectida	25	0
Phoronida	13	0
Placozoa	4	0
Platyhelminthes	13,268	2,918
Porifera	9,288	234
Priapulida	22	0
Rotifera	182	118
Tardigrada	229	1,020
Xenacoelomorpha	455	2

Figure Captions

Figure 1. Rate of species discovery in the ocean. Data from World Register of Marine Species (https://www.marinespecies.org/), downloaded 14th April, 2023.

Figure 2. Disciplines related to taxonomic science showing polarisation between evolutionary taxonomists and eco-taxonomists as well as cross-over areas of scientific research. Phylogeny is taken from Drerup and How, 2021 under Creative Commons License BY 4.0. Photograph is from NERC Cruise JC66 part of the NERC/IUCN Seamounts project. Shows a mixed community of deep-sea invertebrates on Atlantis Bank seamount, South West Indian Ridge, southern Indian Ocean.

Figure 3. Diagram depicting the different aspects of Ocean Census which are aimed at accelerating species discovery and description (Digitisation, Adoption of New Technologies, Capacity development, Expeditions). Images of MinION sequencer is from Oxford Nanopore Technologies (https://nanoporetech.com/products/minion). Micro-CT scan image is from Landscoff et al. (2018). Urchin icon is available under a Creative Commons License 3.0 from Iconfinder (https://www.iconfinder.com/).

Figure 4. Diagram illustrating the digitisation of data related to the collection of a marine organism and the generation of Digital Life Forms, the flow of data into the Ocean Census Cyber-Biodiversity System and flows of data to global databases and data incubators (and return of data to the Cyber-Biodiversity System). Tools will be generated to translate data to actionable knowledge for different user groups (e.g. policy makers, scientists, industry, civil society). OBIS = Ocean Biodiversity Information System, WORMS = World Register of Marine Species, WOD = World Ocean Database, NODCs = National Oceanographic Data Centres, INSDC = International Nucleotide Sequence Database Collaboration. Urchin icon is available under a Creative Commons License 3.0 from Iconfinder (https://www.iconfinder.com/).

Figure 5. The open network structure of the Ocean Census programme. Core to developing a lasting legacy in acceleration of discovery and description of marine species is the development of a network of Biodiversity Centres and Virtual Taxonomy Networks enabling taxonomists to cooperate and coordinate their activities globally. Expeditions generate samples for species discovery and also stories for ocean literacy. Data generated by expeditions and taxonomists are communicated to the Ocean Census Cyber-Biodiversity System. Ocean Census Headquarters (HQ) will coordinate the programme including expeditions, expedition logistics, permitting, some funding bids as well as take on reporting functions to funders.

Figures

Figure 1

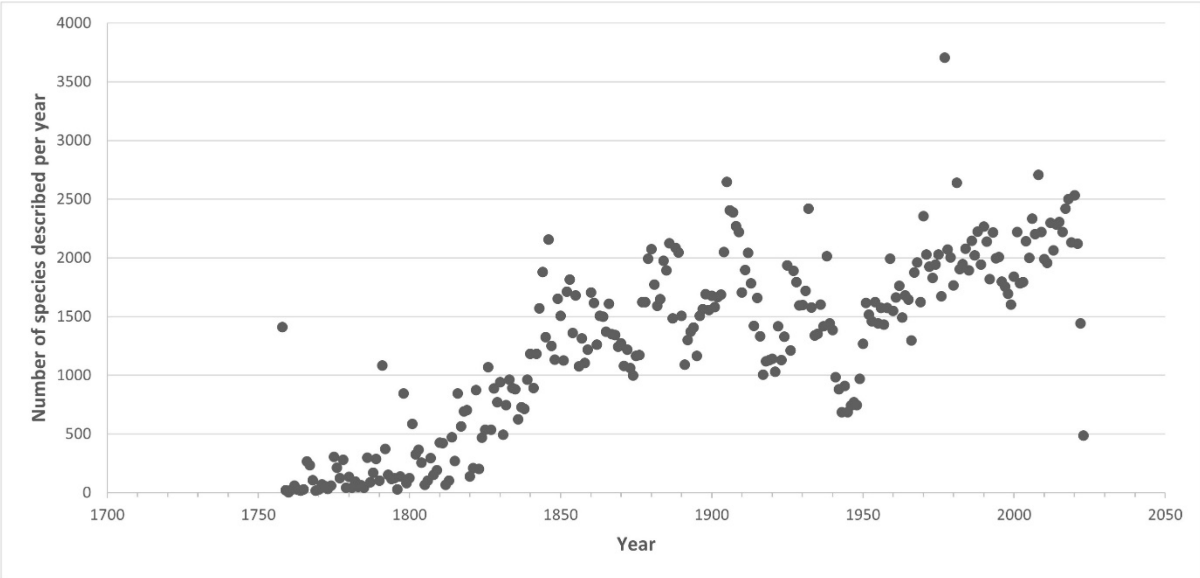


Figure 2

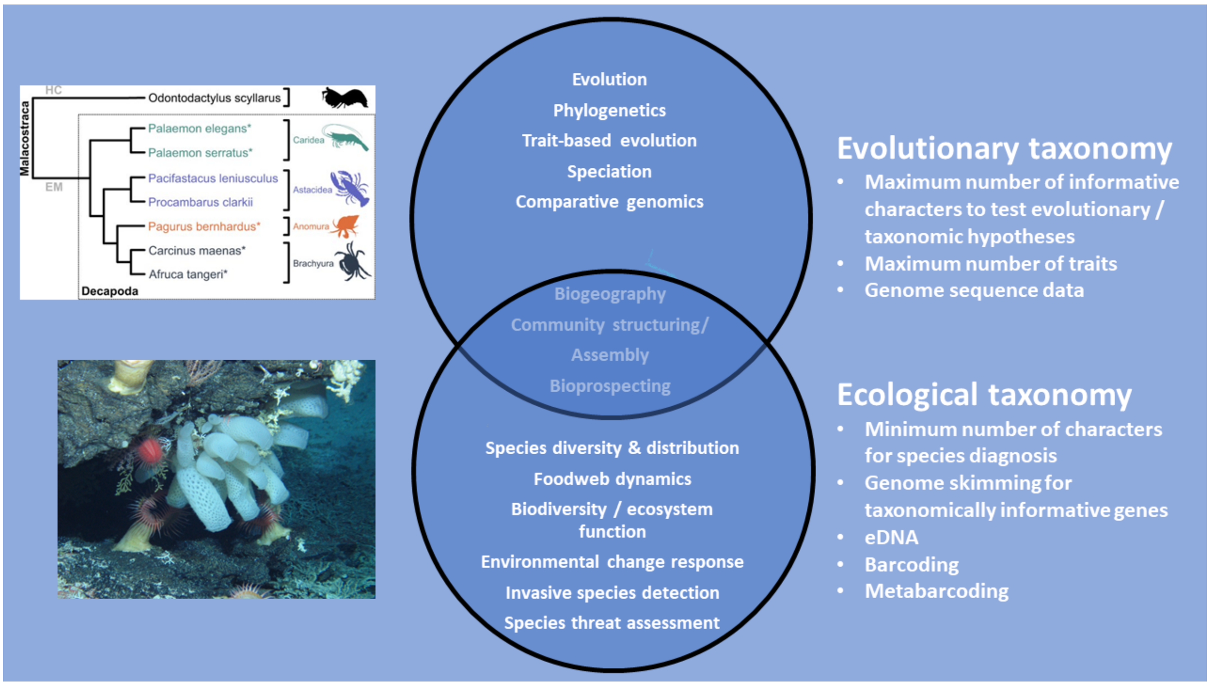


Figure 3

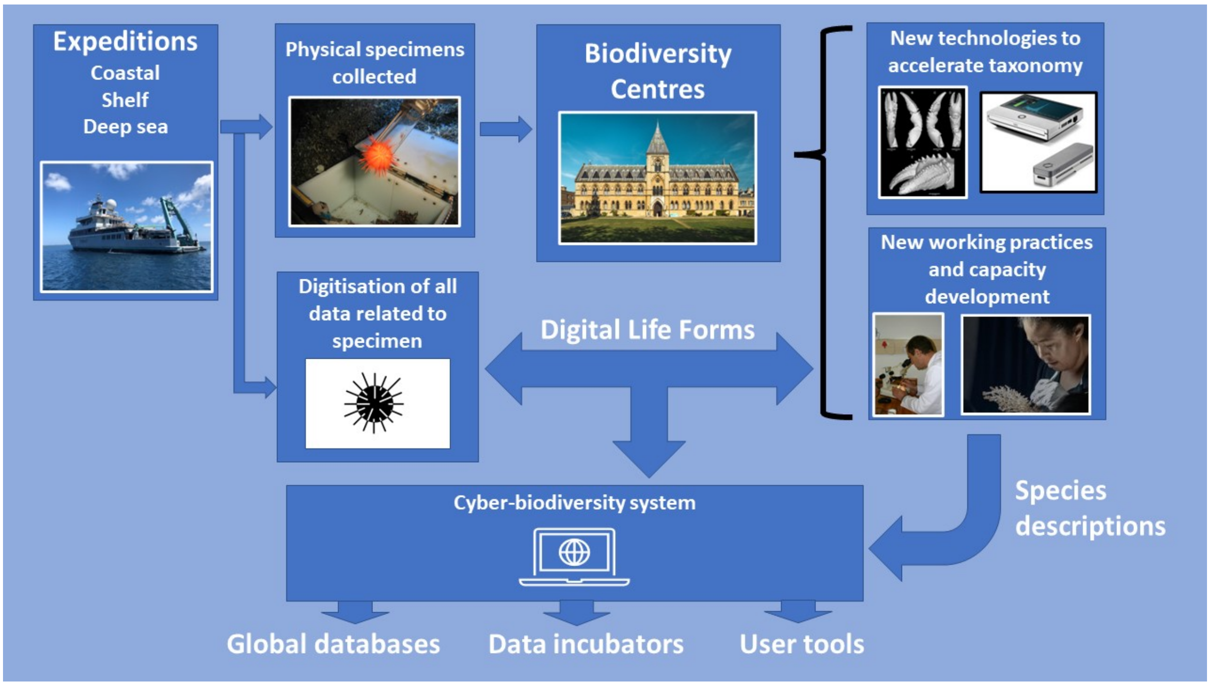


Figure 4

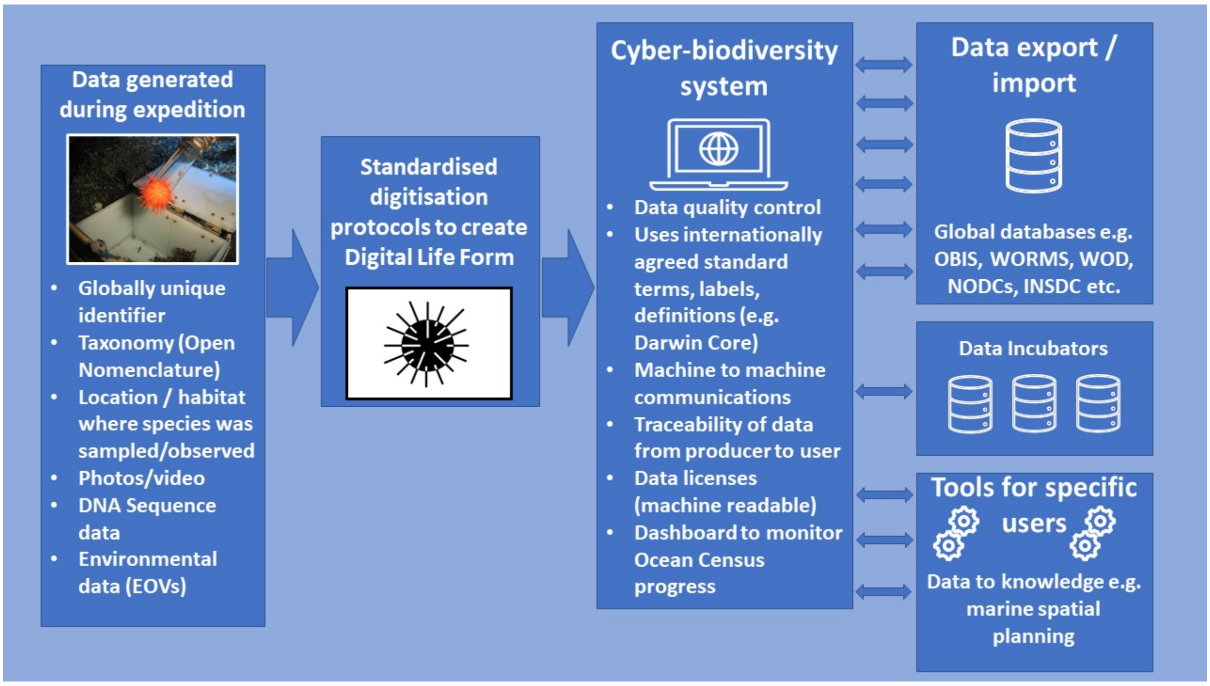
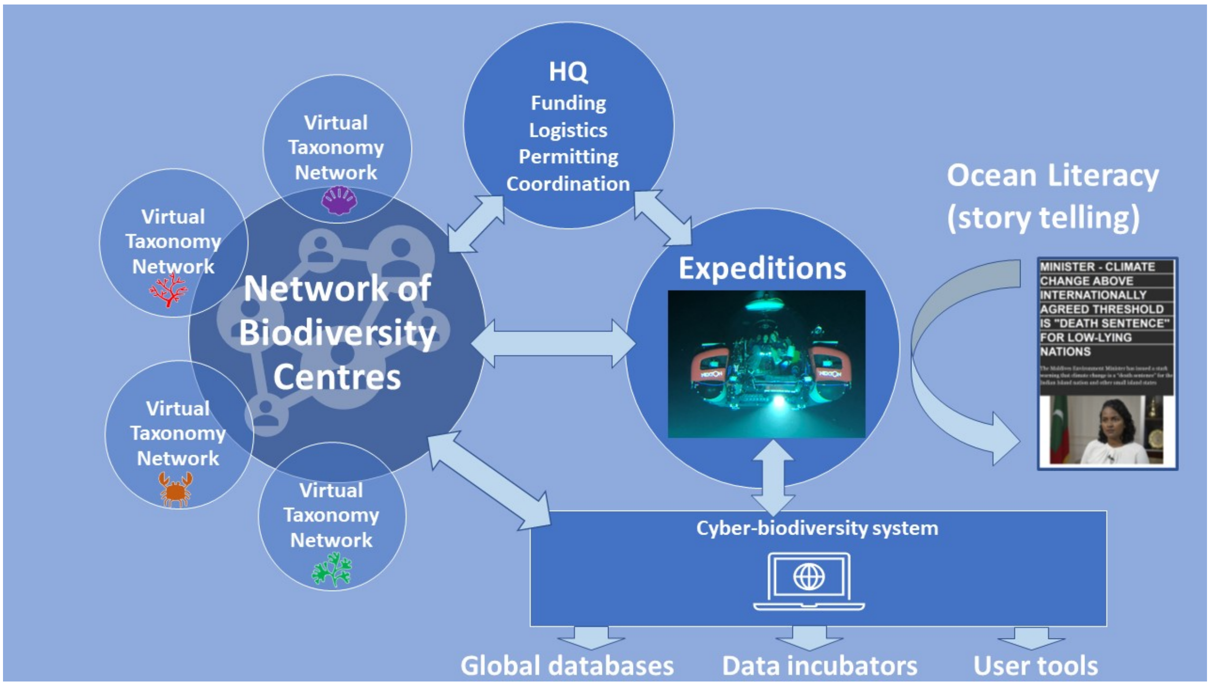


Figure 5


HQ
Funding
Logistics
Permitting
Coordination
Virtual Taxonomy Network
Virtual Taxonomy Network
Network of Biodiversity Centres
Virtual Taxonomy Network
Virtual Taxonomy Network
Expeditions
Ocean Literacy
(story telling)
MINISTER - CLIMATE CHANGE ABOVE INTERNATIONALLY AGREED THRESHOLD IS "DEATH SENTENCE" FOR LOW-LYING NATIONS
Cyber-biodiversity system
Global databases
Data incubators
User tools