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From microscope to management: the critical value of plankton taxonomy to marine policy and biodiversity conservation

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Abstract

Taxonomic information provides a crucial understanding of the most basic component of biodiversity – which organisms are present in a region or ecosystem. Taxonomy, however, is a discipline in decline, at times perceived as 'obsolete' due to technical advances in science, and with fewer trained taxonomists and analysts emerging each year to replace the previous generation as it retires. Simultaneously, increasing focus is turned towards sustainable management of the marine environment using an ecosystem approach, and towards conserving biodiversity, key species, and habitats. Sensitive indicators derived from taxonomic data are instrumental to the successful delivery of these efforts. At the base of the marine food web and closely linked to their immediate environment, plankton are increasingly needed as indicators to support marine policy, inform conservation efforts for higher trophic organisms, and protect human health. Detailed taxonomic data, containing information on the presence/absence and abundance of individual plankton species, are required to underpin the development of sensitive species- and community-level indicators which are necessary to understand subtle changes in marine ecosystems and inform management and conservation efforts. Here the critical importance of plankton taxonomic data is illustrated, and therefore plankton taxonomic expertise, in informing marine policy and conservation and outline challenges, and potential solutions, facing this discipline.

Key words: plankton, indicators, taxonomy, conservation, biodiversity, marine policy

1. Introduction

A fundamental understanding of marine biodiversity is still lacking. Of the estimated 2-8 million species on Earth, 0.7 – 2.2 million are thought to be marine although many (between 33-90%) are yet to be described [see 1, 2]. Since publication of the Convention of Biological Diversity in 1992, 'biodiversity' has become a buzzword, frequently mentioned in the media, but also explicitly named in other pieces of legislation, including those with marine components [3, 4]. This overt inclusion into policy provides the legislative impetus for improving our understanding of marine biodiversity and its conservation; however, in order to conserve marine biodiversity and effectively manage the marine environment, it is important to understand which species are present, the relationships between them, and their roles in marine ecosystem functioning. Taxonomy and taxonomic analysis, the field of science with the ability to provide this essential and basic species-level data, therefore has a clear and crucial role in articulating, understanding, and conserving marine biodiversity.

Taxonomy, and its associated identification and analysis skills, is a discipline in crisis [5]. In terms of investment, taxonomy is highly specialised, involving a long-term training process. There is a lack of positions in which taxonomists can develop their skills because retiring taxonomists are not being replaced, resulting in weak recruitment of young scientists into taxonomy and fewer taxonomists to train the next generation. Furthermore, funding for taxonomy, as with much other assessment science, has been reduced by science funding bodies and monitoring costs are now supplemented by industries for whom ecology is of minor importance [6]. Taxonomy is often considered 'unsexy' or basic 'stamp collecting', rather than innovative science. Thus, the impact factor of taxonomic journals is low, discouraging the publication of descriptive papers, and diminishing respect for the field of taxonomy [7, 8]. This decline in taxonomic expertise is particularly concerning because the requirement for taxonomic information is increasing due to rising impetus placed on biodiversity conservation and ecosystem-based management [6, 9]. Costello et al. [10] optimistically state that there has been an increase in taxonomists, in Asian and South American countries in particular, but their definition includes only scientists listed on publications describing species new to science. Taxonomy is actually a significantly broader area, not only restrained to the discovery and description of new species, but also including the identification, analysis, classification and reclassification, and naming of organisms, all of which rely on specialist knowledge. Authors using this wider definition have observed a decrease in working scientists with taxonomic expertise, highlighting the decline of this discipline [5, 11-13]. In the context of this paper, a wider definition of taxonomy is used, which includes the discipline of taxonomic identification and analysis as well as descriptive taxonomy.

In contrast to its reputation as outdated, taxonomy is in fact an evolving and relevant field. This is particularly evident in the marine environment; for example, between 2000 and 2010, the Census of Marine Life taxonomists described 1200 species new to science, emphasising the number of taxonomic challenges that still exist in the marine environment [14]. A formidable challenge to marine taxonomy is the fact that a significant portion of marine biodiversity is microscopic and therefore either undiscovered, undescribed, or misclassified due to high occurrence of synonyms and cryptic species [1]. Additionally, fewer taxonomists focus on less charismatic and small-sized marine invertebrates, such as plankton, than on megafauna such as fish and mammals [1]. Some of the best-studied plankton groups, including Bacillariophyceae (diatoms) and Copepoda (copepods), are among the least well-known taxonomic groups, and are thought to contain more than 50,000 and 30,000-50,000 undiscovered species, respectively [1]. Due to their small size and apparent lack of distinct morphotaxonomical characteristics, identifying plankton taxa to species level requires a high level of taxonomic skill. For example, taxonomic analysts at the Continuous Plankton Recorder

Survey did not reliably distinguish the trophically-important copepod species *Calanus helgolandicus* and *C. finmarchicus* until 1958, as these cogeners are so morphologically similar [15]. It was only when this taxonomic distinction was made that the relative proportion and importance of the two species as a climate indicator in the Northeast Atlantic was revealed [16]. Up to date and correct taxonomic information, dependent on skilled taxonomic analysts, is thus needed to progress ecological research and further our understanding of marine environmental change.

The new generation of policy mechanisms seeks to manage the marine environment holistically through the ecosystem approach [17-20]. Central to this management method is the incorporation of scientific evidence into the decision making process, which often occurs through the development and informing of environmental indicators [21-24]. Plankton are highly diverse [25] and play a key role in ecosystem functioning [26] that is closely linked to environmental change [27, 28]. Accordingly, plankton can be used as sensitive indicators of ecosystem change and plankton time-series are increasingly used to inform marine policy and management [29]. These time-series both supply essential taxonomic plankton community data needed to inform decision making, but also harbour significant taxonomic expertise. Ensuring the accuracy and credibility of the data, and therefore its usefulness in supporting marine policy and conservation, is closely tied to the skills of the taxonomic analysts analysing the plankton samples.

Taxonomic expertise is required to both generate and interpret the data underpinning and advancing our understanding of the marine environment, and to inform aspects of marine conservation and management. Although other work [e.g.17, 29 among others] convincingly makes the case for applying plankton indicators in marine policy and conservation, the issue of the crucial and threatened role of plankton taxonomy, and its associated identification and analysis skills, as a discipline in supporting policy and conservation indicator development and use remains largely unaddressed. Here, taxonomically-resolved data is referred to as ‘plankton taxonomic data’, which are produced as a direct result of plankton taxonomic identification expertise. This paper aims to illustrate the critical importance of plankton taxonomic data in informing marine policy and conservation, and therefore implicitly the crucial role of plankton taxonomic classification, identification, and analysis expertise. Finally, future challenges, and potential solutions facing this discipline are outlined.

2. Plankton taxonomy and the policy landscape

The Convention on Biological Diversity (CBD) was introduced in 1992, giving a political impetus to marine taxonomy on a global scale. The CBD defines ‘biodiversity’ as: ‘‘the variability among living organisms, from all sources, including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems’’ [30]. This definition specifically recognises the species-level component of marine biodiversity. In support of the critical role of taxonomy in conserving biodiversity, the CBD also established the Global Taxonomy Initiative, to specifically address the “taxonomic impediments” of knowledge gaps in our taxonomic system, the shortage of trained taxonomists and curators, and the impact these deficiencies have on our ability to conserve, use and share the benefits of our biological diversity (https://www.cbd.int/gti/). No cohesive global biodiversity monitoring programme exists, but the Group on Earth Observations Biodiversity Observation Network (GEO-BON) recommends taxonomic diversity as part of a suite of Essential Biodiversity Variables, meant to capture major dimensions of biodiversity change needed to inform science and policy at a global scale [31].

As understanding of the ecological role of plankton in marine systems has developed, so has the aim of statutory plankton monitoring, which has evolved from informing legislation focused on water quality to supporting increasingly complex ecosystem aspects such as food webs and biodiversity under the ecosystem approach. This evolution is clearly illustrated by changes in the role of plankton in European Union (EU) policy during the past 30 years. Since 1991, the Shellfish Hygiene Directive has mandated the monitoring of potential toxin-producing phytoplankton species in shellfish production areas as part of a statutory monitoring programme to protect human health from algal toxins [32]. Passed in 2000, the Water Framework Directive requires the monitoring of composition and abundance of coastal phytoplankton taxa to assess eutrophication, taxonomically broadening the contribution of plankton to informing European policy [33]. Most recently and most holistically, the EU's Marine Strategy Framework Directive (MSFD) requires the monitoring of community-level phytoplankton and zooplankton indicators in support of environmental targets for eutrophication, biodiversity and food webs [3]. These legislative examples use increasingly complex aspects of plankton community dynamics, all of which require taxonomically-resolved plankton data.

In addition to supporting legally-binding policy instruments, taxonomic plankton data feature prominently in recent global-scale assessments of the state of the seas. The fifth report of the Intergovernmental Panel on Climate Change (IPCC) and the United Nation's (UN) World Ocean Assessment both featured comprehensive overviews of inter- and intra-annual changes in regional plankton communities with links to climate and direct anthropogenic pressures [34, 35]. The strong presence of plankton research and explicit links drawn between plankton change and socio-economic responses in the high profile IPCC and UN publications highlight the importance of plankton data in informing international environmental decision making.

3. Taxonomic plankton indicators

Much pioneering progress in creating plankton indicators has been based on species-level data [36, 37 and references therein]. Hardy [37] and Russell [36] recognised that the effect of the environment varies within and between plankton functional groups and individual plankton species, and that these data have uses wider than only scientific research. For example, Hardy developed the Continuous Plankton Recorder (CPR) survey in the 1920s to improve the efficiency of the North Sea herring fishery [15], while Russell constructed 'practical plankton indicators' based on taxa which were large in size and easily identifiable in order to evaluate water movement and conditions [36]. Plankton indicator development for management, conservation, and policy has continued to evolve and now encompasses multiple scales of plankton organisation from bulk indicators (such as chlorophyll and phytoplankton biomass) to aggregated functional group indicators often underlain by taxonomic data (such as the ratio of diatoms to dinoflagellates) to community composition and single species indicators, which are wholly dependent on plankton taxonomic data (Figure 1; Table 1).

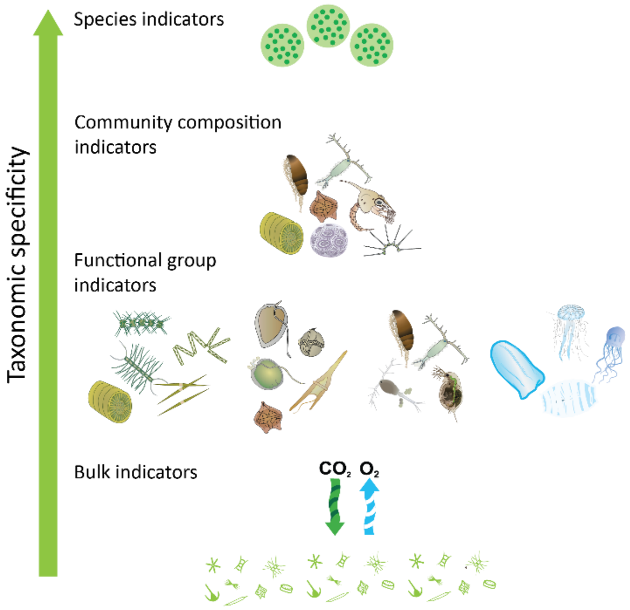

Figure 1: Plankton indicator types require different levels of taxonomically-resolved data. Species indicators have the highest taxonomic resolution and consist of a single species, or species complex. Community composition indicators are comprised of multiple species and are derived from species data. Functional group indicators are comprised of a group of taxa sharing a common functional trait. Bulk indicators are the most coarsely resolved, and are populated with a non-taxonomically dependent parameter or by aggregating taxonomic information.

Insert Figure 1 here

Insert Table 1 here

Table 1. Legislative drivers and ecosystem assessments use different plankton indicator types; there are distinct strengths and weaknesses. A suite of complimentary plankton indicators provides the most comprehensive insight into plankton community structure, function, and productivity. Abbreviations in table: MSFD – Marine Strategy Framework Directive [3], WFD – Water Framework Directive [33], CCAMLR – Commission for the Conservation of Antarctic Living Marine Resources [38], IMOS – Integrated Marine Observing System (Australia) [39], GBRMPA – Great Barrier Reef Marine Park Authority [40], CPR – Continuous Plankton Recorder Survey [41], WoA – World Oceans Assessment [35], IPCC – Intergovernmental Panel on Climate Change [34].

Plankton indicator type	Example	Legislative or assessment application	Role of taxonomy	Strengths	Weaknesses
Species indicators	• *Phaeocystis* spp • *Euphausia superba* • *Pseudo-nitzschia* spp. • *Dinophysis* spp. • *Noctilua scintillans*	• MSFD • WFD • CCAMLR • IMOS • CPR • WoA • IPCC	• Species-level identification required to identify indicator species	• A direct measure of biodiversity • Maximum detail of community composition • Potential to evaluate pressure-state relationship • Captures functional traits of individual species	• Plankton community composition regionally variable, limiting generality of findings • Data may be noisy and obscure trends if drivers of change uncertain/unknown • Not summative of the system • Sample processing expensive and time consuming
Community composition indicators	• Richness indices (e.g. species richness, Margalef's index) • Evenness indices (e.g. Pielou's evenness index) • Dominance indices (e.g. Simpson's dominance index)	• MSFD • WFD • IMOS • CPR • WoA • IPCC	• Species level identification needed to create community data before indices can be calculated	• Provide information on community structure • Captures taxonomic diversity of the plankton assemblage • Easy to calculate • Dependent on taxonomic data	• Responses to anthropogenic and climatic pressure gradients are often non-linear • Reduction to an index ignores specific species identity and abundance leading to overly simplistic outputs • Key indicator species not examined separately

Functional group indicators	• Diatoms • Dinoflagellates • Zooplankton grazers • Gelatinous zooplankton • Calcareous plankton	• MSFD • GBRMPA • IMOS • CPR • WoA • IPCC	• Coarser taxonomic identification required • Often grouped from species level data	• Links to ecosystem functioning; evaluation of ecosystem stability and resilience possible • Can be constructed from datasets with different taxonomic resolutions • Transferable between geographic regions • Dependent on taxonomic data	• Lack taxonomic detail so may provide limited biodiversity information or insights into changes in key indicator species • Patterns in one species might obscure those in another • Functional traits not yet understood for some species
Bulk indicators	• Phytoplankton biomass (e.g. chlorophyll, Phytoplankton Colour Index) • Zooplankton abundance	• MSFD • WFD • GBRMPA • IMOS • CPR • WoA • IPCC	• Taxonomy not needed to inform indicators • Taxonomy required to interpret changes in bulk indicators	• Provide information on plankton production • May have good spatial coverage (e.g. satellites) • Cost efficient to construct	• Provide limited information on biodiversity and community structure • Unclear relationship between plankton diversity and functioning

Most taxonomically-resolved plankton datasets rely on analysis by traditional light microscopy, a relatively simple technique used to identify and enumerate plankton for over a century. These long time-series can support the indicators necessary to reveal insight into climate- and anthropogenically-driven changes in marine plankton communities, many of which take decades to manifest [42, 43].

Some assessments combine and interpret information using the full spectrum of plankton indicators (Figure 1) in a comprehensive and holistic manner, but it is the inclusion of the taxonomic (species) data which offers the added value and unique insights into aspects of ecosystem functioning and dynamics not captured by bulk or aggregated plankton indicators (Table 1). Species-level indicators are necessary to analyse intra-community changes as well as to reveal alterations in plankton diversity [44]. In contrast, bulk indicators, though relatively quick to produce, lack the resolution to detect changes in individual plankton taxa and thus obscure potential plankton-driven implications to marine food webs [45]. In fact, indicators based on taxonomic plankton data are required to interpret changes observed in bulk indicators. For example, the North Sea regime shift was first identified by an increase in phytoplankton biomass, but further species-level analysis revealed that the North Sea zooplankton community had switched from dominance by cold-boreal plankton species to dominance by warm-temperate taxa [46]. The latter discovery was particularly important as these species play distinct functional roles and support different food webs [46]. Though requiring more scientific effort to produce, only taxonomically-derived plankton indicators can aid understanding of the functional role of plankton species through knowledge of species-specific plankton functional traits [such as size, life cycle, feeding ecology, and habitat preferences; see 47]. From a policy and conservation perspective, this information may help articulate the consequences of management decisions.

Descriptor 1 of the European Union’s Marine Strategy Framework Directive (MSFD) requires the maintenance of biodiversity to be assessed through the surveillance of ecological indicators [3]. MSFD biodiversity indicators must capture the status of communities and species, while considering functional traits [48]. In the Northeast Atlantic, a suite of complimentary plankton indicators, providing insight into different aspects of the plankton community, are in development to meet this requirement [29]. Firstly, at the broadest organisational level, indicators for phytoplankton biomass and total copepod abundance provide an indication of phyto- and zooplankton productivity. Secondly, at intermediate scales, the plankton lifeform indicator approach uses functional traits to group plankton taxa into ecologically-relevant lifeform pairs where changes in relative abundance indicate alteration in ecosystem functioning [49, 50]. Thirdly, plankton species information is used to describe community structure parameters such as species evenness, dominance, and richness (Table 1). When used together, these indicators will give insight into plankton biodiversity through examining aspects of plankton community structure (community composition indicators) and function (functional group indicators). Irrespective of the scale of assessment, however, each indicator depends on accurate taxonomic information about the abundance and functional roles of all plankton taxa present. Examples of the application of these indicators, derived from taxonomic expertise, for marine management are given in sections 4, 5, and 6.

4. The role of plankton taxonomic data in biodiversity management and conservation

Current approaches to managing the marine environment focus on direct and manageable anthropogenic pressures, such as fishing and nutrient loading [20]. In addition to these pressures, climate change is acting at broader spatial-temporal scales, confounding management and conservation efforts, and ensuring that no static baseline exists against which management targets can be set [22, 51]. Increasing sea surface temperature (SST) and its associated physical influences, such as changes in water mass movement and stratification, are already affecting plankton [27]. Plankton species are some of the first marine organisms to respond to changes in SST, demonstrating a high degree of 'environmental match' [sensu 28] evident in the changing biogeography of plankton communities. North Atlantic plankton, for example, have undergone distinct shifts in their distributions, with warm-water copepod species moving northward into the North Sea while cold-water copepods are squeezed poleward [16]. A bulk-indicator approach to this work would have revealed only simplistic long-term variations in copepods as a group, masking the underlying relative spatial change of individual temperature-dependent species, and limiting applicability as a climate change indicator useful for management. An understanding of climate-driven changes in plankton communities is necessary for interpreting and determining causality of change and setting realistic management targets.

From a management perspective, invasive non-indigenous species (Descriptor 2 of the MFSD) are considered to be one of the most important direct drivers of biodiversity loss and change in ecosystem services globally [34, 35]. High taxonomic resolution plankton data are essential in providing the first alert of arrivals of such species. For example, evidence from the CPR Survey revealed the introduction and subsequent establishment of a Pacific diatom, *Neodenticula seminae*, in the North Atlantic in 1999, the first trans-Arctic migration in recent times [52]. The survey also identified the introduction of the non-indigenous diatom, *Coscinodiscus wailesii*, in 1977 [53]. Both species are now well-established in the North Atlantic phytoplankton community, with no discernible effects on regional foodwebs. Planktonic species introductions are not always so innocuous, however. The invasive ctenophore, *Mnemiopsis leidyi*, arrived in the Black Sea via ballast water in the early 1980s, and rapidly dominated the ecosystem, causing the collapse of the zooplanktivorous fish stocks, including anchovy, Mediterranean horse mackerel, and sprat [54]. It was not until the arrival of a second invasive ctenophore, *Beroe ovata*, in 1997, also via ballast water, that the ecosystem began to show signs of recovery [55]. Non-indigenous benthic or intertidal invertebrates may also be introduced to an area while in their meroplanktonic life stage, impacting non-planktonic communities. This is the case with the invasive Chinese mitten crab (*Eriocheir sinensis*) and likely also with the American jack knife clam (*Ensis directus*) which were introduced to Europe via ballast water transport of their larval stages [56, 57]. Taxonomically detailed plankton data are required to detect the arrival of new species to plankton communities and monitor the effectiveness of any management strategy implemented to limit or mitigate invasions.

Although plankton themselves are rarely the subject of conservation endeavours, plankton taxonomic data can inform conservation efforts through a 'surveillance' role, aiding in the interpretation of changes observed in higher trophic levels, and thus the management of other non-plankton ecosystem components [21]. For example, North Sea cod biomass has been linked, not only to fishing pressure, but also to the abundance of total *Calanus* copepods as well as the relative proportion of *C. finmarchicus* to *C. helgolandicus* which make up a key component of the diet of larval cod [45]. Because plankton play a fundamental role in the food web of marine megafauna, plankton indicators can be used to inform management of species with high conservation value such as basking sharks [58], marine mammals [59], seabirds [60, 61], and sea turtles [62]. These relationships are taxon-specific, with, for example, kittiwakes and puffins preying on pteropods and euphausiids, respectively, during the non-breeding season [60, 61 and references therein] while basking shark feeding events correspond to aggregations of *Calanus* copepods [58].

The fragmentation and loss of habitat following human activities threaten the persistence of species and can modify their dispersal [63, 64]. Marine Protected Areas (MPAs) are increasingly recognised as a management tool capable of reducing the risk of species extinctions by limiting habitat loss [65, 66]. The placement and size of MPAs is a particularly important consideration if they are to be an effective conservation tool at landscape or regional scales [67]. It is still under debate how dispersal processes affect planktonic communities, but this should be better investigated as many intertidal organisms have a meroplanktonic larval phase [68]. Research has shown that connectivity through larval dispersal, in this case related to meroplankton species, is an essential feature of effective MPA networks . As such, an in depth understanding of when, where and which species occur in the meroplankton is required to underpin decision-making in MPA design and placement. The use of plankton community indicators which include a meroplankton component (e.g. life-form index; see above) coupled with dispersal simulations may provide sufficient information to support the development of MPAs with generic targets, whereas raw species data may be required to underpin species-specific conservation objectives.

5. The role of plankton taxonomic data in understanding and providing ecosystem services and societal goods and benefits

The ecosystem approach to management recognises that humans are part of the ecosystem, and effective management requires a holistic approach; that is, one which considers the environmental and social dimensions explicitly within the management decision making process [24, 69, 70]. Effective ecosystem-based management (EBM) requires transparent links between the environment, social and economic components to be defined [e.g. 71]. Ecosystem services and societal goods and benefits are increasingly used as the metric through which environmental health and societal benefits are linked [e.g. 72, 73, 74], although, the link(s) between environmental health and ecosystem service provision are not well described making it difficult to make trade-offs between conservation objectives and the implementation of management measures that lead to 'success' [see 24].

Plankton biodiversity supports critical ecosystem services such as the production of oxygen, the removal of atmospheric carbon, and the provision of food for commercial fish stocks, all of which are under pressure due to climate change [75, 76]. For example, the size structure and species composition of phytoplankton communities is related to oxygen production and the removal of atmospheric carbon, ecosystem services which are likely to alter due to climate change [77]. Similarly, warming seas have caused a transition of Northeast Atlantic plankton communities from a community dominated by cold-water organisms with large body sizes to a more biodiverse community characterised by smaller warm-water organisms, coinciding with decreased carbon export [78]. The contribution to ecosystem services therefore varies between plankton species, making an understanding of plankton diversity integral to the understanding of current and future provision of ecosystem services [79, 80]. A bulk-indicator approach to this work would have revealed only simplistic long-term variations in copepods as a group, masking the underlying relative spatial change of individual temperature-dependent species, and limiting applicability as a climate change indicator useful for management.

Food provision through fisheries is a culturally and economically important ecosystem service directly dependent on plankton through their position at the base of the marine food web [81]. Many herbivorous zooplankton exhibit considerable selectivity in their diet [82], with the specific nutritional values of individual phytoplankton species playing an important role in the overall efficiency of copepod reproduction, development and survival [83]. The same principle also applies to planktivorous fish and fish larvae which display species and size selectivity when feeding on zooplankton [84]. This is exemplified in the North Sea, where long-term changes in cod recruitment have been linked to climate-driven fluctuations in plankton composition, resulting in the decreased survival of young cod [45]. As previously mentioned, plankton biodiversity is increasing in the North Atlantic [78]. Although high biodiversity is usually considered a positive characteristic of an ecosystem, increasing planktonic biodiversity may be detrimental to higher latitude fisheries, such as those of the North Atlantic. Higher plankton diversity in the North Atlantic has been linked to a shift in species composition to smaller and less energetic species from more southern latitudes [78]. This shift in plankton community composition will have strong repercussions for the food web as temperate and cold water plankton species native to high latitude systems are generally higher in lipid content, making them better food for larval fish [78, 85]. Cold temperate food webs are generally simpler and lower in diversity than those found in warm waters; these systems are also characterised by large populations of exploitable fish species, such as cod in the North Atlantic and Baltic Sea. Consequently, commercial fisheries may have to adapt to exploit the increasingly abundant smaller sized fish, such as anchovy and other small pelagics, with a potential decrease to the overall value of regional fisheries [81, 86].

Taxonomic expertise has a further critical role in ensuring provisioning services from fisheries by protecting local economies and human health from the impacts of harmful algal blooms (HABs). Countries across the globe operate monitoring programmes to protect human health from consumption of shellfish contaminated by harmful phytoplankton species such as paralytic shellfish toxin-producing *Alexandrium* spp., amnesic shellfish-toxin producing *Pseudo-nitzschia* spp. and *Dinophysis* spp., which produces diarrhetic shellfish toxins [87]. In Europe, human health is protected by the EU Shellfish Hygiene Directive (91/492/EEC), part of which is the statutory obligation for Member States to monitor their shellfish production areas for the presence of potential toxin producing species. These phytoplankton cell counts act as an early warning for shellfish farmers for the potential of harvesting closures as well as contributing to risk assessments improving monitoring design [88]. In addition, many fish farmers perform phytoplankton cell counts on a daily basis to provide an alert for HABs, allowing them to take mitigating action where possible to reduce fish losses [89]. In the Mediterranean, monitoring for palytoxin producing genera such as *Ostreopsis* helps inform managers about the potential for beach closures which can negatively impact the local tourism industry [90]. In recent years, ciguatera fish poisoning (CFP) has become a major threat in some regions and the World Health Organization (WHO) has actively entered the Intergovernmental Oceanographic Commission (IOC)/Food and Agriculture Organization (FAO)/ International Atomic Energy Association (IAEA) process of defining a joint strategy for CFP. Monitoring of the causative organism *Gambierdiscus* spp. is critical to implementing a management action plan in the areas affected [91].

6. New developments in plankton monitoring for management still depend on taxonomy

Increasing financial pressure combined with the aforementioned impetus for using plankton indicators in policy and conservation have led to the development of cost effective, technology-dependent plankton monitoring methods. Taxonomic plankton data, however, are still required to support and validate these new methods and test indicators derived from these new types of monitoring. For example, the use of genetics in plankton monitoring is maturing, raising the question: should molecular techniques replace traditional taxonomic analysis? In the last decade, DNA sequencing has become increasingly robust, cheap and able to easily detect thousands of plankton taxa from a small quantity of marine water [92]. Consequently, an explosion of new planktonic species discoveries has recently occurred [25, 93, 94]. In a global study surface plankton were estimated to contain 150,000 operational taxonomic units (OTU) corresponding to different organisms, most of which belonged to the pico- to nano-sized plankton (2-20µm) and which are too small to be accurately identified with light microscopy [25]. One-third of these are likely new to science, hidden as parasites or symbionts in other larger organisms. Even within the larger-sized plankton groups most commonly studied worldwide, new species have been identified, revealing previously unknown diversity [25].

Genetic and taxonomic analyses produce different, but complementary, information about plankton communities. Morphological taxonomy has been used for over a century to reliably produce information on larger plankton taxa, their life-stages, and their quantitative abundance [36, 95, among many others]. Conversely, genetic identification is not size-dependent and so can provide information on small or cryptic species that can be missed by taxonomic methods; genetic techniques, however, are unable to reliably quantify species abundance [96]. The data generated via genetic techniques such as DNA barcoding can only be informative when linked to a known, taxonomically-described specimen. Without this match, barcoding can provide an indication of number of different species, but not their morphological identities, traits, or ecosystem roles, characteristics emergent from traditional taxonomy [97]. A robust and comprehensive picture of the plankton community can best be built through the use of genetics to augment taxonomic plankton monitoring surveys, thereby preserving and extending traditional time-series while expanding the plankton components monitored. This approach has been championed by the DNA barcoding community which requires a voucher or photomicrograph of an organism with a taxonomic description on which to base its DNA barcode [98, 99]. Additionally, it is now good practice for formal systematic descriptions of new species to incorporate genetic information [100]. In this way the integration of traditional taxonomic and new genetic information can build upon each other to provide a more detailed description of marine plankton communities.

Advancements in non-genetic analysis techniques now allow rapid assessment of some aspects of plankton communities. Fluorometry can provide an estimate of chlorophyll-a, while flow cytometry can be used to distinguish phytoplankton based on their size and pigments and recent advances in imaging flow systems now offer the ability to capture a larger size spectrum of phytoplankton organisms rapidly. The ability to use these approaches to identify species remains, however, limited [101-103]. Semi-automated imaging systems such as FlowCam and ZooScan can rapidly photograph plankton organisms, automatically sorting them into coarsely resolved groups, though these are largely based on morphology rather than taxonomy or functional groupings [104, 105]. Although these techniques quickly produce a large quantity of data, taxonomic expertise is required to train the system to recognize and sort individuals [106]. Few taxa can automatically be identified to genus or species level, but the rapid analysis of plankton samples to a coarse level can complement traditional taxonomic and genetic data, particularly over large spatial scales[103].

Remote sensing technology has greatly contributed to phytoplankton observation at high spatio-temporal resolutions. Historic and modern observing satellites, such as CZCS, SeaWiFS, MODIS, MERIS, and now Sentinel 3 can measure phytoplankton chlorophyll in the surface skin layer (top 1 mm) of marine waters, estimating phytoplankton biomass over large oceanic areas [107]. Such observing systems can also discriminate calcareous coccolithophores by their reflectance, allowing detailed observation of blooms [108]. Further refinement of spectroscopic data can separate phytoplankton organisms into broad groups of species which can be modelled into functional types, serving as proxies of real phytoplankton taxa [109, 110]. However, while satellite sensors can detect surface organisms, they fail to detect subsurface and deep-water phytoplankton and their ability to separate chlorophyll from particulate matter in coastal waters is limited [107]. Validating satellite data with taxonomic data collected by *in situ* plankton monitoring programmes is therefore required for a more detailed understanding of phytoplankton species and their ecology.

7. The role of plankton taxonomic data in future management issues

Plankton taxonomy is also valuable for understanding emerging management issues in marine ecosystems. For example, ocean acidification is expected to impact the plankton; calcareous taxa, which form calcite shells or exoskeletons, in particular, are expected to be negatively affected [111, 112]. Coccolithophores, the most globally-important calcareous phytoplankton group, show a varying response to acidic conditions in laboratory experiments [113, 114], even between different strains of a single species [115]. In situ data, however, indicate an increase in coccolithophore abundance during the past fifty years, likely linked to other climate-related drivers such as increased SST and rising atmospheric CO_2 [116, 117]. Whether phytoplankton respond to decreasing pH therefore remains unclear, with individual species predicted to respond differently to future ocean acidification conditions, making it unclear as to how plankton community composition will change in the future [80]. Knowledge of such inter-specific variations is crucial to our understanding of the future consequences of ocean acidification on marine food webs and carbon cycling, and our resultant ability to account for future conditions when setting management and conservation targets.

Expertise in plankton taxonomy and plankton taxonomic data support increasingly important plankton fisheries and enable emerging economic opportunities. For example, approximately 225,000 tonnes of Antarctic krill (*Euphausia superba*) were harvested in 2015 for use in aquaculture, pet food, and dietary supplements for humans [118]. The global jellyfish fishery is also growing, with tens of species now commercially harvested for food, cosmetic ingredients, biomedical research, and dietary supplements [119]. A Norwegian *Calanus finmarchicus* fishery, also for the production of dietary supplements, is now in its infancy and a similar fishery for Iceland is under consideration [120]. These commercial plankton fisheries are at the very base of the marine foodweb and their sustainability is unclear due to uncertainty around current growth, mortality, and biomass estimates;

the delineation of stocks and stock structure due to the complex life histories of plankton; and impacts on wider ecosystem community dynamics including commercially-important fish and megafauna such as turtles, penguins, and whales [119-121]. Commercial uses of plankton continue to emerge with phytoplankton species in development as biofuels [122, 123] and sold commercially as dietary 'superfood' supplements, although support for these claims in the scientific literature is non-existent. Taxonomic understanding of the plankton species involved is the very foundation of their efficient exploitation, safe consumption, and sustainable management – careful consideration must be given to managing exploitation of these organisms upon which the marine food web depends.

Ecosystem modelling is a tool which enables the exploration of future marine conditions, allowing the proactive consideration of policy and management options. Species-specific interactions are crucial to food web modelling and research and are recognised as the most effective method to integrate complex attributes of marine ecosystem structure (taxa composition of the marine ecosystem) and function (biological processes occurring in an ecosystem) such as biodiversity, community organisation, and energy fluxes [79]. Currently, most ecosystem models use aggregated plankton data, which at best adopt the relatively coarse resolution of functional groups, limiting our understanding of ecosystem functioning through the exclusion of species-level data [79, 124]. Species-level data capture functional trait information, which reflects the roles of individual genera or taxa in ecosystem functioning and provide insights into ecosystem resilience; these traits can vary widely between species [47]. For example, in diatoms, individual species can span a large range of sizes and fall on a continuum between r (growth) and K (fitness) strategies [125], attributes not captured by ecosystem models using coarse phytoplankton indicators. Selection strategy in particular is argued to be a key determinant of functional trait performance affecting traits such as survivorship, competitive ability, length of life, rate of development, body size and dispersal ability [see 126 for an in-depth review], which affect the distribution of plankton and therefore the early life-history stages and adult forms of meroplanktonic marine organisms. Taxonomic plankton data are therefore needed to accurately inform models of ecosystem functioning, and ideally predict future ecological changes, so decisions concerning fisheries, climate impacts on marine systems, and organism distribution can be based on realistic model outputs.

8. Conclusions and the future

This paper outlines the importance of policy-relevant plankton taxonomic skills and some of the challenges facing the discipline. Some recent advances, however, are strengthening the role of plankton taxonomic data in policy through ensuring data quality and availability. The development of the World Register of Marine Species (WoRMS) has created a comprehensive resource of taxonomic information, which facilitates the employment of consistent and verified taxonomic nomenclature, allowing comparability of plankton indicators between datasets and regions (http://www.marinespecies.org/). The Global Biodiversity Information Facility (GBIF) acts as depository for species occurrence information, aggregating such data in an open access format linked to taxonomic records, facilitating identification of changes in species distributions (http://www.gbif.org/). Schemes such as the UK's North East Atlantic Marine Biology and Quality Control (NMBAQC) programme actively encourage the development and maintenance of taxonomic skills by promoting best practice methods and skills tests for a number of species groups, including plankton (http://www.nmbaqcs.org/). As part of the scheme, the International Phytoplankton Intercomparison (IPI; formerly BEQUALM) exercise in phytoplankton identification and enumeration serves as a standard for the quality of taxonomy and increases competitiveness for data holders (http://www.nmbaqcs.org/scheme-components/phytoplankton/). Programmes like NMBAQC and IPI add additional confidence to the use of associated datasets in policy analyses and are becoming more important as management mechanisms, such as the MSFD, require a clear quality control audit trail for contributing datasets.

Insert Table 2 here

Table 2 Recommendations to ensure the availability of plankton taxonomic data for policy and conservation, from data production to ecosystem assessment.

Challenge	Recommendation	Desired outcome
Funding insufficient to maintain existing or generate new plankton taxonomic data to underpin scientific research	Mandate from research councils to include access costs for plankton taxonomic datasets in research proposals, in line with inclusion of computer, ship, and laboratory resources	Funding stability for continuation of plankton taxonomic datasets
Loss of taxonomic skills and plankton analysis expertise	Central investment in taxonomy, taxonomic skills training, and taxonomic analysis under national capability programming	Continued development and retention of expertise to ensure availability of reliable taxonomic plankton data
Assurance of plankton taxonomic data quality	Explicit and consistent support for quality assurance schemes	Continued provision of robust and validated plankton taxonomic datasets
Lack of integration of plankton taxonomic data and associated research outputs limiting the efficacy of decision-making in addressing challenges for marine ecosystems	Better incorporation of plankton assemblage data and science into marine policy, conservation, and management	Better scientific underpinning of decision making; illustration of the value of public funding of plankton taxonomic datasets
Limited understanding of links between the environment and ecosystem services is a challenge to delivery of ecosystem-based management	Use of plankton taxonomic datasets to better understand provision of marine ecosystem services e.g. sustainable seafood or climate regulation	Enable trade-offs between environmental/ecological conservation objectives and assessment of management measure performance
Apportioning change in marine ecosystems between climatic drivers and direct anthropogenic pressures difficult	Further research on response of plankton communities to climate- and anthropogenic-driven changes	Development of meaningful and appropriate management targets and measures to inform robust ecosystem assessments
Models of marine ecosystem functioning lack plankton taxonomic data, limiting their accuracy	Explicit inclusion of plankton taxonomic data in ecosystem models	Increased accuracy of predictive models to support better policy, and management scenario analysis, and decision making
Value of plankton taxonomic datasets (especially long-term) to science and policy not well-recognised or maximised; plankton taxonomic data generation may be perceived as too expensive and/or time-consuming	Increase awareness and active promotion of scientific value of plankton taxonomic data. Possible mechanisms include journal-led mandatory citing and increased publication of taxonomic data	Raised profile of taxonomy and associated skills by giving data equal merit and recognition to that of journal articles. Use of (long-term) datasets to address emerging and increasingly complex scientific and policy challenges

Despite these advances, adequate funding to support plankton taxonomy and the development of taxonomic expertise in line with their value to science and decision making remains a key challenge to ensuring the availability of plankton data for marine policy and conservation (Table 2). Much plankton taxonomic expertise is linked to monitoring programmes receiving public funding; as a result, plankton datasets worldwide are in jeopardy due to economic difficulties despite their value for informing marine policy [29, 43]. Additionally, a disconnect exists between funding for developing taxonomic expertise and funding for research using taxonomic data, an issue not unique to marine science [12, 13, 127, 128]. Many publicly-funded plankton monitoring programmes have open data policies; consequently, research projects can use that data without contributing funding towards ongoing taxonomic analysis, resulting in a deficit towards meeting programme costs. Programmes which are partially publicly-funded therefore must make a trade-off between allowing completely free and open access to their data and requiring a funding contribution for the basic taxonomic science supporting data development. This disconnect must be addressed and a method to incorporate funding for taxonomic expertise into research projects that use taxonomic data agreed (Table 2). A possible solution could be the inclusion into research proposals of access costs for non-publicly funded datasets, just as equipment and instrumentation costs are included. Successful projects would then benefit from both knowledge of the dataset and taxonomic expertise provided by the data holders. Furthermore, central investment in plankton taxonomy and analysis under national capability programming is needed to ensure continued development and retention of taxonomic expertise (Table 2).

The relevance and ecological applicability of taxonomy and taxonomic identification skills needs to be clearly articulated and more strongly promoted by taxonomists and analysts themselves if those data are to be more widely recognised by the scientific community, especially those who depend on taxonomic data [128]. Placing higher 'value' on taxonomy may lead to a breaking down of the perceived barriers that are associated with working with taxonomists and analysts, such as high staff costs and length of time taken to obtain data and results (Table 2). Clearly, the scientific expertise (and processing time) required for taxonomic analysis of samples can be considerable and this is reflected in the cost of taxonomic analysis. In the long-term, the availability and use of molecular tools is helping to continually reduce the cost of taxonomy, but a different type of plankton data are generated [103]. In the short term, only recognition of the value of taxonomic data and its application to science and policy applications will ensure that this key area of science remains sustainable [128]. This can be achieved by promoting the lasting legacy of taxonomically-derived biological data; data can continue to be analysed and interrogated for decades to come, revealing new information about short- and long-term trends in marine ecosystem change which is invaluable to decision-making processes [29]. A recent publication by Hawkins et al. [129 and case studies therein] reiterated the value to policy of taxonomic datasets and the increase in their value over time, for instance, by using multi-decadal taxonomic datasets to support major developments in marine management and conservation.

There are a number of key challenges that must be met if the future availability of plankton taxonomic data for marine policy, conservation, and management is to be ensured (Table 2). These challenges occur at multiple points along the microscope-to-management trajectory of the application of plankton taxonomic data to marine policy and biodiversity conservation. Though the challenges are many, a diversity of recommendations for addressing them suggests that multiple, independent pathways exist for securing the role of plankton taxonomic data in decision-making. In other words, assuring the availability of plankton taxonomic data for use in marine policy and conservation does not depend on one single actor or action, but can be supported by taxonomists and analysts, research scientists, modellers, journal editors, and decision-makers.

The successful implementation of marine policy and conservation is intertwined with taxonomy (*ergo* taxonomic expertise) and analysis, which supply the data to inform decision making. Implementation of an ecosystem approach to management, built on scientific evidence, depends on sound and informative ecological data, the collection, analysis and interpretation of which is dependent on taxonomic expertise. As indicators, plankton clearly exemplify the interconnectivity of taxonomy and marine management, illustrating that because the discipline of plankton taxonomy is at risk, so is effective management of our marine ecosystem.

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