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

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21 **Abstract**

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

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

39

40 1. Introduction

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

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

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

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

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

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

115 **2. Plankton taxonomy and the policy landscape**

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

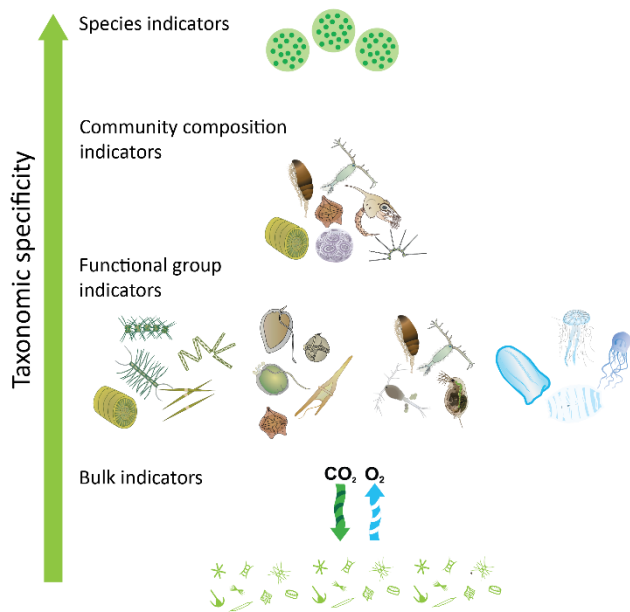
128 capture major dimensions of biodiversity change needed to inform science and policy at a global
129 scale [31].

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

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

152 **3. Taxonomic plankton indicators**

153 Much pioneering progress in creating plankton indicators has been based on species-level data [36,
154 37 and references therein]. Hardy [37] and Russell [36] recognised that the effect of the
155 environment varies within and between plankton functional groups and individual plankton species,
156 and that these data have uses wider than only scientific research. For example, Hardy developed the
157 Continuous Plankton Recorder (CPR) survey in the 1920s to improve the efficiency of the North Sea
158 herring fishery [15], while Russell constructed 'practical plankton indicators' based on taxa which
159 were large in size and easily identifiable in order to evaluate water movement and conditions [36].
160 Plankton indicator development for management, conservation, and policy has continued to evolve
161 and now encompasses multiple scales of plankton organisation from bulk indicators (such as
162 chlorophyll and phytoplankton biomass) to aggregated functional group indicators often underlain
163 by taxonomic data (such as the ratio of diatoms to dinoflagellates) to community composition and
164 single species indicators, which are wholly dependent on plankton taxonomic data (Figure 1; Table
165 1).



166

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

173

174 **Insert Figure 1 here**

175 **Insert Table 1 here**

176

178 Table 1. Legislative drivers and ecosystem assessments use different plankton indicator types; there are distinct strengths and weaknesses. A suite of
 179 complimentary plankton indicators provides the most comprehensive insight into plankton community structure, function, and productivity. Abbreviations in table:
 180 MSFD – Marine Strategy Framework Directive [3], WFD – Water Framework Directive [33], CCAMLR – Commission for the Conservation of Antarctic Living Marine
 181 Resources [38], IMOS – Integrated Marine Observing System (Australia) [39], GBRMPA – Great Barrier Reef Marine Park Authority [40], CPR – Continuous Plankton
 182 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	<ul style="list-style-type: none"> • <i>Phaeocystis</i> spp • <i>Euphausia superba</i> • <i>Pseudo-nitzschia</i> spp. • <i>Dinophysis</i> spp. • <i>Noctilua scintillans</i> 	<ul style="list-style-type: none"> • MSFD • WFD • CCAMLR • IMOS • CPR • WoA • IPCC 	<ul style="list-style-type: none"> • Species-level identification required to identify indicator species 	<ul style="list-style-type: none"> • A direct measure of biodiversity • Maximum detail of community composition • Potential to evaluate pressure-state relationship • Captures functional traits of individual species 	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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) 	<ul style="list-style-type: none"> • MSFD • WFD • IMOS • CPR • WoA • IPCC 	<ul style="list-style-type: none"> • Species level identification needed to create community data before indices can be calculated 	<ul style="list-style-type: none"> • Provide information on community structure • Captures taxonomic diversity of the plankton assemblage • Easy to calculate • Dependent on taxonomic data 	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • Diatoms • Dinoflagellates • Zooplankton grazers • Gelatinous zooplankton • Calcareous plankton 	<ul style="list-style-type: none"> • MSFD • GBRMPA • IMOS • CPR • WoA • IPCC 	<ul style="list-style-type: none"> • Coarser taxonomic identification required • Often grouped from species level data 	<ul style="list-style-type: none"> • 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 	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • Phytoplankton biomass (e.g. chlorophyll, Phytoplankton Colour Index) • Zooplankton abundance 	<ul style="list-style-type: none"> • MSFD • WFD • GBRMPA • IMOS • CPR • WoA • IPCC 	<ul style="list-style-type: none"> • Taxonomy not needed to inform indicators • Taxonomy required to interpret changes in bulk indicators 	<ul style="list-style-type: none"> • Provide information on plankton production • May have good spatial coverage (e.g. satellites) • Cost efficient to construct 	<ul style="list-style-type: none"> • Provide limited information on biodiversity and community structure • Unclear relationship between plankton diversity and functioning

183

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

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

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

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

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

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

262 Although plankton themselves are rarely the subject of conservation endeavours, plankton
263 taxonomic data can inform conservation efforts through a 'surveillance' role, aiding in the
264 interpretation of changes observed in higher trophic levels, and thus the management of other non-
265 plankton ecosystem components [21]. For example, North Sea cod biomass has been linked, not only
266 to fishing pressure, but also to the abundance of total *Calanus* copepods as well as the relative

267 proportion of *C. finmarchicus* to *C. helgolandicus* which make up a key component of the diet of
268 larval cod [45]. Because plankton play a fundamental role in the food web of marine megafauna,
269 plankton indicators can be used to inform management of species with high conservation value such
270 as basking sharks [58], marine mammals [59], seabirds [60, 61], and sea turtles [62]. These
271 relationships are taxon-specific, with, for example, kittiwakes and puffins preying on pteropods and
272 euphausiids, respectively, during the non-breeding season [60, 61 and references therein] while
273 basking shark feeding events correspond to aggregations of *Calanus* copepods [58].

274 The fragmentation and loss of habitat following human activities threaten the persistence of species
275 and can modify their dispersal [63, 64]. Marine Protected Areas (MPAs) are increasingly recognised
276 as a management tool capable of reducing the risk of species extinctions by limiting habitat loss [65,
277 66]. The placement and size of MPAs is a particularly important consideration if they are to be an
278 effective conservation tool at landscape or regional scales [67]. It is still under debate how dispersal
279 processes affect planktonic communities, but this should be better investigated as many intertidal
280 organisms have a meroplanktonic larval phase [68]. Research has shown that connectivity through
281 larval dispersal, in this case related to meroplankton species, is an essential feature of effective MPA
282 networks . As such, an in depth understanding of when, where and which species occur in the
283 meroplankton is required to underpin decision-making in MPA design and placement. The use of
284 plankton community indicators which include a meroplankton component (e.g. life-form index; see
285 above) coupled with dispersal simulations may provide sufficient information to support the
286 development of MPAs with generic targets, whereas raw species data may be required to underpin
287 species-specific conservation objectives.

288 **5. The role of plankton taxonomic data in understanding and providing ecosystem services and** 289 **societal goods and benefits**

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

300 Plankton biodiversity supports critical ecosystem services such as the production of oxygen, the
301 removal of atmospheric carbon, and the provision of food for commercial fish stocks, all of which are
302 under pressure due to climate change [75, 76]. For example, the size structure and species
303 composition of phytoplankton communities is related to oxygen production and the removal of
304 atmospheric carbon, ecosystem services which are likely to alter due to climate change [77].
305 Similarly, warming seas have caused a transition of Northeast Atlantic plankton communities from a
306 community dominated by cold-water organisms with large body sizes to a more biodiverse
307 community characterised by smaller warm-water organisms, coinciding with decreased carbon
308 export [78]. The contribution to ecosystem services therefore varies between plankton species,

309 making an understanding of plankton diversity integral to the understanding of current and future
310 provision of ecosystem services [79, 80]. A bulk-indicator approach to this work would have revealed
311 only simplistic long-term variations in copepods as a group, masking the underlying relative spatial
312 change of individual temperature-dependent species, and limiting applicability as a climate change
313 indicator useful for management.

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

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

353 organism *Gambierdiscus* spp. is critical to implementing a management action plan in the areas
354 affected [91].

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

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

371

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

390

391 Advancements in non-genetic analysis techniques now allow rapid assessment of some aspects of
392 plankton communities. Fluorometry can provide an estimate of chlorophyll-a, while flow cytometry
393 can be used to distinguish phytoplankton based on their size and pigments and recent advances in
394 imaging flow systems now offer the ability to capture a larger size spectrum of phytoplankton
395 organisms rapidly. The ability to use these approaches to identify species remains, however, limited
396 [101-103]. Semi-automated imaging systems such as FlowCam and ZooScan can rapidly photograph

397 plankton organisms, automatically sorting them into coarsely resolved groups, though these are
398 largely based on morphology rather than taxonomy or functional groupings [104, 105]. Although
399 these techniques quickly produce a large quantity of data, taxonomic expertise is required to train
400 the system to recognize and sort individuals [106]. Few taxa can automatically be identified to genus
401 or species level, but the rapid analysis of plankton samples to a coarse level can complement
402 traditional taxonomic and genetic data, particularly over large spatial scales[103].

403

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

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

417 Plankton taxonomy is also valuable for understanding emerging management issues in marine
418 ecosystems. For example, ocean acidification is expected to impact the plankton; calcareous taxa,
419 which form calcite shells or exoskeletons, in particular, are expected to be negatively affected [111,
420 112]. Coccolithophores, the most globally-important calcareous phytoplankton group, show a
421 varying response to acidic conditions in laboratory experiments [113, 114], even between different
422 strains of a single species [115]. *In situ* data, however, indicate an increase in coccolithophore
423 abundance during the past fifty years, likely linked to other climate-related drivers such as increased
424 SST and rising atmospheric CO₂ [116, 117]. Whether phytoplankton respond to decreasing pH
425 therefore remains unclear, with individual species predicted to respond differently to future ocean
426 acidification conditions, making it unclear as to how plankton community composition will change in
427 the future [80]. Knowledge of such inter-specific variations is crucial to our understanding of the
428 future consequences of ocean acidification on marine food webs and carbon cycling, and our
429 resultant ability to account for future conditions when setting management and conservation
430 targets.

431 Expertise in plankton taxonomy and plankton taxonomic data support increasingly important
432 plankton fisheries and enable emerging economic opportunities. For example, approximately
433 225,000 tonnes of Antarctic krill (*Euphausia superba*) were harvested in 2015 for use in aquaculture,
434 pet food, and dietary supplements for humans [118]. The global jellyfish fishery is also growing, with
435 tens of species now commercially harvested for food, cosmetic ingredients, biomedical research, and
436 dietary supplements [119]. A Norwegian *Calanus finmarchicus* fishery, also for the production of
437 dietary supplements, is now in its infancy and a similar fishery for Iceland is under consideration
438 [120]. These commercial plankton fisheries are at the very base of the marine foodweb and their
439 sustainability is unclear due to uncertainty around current growth, mortality, and biomass estimates;

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

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

469

470 **8. Conclusions and the future**

471 This paper outlines the importance of policy-relevant plankton taxonomic skills and some of the
472 challenges facing the discipline. Some recent advances, however, are strengthening the role of
473 plankton taxonomic data in policy through ensuring data quality and availability. The development
474 of the World Register of Marine Species (WoRMS) has created a comprehensive resource of
475 taxonomic information, which facilitates the employment of consistent and verified taxonomic
476 nomenclature, allowing comparability of plankton indicators between datasets and regions
477 (<http://www.marinespecies.org/>). The Global Biodiversity Information Facility (GBIF) acts as
478 depository for species occurrence information, aggregating such data in an open access format
479 linked to taxonomic records, facilitating identification of changes in species distributions
480 (<http://www.gbif.org/>). Schemes such as the UK's North East Atlantic Marine Biology and Quality
481 Control (NMBAQC) programme actively encourage the development and maintenance of taxonomic

482 skills by promoting best practice methods and skills tests for a number of species groups, including
 483 plankton (<http://www.nmbaqcs.org/>). As part of the scheme, the International Phytoplankton
 484 Intercomparison (IPI; formerly BEQUALM) exercise in phytoplankton identification and enumeration
 485 serves as a standard for the quality of taxonomy and increases competitiveness for data holders
 486 (<http://www.nmbaqcs.org/scheme-components/phytoplankton/>). Programmes like NMBAQC and
 487 IPI add additional confidence to the use of associated datasets in policy analyses and are becoming
 488 more important as management mechanisms, such as the MSFD, require a clear quality control audit
 489 trail for contributing datasets.

490 **Insert Table 2 here**

491 Table 2 Recommendations to ensure the availability of plankton taxonomic data for policy and conservation,
 492 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

493

494

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

515

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

534 There are a number of key challenges that must be met if the future availability of plankton
535 taxonomic data for marine policy, conservation, and management is to be ensured (Table 2). These

536 challenges occur at multiple points along the microscope-to-management trajectory of the
537 application of plankton taxonomic data to marine policy and biodiversity conservation. Though the
538 challenges are many, a diversity of recommendations for addressing them suggests that multiple,
539 independent pathways exist for securing the role of plankton taxonomic data in decision-making. In
540 other words, assuring the availability of plankton taxonomic data for use in marine policy and
541 conservation does not depend on one single actor or action, but can be supported by taxonomists
542 and analysts, research scientists, modellers, journal editors, and decision-makers.

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

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