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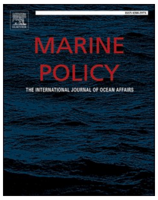

Global marine conservation priorities for sustaining marine productivity, preserving biodiversity and addressing climate change

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ABSTRACT

Marine primary productivity is a critical driver of functioning marine ecosystems, providing a foundation for biological diversity and associated economic productivity, and a key component of the oceanic carbon sink. However, it is largely under-represented within the global marine protected area estate and has been widely ignored in global priority assessments for marine conservation. Using global high-resolution data on marine primary productivity and human cumulative impact to marine systems, more than 18.6 million km^2 of high productivity-low impact areas in the global ocean were identified. These areas occur across all ocean basins and represent the vast majority of marine provinces and ecoregions. Over 80% of these highly productive waters with low levels of human impact lies within national jurisdictions and yet only 11% of the overall identified area is currently safeguarded within designated marine protected areas or sustainable management initiatives, leaving more than 16.5 million km^2 of high productivity-low impact areas without those forms of formal protection. The multifaceted contribution of these areas to preserve biodiversity, support human welfare and help mitigating climate change suggest they are an essential, but currently overlooked, conservation priority for consideration in both global nature conservation and human wellbeing policy fora.

1. Introduction

Highly-productive functioning marine ecosystems are essential for the interrelated global conservation and human sustainability agendas [33,55]. The ecosystem services that the oceans provide, including food security and climate regulation, are dependent on the very structure, composition, and functions of those natural marine systems, which are mediated through productivity across the entire marine trophic web [11,43]. Conservation from the species to the ecosystem-level is based on the premise of safeguarding functional systems that enable key ecological processes, maintain the inter-species relationships and those with their environment [17]. Moreover, the role of functioning ecosystems has been increasingly recognized as an essential prerequisite for the existence of biological diversity [4], and as key to the solutions for climate change and the Sustainable Development Goals [38,46]. Yet, global biodiversity conservation priority setting has to date focused on either the organism level or on species-rich ecosystems, prioritizing resources to preserve the greatest number of species possible in the face of global threats [51].

Marine productivity is a basal condition for diverse and functioning marine ecosystems [43,60]. Marine primary productivity provides energy to sustain first order consumers, whose biomass influences the distribution and abundance of marine megafauna at the top of the web. High productivity areas in the ocean are characterized by large concentrations of primary producers sustaining aggregations of higher trophic levels [62]. Around 90% of global fish catches occurs in the highly productive waters of continental shelves [41], and the major eastern boundary upwelling systems support large multi-species fish stocks, representing around 23% of the global marine catches [12,20]. Some highly productive marine areas also sustain large aggregations of

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marine megafauna, like seabirds and marine mammals, who benefit from the predictability of oceanic fronts and mid latitude shelf seas with seasonal high productivity [14,45]. For instance, the Patagonian shelf, one of the most productive and richest temperate marine ecosystems in the world, holds extensive foraging and feeding grounds for large populations of resident and visiting seabirds and marine mammals [15,2], and at high latitudes, the productivity blooms of the warmer months support summer feeding grounds for most populations of baleen whales in the area [1].

The global oceans play a critical role on climate change mitigation, as they fix about 30% of anthropogenic CO_2 emissions globally [26], with phytoplankton being responsible for about 40% of the total global carbon fixation [19]. In turn, primary productivity supports large aggregations of krill and marine megafauna that contribute further to CO_2 sequestration and fixation [9]. For instance, the high primary productivity of continental shelfs, and upwelling waters sustain important aggregations of marine megafauna (including cetaceans, pinnipeds, seabirds, sharks, and marine turtles) [2,45], which further enhance primary productivity through nutrient enrichment and ecological regulation [39,42]. Marine megafauna also contributes to carbon sequestration through in-tissue storage and by carbon accumulation in the marine soil as carcasses sink [47].

Safeguarding the marine environment has entailed a range of different, and sometimes complementary, approaches from strict "no-take" Marine Protected Areas (MPAs), to MPAs where some resource extraction is allowed, to Other Effective Area-based Conservation Measures (OECMs) that can result in positive outcomes for nature [25]. The choice of a specific conservation or management approach depends on contextual elements such as the intended conservation or management outcome, the resource ownership rights and governance in the specific area, and the effectiveness of these approaches in conserving and restoring Nature is largely context-dependent as well [25].

Here it is argued that *biological marine productivity* should be an important dimension for global marine conservation priorities given its importance to ecosystem functioning. Using global data, the distribution of highly productive waters, MPAs, and OECMs were mapped to investigate the degree to which they are formally safeguarded. Then, to explore the best opportunities for additional protection of productive marine areas, global data on cumulative human impacts in the ocean were used to determine the extent of highly productive marine areas that contain relatively low human impact as candidate conservation priorities. The rationale to identify areas of high productivity and low impact is to select areas that retain both the enabling conditions for marine biodiversity and relatively higher ecological integrity as clear candidates for protection. These areas were evaluated in the contexts of ecological representativeness, national versus international jurisdiction and extent of current protection. Finally, the global patterns of productive waters in a changing climate were explored by visualizing the potential distribution of productive waters under a high-emissions scenario.

2. Materials and methods

2.1. Areas of highest marine productivity and lowest anthropogenic impact

The global distribution of marine primary productivity was investigated using satellite-based data on chlorophyll-a concentration (hereafter chla), widely used as a proxy for marine primary productivity (e.g., [49]). To explore the global patterns of chla, overall and seasonal means for the period 2002–2019 from MODIS-Aqua data were used at the highest resolution available at the global scale (4 km). Then, "highly productive areas" were defined as those with mean chla values within the top quartile of global values. Based on preliminary analyses, this threshold enabled capturing most known high productivity areas without notable omissions in the open ocean. Then, a unique non-null value was assigned to a grid cell if its value was within the top quartile and a null value otherwise, obtaining a 4 km resolution single valued layer representing areas within the top quartile of marine productivity (values above the 75th percentile, PQ4 hereafter).

Next, the extent of human impact to marine systems was investigated using a publicly available global marine cumulative impact score, I_c, based on a combination of 19 anthropogenic stressors for the year 2013, including ocean-based, land-based, fishing, and climate change stressors [28]. The I_c is the average of all combinations of stressor-habitat present in a pixel, with each combination being the stressor intensity weighted by a habitat-specific vulnerability factor [28,29]. These are the most updated, comprehensive, and highest resolution (~1 km) global data on anthropogenic stressors and cumulative impact for the global ocean publicly available, and have been used in numerous studies (e.g., [35, 13]). Following the choice of considering the top quartile of productivity to identify highly productive areas, areas of low level of cumulative human impact were defined as those grid cells with I_c values within the bottom quartile of the global values (values below the 25th percentile). As before, a 1 km resolution single valued layer representing areas within the bottom quartile of cumulative impact (I_cQ1 hereafter) was obtained. This layer was then reprojected from its Mollweide native projection to geographical coordinates (latitude/longitude) to match all other datasets used here, using a nearest neighbor approach.

To identify places with high levels of productivity and low levels of human impact, the overlap between PQ4 and I_cQ1 was considered. To preserve the finer spatial variability native of the impact data, PQ4 was downscaled to the resolution of I_cQ1. Since PQ4 is a single valued layer, each 4 km cell is divided into four 1 km cells, each one with the same value as the original 4 km cell. Then, grid cells present in both PQ4 and I_cQ1 were selected, obtaining a 1 km resolution layer representing highly productive areas with low levels of anthropogenic cumulative impact (PQ4/I_cQ1 hereafter, Figure A.1).

2.2. Jurisdiction, ecological representativeness and extent of protection

The extent of high productivity-low impact areas (PQ4/I_cQ1) within national and international waters was investigated and the percentage of each EEZ covered by these areas was assessed using exclusive economic zones (EEZs) data [21]. First, a continuous 200 nautical miles boundary layer was created, separating national waters from areas beyond national jurisdiction (ABNJ). This boundary was used to mask all PQ4/I_cQ1 grid cells with centers within and beyond this limit, to obtain high productivity-low impact areas of national and international jurisdiction, respectively. To assess PQ4/I_cQ1 coverage of each EEZ, all joint regime areas were excluded to avoid overestimating coverage. Of the 157 coastal countries, 31 have one or more overseas territories, leaving 244 EEZs. Then, for each EEZ and for the Antarctic 200NM zone beyond the coastline, all PQ4/I_cQ1 grid cells with centers lying outside its boundaries were masked.

To evaluate the ecological representativeness of PQ4/I_cQ1, a biogeographic classification that divides the ocean into non-overlapping provinces (depth >200 m, referred to as Pelagic Provinces of the World or PPOWs) and ecoregions (depth <200 m, referred to as Marine Ecoregions of the World or MEOWs) was used [50,52]. PPOWs are large pelagic areas with stable large-scale ocean features, hosting species assemblages with a common evolutionary history, while MEOWs are smaller scale ecologically cohesive units, with homogeneous species composition [50,52]. There are 37 PPOWs nested into 4 broad realms, and 232 MEOWs nested into 62 larger scale units. As before, the degree of coverage of each spatial unit was assessed by masking all PQ4/I_cQ1 grid cells beyond its borders.

The current protection of the global ocean was explored using MPAs and other effective area-based conservation measures (OECMs) for which data are available. For MPAs, the World Database on Protected Areas (WDPA)[58] was used, focusing on areas with existing polygon data, excluding MPAs with no available boundary [57]. To include only recognized MPAs committed to long-term conservation, only "Designated" or "Established" areas were included, while UNESCO MAB Reserves were excluded, since they often include unprotected buffer and transition zones [57,58]. This resulted in a total of 16,274 polygons of designated or established MPAs, which were finally dissolved into a flat layer to avoid double counting of protection [57]. For OECMs, the WDPA and the global dataset on vulnerable marine ecosystems, VMEs (https://www.fao.org/in-action/vulnerable-marine-ecosystems/background/vme-tools/en/) were used, where areas for which closures exist were considered. Both OECMs and VMEs layers were dissolved into flat layers, and areas from the VMEs database which were also included as OECM were considered only once as OECMs. These layers were used to investigate the current protection of PQ4/I_cQ1 areas by masking all pixels beyond the boundaries of MPAs, OECMs and VMEs.

2.3. Species context for prioritization schemes

Next, to provide some context to the spatial extent of this analysis to illustrate possible pathways for prioritization schemes, some basic spatial requirements of marine megafauna were incorporated to the analysis, as marine megafauna is generally dependent on high productivity and important for carbon fixation and storage. Most productivity-dependent marine megafauna (e.g., cetaceans, pinnipeds, seabirds, and sharks), have daily movements on the order of tens of kilometers (e.g., [8,16,5,30]), therefore suggesting minimum connectivity of that order and minimal focal areas size in the order of thousands of square kilometers. This combination of area size and connectivity is particularly relevant for marine conservation frameworks since, currently, less than 3% of MPAs (also less than 3% of "no-take" MPAs), and less than 9% of OECMs have areas of more than 10,000 km^2.

For suitable internal connectivity, grid cells and clusters of grid cells separated by less than 50 km (an intermediate connectivity threshold for highly mobile species) were grouped. For suitable minimal area size, areas deemed "too small" (groups of grid cells with area <50 km^2, which represented less than 1.4% of the overall area), were first discarded and then each remaining group was bounded into a minimal bounding geometry (Figure A.2). A minimum area threshold of 10,000 km^2 was then applied to these geometries, considering focal feeding and breeding grounds for the proxy marine megafauna [45,6]. These resulting polygons represented areas that ensure suitable connectivity and area requirements to enable populations of marine megafauna.

2.4. High productivity areas and climate change

Climate change and global warming can have different effects on marine primary productivity, which in turn can have consequences on the capacity of the ocean to capture atmospheric CO_2 (e.g., [3]). To assess changes in the global distribution of highly productive waters under the influence of climate change, the global patterns of surface chlorophyll concentration were investigated using an ensemble of climate models from the fifth phase of the Coupled Model Intercomparison Project (CMIP5) [53]. Changes in chl were investigated under three different scenarios of climate change describing different pathways of greenhouse gases emissions and other global changes. These include a very strict mitigation scenario (RCP2.6), an intermediate scenario (RCP4.5), and a very high emissions scenario (RCP8.5) [32]. All models for which monthly means of surface chlorophyll concentration were available were used, for the historical and the high-emissions RCP8.5 scenarios (Table A.1). Following previous studies (e.g. [7]), 20 years of historical data (1980–1999) to 20 years of projected future data (2080–2099) were compared. For each model, the mean over each 20-year period was first computed and then re-gridded to a 1°x1° grid to build a multi-model ensemble for each scenario. The multi-model ensemble median was used to describe the global pattern of surface chlorophyll concentration for both scenarios, and as before, areas of high productivity were identified as those areas with surface chlorophyll concentration values above the 75th percentile of global values (PQ4).

3. Results

3.1. High productivity-low impact areas

Marine primary productivity is relatively constant throughout the year in low latitude oceans and has a strong seasonality in mid and high latitudes. Since there is a strong correlation between the overall and seasonal means of chla ($r \geq 0.92$ for all seasons), and the overall mean captures the high productivity areas of mid and high latitudes (Figure A.3), all analyses are introduced using the overall mean of chla.

The distribution of mean chla values was strongly right skewed, with a maximum value of 96.15 mg m^{-3} and more than 90% of values < 1 mg m^{-3}. High-productivity areas, or PQ4, had chla values within the top quartile (chla >0.38 mg m^{-3}). PQ4 included most continental shelf waters, the major eastern upwelling systems, and large areas over the southwest Atlantic, the Southern Ocean, and north of 55°N (Figure A.1). Most of these areas were not covered by the current global MPA estate, OECMs, and VMEs closures. Further, only 30% of chla grid cells within these safeguarded areas is considered as highly productive waters by this analysis (Figure A.4).

The global values of I_c range from 0 to 15.41 and have a 25th percentile value of 2.73. Therefore, I_cQ1 was defined as areas with I_c values between 0 and 2.73. These areas include large extensions in the central Pacific, polar and subpolar waters, the north coast of Australia, the southeastern and northwestern coasts of South America, and other low impact areas in narrower stretches of the coasts of Africa (Figure A.1).

The overlap of PQ4 and I_cQ1 (PQ4/I_cQ1) revealed that there are over 18.6 million km^2 of high productivity-low impact areas in the global ocean. More than half of these areas were small (<10 km^2). The largest areas (>100,000 km^2) occurred in the Southern Ocean, Arctic waters north of 55°N, and along the coasts of Peru, west Canada, Argentina, Uruguay and southern Brazil, the northern coast of Australia, and the southern coast of South Island in New Zealand (Fig. 1). Relatively large areas (>10,000 km^2 and <100,000 km^2) were found along the coasts the United States, Chile, northern Brazil, the Malvinas/Falkland Islands, western South Africa, Mozambique, Singapore, Indonesia, and western and southern Australia (Fig. 1). There were some relatively large areas near the coasts of Ecuador, Gabon, Guinea, and Guinea Bissau.

When seasonal means of PQ4 were used, major differences were found in high latitudes (Figure A.6). Yet, since the overall mean of chla at high latitudes is largely explained by the productivity of the warmer months (Figure A.2), the great majority of PQ4/I_cQ1 waters in high latitudes appearing in seasonal means of the warmer months, also occurred when the overall mean of chla is used (Figure A.5). Nevertheless, some highly productive areas with high variability and important for biodiversity may be missed by the overall mean (e.g., mesoscale fronts) and should be addressed with a more focused approach.

3.2. Jurisdiction, ecological representativeness, and area protection

Over 80% of PQ4/I_cQ1 occurred within EEZs (>15.1 million km^2), leaving about 3.5 million km^2 in ABNJ. The EEZs of 164 countries included some grid cells of PQ4/I_cQ1, but more than 78% of PQ4/I_cQ1 was found within the EEZs of just 10 countries (Table 1). For most EEZs, PQ4/I_cQ1 covered just < 10% of their spatial extent, although 22 countries had > 20% of their waters covered (Table A.2). In addition, more than 100 EEZs with PQ4/I_cQ1 waters within, have less than 10% of these highly productive waters protected under the formal protection of recognized MPAs (Table A.2).

PQ4/I_cQ1 area was similar between pelagic and shelf waters (~9.9 and ~8.7 million km^2 respectively). However, since the extent of pelagic waters is much larger than the extent of shelf waters (>331 million km^2 vs ~31 million km^2), PQ4/I_cQ1 was much more representative of shelf

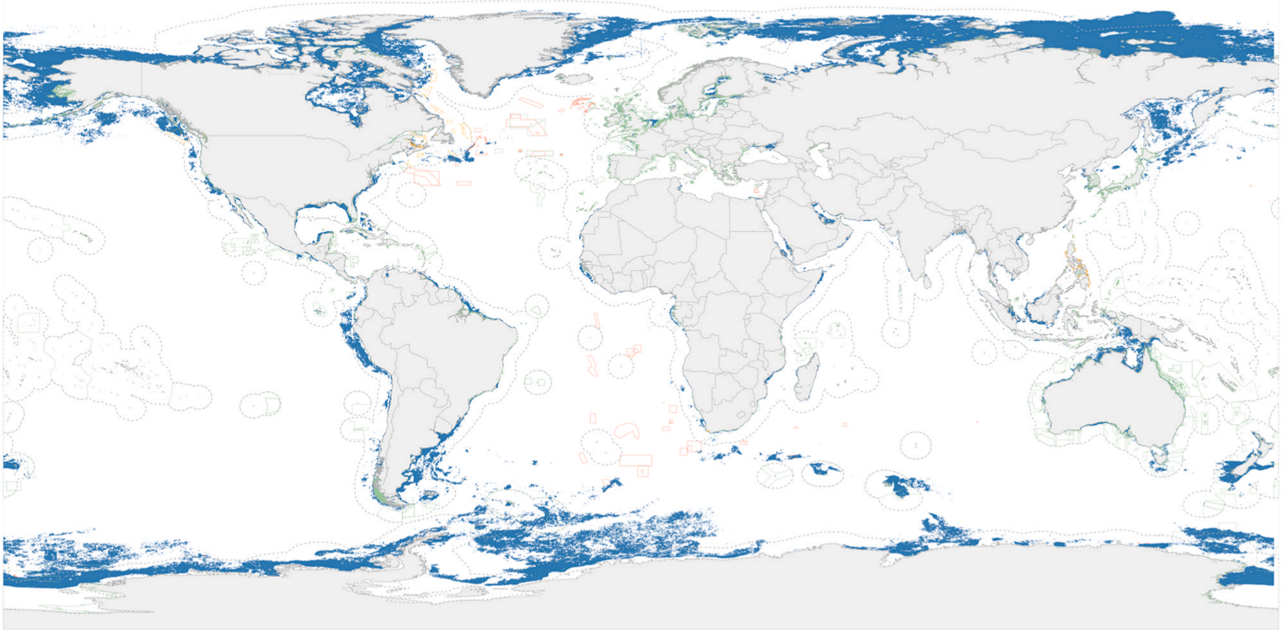

Fig. 1. Global distribution of high productivity-low impact areas (PQ4/I_cQ1) as a result of the overlap between high productivity areas (PQ4) and low anthropogenic cumulative impact (I_cQ1) areas. Dashed gray lines correspond to the outer limits of exclusive economic zones (EEZs), green lines correspond to marine protected areas (MPAs), with status 'Designated' or 'Established', orange lines correspond to other effective area-based conservation measures boundaries (World Database on Marine Protected Areas, July 2020), and red lines correspond to closed areas from the Vulnerable Marine Ecosystems database (FAO/VME Database, 2022).

Table 1

List of top 10 exclusive economic zones (EEZs) with largest coverage by high productivity-low impact areas.

EEZ	EEZ area (km^2)	PQ4/IcQ1 area in EEZ (km^2)	Percentage of EEZ covered by PQ4/IcQ1 (%)	Percentage of PQ4/IcQ1 protected* within EEZ (%)
Russia	7734,809	3618,370	46.8	3.9
Antarctica**	9618,978	2863,498	29.8	23.7
Canada	5740,544	1897,859	33.1	6.6
Alaska	3682,912	1156,395	31.4	1.5
Australia	6871,622	628,256.2	9.1	32.0
Greenland	2268,623	552,205.2	24.3	0.6
New Zealand	4104,551	452,723.6	11	5.9
Peru	854,698	399,066.9	46.7	0.3
Argentina	1072,053	386,685.4	36.1	2.1
United States	2451,023	350,975.6	14.3	5.9

* With formal protection of recognized MPAs.

** Antarctica 200NM zone beyond its coastline.

waters (~3% vs ~28%). Within pelagic waters, PQ4/I_cQ1 was distributed across all realms, although to a very different extent (Northern Cold Water 13.7%, Southern Cold Water 7.4%, and Indo-Pacific Warm Water and Atlantic Warm water <0.5%). PQ4/I_cQ1 was distributed across all but 4 PPOWs (Guinea Current, Leeuwin Current, Mediterranean, and North Central Atlantic Gyre). Most PPOWs had < 1% of their area covered by PQ4/I_cQ1 cells, and only 7 provinces had coverage > 5% (Arctic, Antarctic, Malvinas Current, Subarctic Pacific, Humboldt Current, California Current, and Gulf Stream; Fig. 2).

Almost 60% of MEOWs had > 5% of their area covered by PQ4/I_cQ1 cells, 80 ecoregions had coverage > 20%, and the top 10 covered MEOWs had coverage > 80% (Table A.3). Most ecoregions with high percent of coverage were in mid and high latitudes, although they were also found in the northern coasts of Australia, Brazil, Peru, and the Red Sea (Fig. 2).

In terms of legal protection, only 2.1 million km^2 of PQ4/I_cQ1 were located within currently recognized MPAs (<125,000 km^2 within no-take MPAs), leaving > 16.5 million km^2 of these waters without the formal protection status of an MPA. Large protected PQ4/I_cQ1 areas were found in the Ross Sea in Antarctica and the Arctic Ocean. Over 90% of protected PQ4/I_cQ1 waters were within EEZs, where the extent of protection varies greatly among countries (Table A.2). While some countries have a considerable proportion of PQ4/I_cQ1 waters already protected, others have their PQ4/I_cQ1 waters broadly unprotected, offering new opportunities for marine conservation. Regarding other forms of protection, there are roughly 39,130 km^2 of PQ4/I_cQ1 waters within OECMs (mostly within the Offshore Pacific Seamounts And Vents Closure in the northeast Pacific), and about 23,500 km^2 within VMEs closures. It should be mentioned that unprotected PQ4/I_cQ1 areas might have been overestimated in this analysis, as MPAs or OECMs for which there is no georeferenced shape available were not included. However, the WDPA contains < 10% of point data [57], and more than half of these areas have reported areas of < 1000 km^2 [58]. In addition, OECMs points data are located around Philippines where there is no considerable presence of PQ4/I_cQ1, so the overestimation of unprotected PQ4/I_cQ1 waters is most likely of no major significance.

3.3. High productivity-low impact areas relevant for marine megafauna

There were 104 areas with size and internal connectivity suitable for the spatial needs of the highly mobile species used here as an example (Fig. 3). These areas ranged from ~10,000 km^2 to > 10 million km^2. The largest areas were located in high and mid latitudes (e.g., polar and subpolar waters, the Patagonian shelf, and south of New Zealand), but relatively large areas were also found in lower latitudes (e.g., north of Australia and northern waters of the Humboldt current). Many of these areas of > 10,000 km^2 group multiple smaller MPAs that are within the dispersal ranges of megafauna species. For example, in the Patagonian sea, a large and connected area encompasses the MPAs Península Valdés, Punta Tombo, and Patagonia Austral, which are separated from one another by distances greater than 100 km, and protect habitats for southern right whales, southern elephant seals, and Magellanic penguins among other highly dispersive species.

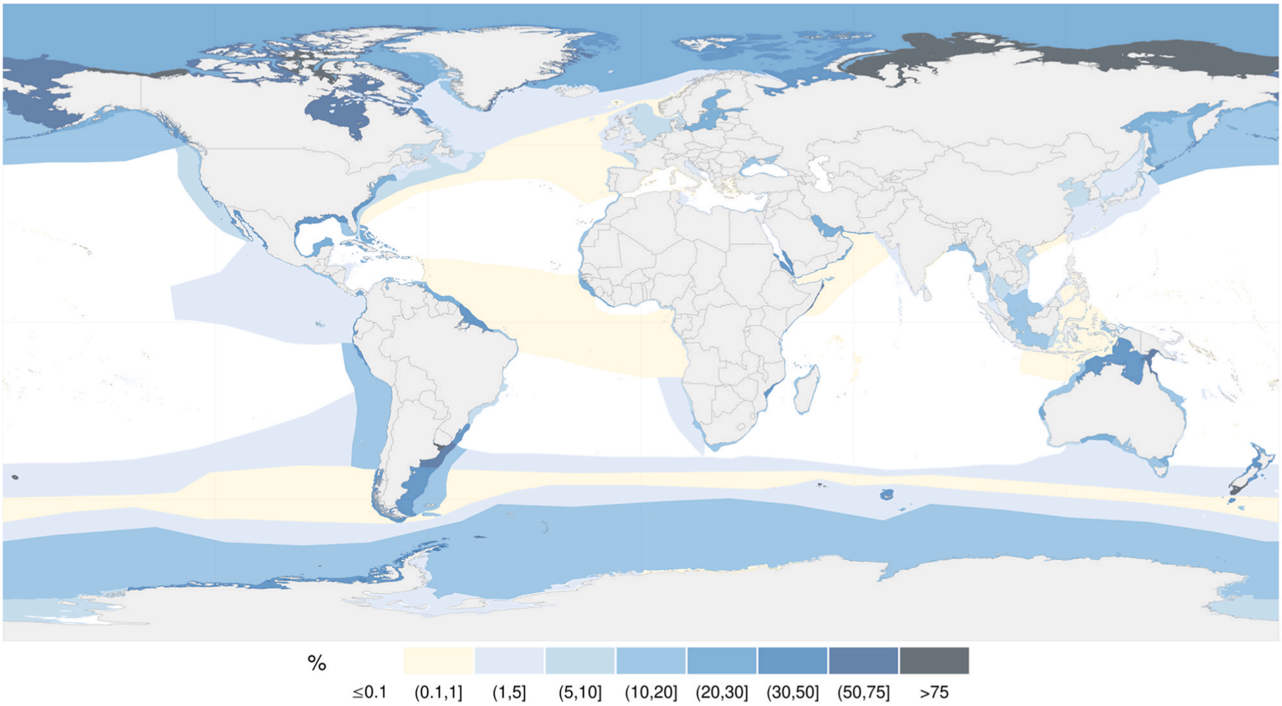

Fig. 2. Pelagic Provinces of the World (PPOWs) and Marine Ecoregions of the World (MEOWs) [50,52] colored according to the percentage of the area that was classified as high productivity-low impact area in this study.

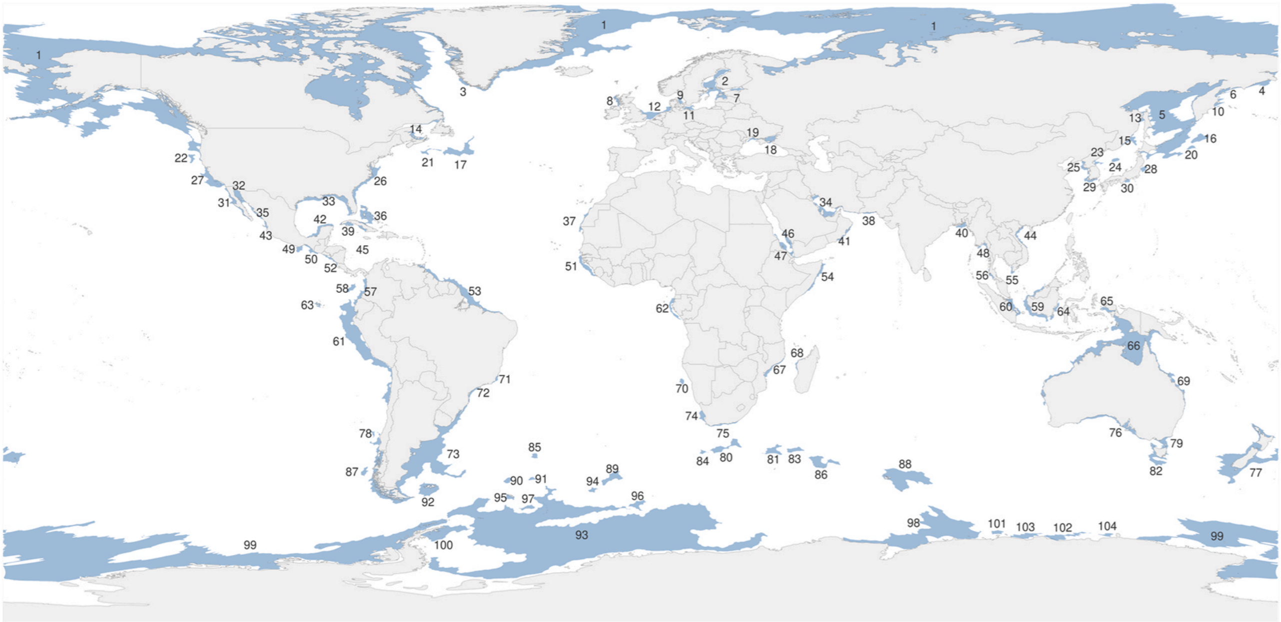

Fig. 3. Minimal bounding geometries enclosing clusters of high productivity-low impact grid cells separated by less than 50 km, an intermediate minimum connectivity requirement of highly mobile species of marine megafauna. A minimal area threshold of 10,000 km^2 was applied, consistent with focal feeding and breeding grounds areas of these taxa. Numbers are presented for the sake of identification and do not represent any particular order.

3.4. Effects of climate change on high productivity patterns

The global spatial pattern of PQ4 under the RCP2.6, RCP4.5, and RCP8.5 climate change scenarios suggested that the extent of areas of high productivity will vary in the future. The different scenarios showed different patterns of change, with higher changes occurring for higher emissions scenarios (Figure A.). In general, common changes to all scenarios showed smaller variation in PQ4 at low latitudes and larger variation at higher latitudes, with increases in the southern hemisphere and decreases in the northern hemisphere (Fig. 4). Model ensembles have a 1° x 1° resolution, roughly 100 km by 100 km near the Equator. This low resolution implies that most coastal areas are not covered by these grids, impeding drawing specific conclusions for such coastal areas.

4. Discussion

Through straightforward analyses of global and available data, over

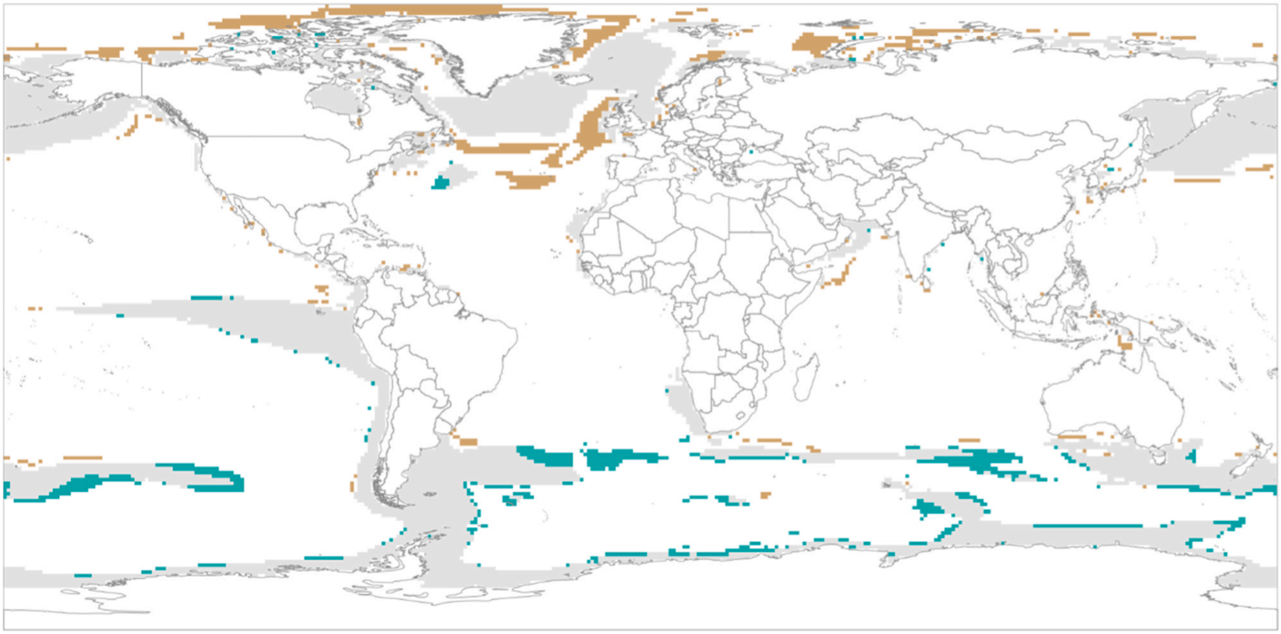

Fig. 4. Global pattern of changes in PQ4 common to all RCP scenarios: green shows expansion in the extent of PQ4 areas, gray shows no changes in the extent of PQ4 areas, and brown shows contractions in the extent of PQ4 area (areas that will no longer have productivity values in the highest quartile).

18.6 million km^2 of high productivity marine areas with low levels of anthropogenic impact were identified, distributed across the global oceans, associated with both pelagic and continental shelf systems. Only 2.16 million km^2 of these waters were under the legal protection of MPAs or guided management such as OECMs and VMEs. Most of these areas, which are essential for biodiversity, human wellbeing and climate change mitigation, occur in waters of national jurisdiction, where clear conservation and sustainable management schemes can relatively readily be implemented.

Despite the current understanding of the importance of marine productivity for the wellbeing of our planet, there has not been yet a comprehensive analysis linking marine productivity to conservation. This work identifies highly productive and relative low impact areas, and highlights those with current low conservation attention and broad ecological representativeness. This study also explores candidate areas that feature significant internal connectivity as examples of potential conservation priorities for a wide range of marine taxa and overall ecological functionality, sustaining system-wide patterns and processes needed to enable resilient systems [18]. Several studies have shown that the global MPA state is not yet efficient enough to protect global biodiversity (e.g., [36]), and not representative enough in terms of bioregions and coastal versus pelagic realms [23,34]. However, these studies also highlight that good opportunities exist to improve the global ocean protection through the identification of key areas for marine biodiversity (e.g., breeding and feeding grounds) and better management of human activities (e.g., marine traffic and fishing activity). Therefore, the creation of new MPAs should be well informed and targeted, and this study provides one aspect of critical areas for marine megafauna that should be considered. For example, the resulting patterns presented here could be instructive to address the current need to scale up marine protection beyond the CBD Commitments for 2020 [40]. More specifically, as the global marine community addresses the need to jump from the current 10% protection goal for 2020 to tripling this percentage for 2030, the need to bring together complementary and ambitious approaches for strict protection and effective management is more evident than ever [37,44,61]. While we focused on areas of low relative impact as candidates for protection given their relatively high ecological integrity, this type of analysis can also help identify areas of high productivity and medium impact for restoration initiatives that can rebuild the enabling conditions for marine life to thrive. We caveat the selection of highly degraded areas for conservation given the relatively smaller likelihood of success in re-building the basic enabling conditions for biodiversity wellbeing once ecosystem-level properties (e.g. composition, structure, function) are degraded. Although the treatment of areas for marine megafaunal movement and dispersal is surely imperfect, the rationale here was to provide a new framework to promote large networks of MPAs that ensure areas suitable for marine megafauna in terms of size and connectivity, especially in a context where the vast majority of MPAs have areas of less than 100 km^2. This analysis allows to visualize the relative national contributions to broader areas of international and global importance, ensuring connectivity between coastal and pelagic waters featuring high levels of productivity [23,24]. Lastly, the global patterns of high-productivity in the context of climate change highlight the potential of a future where global collaboration results in the protection of increasingly productive international waters, such as those in the southern oceans. More generally, climate change scenarios highlight the need for dynamic approaches in space and time, that can follow changes in key areas for biodiversity (e.g., seasonally), and to promote the safeguard of large and connected areas that can anticipate and accommodate such variations [54].

As most global analyses, these results are subject to the availability and limitations of data, in this case, marine primary productivity and anthropogenic cumulative impact across the oceans. These limitations might result, for example, in an under-detection of productive areas and under-estimation of human-related impact to marine systems. Specifically, productivity was assessed using satellite-based estimates of chla as a proxy, which are based on the near-surface concentration of chlorophyll-a. Because, to a smaller degree, productivity also occurs in deeper ocean layers that are still important for marine megafauna [45], this analysis might omit some important productive areas deeper in the water column.

It should also be noted that the cumulative impact score used here is built upon anthropogenic stressors for which global data exist or may be modeled [28,29], so as it is pointed out by the authors, this cumulative impact score is hindered by the uncertainties and limitations of each individual stressor. As a consequence, the levels of real anthropogenic impact might differ from those shown here. Moreover, the cumulative impact score used here may not capture high impact areas at the local scale (e.g., [31]). Yet, as it is pointed out elsewhere [48], this score is best used for broad comparisons among regions and for global priority setting, which is precisely the purpose in this manuscript. The WDPA is the most updated and comprehensive database on marine protected areas and OECMs at the global scale, but it has limitations. The data on the WDPA corresponds to data provided by different parties, so some MPAs or OECMs may not be present in the database although they are established in their own countries. Therefore, for local analysis, a local database on MPAs and OECMs may be more reliable. Finally, the bounding of clusters of grid cells of high productivity-low impact waters used to ensure the internal connectivity threshold in this analysis may result in the inclusion of internal patches with lower productivity, or higher cumulative impact, or both. Yet, these bounding geometries just represent an illustrative approach to identify broad marine areas where animals can benefit from plenty of highly productive places with low levels of anthropogenic impact.

There is global consensus on the urgent need for efforts to conserve and effectively manage marine ecosystems in the face of unabating human-related threats to the oceans and coasts, which compromise human wellbeing, biological diversity, and ecological integrity [10,38,56,59]. While notable achievements have been made in terms of large-scale protection and the sustainable management of coastal and marine areas [22], the scale of the problem and increasing degradation rates [27] require redoubling our efforts to implement sustainable and effective ocean management in order to maintain ecological functionality at a meaningful scale [35]. This analysis supports these notions and provides a first roadmap to a portfolio for safeguarding our oceans' highly productive systems.

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CRediT authorship contribution statement

Watson James E.M.: Writing – original draft, Writing – review & editing. **Fermepin Solange:** Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Mendez Martin:** Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing. **Grantham Hedley S.:** Writing – original draft, Writing – review & editing.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2024.106016.

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