Title: Global distribution, quantification, and valuation of the biological carbon pump

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Abstract

The biological carbon pump (BCP) sequesters vast amounts of carbon in the ocean but its importance for conservation, climate finance, and international policy has not been properly assessed. Here, using spatial analysis and financial valuation of the BCP service, we estimate that, annually, the BCP adds 2.81 Gt of carbon (range 2.44 - 3.53) to the ocean with a storage time of at least 50 years (±25 years). This ecosystem service is worth US$545 billion/year (471 - 694) in areas beyond national jurisdiction and US$383 billion/year (336 - 471) within all Exclusive Economic Zones where the sum of its discounted values for 2023-2030 is US$2.2 trillion (range 1.9 - 2.7). These results quantify the climate and economic importance of the BCP and the important role of large ocean states in carbon sequestration. These findings can support discussions in climate finance and in the COP global stocktake for climate action.

Main Text:

The ocean's ecosystem services are globally important and include climate regulation, biodiversity, and food provisioning[1,2], and sustain a global economy worth US$1.5 trillion[1]. Human activities, such as unsustainable fishing, resource extraction, and shipping threaten the ocean's key functions[2–5]. Other emerging activities include deep-sea mining and mesopelagic fishing, whose impacts are actively studied (e.g.[6,7]). The biological carbon pump (BCP), the transport of organic carbon from the surface to the depths, is particularly important: it was estimated that without it atmospheric CO_2 concentrations would be roughly 200 ppm higher[8,9]. Phytoplankton aggregates, zooplankton, fish, marine mammals, and other marine organisms mediate this sequestration passively (e.g., sinking as aggregates, fecal pellets, and carcasses) and actively (e.g., vertical migrations and respiration) by transporting carbon to depths where it remains stored for years to centuries[10–12].

Protecting and restoring the BCP and its carbon service is essential to promote natural solutions to climate change[13–15], reduce emissions from ocean-based human activities[16,17], and increase resilience of fish stocks[18]. Ecosystem recovery and BCP enhancement have also been suggested as potential marine CO_2 removal strategies and integration in carbon offset markets[19,20]. However, these strategies are in the early stages of discussion and require further research before deployment. Mapping and quantifying BCP carbon services can help their protection through area-based management (e.g., marine protected areas, MPA) and environmental assessments (e.g., impact and strategic) for promoting benefits for climate, biodiversity, and people[21,22]. Yet, few management efforts are designed to protect the BCP nor include climate change adaptation goals[23].

Deploying large-scale conservation, management, and mitigation actions requires substantial financial investments and a more sustainable ocean economy[1,24]. Currently, there is no financial incentive to protect the BCP for its climate regulating function even though this would benefit humanity[25]. Valuation of ecosystem services, including carbon sequestration, is useful to assess non-market value of species[26], economic damages inflicted by greenhouse gases emissions[27], and nature's contribution to welfare[28]. Valuation is a key step to financing nature protection through payments for the carbon service benefits provided by species[24,29], which have been shown to be of substantial value[29,30]. Valuation of carbon services can contribute to financing mitigation and adaptation initiatives and financial negotiations (debt relief and restructuring, and financial support)[31,32] with important implications for developing countries[28,33]. However, the focus of the blue carbon/economy, climate benefits of MPA, and financial valuation has been on coastal ecosystems and the social cost of carbon[22,28,34]. The new Biodiversity Beyond National Jurisdiction (BBNJ) Treaty opens new opportunities for conservation and research, and capacity building beyond coastal areas but needs to be supported by science[35]. However, for attracting large-scale financial investments, the valuation needs to speak the language of financial and policy experts and be based on market prices. Despite its importance to climate regulation, a global geopolitical assessment and valuation of the BCP is missing (a regional estimation already exists[36]).

Accounting for sequestration time of BCP carbon-capture

Here, we fill these gaps by mapping the BCP carbon sequestration based on global estimates from an Earth System model[10] and by valuing its carbon service using market-based prices. BCP service was analyzed in relation to different area-based management and political boundaries, including Exclusive Economic Zones (EEZ) and areas beyond national jurisdiction (ABNJ), and national economies. We estimated the amount of annually exported carbon (i.e., the carbon that is transferred from the atmosphere to the ocean and injected at specific depths) that will remain sequestered in the ocean for at least 50 years (±25) (see Methods). We refer to this rate as the "50-year carbon sequestration rate (GtC/year)" or "50-year sequestration" for short, which we used to valuate the BCP sequestration service across geopolitical boundaries. Carbon residence time is a critical parameter often neglected, or arbitrarily set[37], in estimations of carbon sequestration and valuation of carbon services[36,38]. What is considered "long-term" residence (or permanence) time in policy and sequestration schemes varies greatly from 25 to 100 years[39]; regardless, temporary carbon storage can help transition to "2050 net-zero" and reduce peak warming[40]. We chose 50 years (±25) as a compromise between climate mitigation potential and human-timescale decision making (e.g, policy and investment horizons). Our analysis of the BCP includes processes driven only by phytoplankton, zooplankton, and fish (see Methods), which together are the biggest contributors of sinking organic particles in the open ocean[10,41]. Our results include a sensitivity analysis of: carbon residence time to capture some of the uncertainty of modelling biological carbon export[41]; and carbon credit price and real discount rates to capture the global variability in these parameters. We also identify hotspots of carbon sequestration for prioritizing conservation. We provide a baseline to measure ecological and economic loss when natural assets are mismanaged or damaged, that could incentivize countries to protect the BCP, and support international climate finance negotiations. These results provide information to support the development of international financial markets for carbon if the effects of management and conservation actions can be measured in terms of avoided/reduced emissions and/or carbon additionality, similarly to carbon offset initiatives in other ecosystems[25].

Spatial patterns and magnitude of BCP carbon sequestration

We calculated 50-year sequestration rates by multiplying the annually-injected carbon, provided by a widely-used global biogeochemical ocean model[10], by the fraction of injected carbon that remains stored in the ocean after accounting for ocean circulation and depth of injection[38]. Carbon injection refers to carbon that is exported and transformed into dissolved inorganic carbon (i.e. respired, either by animals or bacteria degrading organic matter), so that it cannot be reused by marine animals. As organic matter sinks at various speeds, carbon export and injection do not occur at the same place in the water column.

Spatial patterns of 50-year carbon sequestration rates varied greatly (Fig. 1a) and globally totaled 2.81 GtC/year (range 2.44 - 3.53) (Fig. 1b). The highest 50-year sequestration rates were concentrated primarily in the tropics and secondarily in temperate areas (Fig. 1a). Fifty-year sequestration rates peaked in the eastern Pacific, western Indian Ocean, the Americas and Africa's western coasts. Sequestration was intermediate in subtropical areas and in the Southern Ocean. In coastal waters, sequestration rates varied considerably but were generally lower in eastern coasts, particularly in southern America, North America, and the East China Sea.

The majority of 50-year sequestration occurred in ABNJ, estimated at 1.65 GtC/year (range 1.43 - 2.10; 59% of global carbon sequestered per year), and the remaining sequestration in EEZ was 1.16 GtC/year (1.02 - 1.43; 41%). Roughly 27% (0.77 GtC/year, 0.67 - 0.95) of global 50-year sequestration was concentrated within Ecologically and Biologically Significant Areas, as defined by the Convention on Biological Diversity; these areas are predominantly (~80%) in international waters. On the contrary, MPA are 93% located within EEZ but only represent a 0.19 GtC/year sink (0.17 - 0.24; 7% of global 50-year sequestration) (Fig 1b). The bulk of the carbon exported (~80%) that remains sequestered for at least 50 years is the carbon reaching depths between 300 m and 2000 m (Extended Data Fig. 1). At these depths, the spatial patterns of carbon sequestration are very consistent with the ones described previously (Extended Data Fig. 2 and Fig. 1a).

BCP sequestration in countries – the important role of SIDS

In terms of 50-year carbon sequestration per area (tC/km^2), the total sequestration by country was not always proportional to its EEZ extension (Complete list in Supplementary Table 1). The five countries with the largest EEZ, including their large overseas territories (Australia, France, Russia, UK, and USA), comprised 23% of the total 50-year sequestration rate at 246 Mt/C per year (Fig. 2). However, in countries with smaller EEZ (e.g., Chile, Ecuador, Oman, Peru and Namibia), the 50-year sequestration rate per area was higher than the global average and resulted in noteworthy rates of sequestration. On the contrary, countries such as United States, Canada, Brazil, and Australia had lower-than-average sequestration rates despite their large EEZ. A potential explanation for these differences is that the first group of countries have a narrower shelf where carbon is exported deeper compared to the second group. In Africa, the majority of the 50-year carbon sequestration rate was contained primarily within countries in the Indian and South Atlantic Oceans (Fig. 1a and 2). The EEZ of Small Island Developing States (SIDS, some of which are self-identifying as "*large ocean states*") such as Kiribati, Micronesia, or Seychelles comprised 11% of the total 50-year sequestration rates (Fig. 1a and 2) and up to 13% if non-sovereign SIDS were also included. This is substantial considering that there are only 39 sovereign SIDS, and 20 non-sovereign SIDS. In more than 60% of countries, the surface covered by MPA accounted for less than 3% of their national 50-year sequestration; MPA covered at least 10% of total carbon sequestration in 20% of all countries (Fig. 2).

Value of the BCP sequestration service

We estimated the global value (sum of ABNJ and all EEZ) of the BCP carbon sequestration to be roughly US$1 trillion/year (range 0.8 – 1.1) based on the 50-year sequestration rate at a price of US$90 per t/$CO_2$. The BCP carbon service is worth $383 billion/year (336 - 471) within all EEZ combined and $545 billion/year (471 - 694) in ABNJ. Country-specific carbon service values vary considerably following the spatial distribution of sequestration rate (Fig. 1 and complete list in Supplementary Table 1). The top three countries in terms of value (USA, Chile, and Australia) surpassed $18 billion/year per country. For an additional 53 countries, the value was > US$1 billion/year. The remaining countries, representing ~40% of all countries, had a carbon service value of > US$100 million/year. The annual values are based on the current ecosystem service benefits without any discount rate. The sum of Present Value (i.e., future cash flow) of carbon services of all EEZs from present until 2030 amounted to US$0.9-2.7 trillion and US$2.4-7 trillion until 2050, depending on price of carbon, carbon residence time, and real discount rates (Table 1); this Present Value is the discounted sum of annual payments until 2030/2050 based on the 50-year sequestration rate. Discount rates affect primarily longer-term investments. By doubling the discount rate, the 2030 valuation declines by 10% (Table 1), while the 2050 valuation declines by 27% (Table 1). Instead, changes in carbon prices scale linearly with the Present Value (Table 1); for example, the 2030 valuation declines by 10% for a 10% decline in carbon prices. The per-country summed Present Value until 2050 ranges between US$544 billion and US$1 billion, at 2% real discount rate (Supplementary Table 1).

Large differences in the area of each country's EEZ overshadow the importance of the financial value of BCP carbon services for national economies. This aspect emerges clearly when the value is analyzed in relation to the gross domestic product (GDP). For many low, lower-middle, and upper-middle income countries, the market value of the BCP carbon service accounted for a major percentage of their GDP (Fig. 3a). In many cases, market value represented 10% or more of the GDP. The countries with the highest market value:GDP ratio are Pacific SIDS, including Kiribati where market value is 38 time its GDP (US$ 8.5 billion/year, Fig. 3b). Even though these percentages are highly dependent on the price of carbon, which does not have a global price and is variable from country to country, the majority of countries with a high value were small countries that are either highly indebted or have limited lending power (Fig. 3a, lending group IDA). The list includes SIDS (Fig. 3a and 3b) that are already being affected by climate change and other countries needing funding to cope with climate change and energy transition[42]. If a viable market for ocean carbon existed, a number of "Highly-indebted Poor Countries", as defined by the World Bank, could significantly reduce their debt and potentially turn from debtors to creditors by obtaining payments for their BCP carbon services.

Hotspots of carbon sequestration

Following the 30x30 target set by the Global Biodiversity Framework (conserve 30% of the Earth by 2030), we highlighted "hotspots" that would maximize the coverage of BCP carbon services if 30% of the ocean area were to be protected (Fig. 4). These top 30% carbon hotspots would hold a combined 1.64 GtC/year of 50-year sequestration rate (58% of global sequestration). A more conservative target of conserving the top 10% areas of carbon sequestration would cover 0.86 GtC/year or 30% of this global service. The top 10% areas include the eastern and northern Pacific, the West coast of Africa and the Americas, the Indian Ocean, and the Mediterranean Sea (Fig. 4). Within the 10% hotspots, 4% of total carbon sequestration (0.03 GtC/year) was within MPA, 58% was within EEZ (0.48 GtC/year), of which 90% concentrated in 40 countries.

Policy, climate finance, and conservation implications

Quantification of carbon sequestration and valuation of its services are central in climate finance, policy, and conservation[24,28,32,34]. Our spatially explicit analyses of ocean carbon sequestration sheds light on the geo-political distribution of the BCP, its magnitude and financial value. We highlight locations and jurisdictions that can play important roles in protecting, restoring, or enhancing carbon services to address the climate and biodiversity emergencies. These results can help to inform the implementation of international agreements to manage ocean carbon services in both EEZ and ABNJ. Protection will imply managing human activities (through limitation or exclusion) to prevent harm to the BCP. These activities might include fishing, deep-sea mining, dredging, shipping, and pollution. For example, we note that many of the carbon hotspots overlap with areas of medium to high fishing pressure[43,44] and deep-sea mining designated areas[6] (e.g., Pacific ocean Clarion-Clipperton Zone). Enhancing the BCP might include ecosystem restoration and other marine CO_2 removal strategies that could increase the BCP efficiency at large scale[19,20], although these strategies will have to be thoroughly and scientifically tested before any large-scale deployment and their cost-effectiveness evaluated[45].

The recently-agreed Global Biodiversity Framework calls for protecting 30% of the Earth to support ecosystem services, including climate regulation, for biodiversity and for people. Ecosystem and area-based management tools and environmental impact assessments play a central role in the Framework. Consequently, all areas (i.e., the entire territory of each country) are to be under effective spatial planning by 2030 and ecosystem-based environmental impact assessments must be undertaken for new human activities. We show that more than 41% of global 50-year carbon sequestration takes place in EEZ; consequently, countries can independently manage and protect marine ecosystems for socio-economic and climate benefits[28] by restoring or enhancing the BCP[19,20] or reducing/avoiding emission of human activities (e.g., fishing)[15]. For highly-indebted countries or with limited lending power, and under a nature-based economy, BCP carbon services could represent an important part of their natural capital that would provide funding to implement adaptation strategies. Adaptation actions and conservation could be financed through payments for the carbon service, in debt-for-nature swap schemes[24], or emerging alternative financing (discussed later). Climate financing should account for the significant global importance, in climate and economic terms, provided by the BCP carbon service of low-income countries and SIDS. Changes in monetary policy could be directed to benefit local communities and regions that invest in maintaining or restoring marine ecosystems that can keep sequestering carbon. Countries could include the BCP in their accounting[46] (e.g.; national balance sheets) of natural resources and invest payments for carbon credits to improve long-term conservation and research on the effects of human activities on marine ecosystems and marine CO_2 removal strategies[19].

Furthermore, the recently agreed BBNJ treaty calls for the creation of open sea MPA and the advancement of scientific knowledge on marine ecosystems[35], and includes in its principles the ocean's role in sequestering carbon. Roughly 60% of the global ocean is in ABNJ. Thus, if effectively implemented, BBNJ treaty will protect large areas through an ecosystem-based approach that promotes climate services. We document locations in the high seas that, if protected, can play an important role in long-term carbon storage. In ABNJ, 50-year sequestration rates are significant but will require wide-scale cooperation for protection.

Challenges and opportunities for developing a BCP market

Currently, there is no clear definition or consideration of acceptable sequestration (residence) time in the Paris Agreement global stocktake nor carbon offset projects[38]. We overcome this limitation by accounting for carbon residence time. Our 50-year (± 25 years) residence time might be different compared to other carbon projects. Nonetheless, accounting for it increases the transparency of the global stocktake and provides investors in carbon projects with an additional metric to evaluate investment risks and offset quality. Most importantly, carbon credits generated by the BCP, and sold on the carbon market, would have to clearly show the carbon additionality (or avoided emissions) produced by the action taken to protect or restore the BCP, as it is also required in other land or blue carbon schemes[39]. This also applies for any contributions toward Nationally Determined Contributions as part of the COP Paris Agreement. Several challenges will need to be overcome to develop a market for BCP credits, these include scientific, financial, and technical ones. The values of the BCP service remain potential until offset projects can meet accreditation criteria including baseline, additionality, risk of non-additionality, permanence, leakage, post-credit monitoring, and co-benefits[39], which are necessary in valuation and carbon accounting[27]. Alternative financial instruments such as bonds and ecosystem service insurance may be considered to fund restoration and conservation of the BCP that are not solely based on carbon offsets but other co-benefits[47] (e.g, biodiversity, sustainability, social, etc.). Complementary market-based mechanisms have been actively implemented in blue carbon projects and include a mix of public and private funding, and could potentially include repurposing harmful subsidies, taxing harmful activities, and debt-relief schemes to indebted countries[47,48]. Here we provide data on baseline and permanence but the rest is still missing. In the near future, there should be consideration on how future marine mismanagement or inaction may harm the BCP and create climate change costs. This will require quantification of how various human activities could affect 50-year carbon sequestration rates, where work is currently ongoing.

The price per t/CO_2 is a key parameter in the valuation and varies considerably across countries, from less than US$20 in several countries up to US$160[49]. The price is likely subject to increase. In the European Union Emission Trading System, one of the largest in the world, the last 2-year average price was ~EUR 80 per t/CO_2 and the World Bank and IPCC suggests a price range of US$60-120 t/$CO_2$ for building an effective carbon market and meeting the 2°C target [49]. CO_2

concentrations have global effects and should be handled with a global carbon price. Even at a very conservative price of US$5 t/$CO_2$ the value of BCP annually-stored carbon would be of great monetary value. This implies that each country has the potential to attract sizable public or private investments that could finance climate change actions including national adaptation plans designated by the UNFCCC. For purely comparative purposes, the global median social cost of carbon was estimated at US$ 417 t/CO_2 (c.i. US $177-805)[50], ~4.5 times higher than the carbon price we used. As the total value scales linearly with changes in the price of carbon (Table 1), it is trivial to realize that even a small loss of the BCP would incur a huge cost for our society.

Conclusions

Present and future human activities might diminish the capacity of the BCP to sequester carbon but many uncertainties still remain[3,6,51]. The contribution of different organisms to carbon sequestration is still actively investigated with increasing evidence showing important contributions of fish (including commercial species, pelagic species, sharks, etc)[15,52–55], whales[56], copepods[57], and cephalopods[58]; although direct carbon sinking and migrations of lower trophic level animals remain the main drivers of the BCP. In our analysis, we could not account for the contribution of particular groups of marine organisms to carbon sequestration. Consequently, we cannot produce punctual estimates of how the removal or protection of particular species would affect BCP carbon services. Our results are based on one BCP model projection and are sensitive to different model estimates of present and future changes in carbon export including large spatial uncertainties in terms of magnitude and direction of change[41,59]. However, projected changes are based primarily on export in shallow waters (e.g., 100 m) where most carbon is outgassed quickly in the atmosphere. Consequently, projected changes in shallow carbon exports might not equate to similar changes in the 50-year sequestration rate.

What we provide is a ready-available, high-level analysis of BCP geographical patterns that can be integrated with current research, guide modeling studies for the global stocktake, and develop efforts for Nationally Determined Contributions and carbon market policy. Because the main factors influencing the BCP relate to changes in ocean conditions brought by climate change, including acidification, changes in nutrient supplies or temperatures, human interventions might have limited effects on the BCP. Consequently, the potential and net contribution of ecosystem restoration to climate mitigation should be evaluated by accounting for the effects of climate change[60,61]. Ideally, the effects of human activities on the BCP need to be thoroughly quantified and compared to the effects of climate change. Until then, we suggest a precautionary approach to protect marine organisms to reduce cumulative impacts of humans and climate. In addition to carbon sequestration services, protection will also increase the resilience of marine ecosystems to cope with climate change[18].

Marine organisms account for roughly 1% of all the dissolved inorganic carbon stored in the ocean but atmospheric CO_2 levels would be ~50% higher without the BCP[8]. Marine organisms should be part of climate mitigation strategies to broaden the portfolio of natural climate solutions[13,62,63]. The BCP carbon services are neither protected nor yet included in the global stocktake or carbon offset market despite their substantial economic value and climate importance. Area-based management tools can be used with financial instruments to support the protection of the BCP by generating additionality, avoiding emissions, and promoting co-benefits[64]; for example through sustainable fisheries management. The climate benefits arising from the BCP are not necessarily experienced or measurable at a given local or regional scale, but do influence global concentrations of CO_2 and should be protected for the benefit of humanity.

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Competing Interests Statement: Authors declare that they have no competing interests.

Tables

PV in trillions of US$ summed through year @ price of carbon	2% discount rate	4% discount rate
2030 @ US$ 90 t/CO_2	2.2 (1.9 - 2.7)	2 (1.8 – 2.5)
2050 @ US$ 90 t/CO_2	7.0 (6.1 - 8.7)	5.5 (4.8 – 6.9)
2030 @ US$ 45 t/CO_2	1.1 (1.0 - 1.4)	1.0 (0.9 – 1.3)
2050 @ US$ 45 t/CO_2	3.5 (3.1 - 4.4)	2.7 (2.4 - 3.4)

Table 1. Effects of price of carbon and discount rates on valuation of the BCP service in all EEZs combined. Present Value is expressed in trillions of US$ summed from 2023 through 2030 or 2050. The lower and upper bounds of the Present Value is indicated in parenthesis and was calculated by using a residence time of carbon of respectively 25 and 75 years (see methods for more details).

Figure Legends/Captions

Fig. 1. Spatial and geopolitical distribution of BCP carbon sequestration. Fifty-year carbon sequestration rate (**a**) spatial distribution and (**b**) within management and political boundaries. Fifty-year sequestration rate is the fraction of annually exported carbon that remains in the ocean for at least 50 years through passive and active processes driven by phytoplankton, zooplankton, and fish. In (**a**): azure lines indicate EEZ boundaries; areas with sequestration rates <1 ktC/year were grouped for facilitating visualization; contour lines indicate areas between 1, 10, 25, 50, and above 100 ktC/year. Margin bar plots (top & right) show average seq. rate across latitude/longitude bands. In (**b**): bars indicate the sum of 50-year sequestration rate globally and in ABJN, EEZ, ecologically and biologically significant areas (EBSA), and MPA. Whiskers indicate the total 25-year (lower) and 75-year (upper) sequestration rates for each group.

Fig. 2. 50-year carbon sequestration rate within countries' EEZ and MPA, grouped by continent. Detached (overseas) territories were grouped with their sovereign state EEZ. The "Rest of …" includes the sum of all countries that had less than 3% of their continent's 50-year sequestration; "transboundary" is the sum of all areas managed or claimed by more than one country. The UK has overseas territories where MPAs extend beyond EEZ, resulting in more carbon sequestered within its MPA than its EEZ. The Chagos Archipelago is a particular case as the UK is handing over sovereignty to Mauritius.

Fig. 3. BCP carbon service value in relation to Gross Domestic Product. Value of annual carbon sequestration was calculated based on $90 per t/$CO_2$ and divided by nominal GDP. (**a**) Carbon service value by countries' income levels, only countries with % of GDP > 1 are shown (complete list in Supplementary Table 1). Lending groups (classification by the World Bank) relate to countries' creditworthiness and gross national income: IDA includes the poorest countries receiving low-interest loans, IBRD are credit-worthy poor countries, "Blend" are countries in both IDA and IBRD, and "None" are countries with no particular borrowing constraints. The hatched bars indicate Heavily Indebted Poor Countries (HIPC). (**b**) EEZ of the top-8 countries with the highest BCP carbon service value to GDP ratio and classified according to their income group. All these countries are SIDS in the South Pacific.

Fig. 4. BCP 50-year sequestration hotspots covering 10% and 30% of the ocean surface and relative global coverage. EEZ are indicated with azure lines. The EEZ of certain countries are fully covered by the carbon hotspots; countries might not be able to fully protect their EEZ just for carbon services.

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Materials and Methods

Overview

We gathered estimations of carbon exported annually by the BCP simulated by the state-of-the-art global ocean dynamics model NEMO-PISCES-APECOSM [10]. From NEMO-PISCES-APECOSM output, we then calculated the fraction of the exported carbon that remains sequestered in the ocean for at least 25, 50, and 75 years based on OCIM, an ocean circulation model [38]. We chose 50 years as the average carbon residence time as this will allow the carbon to remain stored well past 2050, when humanity should be close to its net-zero goal. Fifty years is also more relevant for near-term climate change policy and understandable on a human time-scale than longer residence time. The

25 and 75 years of residence time were used to calculate the lower and upper bounds of our calculations. This annually-sequestered carbon was then valued according to current carbon-offset market prices for an investment horizon until 2030 and 2050. Valuation is highly dependent on the BCP model results given the large variability among models [41], in addition to discount rate, and price of carbon, which currently differs from country to country until local carbon markets are coordinated in a single global market. The investment horizon is the length of the contract signed by the buyer of carbon offsets. Carbon offsets generated by nature, in this case the ocean, are issued to the buyer that receives carbon credits for a specific duration (based on the yearly sequestered carbon). Part of the funding will need to be earmarked for the conservation of the ocean so that it can keep generating the carbon service [24] or can be used to restore the ecosystem to increase the provision of the service. The service is provided because nature remains in the public domain and under national or international jurisdiction; this helps managing the ecosystem to maintain its resilience and functioning so that the service is continuously provided. As discussed later, the provision of the service is also dependent on the effect of major drivers such as climate change that cannot be directly controlled. The 50-year sequestration time and the 2030/2050 years investment horizon time are conservative thresholds chosen so that carbon offsets sold remain sequestered for a time period much greater than the investment horizon.

Biological carbon pump carbon long-term sequestration rate

We used carbon export estimates from a global dynamic model of ocean biogeochemistry and biology called the NEMO-PISCES-APECOSM [10]. The NEMO-PISCES-APECOSM is a widely-used biogeochemical model and is part of the Earth System Models that contribute to the Intergovernmental Panel on Climate Change reports and the Inter-Sectoral Impact Model

Intercomparison Project (https://www.isimip.org/impactmodels/)[59]. NEMO-PISCES-APECOSM combines an ocean circulation model (Nemo), a biogeochemical model of lower trophic levels of marine ecosystems (PISCES), and an upper trophic levels model of epipelagic communities (APECOSM). Note that various fully-coupled Earth System models produce estimates of biological carbon pump export but NEMO-PISCES-APECOSM is the only one with an explicit representation of fish and zooplankton vertical migration[41], which are important processes in the BCP[10]. Briefly, the model was run offline and forced by the output of the IPSL Earth System model for 300 years. Note that running the NEMO-PISCES-APECOSM model fully coupled (i.e., online) with an Earth System model does not have any noticeable effects on carbon export by the BCP[65]. In the first phase, a spin-up simulation was used to reach APECOSM open pelagic community steady-state. During a second phase the APECOSM was used fully-coupled with NEMO-PISCES and run for 1,000 years so that biology and biogeochemistry reached steady state. The lower trophic levels include two phytoplankton groups (nano phytoplankton and diatoms) and two zooplankton size classes (micro and meso-zooplankton). Upper trophic levels include visual predators and filter feeders ranging from 1 mm to 2m divided in 20 size classes. Upper trophic levels communities are of three types: epipelagic (first 200m), mesopelagic and bathypelagic (200-1000 m), and migratory, which perform daily vertical migration. The NEMO-PISCES-APECOSM model carbon export was previously validated against observation data of marine organisms' biomass [10]. Carbon export is the result of the marine community biological processes including predation, respiration, egestion, excretion. The model estimates the exported carbon at 29 depth levels from 10 m to 5000 m. The model does not include other modest contributors to the BCP such as marine mammals, cephalopods, or jellyfish. As such, these are not included in our analyses. Further, we do not consider carbon fluxes from coastal shallow-water processes driven by kelp or seaweed, which are not usually considered to be part of the BCP.

Carbon exported in the ocean has different residence times, from a few days to centuries depending on depth and location of injection because ocean dynamics might transport carbon molecules close to the surface where it can go back to the atmosphere [38]. It is thus critical to consider ocean circulation when estimating what fraction of exported carbon remains sequestrated and for how long. The output of an inverse ocean circulation model provided the fraction of exported carbon that remains in the ocean as a function of depth and location of export/injection [38]. Specifically, the Siegel et al. data provide at each depth horizon from 15 m to ~4500 m (29 depth levels in total) the percentage of carbon export that remains stored for a certain number of years, namely from 1 to 1000 years. We matched the level depths of NEMO-PISCES-APECOSM with the ones in the ocean circulation model and calculated the amount of yearly exported carbon at each of the 29 level depths that will remain stored for at least 50 years by multiplying carbon export from NEMO-PISCES-APECOSM by the fraction of remaining carbon after 50 years according to the ocean circulation model. We call this the "50-year carbon sequestration rate", in GtC/yr (shortened "50-year sequestration rate"), which is the sum of sequestered carbon at each depth layer following the formula:

$$C50 = \sum_{i=1}^{n} Cexport_i \times \%C50_i$$

Where *C50* is the total 50-year carbon sequestration rate, *i* is the depth level going from 10 m to 4500 m, *Cexport* is the export rate from NEMO-PISCES-APECOSM, and *%C50* is the percentage of exported carbon that will remain in the ocean for at least 50 years.

Both NEMO-PISCES-APECOSM and the ocean circulation model provide 3-D outputs, consequently we matched their output horizontally and vertically to the closest possible depth. This "50-year sequestration rate" was used to compute the total carbon exported from now until

2030 (and 2050) that will remain sequestered for more than 50 years. The total exported carbon was analyzed in relation to area-based management and political boundaries. Finally, a valuation of the BCP carbon service was performed for each of the different boundaries.

Political and management boundaries

We analyzed global patterns of BCP carbon storage according to several boundaries that are relevant to national and international policies, fishing, conservation, and natural resources management. These boundaries included Exclusive Economic Zones, areas beyond national jurisdiction, Marine Protected Areas, and Ecologically or Biologically Significant Marine Areas. Shapefiles of these boundaries were obtained from the sources specified in Extended Data Table 1. Marine protected areas and EEZs were assigned to countries according to their sovereign State. Certain EEZs are joint or disputed between multiple countries and were marked as “transboundary” in our analysis.

Carbon hotspots

The international conservation initiative called “30x30” was signed at the COP15 meeting of the Convention on Biological Diversity and has now been signed by more than 150 countries. This initiative has a target of designating 30% of the Earth as protected areas [66]. We used this target to highlight the areas of the ocean that would maximize carbon sequestration if 30% of its surface would be protected. As a more conservative target we performed the same calculation with a 10% threshold.

Gross domestic product and economic data

GDP data and countries income and lending classification were obtained from the World Bank website and are relative to the year 2022. The GDP of 33 countries was not reported for the year 2022. In such case, we used the first GDP reported from the year closest to 2022.

Financial valuation

We used an investment horizon until 2050 (27 years from 2023) and 2030 (7 years from 2023) and a 2% real discount rate to calculate the present value of the annuities along this investment horizon based on each country's estimated annual carbon sequestration (within EEZ). The real discount (or interest) rate is approximated by the difference between the actual discount rate and the expected inflation rate. The financial markets estimate of the real interest rate for long term investments can be measured by the difference between the 10-year US government bond rate and the 10-year inflation protected US government bond rate[67]. This measure is 2.12% with standard deviation of 0.43 over the five years from 2019-2024 (Data from the Federal Reserve Bank of St. Louis database “Federal Reserve Economic Data” https://fred.stlouisfed.org/). Because of no-arbitrage between high-income countries’ investors, similar real rates of return are on the order of 2% in high-income countries[67]. A 2% real discount rate was also recommended by 197 experts[68]. This real rate of return is higher when there is additional risk, so it might be adjusted in particular cases of high-risk investments. In addition, the Department for Business, Energy and Industrial Strategy of the UK uses a policy discount rate of 3.8% in their Carbon Price Model. Thus, we also calculated the effect of a 4% discount rate for the global calculation of Present Value. Annuities were calculated using the “pv.annuity” function from the R package “FinCal” [69]. Carbon was multiplied by 11/3 to convert carbon to CO_2 and by the average price of US$ 90 per metric ton of CO_2. This price is the average price of a future contract per t/CO2 within the US$ 61-122 2030 Carbon Price Corridor estimated by the World Bank High-Level Commission on Carbon Prices adjusted for

2023 terms from the US$ 50-100 range proposed in 2017 [49]. The Commission proposed the Price Corridor as functional for developing a potential global carbon market that to would limit global warming to below 2°C [49]. The Intergovernmental Panel on Climate Change Working Group III also indicated in their Sixth Assessment Report a price of roughly US$ 90/tCO_2 by 2030 in 2015 terms or US$ 115 in 2023 terms would be needed to reach a mitigation pathway limiting warming to 2°C [49]. The Network of Central Banks and Supervisors for Greening the Financial System recommends a price of $70/t$CO_2$ by 2030 and $276 by 2050 to achieve a 2°C scenario. For example, in the European Union Emission Trading System, one of the largest in the world in terms of volume, the average future price per tCO_2 for the last two years (7-2022 to 7-2024) was US$ 84. Finally, we preferred to use market-based prices of carbon offsets instead of the social cost of carbon which is represented by shadow prices, willingness to pay, or other implicit or indirect measurements. Social cost of carbon is more focused on evaluating potential economy damages and the cost to society (health, agriculture, and sea-level rise, etc.) expected from CO_2 emissions. In general, the market price of carbon is lower than the social cost, since the social cost includes both private and public costs. Our choice of using only carbon credit prices is motivated by the potential of market-based valuation to generate potential investments in emission avoidance or reduction activities, in ecosystem restoration that could generate carbon sequestration additionality [13,25,30], or investment through other financial instruments [47].

Data availability: Data used to perform the analysis are available from their respective sources indicated in Extended Data Table 1. The output from the NEMO model is available in a Zenodo repository[70] at https://doi.org/10.5281/zenodo.14773923.

Code availability: The code is available in a Zenodo repository[71] at https://doi.org/10.5281/zenodo.14773923.

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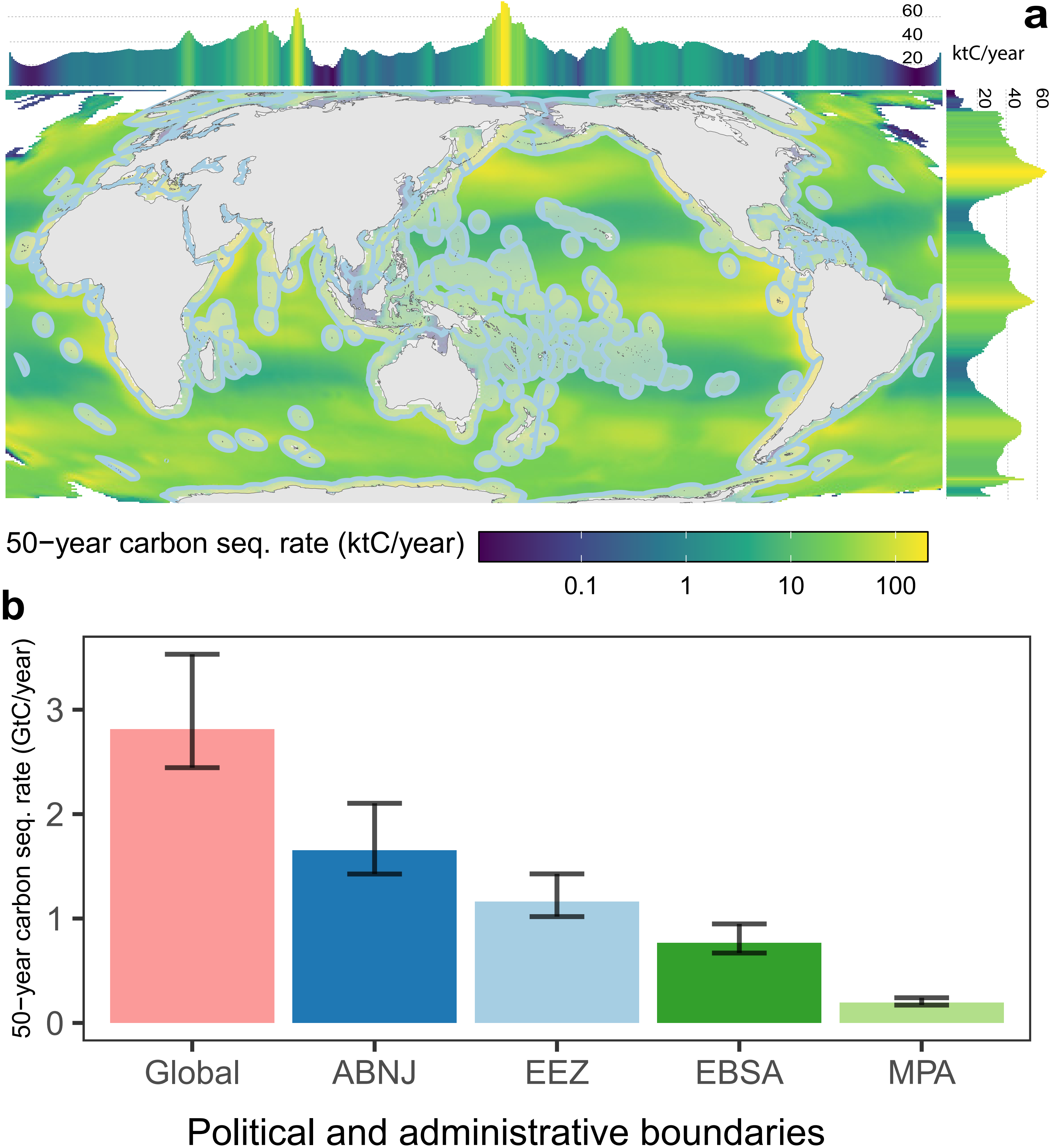
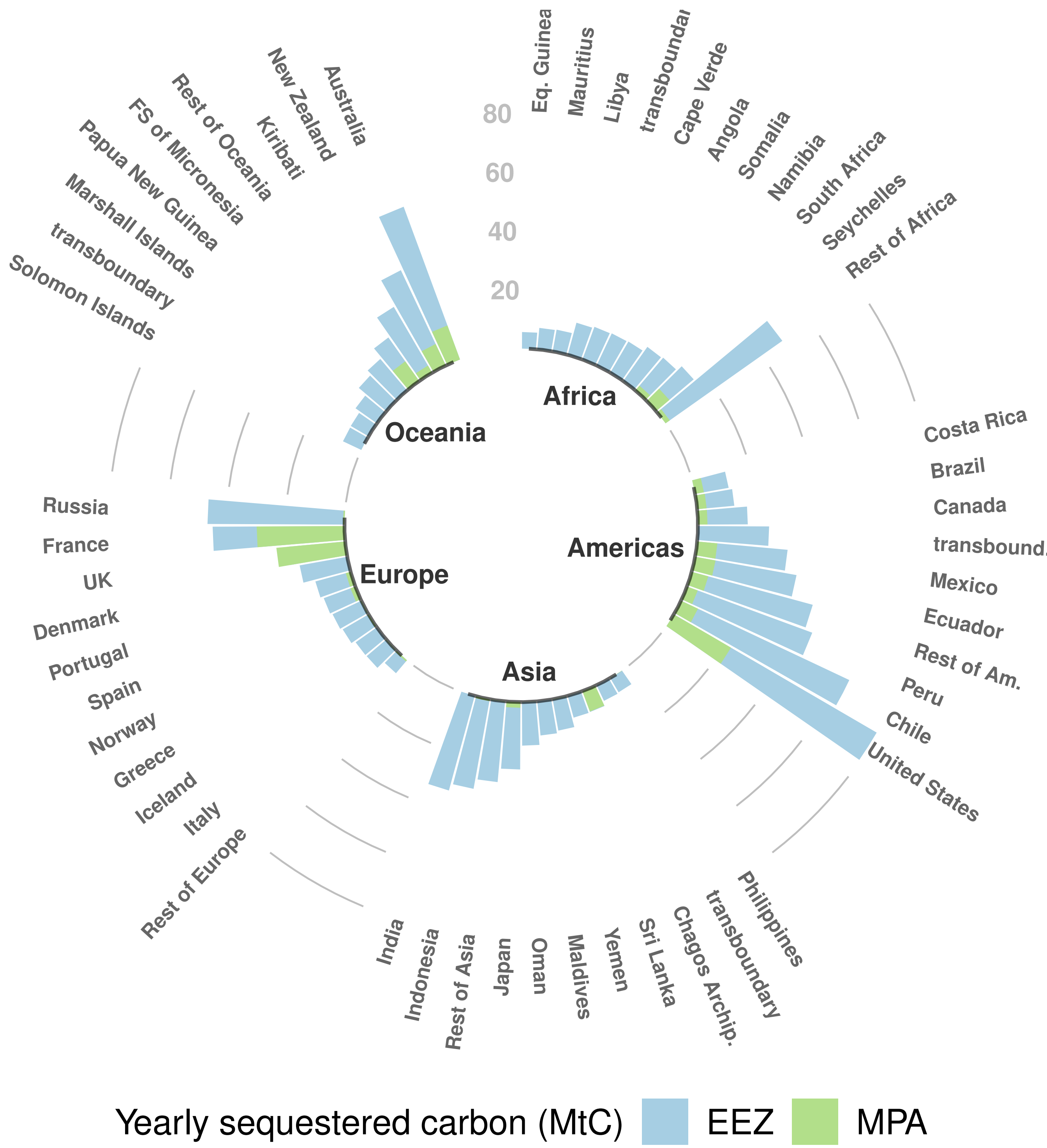
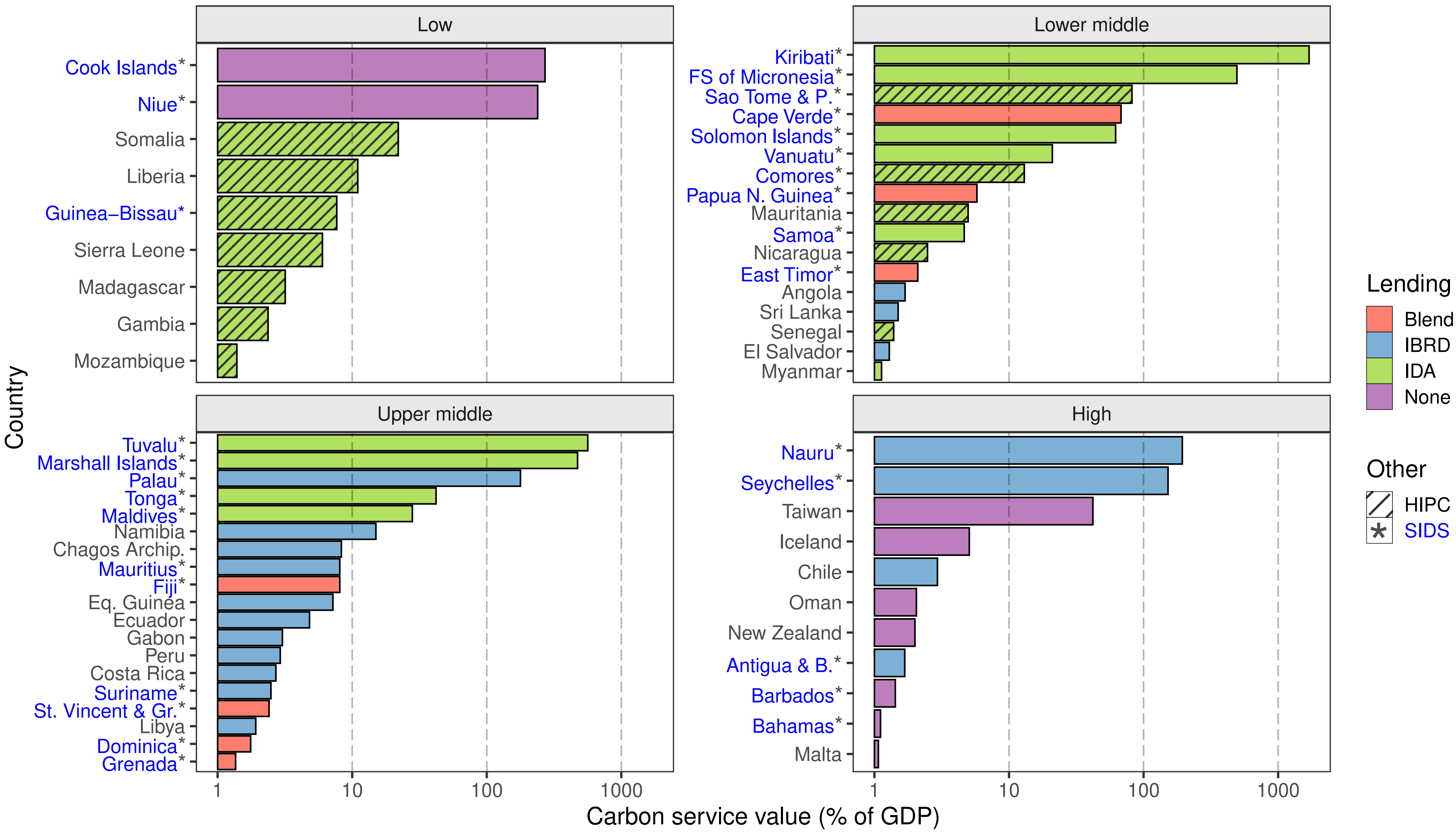
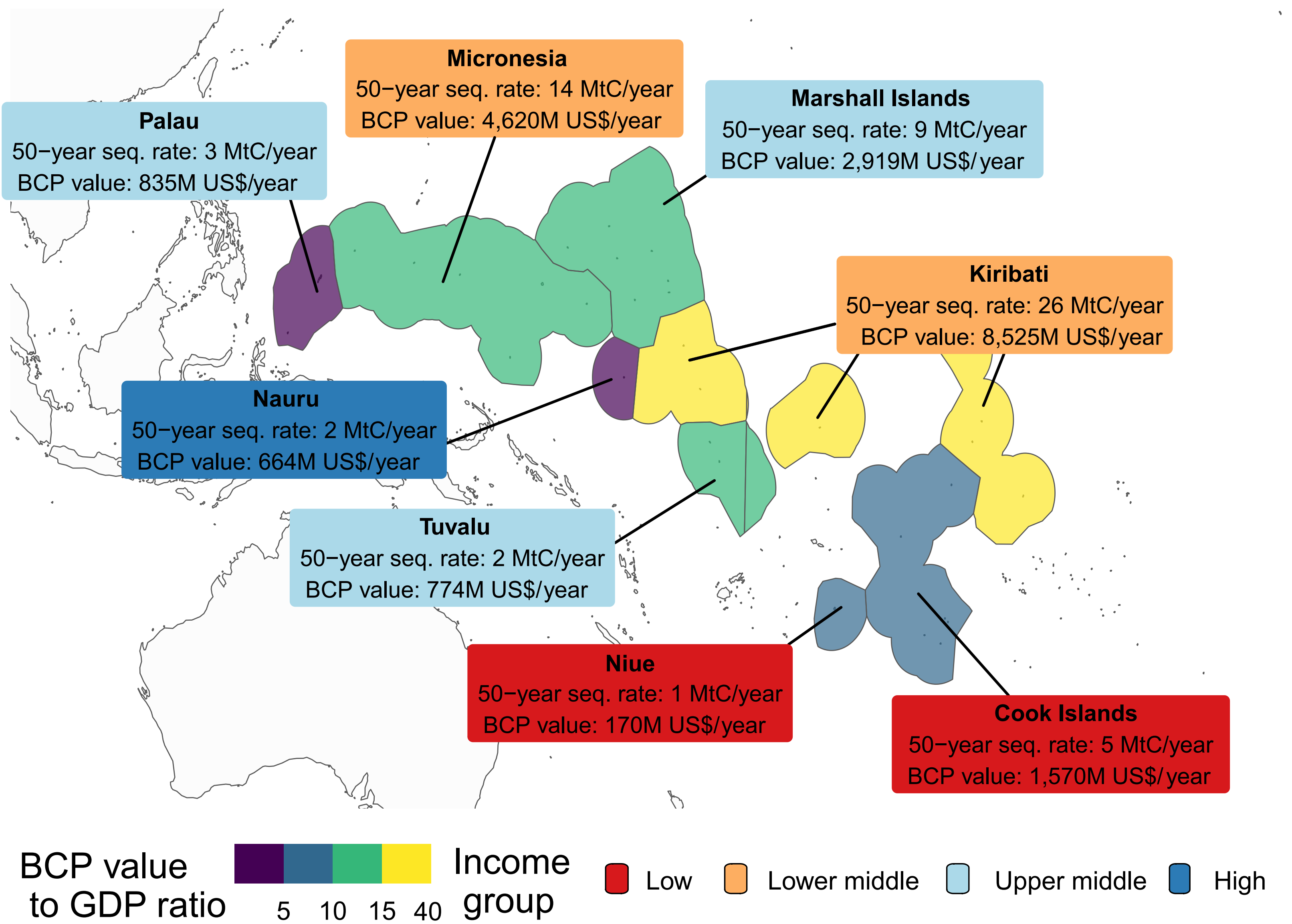

a
60
40
20
ktC/year
20
40
60
50−year carbon seq. rate (ktC/year)
0.1
1
10
100
b
50−year carbon seq. rate (GtC/year)
0
1
2
3
Global
ABNJ
EEZ
EBSA
MPA
Political and administrative boundaries



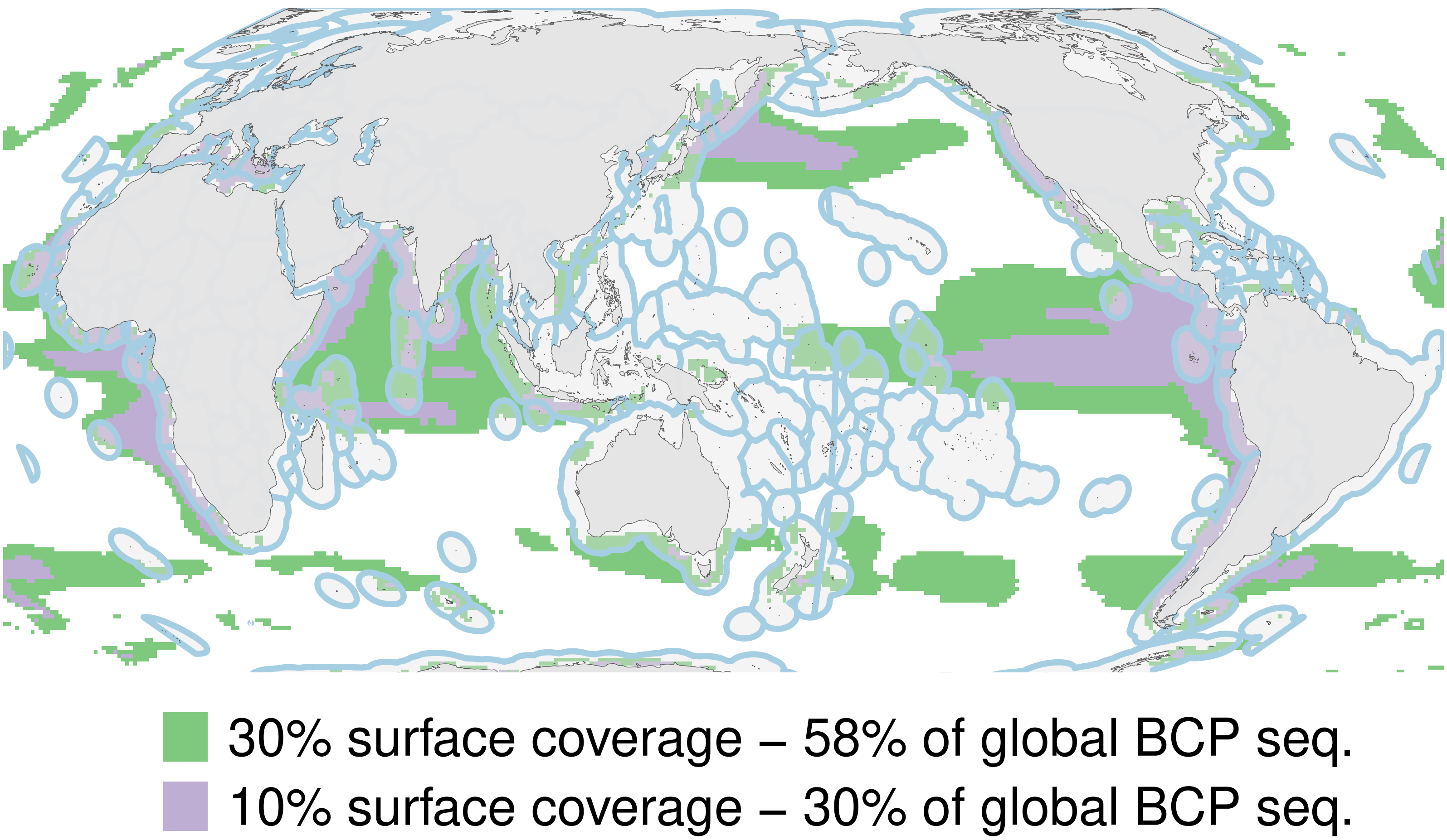
80
60
40
20
Africa
Eq. Guinea
Mauritius
Libya
transboundar
Cape Verde
Angola
Somalia
Namibia
South Africa
Seychelles
Rest of Africa
Americas
Costa Rica
Brazil
Canada
transbound.
Mexico
Ecuador
Rest of Am.
Peru
Chile
United States
Asia
Philippines
transboundary
Chagos Archip.
Sri Lanka
Yemen
Maldives
Oman
Japan
Rest of Asia
Indonesia
India
Europe
Rest of Europe
Italy
Iceland
Greece
Norway
Spain
Portugal
Denmark
UK
France
Russia
Oceania
Solomon Islands
transboundary
Marshall Islands
Papua New Guinea
FS of Micronesia
Rest of Oceania
Kiribati
New Zealand
Australia
Yearly sequestered carbon (MtC)
EEZ
MPA

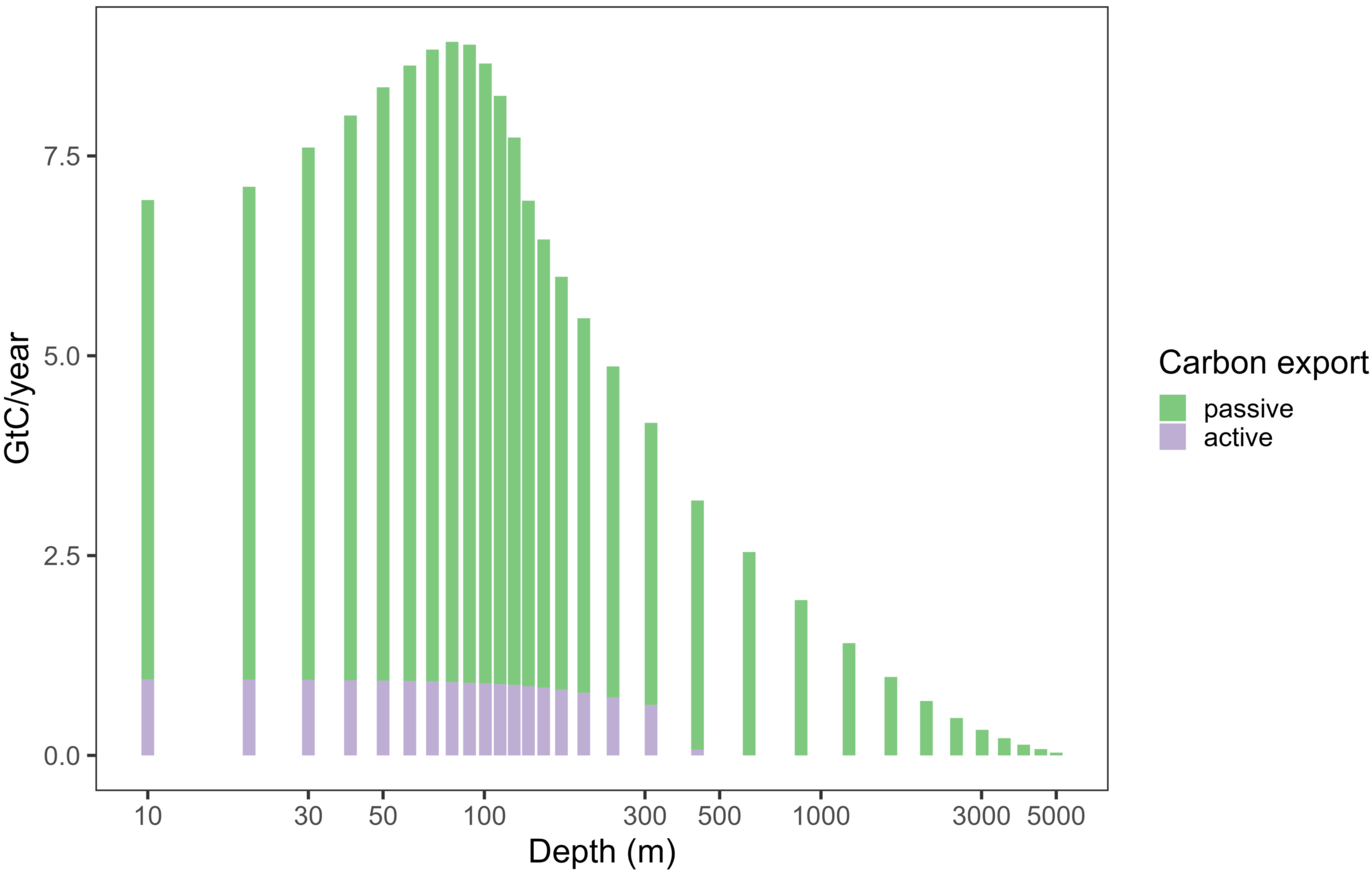


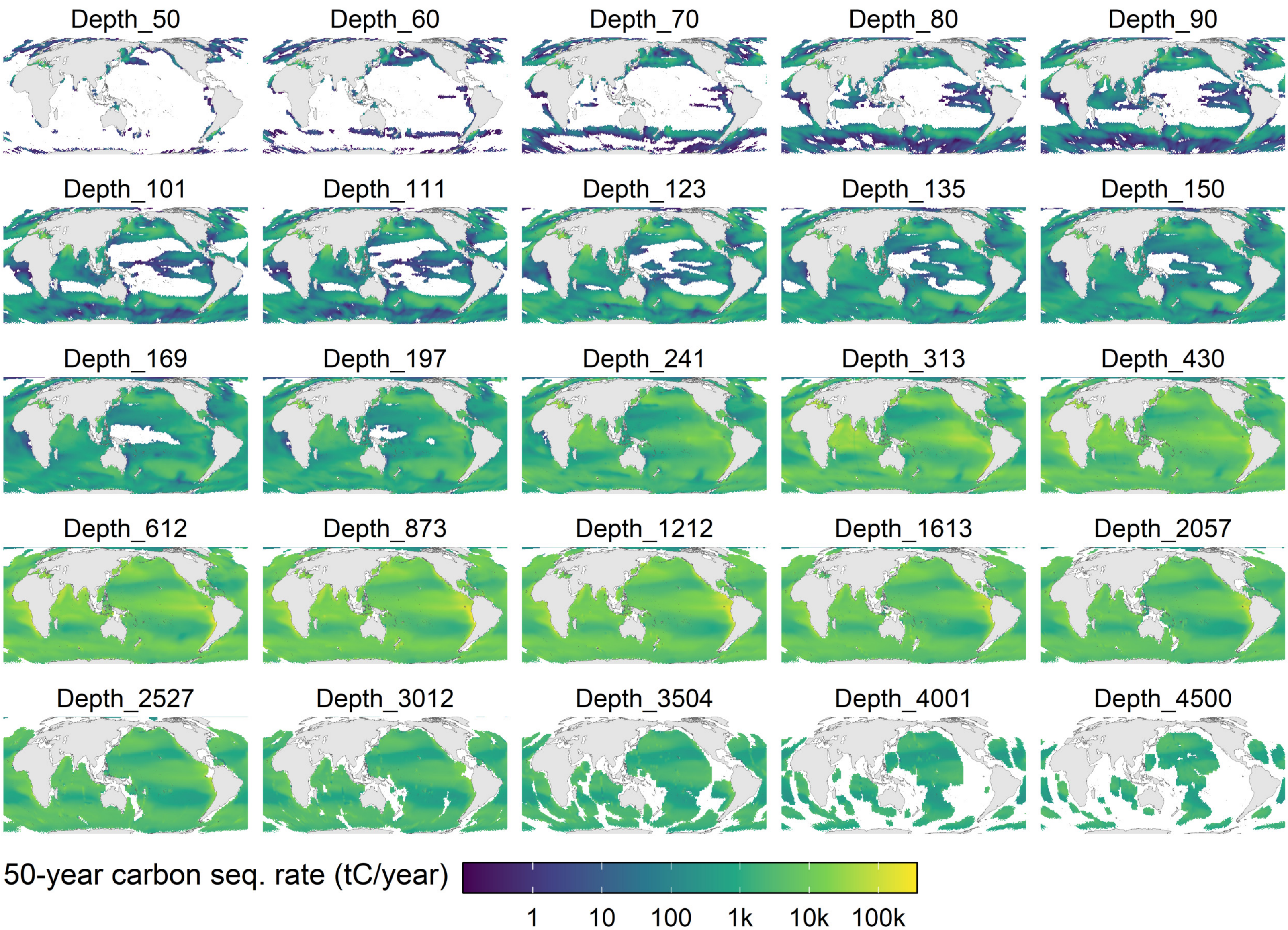
Low
Cook Islands*
Niue*
Somalia
Liberia
Guinea–Bissau*
Sierra Leone
Madagascar
Gambia
Mozambique
Lower middle
Kiribati*
FS of Micronesia*
Sao Tome & P.*
Cape Verde*
Solomon Islands*
Vanuatu*
Comores*
Papua N. Guinea*
Mauritania
Samoa*
Nicaragua
East Timor*
Angola
Sri Lanka
Senegal
El Salvador
Myanmar
Upper middle
Tuvalu*
Marshall Islands*
Palau*
Tonga*
Maldives*
Namibia
Chagos Archip.
Mauritius*
Fiji*
Eq. Guinea
Ecuador
Gabon
Peru
Costa Rica
Suriname*
St. Vincent & Gr.*
Libya
Dominica*
Grenada*
High
Nauru*
Seychelles*
Taiwan
Iceland
Chile
Oman
New Zealand
Antigua & B.*
Barbados*
Bahamas*
Malta
Country
1
10
100
1000
Carbon service value (% of GDP)
Lending
Blend
IBRD
IDA
None
Other
HIPC
SIDS



Micronesia
50−year seq. rate: 14 MtC/year
BCP value: 4,620M US$/year
Palau
50−year seq. rate: 3 MtC/year
BCP value: 835M US$/year
Marshall Islands
50−year seq. rate: 9 MtC/year
BCP value: 2,919M US$/ year
Kiribati
50−year seq. rate: 26 MtC/year
BCP value: 8,525M US$/year
Nauru
50−year seq. rate: 2 MtC/year
BCP value: 664M US$/year
Tuvalu
50−year seq. rate: 2 MtC/year
BCP value: 774M US$/year
Niue
50−year seq. rate: 1 MtC/year
BCP value: 170M US$/year
Cook Islands
50−year seq. rate: 5 MtC/year
BCP value: 1,570M US$/year
BCP value to GDP ratio
5 10 15 40
Income group
Low
Lower middle
Upper middle
High


30% surface coverage – 58% of global BCP seq.
10% surface coverage – 30% of global BCP seq.


GtC/year
7.5
5.0
2.5
0.0
10
30
50
100
300
500
1000
3000
5000
Depth (m)
Carbon export
passive
active


Depth_50
Depth_60
Depth_70
Depth_80
Depth_90
Depth_101
Depth_111
Depth_123
Depth_135
Depth_150
Depth_169
Depth_197
Depth_241
Depth_313
Depth_430
Depth_612
Depth_873
Depth_1212
Depth_1613
Depth_2057
Depth_2527
Depth_3012
Depth_3504
Depth_4001
Depth_4500
50-year carbon seq. rate (tC/year)
1
10
100
1k
10k
100k

Data type	Acronym	Description	Data source
Marine protected areas	MPA	Developed by the United Nations UNEP and our analysis includes Other Effective Area-Based Conservation Measures (OECM)	UN-UNEP https://www.protectedplanet.net/en
Areas beyond national jurisdiction	ABNJ	This area was calculated as the global ocean minus all EEZs.	Same as EEZ source
Exclusive economic zones	EEZ	Global EEZ boundaries are the layers gathered from gazetted datasets that the Pacific Community (SPC) has received from the project countries. In areas where there are no gazetted datasets provisional layers are being sourced from the Global Marine Regions database (https://www.marineregions.org/).	Forum Fisheries Agency https://pacificdata.org/data/dataset/global-exclusive-economic-zone-200-nautical-miles/resource/417d95b1-a25f-483c-a8cd-f8ba3301ccee
Ecologically or Biologically Significant Marine Areas	EBSA	These areas were defined by the Convention of Biological Diversity Conference of Parties.	UN-UNEP https://www.protectedplanet.net/en
Other effective area-based conservation measures	OECM	These areas were defined by the Convention of Biological Diversity Conference of Parties.	UN-UNEP https://www.protectedplanet.net/en
Gross domestic product	GDP	Gross domestic product in USD dollars.	https://data.worldbank.org/indicator/NY.GDP.MKTP.CD

Extended Data Table 1. Sources, acronyms, and description of data used in the BCP spatial analysis of carbon sequestration and valuation of its service.