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Status of Polar Blue Carbon: Toward Recognition and Integration in Marine Policy

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1 | Introduction

Sustained increases in greenhouse gas (GHG) emissions from burning fossil fuels and the loss of natural habitats through human actions have caused unprecedented warming of the globe and biodiversity loss, threatening ecosystems and humanity (IPCC 2024). While it is indisputable that the most effective pathway to slow climate change is to phase out burning of fossil fuels, there is growing recognition that reduced consumption of global resources and energy and protection of ecosystems can also contribute to the reduction of atmospheric CO₂ concentrations (IPCC 2024).

The Arctic and Antarctic regions constitute approximately 20% of the global oceans and include some of the world's most productive ecosystems (Figure 1) (IPCC 2019). The polar oceans are hotspots of climate change, warming at a rate up to four times above the global average (Casado et al. 2023; Rantanen et al. 2022). Physical changes, such as the loss of sea ice and subsequent increase in surface temperatures alter the physical and chemical properties of these oceans, affect the

distribution of associated taxa and reshape coastal habitats (Ardyna et al. 2020; Barnes et al. 2018; Oziel et al. 2020; Sejr et al. 2024; Thyrring 2025). The available evidence suggests that the physical carbon pump in both polar regions reacts differently to climate change: the Arctic is expected to take up more atmospheric CO₂ with retreating sea-ice (Yasunaka et al. 2023), while increased upwelling in the Southern Ocean acts to reduce CO₂ uptake (Hauck et al. 2023). However, biotic pathways of CO₂ uptake and subsequent cycling of organic carbon are predicted to become amplified in both Arctic and Antarctic seas (Krause-Jensen et al. 2020; Peck et al. 2010).

So-called Nature-based Solutions (NbS) are a management action to address societal challenges such as climate change whilst at the same time supporting livelihoods, biodiversity and ecosystem resilience by managing, protecting and restoring natural ecosystems (Fetting 2020; IUCN 2020; UNEP 2022). Current guidance and frameworks exist for temperate to low latitude blue carbon systems to be integrated into these management approaches, yet polar blue carbon habitats are rarely considered in an international setting and within global studies.

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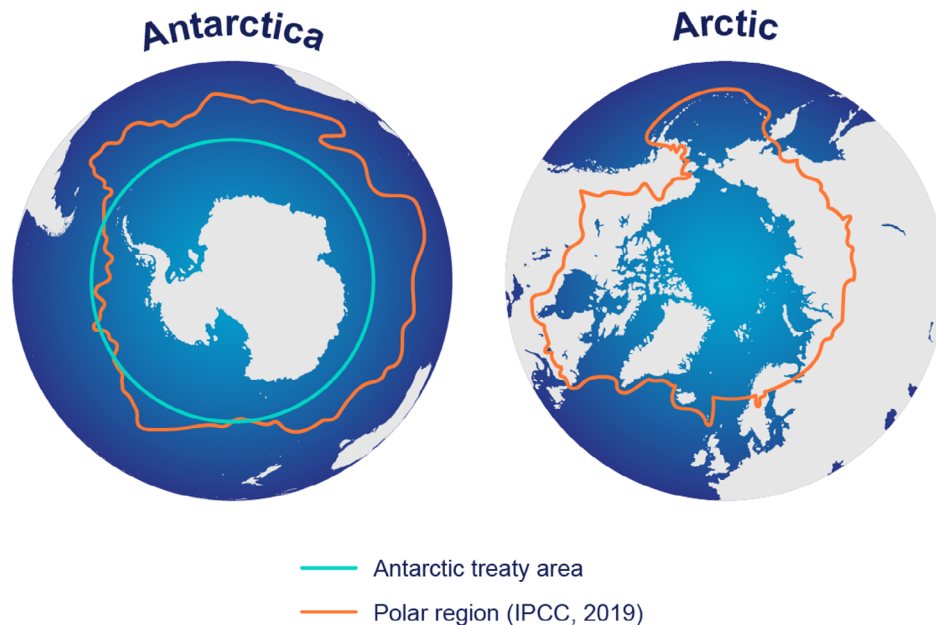


FIGURE 1 | Relevant geographic boundaries of the Antarctic and Arctic region as defined by the IPCC (2019).

Here, we review and assess the potential for including blue carbon in the active management of polar marine ecosystems. We highlight relevant habitats and strategies in the blue carbon context, and identify challenges, knowledge gaps, and opportunities for coordinating and implementing blue carbon management actions in the polar regions.

1.1 | Current Policy Setting and Framework for Blue Carbon Habitats

Increasingly, climate policy interventions are being implemented (Stechemesser et al. 2024), which include the management of blue carbon habitats as a NbS into international, national and regional policy frameworks (Sutton-Grier and Moore 2016; Wedding et al. 2021). Nationally Determined Contributions (NDCs) serve as the primary instrument for achieving the global objectives outlined in the Paris Agreement and drive some of these policy interventions. Under this framework, countries present climate action plans aimed at mitigating and adapting to climate change (United Nations 2021). NDCs follow a 5-year cycle, with each submitted plan expected to be more ambitious than the previous one (Article 4.3, Paris Agreement). This process, theoretically, provides a flexible and transparent mechanism to accelerate progress toward global climate change goals by allowing countries to prioritize national interests, enabling nations to set ambitious targets, and subjecting unmet commitments and inadequate goals to public scrutiny. The focus of NDCs is usually related to emissions and emissions-reductions for CO₂ and other greenhouse gasses but can also include wider aspects such as climate change adaptation and other co-benefits, for example, reducing nature loss, supporting biodiversity and habitat restoration, and increasing human societal welfare (Pörtner et al. 2021, 2023). Ideally, NDCs can mirror development plans to shift to ‘greener’ industrial and economic pathways, thereby benefiting national interests while helping to achieve Paris Agreement targets.

International efforts to encourage the protection of nature have accelerated over the last years. The recent Kunming-Montreal Global Biodiversity Framework (GBF) (UNEP 2022) commits nations to protect 30% of coastal and marine waters by 2030. The aim of the framework is to support biodiversity and renew the commitment to global ocean conservation. The High Seas Treaty, first adopted in 2023 (Agreement on Marine Biological Diversity of Areas beyond National Jurisdiction—BBNJ) will come into force in 2026 and aims to conserve and sustainably use marine biodiversity beyond national EEZs (10. Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction 2023). And in 2025, the European Union signed the Ocean Pact, a framework to support ocean conservation, and is moving from basic science toward implementing marine conservation measures (Directorate-General for Communication 2025) and initiating tools for private and corporate investments in credits that support biodiversity and conservation (European Commission 2025). This means the policy mechanisms are in place to strengthen the protection of natural carbon stores, but the polar areas have not received explicit considerations within them.

1.2 | Polar Blue Carbon Habitats

Since the concept of blue carbon originated in highly productive tropical and temperate coastal wetlands, the polar regions may seem an unlikely contender when looking for blue carbon habitats. However, recent work shows that high organic carbon storage in sediments shifts toward the poles during warmer interglacial periods (Cartapanis et al. 2016). Additionally, recent studies document and map the growing extent of potential blue carbon habitats (Table 1) (Krause-Jensen et al. 2020; Marbà et al. 2018; Ward 2020). Coastal blue carbon habitats include sea-grasses and salt marshes in the Arctic, both already designated as actionable, as well as the expanding macroalgal habitats on both

TABLE 1 | Overview of actionable (*) and emerging (°) polar blue carbon systems (Howard et al. 2023), their current extent (spatially or in terms of biomass [DW = dry weight, WW = wet weight]) and expected growth (+) or decrease (–) with climate change, associated carbon accumulation rates (CAR), and human threats.

Extent	Loss/Growth	Carbon accumulation rates in sediments (CAR)	Anthropogenic pressures (identified by author team and literature)
Saltmarsh (*)			
Arctic 5580–10,410 km ² (Worthington et al. 2024)	Arctic –1.5 to +1.8 km ² year ^{–1} (Murray et al. 2022)	Arctic 19–603 gC m ² year ^{–1} (Northern Norway) (Ward 2020)	– Coastal Infrastructure – Pollution – Non-indigenous species – Resource extraction (Murray et al. 2022; Newton et al. 2020)
Antarctic Not known	Antarctic Not known	Antarctic Not known	
Seagrass (*)			
Arctic Min 170 km ² (Krause-Jensen et al. 2022; Olesen et al. 2015; Ward et al. 2022)	Arctic –2.2% year ^{–1} (Canada) (Leblanc et al. 2023)	Arctic 1.3–10.5 gC m ² year ^{–1} (Greenland) (Marbà et al. 2018)	– Coastal Infrastructure – Pollution – Non-indigenous species – Resource extraction (Newton et al. 2020)
Antarctic Not known	Antarctic Not known	Antarctic Not known	
Macroalgae (°)			
Arctic 340,658 km ² potential area (Krause-Jensen et al. 2020)	Arctic +11,168 km ² year ^{–1} /893,400 km ² (by 2100 modeled area) (Assis et al. 2022)	Arctic Not known	– Coastal infrastructure – Dredging – Resource extraction – Harvest (Eger et al. 2026)
Antarctic ~21,000 km ² (Estimated by authorship based on Amsler et al. (2023) and Barnes (2017))	Antarctic +0.005–0.012 km ² year ^{–1} (Deregibus et al. 2023)	Antarctic Not known	
Microphytobenthos (°)			
Arctic Production 11–16 Tg Cyr ^{–1} Extent 931,231 km ² (median 1999–2018) (Attard et al. 2016, 2024)	Arctic 1.67-fold increase from 1999 to 2010 (600,000–1,000,000 km ²), possible decline toward 2019.	Arctic Not known	– Seafloor disturbance
Antarctic Production = 0.059 Tg Cyr ^{–1} Extent 2507 km ² (Calculation by Attard et al.)	Antarctic 3.5-fold increase from 1999 to 2010 (1000–3500 km ²), followed by rapid decline from 2010 to 2019. (Calculations by Attard)	Antarctic Not known	
Phytoplankton (°)			
Arctic 419 ± 33 Tg C year ^{–1} (Pabi et al. 2008)	Arctic +6.8 Tg C year ^{–1} (Lewis et al. 2020)	Arctic Export rate below photic zone for Beaufort Sea:	Pollution (Häder and Gao 2015)
Antarctic 1949 ± 70.1 Tg C year ^{–1} (Arrigo et al. 2008)	Antarctic Not known but increases in duration and biomass expected (Fisher et al. 2025; Rogers et al. 2020)	1–15 mg C m ^{–2} day ^{–1} (Miquel et al. 2015) and 38–104 mg C m ^{–2} day ^{–1} (Sallon et al. 2011)	
		CAR in sediment: ~4.5% of PP (Gulf of St. Lawrence) (Silverberg et al. 2000)	
		Antarctic CAR in sediments 0.68–19.08 gm ^{–2} year ^{–1} (WAP) (Isla et al. 2004)	

(Continues)

TABLE 1 | (Continued)

Extent	Loss/Growth	Carbon accumulation rates in sediments (CAR)	Anthropogenic pressures (identified by author team and literature)
Ice-associated algae (°)			
<i>Arctic</i> Equivalent to area of seasonal sea ice extent (15.5 mil–5.58 mil km ² sea ice extent winter—summer) (European Environment Agency 2025)	<i>Arctic</i> +4.02 Tg C year ⁻¹ (Tedesco et al. 2019) <i>Antarctic</i> +0.093 Tg C year ⁻¹ (Pinkerton and Hayward 2021)	<i>Arctic</i> Not known <i>Antarctic</i> Not known	Pollution (Dilliplaine et al. 2021)
<i>Antarctic</i> Equivalent to area of seasonal sea ice extent (19–3 mil km ² , sea ice extent winter—summer) (NOAA 2023) Total standing stock: 26.8–32.9 Tg C year ⁻¹ (Dalman et al. 2025)			
Fjord sediments (°)			
<i>Arctic</i> 215,032 km ² ± 43,539 km ² (Laruelle et al. 2024) <i>Antarctic</i> Not known	<i>Arctic</i> +150 km ² year ⁻¹ (based on glacier retreat rates 1980–2015) (Li et al. 2019) <i>Antarctic</i> +41 km ² year ⁻¹ (based on glacier retreat rates 1980–2015) (Li et al. 2019)	<i>Arctic</i> Canada: 28.0 ± 3.1–34.8 ± 71.6 gCm ⁻² year ⁻¹ Greenland: 356.6 ± 849.4 gCm ⁻² year ⁻¹ (ref?) <i>Antarctic</i> (WAP): 73.4 ± 80.6 gCm ⁻² year ⁻¹ (Bianchi et al. 2020)/56,909 ± 29,833 tCyr ⁻¹ (Zwerschke et al. 2022)	Seafloor disturbance (Zhang et al. 2024)
Shelf sediments (°)			
<i>Arctic</i> ~10 ³ × 7000 km ² (extended shelf disputed) (Harris et al. 2014) <i>Antarctic</i> ~10 ³ × 7000 km ² (extended shelf disputed) (Harris et al. 2014)	<i>Arctic</i> Unchanging <i>Antarctic</i> Unchanging, except for proportion under ice shelf	<i>Arctic</i> 1.7–13.4 g C m ⁻² year ⁻¹ (Barents Sea) (de Freitas et al. 2024) <i>Antarctic</i> 5–23 g C m ⁻² year ⁻¹ (Sinclair et al. 2025)	Seafloor disturbance (Zhang et al. 2024)
Glacial troughs sediments (°)			
<i>Arctic</i> ~24% of shelf area (Harris et al. 2014) <i>Antarctic</i> ~40% of shelf area (Harris et al. 2014)	<i>Arctic</i> Unchanging <i>Antarctic</i> Unchanging	<i>Arctic</i> 9.29 ± 6.89 g C m ⁻² year ⁻¹ (Norwegian Shelf) (Diesing et al. 2024) <i>Antarctic</i> 3.5–19.08 g C m ⁻² year ⁻¹ (Gerlache Strait) (Isla et al. 2002)	Seafloor disturbance (Zhang et al. 2024)
Deep sea sediments (°)			
<i>Arctic</i> Arctic basins proper 10 ³ × 4737 km ² (Harris et al. 2014) <i>Antarctic</i> ~15 × 10 ⁶ km ² (70%–80% of Southern Ocean) (Harris et al. 2014)	<i>Arctic</i> Unchanging <i>Antarctic</i> Unchanging	<i>Arctic</i> 5.26 ± 2.18 g C m ⁻² year ⁻¹ (Norwegian abyss) (stock 500 g m ⁻²) (Diesing et al. 2024) <i>Antarctic</i> Not knowm	Seafloor disturbance (Zhang et al. 2024)

Note: To provide a better understanding of available knowledge on some blue carbon systems (e.g., marine sediments and primary producers) they are split into different components.

poles, currently under consideration (Tables 1 and 2) (Howard et al. 2023). Although the current extent of these habitats can be quite substantial, with approximately 17% of the global extent of saltmarshes located in the Arctic (Worthington et al. 2024), their global role is likely to be underestimated, as few global studies include them. Whilst the carbon accumulation rate of these rooted macrophyte dominated ecosystems is still relatively low in the Arctic compared to temperate and tropical regions, other polar marine ecosystems, such as kelp forests or fjord sediments, may support larger carbon storage (Table 1). In the polar coastal realm, a particular focus has been on the blue carbon potential within fjord habitats, which dominate part of the Arctic (e.g., Canada, Greenland, Norway) and the West Antarctic Peninsula (WAP). Here, high primary production coupled with rapid sedimentation processes fuelled by marine terminating glaciers (Meire et al. 2017; Zwierschke et al. 2022) and short carbon capture to sequestration pathways have suggested their potential significance as a carbon sink (Table 1). However, the extent to which processes in the open ocean and within shelf and deep-sea sediments contribute to carbon storage is often overlooked. Primary production in the open polar ocean, for example, is expected to increase with decreases in sea-ice cover, which may lead to greater amounts of captured carbon reaching carbon sinks (Table 1). While the literature aiming to quantify carbon uptake, storage, and sequestration rates within these individual habitats is growing, there are still substantial knowledge gaps related to the distribution, production, and sequestration potential of polar blue carbon habitats, currently and under climate-change scenarios (Tables 1 and 2). Importantly, there are to our knowledge no reports on the effects of management outcomes for polar blue carbon despite their increasing accessibility and vulnerability to anthropogenic pressures (Table 1), which may hamper their designation as blue carbon habitats.

2 | Ideal Management Scenario

Currently, only ~10% of the world's ocean areas are protected, and the polar regions remain the least protected amongst them (Pike et al. 2024). Only 4.6% of the Southern Ocean is a “no take” zone and only 5.2% of seas in the Arctic are “managed” (Barry et al. 2023; Brooks et al. 2020). As one of the least anthropogenically disturbed, yet highly vulnerable systems, the polar oceans would be an obvious target for an integrated ecosystem approach that focuses on a timely and lasting implementation of management strategies in order to fulfill the GBF's 30 by 30 target (Shin et al. 2022).

2.1 | Holistic Management

Protection of natural ecosystems has typically had narrow aims, for example conservation of a specific species or habitat, without much consideration of closely linked ecosystem services such as climate mitigation (e.g., carbon storage and sequestration). Across many environments, biodiversity in blue carbon habitats can be positively linked with the ability of these ecosystems to store carbon (Xu et al. 2020) and efficacy of management is typically higher if wider aspects, such as benefit to humanity are considered and enacted (Pörtner et al. 2023; Shin et al. 2022). Although there is no indigenous and traditional/local knowledge around

Antarctica, such knowledge exists in the Arctic, and can greatly assist in the design and permitted use of newly protected areas (Fink-Mercier et al. 2024). For some habitats under consideration for actionable blue carbon, such as kelp forests, there is also a need to consider the spatial aspect of the capture-to-sequestration pathway because these habitats export organic carbon to sinks beyond the habitat (Krause-Jensen and Duarte 2016). Protecting, for example, the coastal kelp habitat would therefore offer only partial protection and would require additional consideration of any captured carbon that reaches shelf sediments or the deep sea (Filbee-Dexter et al. 2024). Sequestration in carbon reservoirs beyond the coastal habitats are challenging to identify and quantify. Modeling efforts (Krumhansl et al. 2025), improved remote sensing techniques (Mahdianpari et al. 2026) and observational data (Zwierschke et al. n.d.) could guide identification of relevant habitat types for an ecosystem based management approach, such as adopted by the Arctic Council in the Kiruna Declaration (Kiruna Declaration 2013). This would aim to protect all components of a polar blue carbon habitat from source to sink (Stechemesser et al. 2024).

2.2 | Ensuring Timely and Relevant Management Interventions

Short timescales for meeting key global climate and biodiversity targets, coupled with the likelihood of increasing human pressure in the polar regions, call for an acceleration in the designation of protected areas across these vulnerable regions. Ideal targets for designation are near-intact and mature, carbon rich and diverse ecosystems (Goldstein et al. 2020). Considerations of which habitats and regions should be prioritized could include dimensions outlined by Goldstein et al. (2020) such as (i) manageability at the local scale—or whether the carbon stock in the ecosystem can be directly positively or negatively influenced by human actions; (ii) magnitude of vulnerable carbon—or how much carbon would be released through the destruction of the ecosystem; and (iii) recoverability of ecosystem carbon—or could carbon that was released after a disturbance event be recovered within meaningful time scales. These considerations contribute toward estimation of avoided emissions, that is, preventing already sequestered carbon from re-entering the atmosphere. Ideally, protection would focus on relevant ecosystems with already high carbon stocks, a known potential for high sequestration rates, or those most vulnerable to human impact such as areas on the cusp of becoming sea-ice free (Table 2). Since relevant knowledge about the majority of these potential Polar blue carbon habitats is largely lacking (Table 2), the best current approach is likely to apply the precautionary principle and minimize potential harmful human activities until a better baseline of science about different polar blue carbon habitats is available to inform management activities.

2.3 | Consistency of Management Across Large Temporal and Spatial Scales—Ensuring Permanency

Current designation processes are set by governments and economic imperatives based on internationally agreed targets and

TABLE 2 | Overview of climatic drives and key scientific knowledge gaps (GHG = greenhouse gas emissions, CAR = carbon accumulation rate) for the actionable (*) and emerging (°) emerging polar blue carbon systems (according to Howard et al. (2023)).

Habitat	Climatic drivers	Key knowledge gaps
Saltmarsh (*)	Sea level rise Coastal erosion	Extent and standing stock Carbon accumulation in sediment (CAR) GHG across polar habitats Response to climate change
Seagrass (*)	Increased waves due to loss of sea ice Changes in light availability Warming and potential range expansion	Extent and standing stock Status (condition) CAR and GHG across polar habitats Response to multiple climatic drivers
Macroalgae (°)	Underwater light climate Ice scour and wave action Urchin grazing	CAR Extent and standing stock Remineralisation rates
Microphytobenthos (°)	Changes in light availability	Extent and standing stock Impact of grazing CAR Remineralisation rates
Phytoplankton (°)	Changes in light availability Changes in nutrient availability Warming temperatures	Response to multiple drivers Impact of changing grazing pressure Sequestration rates Size of under ice production Impact of changes in dominant species
Ice algae (°)	Changes in light availability linked to ice and snow thickness	Extent and standing stock CAR
Marine sediments (°)	Loss of cryosphere	Few observations of CAR Carbon sources (terrestrial, marine) Impact of climate change on biota Impact of terrestrial carbon (Arctic) delivery

incentives. At the same time, rhetoric around climate change and nature protection has dramatically shifted within the recent political landscape (Gruber 2025), often ignoring the fact that climate change is a real and growing threat to human wellbeing. This development is of concern for the global population and stresses the need for a multilateral approach to climate change mitigation and nature protection which prioritizes internationally agreed targets and initiatives over short-term political aims of individual nations. For major natural carbon stores that span across or lie beyond national borders, such as deep-sea sediments (Atwood et al. 2020), it is in the global interest to secure their long-term protection and create incentives for all governments to uphold it. Intergovernmental bodies such as IPCC, IPBES, and the International Seabed Authority could aid these goals with collation, evaluation, and best-practice advice for achieving the permanent protection of polar blue carbon resources.

3 | Roadblocks

Meaningful and lasting protection of polar blue carbon habitats is currently hampered by a set of societal challenges and scientific uncertainties. The most important of these roadblocks are described below.

3.1 | Integration Between Science and Policy

Polar blue carbon habitats and the avoided emissions their protection against human pressures represent are currently not considered in blue carbon policy frameworks. Blue carbon terminology has been developed with a focus on coastal wetlands in tropical and temperate regions, which limits its adaptability for non-traditional blue carbon habitats including polar blue carbon habitats. To be relevant in climate policies, blue carbon habitats must represent a significant scale of greenhouse-gas (GHG) fluxes and long-term carbon storage and, they must be actionable implying that management actions such as protection of threatened habitats or restoration of lost ones can lead to net reduction of GHG emission, which is measurable and additional to what would have happened in the absence of the action (Howard et al. 2017, 2023; Lovelock and Duarte 2019). These are not obvious criteria for carbon-rich habitats in the polar region because effects on the carbon storage of the emerging threats resulting from increased human impacts as the regions become more accessible are difficult to quantify. This means there is no clear policy pathway to recognize the large emissions that the loss of these habitats would constitute globally. Additionally, no consideration has been given to polar blue carbon habitats currently emerging (from loss of ice cover) or growing as a consequence of climate

change (Table 1). These habitats may take decades to mature (see Peck et al. 2010; Zwierschke et al. 2021), and their overall contribution to climate change mitigation may only become significant within centuries (Węśławski et al. 2017), yet their protection now could be beneficial to future generations. This lack of recognition also reduces policy-motivated funding opportunities to fill prevalent knowledge gaps to enable the inclusion of polar blue carbon habitats in policy frameworks in the near future.

3.2 | Standardization

A lack of standardization in measuring processes along the source-to-sink carbon pathways is complicating the assessment of an ecosystem's blue carbon potential across wider regions (Morley et al. 2026). Definitions of specific terms and their measures, such as sequestration, are also not unanimously agreed upon and often cause misunderstandings across policy and science (Visser 2025) (Table 1). Further, consistency in both terminology and measurement is necessary for carbon accounting to show storage and additionality of each system and avoid double counting of carbon pools. The time scale of sequestration typically ranges from decadal to century scale in blue carbon projects in opposition to a more absolute understanding of sequestration over millennial scale (e.g., Visser 2025). Likewise, blue carbon projects require assessment of additionality relative to the scenario without the specific project (e.g., VERRA 2026) rather than against a millennial scale baseline of global carbon fluxes (Visser 2025). While strict standards for additionality relative to specific baselines are key criteria in relation to carbon credits, there is a need to consider whether/how the protection of the large polar carbon stores against human pressures can be embedded in blue carbon policies under other standards and without associated carbon credits.

3.3 | Jurisdiction

Governance mechanisms currently in place both require and incentivize protection and enhancement of blue carbon systems. Mixed jurisdictional frameworks, however, hinder the use of mechanisms such as Nationally Determined Contributions (NDCs) and often require multi-national cooperation. In Antarctica (Figure 1), the key framework for governance is the Antarctic Treaty, signed by 12 nations. This treaty bans military activity and mineral extraction. Efforts to include the protection of areas of high biodiversity and importance for carbon burial cannot be considered in the NDCs for Antarctic waters as this region is beyond national jurisdiction. However, the Convention for the Conservation of Antarctic Marine Living Resources (CCAMLR) provides a means to include blue carbon goals and priorities in current guidelines and monitoring activities. Any proposal for designation requires consensus support of all signatory nations, which in practice is very hard to achieve for a variety of reasons beyond merely the appropriateness of the area in question to meet synergistic nature and climate goals. This is evident in the ongoing

efforts to protect the Weddell Sea (Teschke et al. 2022). Areas of the Southern Ocean not covered by the Antarctic Treaty are part of the adjacent nations' EEZ, which may provide an opportunity to protect Antarctic blue carbon systems on a national level.

In the Arctic (Figure 1), seven nations have exclusive economic zones (EEZs) in Arctic waters: Canada, Greenland/Kingdom of Denmark, Finland, Iceland, Norway, Russia, and the United States. This means that any inclusion into NDCs could be implemented on a national basis. The rest of the Arctic Ocean, outside the EEZs that stretch 200 nautical miles from the coast, is under the jurisdiction of the United Nations Convention on the Law of the Sea. Additionally, the central Arctic Ocean is considered international waters covered by the Biodiversity Beyond National Jurisdiction Agreement. Research related to Arctic ecosystems, biodiversity, and pressures is coordinated through several working groups under the Arctic Council and the International Council for the Exploration of the Seas (ICES). As in Antarctica, legal frameworks for the integration of national and transnational management actions exist in the Arctic; however, their implementation is often hampered by the current geopolitical situation (Leclerc 2024).

3.4 | Uncertainties

"Blue Carbon" is a concept that has only recently been considered in polar regions and is surrounded by uncertainties which include lack of knowledge, predictability, and guidance for, but also from, policy makers.

3.4.1 | Lack of Knowledge or Data

Polar habitats are expensive and logistically difficult to access and study. Hence, we often lack the most basic knowledge, such as coastal substratum characteristics, which hampers our ability to establish a baseline and reliably project the emergence of polar blue carbon habitats (Thyrring et al. 2025). Some essential environmental variables, such as sea-surface temperature, light attenuation, or primary production, can be extracted from remote sensing products. Yet, owing to low spatial resolution, cloud coverage, abundance of ice, bias due to organic matter inputs from land, and the fact that micro-algae concentrations in polar regions often occur below the depth of remote sensing penetrations or even under or within sea ice, these data still do not provide a reliable baseline for our estimates (Ardyna et al. 2020). Even less is known about actual carbon capture, storage, and sequestration rates across large regions of the Arctic and Antarctic (but see Sinclair et al. 2025). Except for some specific locations (Table 1), very few studies have quantified the potential of blue carbon habitats across larger regions of the polar seas (Table 1). Whilst some of these habitats exist and more are likely to emerge in polar regions (Table 1), we are currently struggling to pinpoint exact locations, carbon stocks, and potential threats from increasing human pressures they are facing (Table 1), thereby impeding the integration of polar blue carbon habitats into NDCs or other national and international frameworks.

3.4.2 | Lack of Predictability

Whilst we have a clear understanding of how climate change affects some of the physical large-scale processes in the polar regions, such as ice-loss or ocean warming, we know less of the wider implications of these changes to the biology and carbon-related ecosystem services in these areas (e.g., Ager et al. 2025). It is often unclear even what the direction of change will be: whether these changes will increase carbon uptake/storage/sequestration or promote greater emissions of carbon. Increasing seawater temperatures, retreating sea-ice, altered ocean currents, increased stratification and input of freshwater and terrestrial material are expected to alter current CO₂ uptake rates in the polar oceans (Hauck et al. 2023; Oziel et al. 2025; Yasunaka et al. 2023). For example, warming and increased light availability owing to sea-ice retreat and less snow cover on sea ice may stimulate marine photosynthesis and thereby increase CO₂ uptake by marine primary producers in the Arctic and Antarctic (Ardyna et al. 2020; Arrigo et al. 2008; Attard et al. 2024). However, in the Arctic, many coastal regions are experiencing high rates of coastal erosion (Nielsen et al. 2022), as well as increased river run-off, including from land-terminating glaciers, leading to increased turbidity and light attenuation and potentially reducing phytoplankton and macroalgal production and carbon storage rates (Feng et al. 2021; Lebrun et al. 2022; Meire et al. 2023). These changes often occur at a local or regionally restricted level and their knock-on effect to the wider ocean functioning is poorly understood, making reliable large-scale projections across the polar regions difficult.

3.4.3 | Lack of Guidance

Because the field of blue carbon is relatively young and has only recently gathered the attention of policy makers, there is an overall lack of guidance and clarity for policy-relevant uncertainties. The definition of blue carbon in a policy context is continuously evolving, with different research groups exploring the consequences of broadening (Howard et al. 2023; James et al. 2024), altering (Sheehy et al. 2024), or narrowing of the blue carbon terminology (Williamson and Gattuso 2022). Private and national foundations have built on this and shaped definitions toward their own focus. In order to incentivize individual nations to protect carbon-rich habitats outside the current blue carbon scope, there is a strong need to update, harmonize, and standardize the current legislative approach toward such carbon-rich habitats through international bodies based on the most up-to-date science (Wartman et al. 2025).

While the current Blue carbon terminology is not adapted for polar blue carbon habitats, the roles of the individual stakeholders are even more blurred. Science can provide evidence on the carbon sequestration potential of a habitat, but it is unclear who sets thresholds on what constitutes a blue carbon habitat and who will adapt terminology to be more inclusive. Such decisions are more easily implemented on local and national levels which do not require international agreement and transferability (e.g., Japan's J-Blue Credit) (Asadnabizadeh and Moe 2024), but are much more complex to achieve on an international level.

4 | Recommendations

We recommend the following actions be taken to safeguard polar marine ecosystems including their climate mitigation services (Figure 2).

4.1 | Phasing Out Fossil Fuels and Ultimately Reduction of CO₂ Emissions to Zero

Although beyond the scope of this work, our first priority must be to phase out fossil fuels and ultimately reduce CO₂ emissions to near-zero. Currently 55% of the anthropogenic CO₂ emissions are captured by natural systems and this fraction is already affected by human-made climate change (Friedlingstein et al. 2025). Therefore, it is crucial to understand that nature-based solutions can only be effective if CO₂ emissions are reduced drastically in conjunction with the protection of natural carbon capture and sequestration habitats.

4.2 | Improve Scientific Understanding of Polar Blue Carbon Habitats

Our current understanding of polar habitats and their processes and drivers is still limited. Here, we have highlighted some of the most obvious knowledge gaps on the sequestration potential of existing and physically emerging polar blue carbon systems (Table 1). These include the response of carbon pathways to climate change and anthropogenic pressures, and a clear demonstration of the relationship between carbon capture potential and biodiversity. Working with policy makers to prioritize scientific investigations to promote effective management measures for polar blue carbon habitats will be essential.

4.3 | Recognition and Inclusion of Polar Blue Carbon Habitats by Policy

Clearer guidelines, internationally accepted standardization of measures and pathways for the recognition of non-traditional blue carbon habitats are required for integration of polar blue carbon into policy frameworks. If this can be rooted in sound scientific evidence, it could lead to more targeted protection of these important carbon reservoirs. To simplify and accelerate the process, carbon uptake, storage and sequestration potential of a habitat could be included as a designation feature in national management frameworks of polar nations as is already occurring in Australia (Department of Climate Change, Energy, the Environment and Water 2025). Initial focus could be on protecting polar habitats that are known for their high and unrecoverable carbon content, efficient pathways or unique ecosystem properties:

- Marine polar sediments: encompass some of the least disturbed regions of the world (Atwood et al. 2020; Zhang et al. 2024). Thus, some of their organic carbon stores have remained largely intact throughout the industrial revolution and the 20th century.

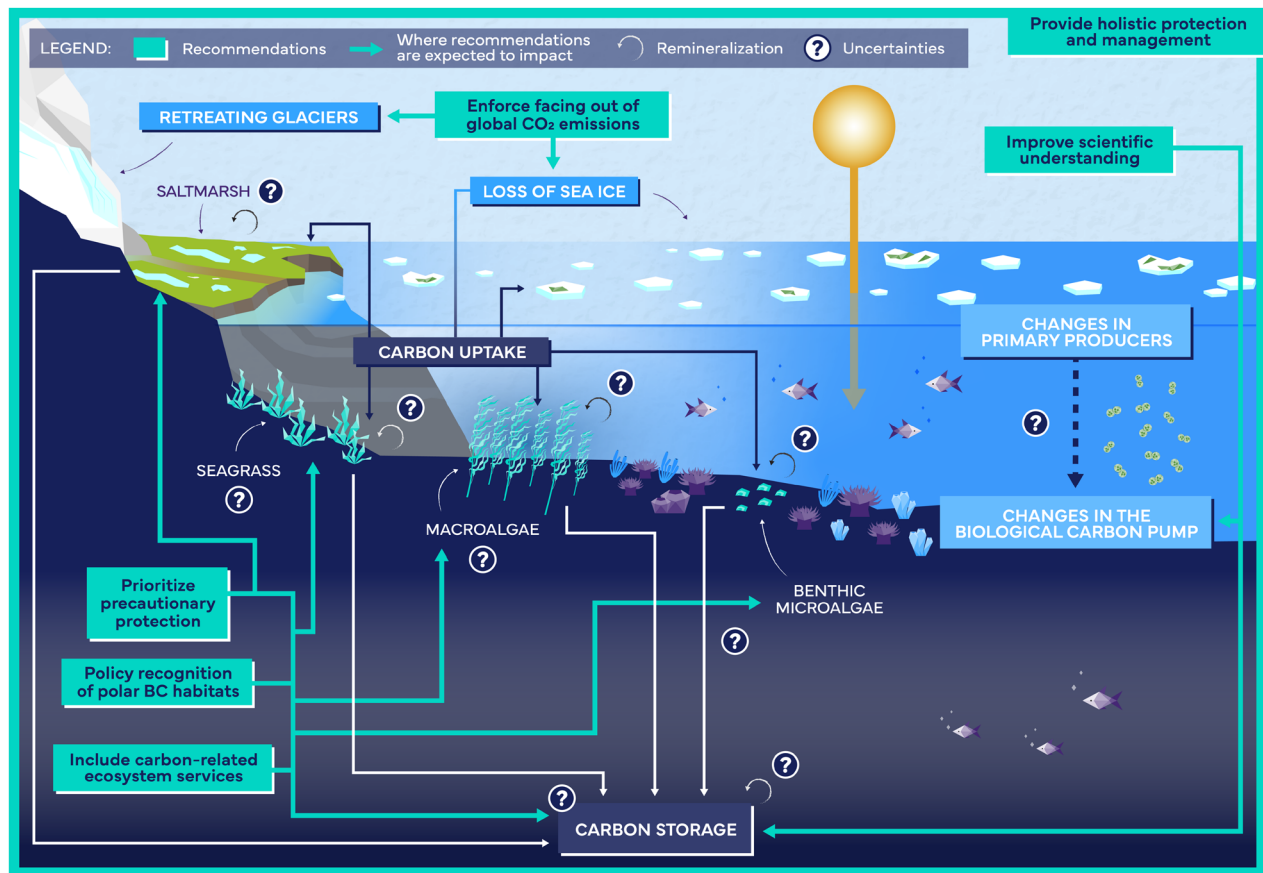


FIGURE 2 | Expected climate and ecosystem changes and uncertainties in polar environments and recommendations for better management and protection of these carbon rich habitats.

- Fjord systems: store disproportionately high concentrations of carbon and have short and local carbon pathways (Bianchi et al. 2020).
- On a global level, the Southern Ocean has anomalously high and unique biodiversity (Rogers et al. 2020) and high sediment carbon richness (Sinclair et al. 2025).

4.4 | Application of Precautionary Principle

Although polar blue carbon systems are still surrounded by great uncertainties, they remain the most pristine systems of our planet. The UN target of protecting 30% of nature by 2030 provides a great incentive to implement greater protection of carbon rich habitats in the polar regions, especially in areas with limited anthropogenic influence. Not only would this encompass the preservation of endemic and rare species as well as biodiversity hotspots but also large carbon stores. Protection of such natural habitats (e.g., fjords, pristine seafloor, and the Southern Ocean) would avoid further emissions from natural carbon reservoirs through anthropogenic exploitation.

5 | Conclusions

The polar oceans and their ecosystems host unique biodiversity and play a critical role in the global climate system that must be

protected. The concept of polar blue carbon habitats is valuable because it underscores the need to account for carbon storage among the key functions provided by polar marine ecosystems—functions that must be integrated into a holistic approach to ecosystem management. We urge decision-makers to recognize that global human well-being is closely linked to healthy ecosystems and to use existing policy frameworks to fulfill our ethical obligation to protect these ecosystems for future generations. Here, we demonstrate that significant scientific knowledge gaps and insufficient management frameworks currently make it difficult to ensure additionality and permanence in polar blue carbon initiatives. These limitations prevent the robust and transparent incorporation of polar blue carbon into current climate policy. However, we recommend that CO₂ uptake and carbon storage by polar marine ecosystems be recognized as important ecosystem services, and that focused research is needed to resolve identified knowledge gaps related to their response to climate change and direct anthropogenic stressors. Analogous to the widespread recognition of forestation as an important land-based Nature-based Solution, the protection of carbon-rich marine habitats and the maintenance or enhancement of living biomass in the polar ocean should become an urgent policy goal. While such actions cannot be framed as offsets (at this stage), it would be beneficial on both a societal and political level by (i) satisfying the need for implementing greater protection of our seas by 2030; (ii) laying the groundwork for future recognition of their carbon storage potential once science and policy have caught up; and (iii) ensuring

carbon-rich habitats are protected from destructive actions that would hamper or reverse their carbon storage abilities; as well as (iv) strengthen their resilience to climate change.

Glossary

Term	Definition
Blue Carbon	All biologically driven carbon fluxes and storage in marine systems that are amenable to management (IPCC 2019)
Polar Blue Carbon Habitats	Carbon rich marine habitats in polar regions
Actionable blue carbon habitats	Habitats such as seagrass beds or saltmarshes for which scientific evidence suggests clear potential for an inclusion in blue carbon policy frameworks, and for which management activities can reduce greenhouse gas emissions or enhance carbon sinks (Howard et al. 2023)
Non-actionable blue carbon habitats	Habitats without sufficient scientific evidence underpinning their climate mitigation potential (Howard et al. 2023).
Physically emerging environments	Newly generated or expanding physical environments (e.g., embayments becoming ice-free following ice shelf collapse) or key modification to existing habitats (e.g., changes to ocean temperature, chemistry or light conditions enabling greater photosynthetic uptake of CO ₂ (Peck et al. 2010))
Emerging blue carbon habitats	Habitats that could be considered for management when scientific and policy related uncertainties are resolved (e.g., the inclusion of macroalgae or unvegetated sub-tidal sediments) (Howard et al. 2023)
Carbon sink	A reservoir (natural or human, in soil, ocean, and plants) where a <i>greenhouse gas</i> , an <i>aerosol</i> or a <i>precursor</i> of a greenhouse gas is stored (IPCC 2022)
Sequestration	The long-term removal of CO ₂ or other forms of carbon from the atmosphere, with secured storage on climatically significant time scales (decadal to century). The period of storage needs to be known for climate modeling and carbon accounting purposes (IPCC 2019)

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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