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REVIEW

Counting (on) blue carbon—Challenges and ways forward for carbon accounting of ecosystem-based carbon removal in marine environments

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Abstract

The latest IPCC assessment report highlights once more the need for negative emissions via carbon dioxide removal (CDR) measures to reach ambitious mitigation goals. In particular ecosystem-based CDR measures are currently the focus of national net-zero strategies and novel carbon crediting efforts. Blue carbon dioxide removal (blueCDR) options are anthropogenic activities that aim to enhance such ecosystem-based carbon sinks in the marine environment. The protection and conservation of existing marine ecosystems that naturally sequester carbon, does not qualify as CDR. Using blueCDR as an example, we highlight key challenges concerning the monitoring and evaluation of marine carbon fluxes for carbon crediting. Challenges specific to ecosystem-based CDR measures are i) the definition of baseline natural carbon fluxes, which is necessary for ii) clear anthropogenic CDR signal attribution, as well as iii) accounting for possible natural or anthropogenic disturbances of the carbon stock and hence an assessment for the durability of the carbon storage. In addition, the marine environment poses further monitoring and evaluation challenges due to i) temporal and spatial decoupling of the carbon capturing and sequestration processes, combined with ii) signal dilution due to high ecosystem connectivity, and iii) large pre-existing carbon stocks which makes any human-made increase in carbon stocks even harder to quantify. To increase the scientific rigour and ensure additionality behind issued carbon credits, we support the current trend of focusing monitoring efforts on carbon sequestration rather than on capturing processes, and on establishing a baseline for natural carbon sequestration in diverse marine ecosystems. Finally, we believe that making carbon credits subject to dynamic adjustments over time, will increase their credibility.

Introduction

The latest Intergovernmental Panel on Climate Change (IPCC) assessment report highlights once more the need for carbon dioxide removal (CDR) measures to achieve net-zero emissions by mid-century to limit global mean temperature increase to 1.5 or 2°C by the end of the century [1,2]. Increasing interest from industry and governments to achieve their net-zero goals puts pressure on

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science and technology to deliver CDR options that are effective in durably removing carbon, technologically feasible, economically viable, and ideally with co-benefits to the environment and/or society. A trillion dollar market for carbon credits is arising [3], while verification companies are establishing protocols for standardised monitoring, reporting and verification (MRV) to avoid double counting and greenwashing (e.g., [4,5]). On another level, the European Union is currently collecting feedback on their proposal for a regulation of carbon removal certificates [6]. Most of the carbon removal within the national determined contributions originate from terrestrial CDR measures [7,8]. However, as resources (freshwater and fertiliser) and space limitations become more evident for terrestrial ecosystem-based CDR options [9–12] interest in marine CDR (mCDR) options, and especially those focusing on ecosystem based carbon sequestration is increasing [13–17]. Marine CDR options appear attractive because they have a large theoretical potential in terms of upscaling, provide potential co-benefits for biodiversity, food security and coastal protection and in some cases are low cost (e.g., [18]). And while some carbon credit frameworks are being brought forward for tidal wetland systems, including mangroves, tidal marshes, tidal forested wetlands, and seagrass meadows (e.g., Verra Carbon Standard v2.0, 2021), almost no verification protocols are in place for CDR in the open ocean environment [19]. Furthermore, the VCS protocol as well as the core carbon principles of the integrity council for the voluntary carbon market (ICVCM) refer to conservation and restoration activities or climate mitigation activities to generate carbon credits, outlining how to get estimates for emissions reductions and removals, without clearly distinguishing between the systemic effects of the two [20–23]. As a critique and way forward away from such arbitrary accounting practices of avoided, reduced or removed emissions, initiatives are calling for a dedicated framework for carbon removal, recognizing the different roles that emission reduction and removals will play in the coming years to decades [24,25].

All carbon captured via biological processes and sequestered in marine ecosystems from the coast to the open ocean is what we refer to as blue carbon (Fig 1). This includes mangroves,

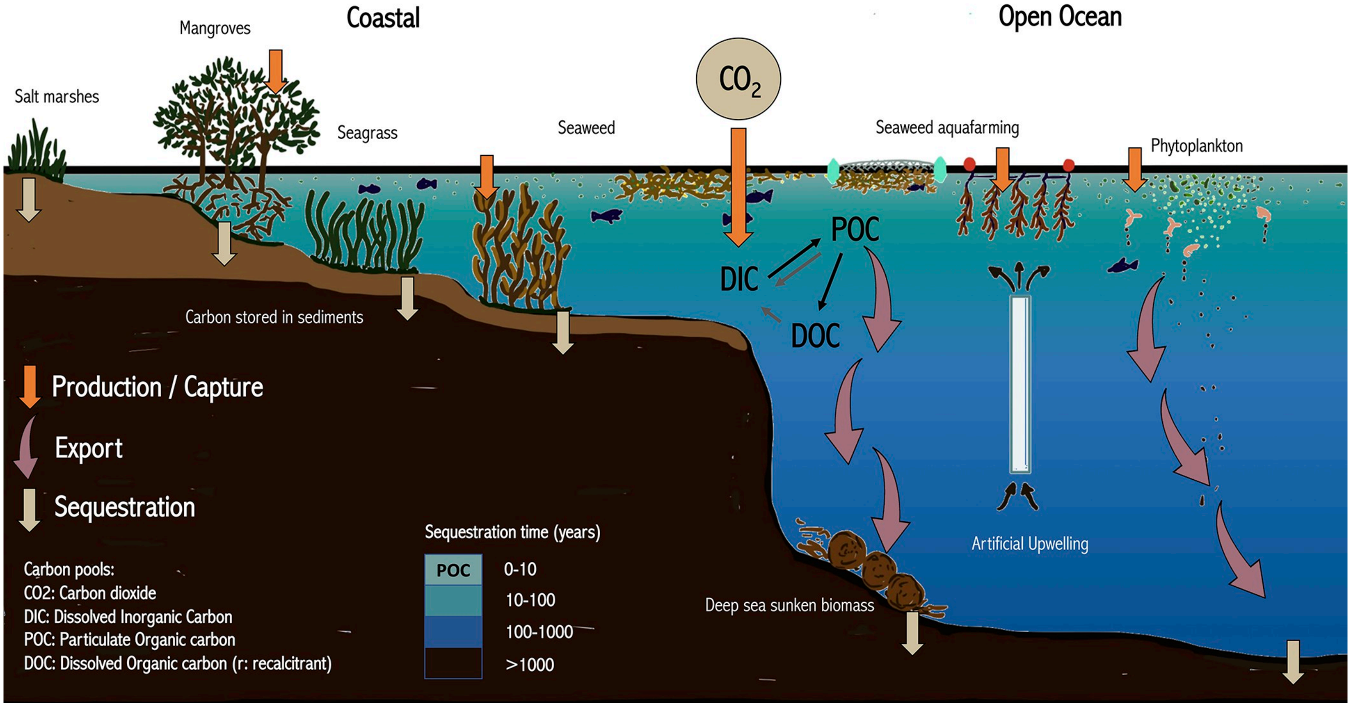

Fig 1. Overview of blue carbon dioxide removal approaches. Various approaches are brought forward to enhance the biological carbon uptake in coastal to open ocean ecosystems.

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seagrasses, saltmarshes, macroalgae, and phytoplankton. Carbon sequestration in these marine ecosystems occurs in the primary producer biomass, with time scales of carbon storage in biomass from decades to centuries, with longer term storage possible in the sediments where the carbon is stored from centuries to millennia or in the excreted dissolved organic recalcitrant fraction (see Box 1). Note, that due to this gradual distinction of carbon storage time scales, we refer to carbon storage duration, rather than permanence.

Box 1: Carbon capture and sequestration in the marine environment (see Fig 1)

The ocean holds 50 times more carbon than the atmosphere [26]. This carbon is partitioned into three main carbon pools: the dissolved inorganic carbon (DIC), the dissolved organic carbon (DOC) and the particulate organic carbon (POC). Carbon can be taken up by both physico-chemical and biological processes which determine the concentration of carbon in the ocean and the rate at which it takes up carbon dioxide (CO_2) from the atmosphere.

Submerged coastal vegetation (e.g., seagrasses and benthic macroalgae), floating macroalgae and phytoplankton consume DIC, and biologically capture carbon through photosynthesis, release part of it as DOC [27–29] and use the rest to build up their biomass (POC). From the carbon that is released into the water, the easy to digest part is eaten by bacteria or degraded by ultraviolet radiation in the surface ocean, returning the carbon within days to the DIC pool. A significant proportion of the DOC is however so difficult to digest that it remains in the ocean for centuries. This remains a vast but poorly quantified pool of sequestered carbon in the ocean [30].

The concentration of DIC in surface waters is determined by its exchange rate with the CO_2 in the atmosphere. This means that, if DIC is consumed in a parcel of water by algae, more CO_2 will be absorbed from the atmosphere when the surface water re-equilibrates with the air. This process is fast and occurs within minutes, hours or days depending on temperature, wind speed and the depth of mixing in the water [31].

Carbon stored in the biomass is either grazed upon and enters the food web (~10% of primary producer biomass, [32], or it sinks to the deep ocean or sediment when the phytoplankton, macroalgae or seagrass dies. Phytoplankton sinks slower (0.2~400 m d^{-1}, [33,34] than macroalgae [35]. Storage durability for phytoplankton carbon depends on sequestration depth and location and can range from a few decades to thousands of years [36,37]. While the permanence of sunken macroalgae carbon into the deep sea is unknown but could be >1000 years if the macroalgae is buried in the sediment [14,38]. The part that enters the food web is either consumed immediately and returns to the DIC pool, or it forms part of the biomass in the next trophic level, or it is released as faecal material and sinks to the seafloor. At the seafloor, part of the sunken biomass is consumed by benthic organisms or by sediment microbes and only a very small percentage is preserved for centuries in the seafloor sediments. Consumption rates at the deep sea are very slow [39,40] and even if all the sunken biologically sequestered carbon would return to the DIC pool, current ocean circulation patterns would ensure that carbon would stay in the deep waters for between 500–1500 years depending on the depth and the location of the deep water [31]. Thereafter ~70% of the DIC-enriched waters would return to the surface again and could then re-exchange the DIC with the atmosphere [37].

Blue carbon dioxide removal (blueCDR) options are anthropogenic activities that aim to enhance such ecosystem-based carbon sinks in the marine environment. While the potential scalability of blueCDR options is enormous, especially in the open ocean [41], uncertainties remain concerning the assessment of their efficacy, potential side-effects, economic viability and the legal framework to regulate them [42]. A limited availability of high-quality data adequately resolved in time and space is the main reason why the ocean's role in the global carbon budget continues to be subject to large uncertainties [43–45]. In addition, marine ecosystems have a very high natural variability, which makes quantifying baseline carbon stocks and fluxes challenging [44]. For accurate carbon accounting of blueCDR, the monitoring and evaluation of durably stored carbon over time, however, needs to be understood against this background of natural variability in the sparsely sampled marine environment. This is why, especially in the context of blueCDR options, accurate carbon accounting remains a key challenge.

In the following we will use blueCDR options as an example to highlight accounting challenges specific to ecosystem-based CDR options and the marine environment (Section 2), to point out how these challenges can interfere with the legal, and socioeconomic assessment of blueCDR options (Section 3), and provide suggestions for best practices on how to address these challenges (Section 4). This paper is meant to provide a natural-science perspective to the ongoing debate on carbon accounting, clarifying key concepts of carbon cycle dynamics and their implications for additionality and efficiency of carbon removal crediting.

2. Identifying carbon accounting challenges for blueCDR approaches

BlueCDR approaches incorporate two features that bring about their own specific challenges for carbon accounting: First, blueCDR measures are ecosystem-based, which means that they attempt to increase or expand natural carbon sink mechanisms to achieve additionality. Second, given that blueCDR are set in the marine environment, the effort for monitoring campaigns to quantify anthropogenic enhancements on the necessary scale is immense. Following these two features, we will describe specific challenges they bring about.

2.1 Carbon accounting challenges for ecosystem-based CDR—signal attribution, disturbances, baselines

Signal attribution. CDR per definition 'excludes natural CO_2 uptake not directly caused by human activities' [42], since the natural carbon sinks are already accounted for in the transient climate response to cumulative CO_2 emissions [46,47]. Accordingly, the concept of net-zero anthropogenic CO_2 emissions refers to anthropogenic CO_2 sources to the atmosphere being compensated by anthropogenic carbon sinks. An essential aspect of ecosystem-based CDR is the accurate quantification and evaluation of the carbon removed from the atmosphere by anthropogenic activities that is distinct from and additional to the already existing natural carbon sinks [42].

In this context, monitoring and evaluation of blueCDR has to deal with high temporal and spatial variability and complexity of carbon pathways in marine ecosystems [43–46]. This is especially true for coastal ecosystems located in shallow waters, which experience highly variable light and temperature due to the heightened turbulent mixing from waves and tides in these systems. Such factors can influence seagrass meadow or mangrove sediment organic carbon content and burial [48]. In addition, carbon uptake rates of seagrass, macroalgae and mangroves can fluctuate seasonally by up to three orders of magnitude, especially in high latitudes [49,50]. Therefore, it is important not to draw general conclusions on the carbon sequestration capacity of a marine ecosystem type based on scarce, statistically not robust data [51]. The signal of any ecosystem-based CDR measure, would need to be detectable against the existing natural variability of carbon sequestration (noise) in the already existing ecosystems to ensure additionality.

Baseline determination. Accurate blueCDR accounting relies on a clear attribution of anthropogenic carbon removal beyond natural sinks, as well as the additional carbon removed compared to a baseline scenario. Long-term monitoring of carbon stocks in natural ecosystems are needed to establish natural carbon uptake baselines and their uncertainty before CDR deployment signals can be accounted for. Such long-term, abundant direct measurements do not currently exist at a global scale to distinguish anthropogenic carbon sinks from the natural background noise, natural variability and other disturbing or counteracting signals.

Furthermore, the additionality of anthropogenic activity needs to be determined. An example to differentiate between natural and anthropogenic enhancement of a carbon sink (i.e., CDR option) is the naturally occurring pelagic macroalgae *Sargassum fluitans* and *S. natans*. This macroalgae escaped the Sargasso Sea due to extreme climatic events likely caused by climate change [52]. This, together with the extra nutrient runoff from main rivers such as the Amazon, have led to the expansion of Sargassum blooms across the Atlantic [49], known as the Great Atlantic Sargassum Belt (GASB) [54]. Even though the GASB is currently sequestering more carbon than before, this is a natural sink increased without direct human intervention and should not be accounted for as CDR. Only if Sargassum growth would be enhanced and the carbon contained in the biomass would be stored in long-use products or in the sediments of the deep sea, could the activity be counted as additional carbon sequestration and considered a blueCDR option. Sinking of sargassum that would have otherwise beached decomposing should be accounted for as avoided emissions.

Leakage via natural and anthropogenic disturbances. Ecosystem carbon sequestration and as such blueCDR measure efficacy are vulnerable to natural and anthropogenic disturbances, including the impacts of climate change itself [50]. Biological disturbances that could affect the carbon balance of ecosystems include increased consumption by microorganisms, and calcification by calcium carbonate forming organisms such as bryozoans or coccolithophores that can grow as epiphytes on seagrasses and macroalgae [51]. Both these processes can lead to CO_2 emissions and would need to be quantified and monitored over time to be considered in the efficacy of marine CDR approaches. Beyond that, coastal ecosystems are heavily impacted by anthropogenic disturbances such as overfishing including bottom trawling, pollution from rivers and waste water discharge systems (coastal eutrophication), or dredging [52]. Now, with climate change in addition to the marine environment as such becoming warmer and more acidic, extreme events like storms and floods are becoming more frequent, threatening especially ecosystems where the majority of the carbon is stored in living biomass or sediments [52]. Disentangling these stressors' impact on the carbon sequestration and storage capacity of a marine ecosystem and blueCDR options remains challenging.

2.2 Carbon accounting challenges due to the marine environment—spatial and temporal decoupling, signal dilution, access

Spatial and temporal decoupling of capture and sequestration. The iron fertilisation experiments in the early 2000s showed clearly that one of the main challenges of open ocean blueCDR approaches will be linking of carbon capture and sequestration signals [53]. If phytoplankton growth were to be enhanced by the addition of the limiting nutrient (e.g., iron, nitrate or phosphate) to increase biological carbon export to the deep ocean, it is critical to evaluate what amount of carbon is reaching a critical depth and is therefore considered permanently sequestered and what amount remains in fast-cycling pools as it was demonstrated in the last iron fertilisation experiments [53,54]. In fast-cycling pools, the biologically captured particulate carbon in the phytoplankton is partially re-mineralized to dissolved carbon while sinking through the water column and eventually released back to the atmosphere as CO_2 once the water masses resurface. This leakage process can take hundreds to thousands of years depending on the location and depth of remineralization [37]. The difficulties for carbon accounting in this example of an open ocean blueCDR measure arise from the decoupling of the growth (capture) and export (sequestration) processes in time [55] as well as space [56] due to particle transport via subsurface currents. These vary depending where the CDR measure is deployed, which makes tracking and evaluating the fate of the carbon, and hence quantifying the durability of the CDR measure less challenging in well monitored areas like long-term monitoring stations or very low productivity areas like the subtropical gyres. In contrast, approaches based on the active increase of coastal vegetated ecosystems above the natural baseline, such as planting mangroves or seagrasses in places where they did not exist before, the attribution of a blueCDR measure is easier, since the carbon sequestration predominantly occurs in the same place.

Signal dilution. In addition to the difficulties in accurate tracking of carbon capture and sequestration signals arising from spatiotemporal decoupling of production and export processes, the signal of the CDR measure in the marine environment will be diluted over time. Hence, the resulting carbon sequestration will be increasingly difficult if not impossible, to distinguish, measure and evaluate over relevant carbon accounting time scales. In the case of ocean alkalinity enhancement, the effects of mineral addition by ship will quickly spread across large areas and thereby immediately dilute the original concentration of minerals. And while dilution can be beneficial to minimise local ecosystem perturbations from point source addition of alkalinity and maximise carbon uptake potential, but increases the uncertainty associated with the amount of carbon chemically captured. Furthermore, monitoring secondary precipitation of the minerals from alkalinity–a process that reduces carbon uptake efficiency—is essential to verify the uptake potential and duration of the carbon stored yet may occur on time frames or locations outside monitoring programs connected with the CDR deployment site [57]. Similarly, in cases of seaweed aquafarming, the carbon export through natural sinking of part of the cultivated seaweed to the seafloor is subject to currents transporting seaweed away from the source point diluting the biomass concentration [27,38], making attribution and monitoring of natural sinking of parts of the biomass or carbon sequestration in the dissolved organic carbon pool challenging. Approaches that include active baling and monitoring the fate of the sunken biomass at selected sites in the deep sea can be more precise in attributing the carbon sequestration.

Access for monitoring operations. Carbon monitoring and signal attribution to a specific CDR measure pose the most substantial challenges for blueCDR measures, in particular for open ocean deployment in remote locations. While it is gradually being overcome by seagoing expeditions, moorings, ground-truthed satellite data and the network of ARGO floats, limitations remain. Current large-scale monitoring tools such as satellites only scratch the surface of the marine environment and have large geographic biases due to remoteness of some ocean regions like the Southern Ocean. This implies that a certain degree of uncertainty will be inherent in any flux or stock quantification and must be accepted for any blueCDR deployment. The necessary, additional in-situ monitoring for verification and calibration is time and money intensive, reflected by the limited number of time series of in-situ observatories around the world monitoring only a small percentage of the deep ocean [58], where the long-term carbon sequestration occurs. Monitoring coastal vegetated ecosystems [59] such as mangroves, saltmarshes, seagrasses and benthic macroalgae also poses challenges mostly due to their high temporal variability (see Section 2.1) and remoteness from infrastructure [64]. Yet, knowing that most of the long-term stored carbon in coastal ecosystems is not in the biomass but in the sediment [60], in-situ sampling makes it possible to determine the amount of stored, recalcitrant carbon that is unlikely to be rapidly re-mineralized.

3. Identifying interdisciplinary challenges that arise from uncertainty in carbon accounting

These remaining uncertainties in quantifying and monitoring carbon fluxes in the ocean translate into challenges for governance, social and economic considerations [61] related to blue carbon accounting which we want to briefly point to in the following.

Unlike land, the ocean is a continuum difficult to compartmentalise and legislate. Since marine CDR approaches are emerging fast, international regulating structures are needed, ideally informed by impartial scientists and lawyers, to enable well-regulated CDR implementation [62]. Existing legal frameworks like the Convention on the Law of the Sea (UNCLOS, Part XII, XIII) and the London Protocol for the Dumping of Waste at Sea [63,64] that partially apply for some blueCDR approaches were, however, not developed with CDR strategies in mind, resulting in a governance gap [42]. In terms of CDR governance, three monitoring and verification challenges in particular seem relevant: Baseline determination, uncertainty in carbon fate and ecosystem connectivity. Missing baseline determination results in a governance challenge, since it links to establishing the body to be monitored and governed (similar to governance of fisheries [65,66]) as well as the ability to attribute anthropogenic disturbances. As such a disturbance might very well be transported from a regional intervention into the open ocean (outlined in Section 2). The high level of uncertainty in carbon fate, and hence benefit and disturbance attribution makes governance of such interventions subject to higher disputability. Finally, the ecosystem connectivity and downstream effects of blueCDR would require a higher level of international coordination like the safeguarding of the ocean as a common interest [67], moving away from individual sovereign rights.

In terms of public perception of marine CDR measures there is a divide between perceived natural and engineered methods [68]. Other determinants of perceptions identified are controllability, environmental impacts, containment, durability of carbon storage, and risks and benefits for the local population. It is likely that the public will be supportive of blue carbon management irrespective of its actual carbon sequestration potential, due in part to the perceived bad state of marine ecosystems worldwide [69] and the co-benefits arising from coastal blue carbon protection and enhancement. However, in terms of public support for blueCDR approaches, three monitoring and verification challenges in particular seem relevant: uncertainties in signal attribution, potential of disturbances, and secondary ecosystem impacts. While the first challenge speaks to the public scepticism concerning carbon sequestration potential as well as controllability and containment, the second refers to the scepticism of long-term storage potential of blueCDR options and hence also the durability of carbon storage. However, the time scales of carbon storage in the ocean are in general much longer than on land, where planting trees is mostly seen as a positive CDR approach. Uncertainties concerning potential environmental side effects, including secondary ecosystem effects, influence the perception of humans on blueCDR approaches which can be perceived as polluting the marine environment through anthropogenic interference.

Finally, the economic component of blueCDR is probably the most impacted by uncertainties and remaining challenges concerning quantifying and monitoring carbon fluxes. For example, growing kelp might be limited by the high production costs and the energy-intensive operations as well as accounting uncertainties linked to high monitoring costs [74]. The issuance of carbon removal credits in a market-based approach requires that an equivalent amount of carbon has been removed and stored for a sufficient amount of time [70]. The attribution of such a human-made carbon sink in the context of blueCDR is directly linked to the three already discussed challenges: signal attribution, baseline definition, uncertainty of carbon fate. Furthermore, attribution of co-benefits as well as monitoring leakages in the context of blueCDR measures is directly linked to the quantifying and monitoring challenge due to ecosystem connectivity. The insurmountable challenge of large-scale, long-term ocean monitoring, will likely result in the fact that carbon capture and sequestration relying on chemical and biological processes such as blueCDR will require model-based assessment to determine the amount of carbon removed [71]. This in turn will inform the type and frequency of in situ measurements necessary for verification.

Accounting methods are available to deal with the different characteristics of carbon storage reservoirs, distinguishing for example between permanent and temporary credits whereby the latter need to be replaced at some point in time with "regular" allowances and are therefore particularly suitable for temporary carbon storage [72,73]. For example, in some projects the number of credits issued is reflective of the lifecycle of the approach. In some cases, a credit 'buffer' can be held back that reflects the risks of emissions from natural or anthropogenic disturbances. Furthermore, current pricing and payment schemes of carbon credits only compensate blueCDR carbon sequestration rather than taking into account co-benefits like coastal protection, food security, biodiversity enhancement etc, which could create tradeoffs at the expense of other important ecosystem services and might not result in socially or environmentally optimal outcomes [74].

4. Ways forward

4.1 Defining carbon fluxes and their systemic impact

For carbon accounting and reporting in the context of ecosystem-based CDR measures, there are some important distinctions that need to be made to account for the systemic effect the measures have (systemic in the sense of contributing to achieving a net-zero CO_2 emission system, as a necessity arising from the concept of the TCRE and remaining carbon budgets, IPCC AR6 WGIII). These distinctions are applicable to any ecosystem-based CDR measure, both in terrestrial and marine environments:

A clear distinction needs to be made between what is an **existing natural carbon sink that is being conserved or restored** and what is an **anthropogenically created or enhanced carbon sink**. Protection and conservation of existing ecosystems that naturally sequester carbon with the aim of preserving the carbon sink, does not qualify as a CDR measure (see Fig 2). In the same way, natural recovery of an ecosystem (in e.g., marine protected areas) with the likely effect of increased natural carbon uptake by said ecosystem due to removed anthropogenic stressors like pollution does not qualify as an anthropogenically created carbon sink. Only, when human activities cause an enhancement of existing carbon sink mechanisms, by for example actively expanding or managing an ecosystem can the net carbon removals be accounted for as negative emissions (Fig 2). This distinction between what is a restored or expanded ecosystem needs a defined reference of an ecosystem's state and the defined natural state of the ecosystem i.e., baseline definitions. In current national carbon accounting exercises like the ones for the UNFCCC process, a business-as-usual 2020 assumption for ecosystems, is used as the baseline (e.g., UBA [75]). This would imply any expansion of existing ecosystems relative to today would count as CDR. In contrast, national emissions goals are referenced relative to 1990 [80]. We suggest consolidating these system baselines, and henceforward use the

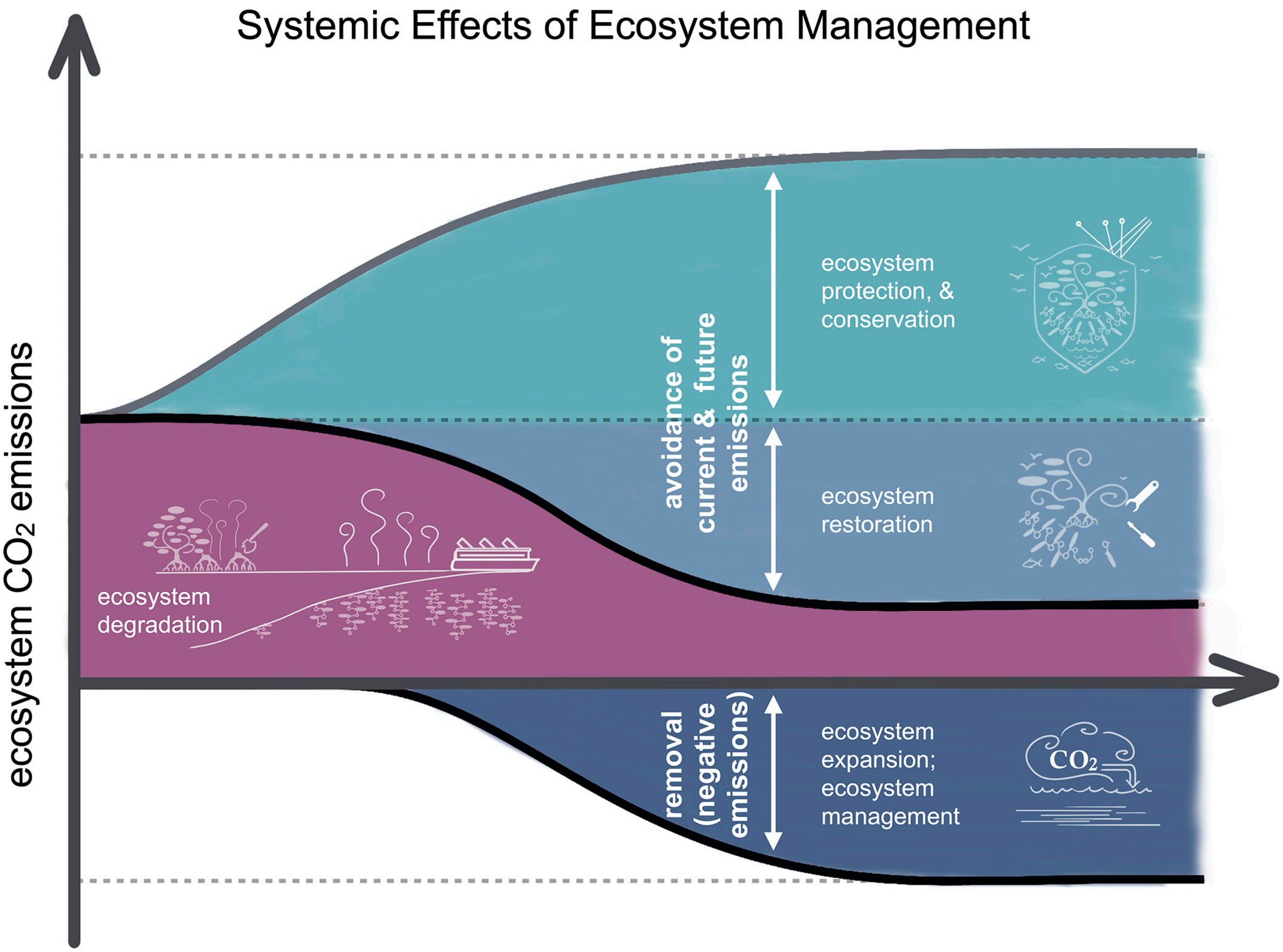

Fig 2. Systemic effects of ecosystem management. Ecosystem degradation currently causes emissions (purple). Ecosystem protection and conservation avoids further degradation and conserves carbon reservoirs to avoid future carbon emissions (light blue). Ecosystem restoration returns the ecosystems to their natural state and reduces current emissions (blue). Finally, ecosystem expansion and management can enhance the natural carbon uptake and create anthropogenic carbon removal (dark blue).

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state of 1990 for ecosystem carbon accounting as the baseline period (Annex VII—Glossary, IPCC AR6 WGI).

A clear distinction concerning **usage** or **storage** of the captured carbon is also important, especially when it comes to storage in products. If biomass from ecosystem-based CDR options is harvested and transformed into short-lived (e.g., less than century) products like biofuels, fertilisers, textiles or other consumables, this can count as CO_2 emissions displacement if their use reduces fossil CO_2 emissions. This is not CDR. Only if products are long-lived (i.e., if the storage time scale is substantially longer than the time scale necessary for carbon capture by e.g., growing wood biomass) in the case of construction materials or non-degradable plastics, can harvesting and usage of ecosystem-based carbon be counted as CDR.

Lastly, ecosystem-based CDR measures need to distinguish between the type of CO_2 emissions that are being mitigated or removed. From a systemic CO_2 emissions reporting point of view, there is a difference between i) **avoided current CO_2 emissions**, ii) potentially **avoided future CO_2 emissions**, and iii) **removed/negative CO_2 emissions**: Current net carbon fluxes from an ecosystem to the atmosphere can be reduced or avoided by ecosystem restoration, if for example organic soils are rewetted and thereby their current CO_2 release is reduced (see blue area in Fig 2). Protecting, stabilising or conserving an ecosystem with respect to possible future perturbations to preserve the existing carbon stock, can prevent/avoid the release of future carbon, if for example seagrass meadows are conserved and thereby degradation of sediment carbon stocks by stressors like storms is averted (see light blue shading in Fig 2). Finally, human activities to enhance the existing carbon sequestration or capturing mechanism of an ecosystem are CDR measures and can be counted as a contribution to negative CO_2 emissions. For example, if seagrass meadows are enlarged, mangrove forests managed, or macro-algae cultivated and sunk to increase carbon sequestration (see dark blue shading in Fig 2).

4.2 Overcoming monitoring challenges

Monitoring programs for carbon standing stocks and fluxes need to be tailored to the spatio-temporal scale and type of blueCDR option, be comprehensive in nature, and preferably build upon existing observational infrastructure. Initiatives such as Surface Ocean Carbon Dioxide Atlas (SOCAT) [76], Global Ocean Data Analysis Project (GLODAP, [77], OceanSITES [78] and GOOS [78,79] compile available information from in-situ measurements from moorings, ship-based time series and ARGO floats [80] to enhance data availability and resolution, and provide a common and open-access database. New technologies like the wave glider, or other autonomous measuring systems are now increasingly able to transmit in-situ measurements in real time [81]. In addition, drone applications could be a way forward for monitoring coastal and open ocean floating ecosystems on a more local scale with the added benefit of enabling observations below the cloud level that often hinders satellite detection [82,83].

In addition to in-situ measurements of biological carbon uptake, the extent and success of large-scale deployment of blueCDR activities (Mt to Gt CO_2 uptake and/or km^2 scale projects) could be monitored, and even audited, from space using satellites. Even though satellites cannot currently measure dissolved carbon in the surface ocean and have limited depth of observation, proxies like sea surface temperature combined with pCO_2 in the atmosphere above the ocean could be used to identify changes in the regional sink or source behaviour of the ocean. Such advances in the aerial monitoring and remote sensing of carbon fluxes and standing stock are rapidly improving our estimates and our capacity to monitor changes in carbon inventories at the local up to the global scale [84–86]. In addition, observational data could be overlaid by open source and standardised model simulations to address gaps in sampling spatiotemporal resolution based on this specific ecosystem variable parameterisation. Here, we highlight open source and standardised models that enable transparency and consistency in the quantification of carbon removed and simplify potential auditing (e.g., the non-profit [C] Worthy). Digital twins of the ocean based on Earth system modeling, might be able to supplement the carbon monitoring and account for uncertainty in in-situ or remote observations [87,88], as well as the additionality compared to a "no action" scenario.

Continued efforts and advances in in-situ and remote-sensing data products in combination with modeling efforts will allow quantification of spatiotemporal natural variability in ecosystem productivity and carbon stocks (e.g., [89,90]) and hence guide baseline definitions. In the same way, targeted efforts are needed to successfully monitor and quantify changes in marine carbon pools due to marine CDR implementation. Monitoring plans approved by scientific, independent expert panels would ensure comprehensive and appropriate observations to enable accurate monitoring and evaluation of blueCDR activities within an acceptable range of uncertainty [91].

4.3 Implementation plan for carbon accounting

After a comprehensive assessment of the feasibility of a blueCDR approach, having led to the decision to deploy this approach, there are certain steps that can be taken, leading to successful and comprehensive carbon accounting. The process of making a blueCDR approach into a marketable CDR solution providing carbon removal credits requires a transparent and interdisciplinary implementation plan that is supported by comprehensive in-situ monitoring over sufficient time periods (Fig 3).

Step 1: Evaluating the systemic effect and the sequestration durability of blueCDR

The systemic effect of the carbon fluxes of blueCDR approaches will likely be a combination of future avoided and removed carbon (see section 4.1 for more details).Ideally this will result in different types of carbon credits that could be issued for one approach [92,93]. Baseline definitions of ecosystem states (i.e., what is the natural state and what is the current state) that are consistent across the assessed systems (as a result of e.g., the EU's guidelines for carbon certification, [6]) need to be in place to ensure the systemic effect is accounted for consistently, and to avoid moving baselines.

Step 2: Life Cycle Assessment of net carbon avoidance & removal

Any blueCDR approach should be assessed in a transparent, holistic way to take into account both carbon stored and carbon emitted throughout the entire life cycle (e.g., process/implementation emissions). During the process of sequestering carbon through a given CDR approach, CO_2 emissions will be produced when constructing the materials or machinery needed, during transportation or processing of biomass, and for maintenance of materials (upstream emissions). If the approach has a limited deployment lifetime, disposal of all

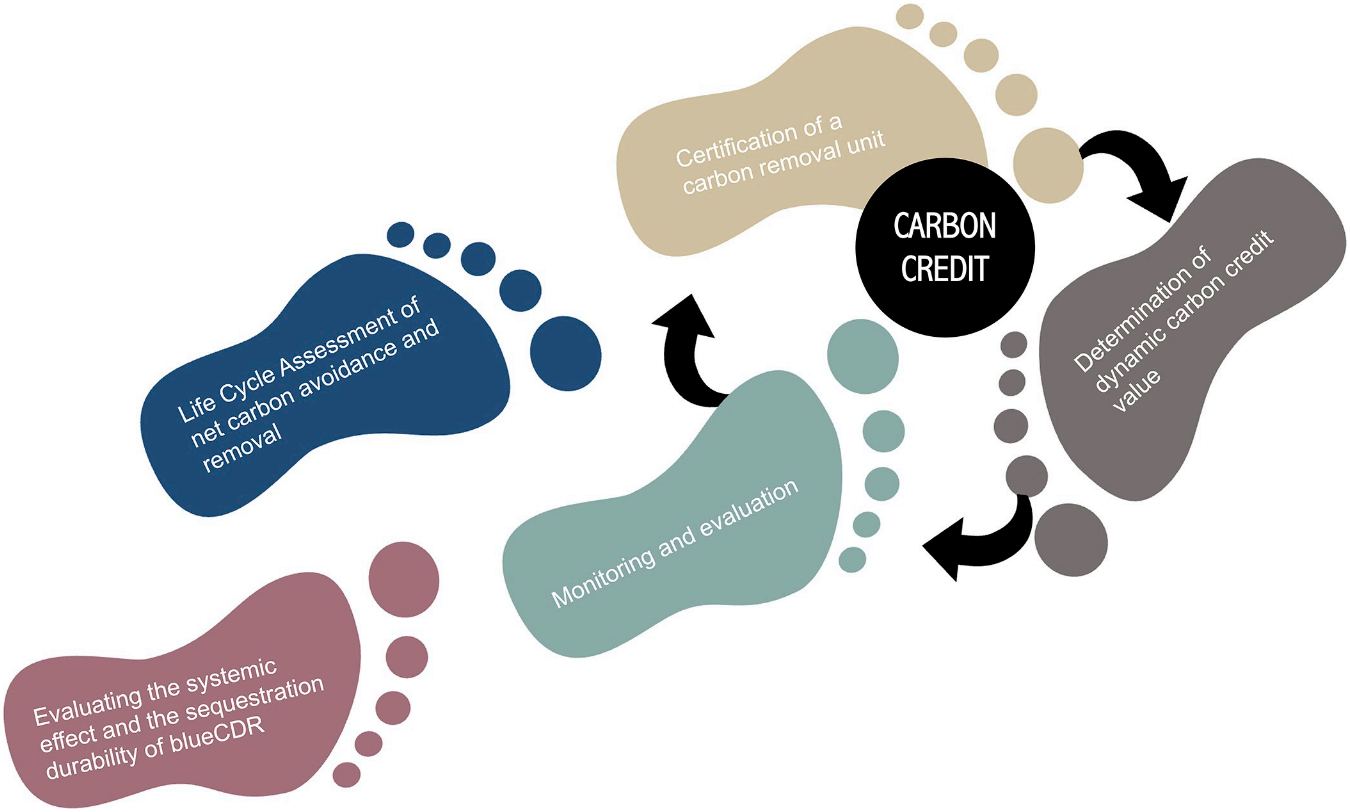

Fig 3. Overview over the key steps for carbon accounting. Suggested steps to be taken for improved carbon accounting in the context of blueCDR. Note the iterative process of carbon credit value determination and the central role of monitoring and evaluation.

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materials and associated emissions must also be considered (downstream emissions). All of these emissions need to be considered when claiming the final net carbon removal or avoidance potential of the approach for carbon crediting [92].

Step 3: Monitoring and evaluation

This is a key step underpinning robust quantification of the carbon removed and of the sequestration time scales for any CDR project. Carbon in marine ecosystems can be stored as biomass (POC), DIC and hard to digest DOC. Quantifying and monitoring those three pools in the water column as well as in the sediments on the relevant spatial and temporal scales in the complex and expansive open ocean realm poses methodological challenges but is possible with adjusting current techniques. Each ecosystem should be characterised in terms of key variables for MRV. This set of observational data should be used to parametrize key processes that determine carbon sequestration (e.g.,[94]) and thereby minimise the observational investment required. In addition, sustained long-term monitoring needs to be in place before and after interventions to detect possible changes in ecosystem processes the rate of consumption, and/or leakage of carbon to the atmosphere (i.e. the carbon cycle's response to CDR [95], all of which may impact the durability of the sequestered carbon and thereby the effectiveness of a given blueCDR approach. Accurate carbon quantification and monitoring strategies for a blueCDR approach need to be developed in addition to the existing carbon cycle monitoring infrastructure. This requires close partnerships between academia and industry.

The carbon verification process should include independent experts to review the proposed CDR strategy, before companies are able to certify their CDR option and sell carbon credits, both in the prototype and upscaled deployment stages. Such third-party verification incorporating independent measurements of the relevant carbon pools and fluxes needs to occur regularly even after deployment.

Step 4: Carbon certification

Once a blueCDR project is running, that is CO_2 removal and storage are being monitored and evaluated, the carbon verification companies could issue a unique carbon certificate detailing how many tons of CO_2 have been additionally removed from the atmosphere. Attribution of the additional carbon removed to the activities of a certain company or project is critical in this step from an economic perspective and should result from a strict monitoring and evaluation plan and be based on the Life Cycle Assessment (Steps 3 and 4). This quantity is independent of any carbon market value and is purely "carbon-based".

The carbon certificate should be a unique, transparent and traceable unit that contains all the information regarding where and for how long the carbon is stored. Tokenized credits might be an appropriate way to ensure transparency and avoid double counting. If the sequestration lifetime of the removed carbon is limited, the validity of the certificate should also be limited. In the same way, if the monitoring of the blueCDR approach detects a leakage in the carbon storage (e.g., due to remineralization of the biomass and release of the inorganic carbon back to the atmosphere), the carbon certificate associated with that project loses carbon value or in the worst case its validity.

Step 5: Determination of dynamic carbon credit value

Once the quantity of the removed carbon is certified, carbon credits as a monetary value for this removed carbon can be determined. A carbon credit should be a dynamic currency whose value changes not only due to economic market influences but also depending on the quality of the carbon sequestered (e.g., storage durability, avoided vs. removed emissions). We suggest adjusting the value of the carbon credit depending on findings regarding the durability of the carbon storage, environmental risks or co-benefits of the approach, as well as sudden release of the sequestered carbon according to the carbon certification process. This would encourage good quality blueCDR projects to be implemented.

Table 1. Overview of challenges in marine ecosystem-based CDR measures from the coast to the open ocean, and suggestion of possible ways forward.

	Challenge	Coast	Open Ocean	Possible Solutions
Challenges present in all ecosystem-based CDR	SIGNAL ATTRIBUTION	Natural ecosystems have high variability in time and space. This increases complexity in carbon fluxes and stocks as well as uncertainty in impacts of climate change on carbon fluxes. BlueCDR measures will likely have small impact compared to this background noise, leading to challenges in signal attribution against this natural variability in diverse ecosystems.		Site-specific ecosystem characterisation: Employ comprehensive long-term monitoring, including targeted in-situ carbon flux and stock quantification. Ecosystem modelling for scaling up effects.
	BASELINE DETERMINATION	Detecting the anthropogenic signal needs defined baselines of the ecosystem's carbon flux. Again, high temporal variability (diurnal, seasonal, interannual) and spatial variability in the diverse ecosystems leads to high uncertainties in baseline estimates.	A lack of comprehensive observational data is the main challenge in defining baseline states, in addition to the large diversity of ecosystem types and high spatial and temporal variability.	Employ comprehensive long-term monitoring, including targeted in-situ carbon flux and stock quantification. Digital twin approaches could help determine baselines.
	POTENTIAL FOR DISTURBANCE	Continuous anthropogenic activity in coastal environments poses a risk of anthropogenic disturbances of carbon stocks and might impact storage durability of blueCDR options.	Global warming and ocean acidification affect every part of the ocean regardless of the presence or absence of direct anthropogenic disturbances such as over-fishing or excess nutrient runoff.	Ecosystem risk assessment, and establishing marine protected areas (co-benefit of avoiding future emissions from ecosystem degradation)
	SECONDARY ECOSYSTEM IMPACTS	Living ecosystems are dynamic and carbon fluxes can change over time with potential modification of original sequestered carbon.		Comprehensive long-term ecosystem monitoring plans employed to support environmental assessment and ecosystem service quantification.
Specific challenges for CDR in the marine environment	OCEAN MONITORING	Challenges in accessing locations which are often far from well-developed infrastructure and in harsh environments.	Potential scale of CDR measures and necessary carbon monitoring is unprecedented ($>$100,000 km^2), and often located in remote ocean areas (100 km + offshore).	Remote sensing, autonomous vehicle monitoring (ROVs and drones) and in-situ verification programs, supported by modelling or digital twin approaches.
	UNCERTAINTY IN CARBON FATE	Coastal waters are dynamic mixing regimes, which means the signal of the CDR measure in the marine environment will be diluted and the resulting carbon sequestration will be difficult to measure and evaluate.	Spatial and temporal decoupling of carbon capture and storage processes in the open ocean leads to signal dilution and uncertainty in attribution.	Use models to define likely uncertainty in carbon fluxes over a range of spatial and temporal scales. Comprehensive long-term observation campaigns of the physical and biogeochemical properties of the ocean.
	ECOSYSTEM CONNECTIVITY	Ecosystems like seagrass meadows or kelp forests that cross national boundaries or might cause downstream effects like leakages.	Monitoring downstream effects from marine CDR options in the open ocean is even more difficult due to access to comprehensive monitoring and signal dilution.	Cross-boundary collaboration for comprehensive monitoring campaigns. Regional or global scale model studies for the assessment of downstream effects.

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5. Concluding remarks

Accounting for carbon fluxes of marine ecosystem-based CDR measures is and will remain subject to monitoring and evaluation challenges and associated remaining uncertainties, which need to be taken into account when issuing carbon removal credits (for a summary, see Table 1). However, despite the challenges, there are feasible ways forward to upscale and properly account for blueCDR credits. This requires interdisciplinary collaborations between natural and socio-economic scientists both from academia and industry. The current hype towards financing blueCDR projects (e.g., Shopify, Microsoft, Frontiers, Ripples, etc.), needs to be accompanied with a higher scrutiny and transparency of the actual effect of the interventions to account for the carbon removed. If such pilot projects fail to convincingly deliver carbon removal, this might impact the perception of follow-up projects. To increase scientific rigor of blueCDR credits, we support recent proposals suggesting to concentrate monitoring efforts on carbon sequestration (e.g., carbon content and processes in the sediment) rather than capturing processes (e.g., biomass standing stock or primary productivity). This will allow for increased accuracy concerning carbon storage durability, as well as prioritisation of efforts for baseline definitions and be beneficial for building confidence and trust of the general public in the carbon credit system. These baselines are necessary for the clear distinction of natural and anthropogenic carbon sources and sinks, as well as the distinction between avoided and removed emissions and need to be established as soon as possible. Finally, we propose to make carbon removal credits subject to dynamic adjustments in light of new scientific findings and natural or anthropogenic disturbances of the carbon stocks.

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