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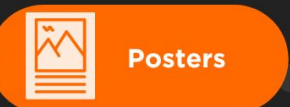
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E-mail: Philip.boyd@utas.edu.au**Keywords:** carbon dioxide removal, climate mitigation, shellfish, seaweed, blue carbon, whales

1. Introduction

To limit warming to <2 °C, we need both emissions reductions and carbon dioxide removal (CDR) (IPCC 2022). A diverse range of potential CDR methods have been proposed to achieve billion-tonne (i.e. gigatonne, Gt) annual CO₂ removal rates within 30–50 years (IPCC 2022), with multiple approaches needed to be developed and upscaled massively to achieve that goal. The need for robust criteria to assess the viability of candidate CDR mechanisms has long been recognised (Boyd 2008), yet new methods are being proposed regularly with insufficient exploration of such checks or balances. This is particularly true for ocean-based CDR, now attracting greater interest (NASEM 2022) as the constraints on land-based methods become apparent.

Here, we focus on four ocean-based CDR methods that, in our opinion, are being advocated, not only by scientists, but also in many cases by the private sector, without due diligence on the underpinning fundamental science. We consider proponents of these methods to have an incomplete or incorrect grasp not only of how the ocean carbon cycle functions, but also the up-scaling needed to provide significant climatic benefits. Such upscaling brings other ocean processes into play that could nullify the effectiveness of the proposed CDR approach. In each case, misunderstanding and knowledge gaps affect the credibility of carbon offset schemes. Our case studies are: calcification-based approaches, expansion of seaweed farming, coastal blue carbon restoration, and 're-wilding' whale populations. We consider that the non-climatic benefits of all these actions have potential to greatly exceed their modest (or non-existent) possible contributions to ocean-based CDR.

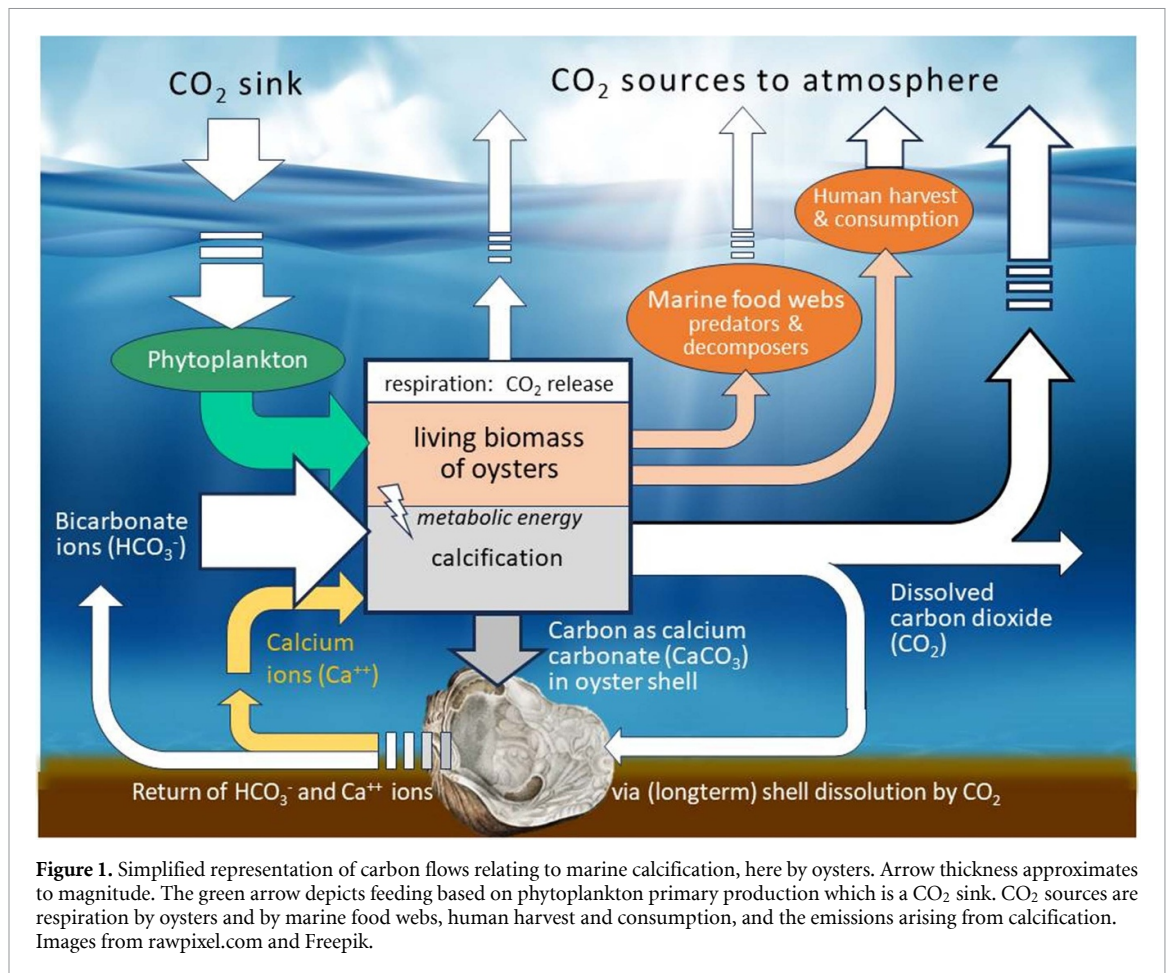
2. Calcification and shellfish aquaculture

Calcium carbonate (CaCO₃) plays a fundamental role in the carbon cycle, although several associated processes are counterintuitive and thereby confusing (Gattuso *et al* 1999). Calcification involves CaCO₃ production from bicarbonate and calcium ions, releasing CO₂. In seawater, the molar ratio of CO₂ released to CaCO₃ precipitated is ~ 0.6 (Frankignoulle *et al* 1994). On geological time-scales, CaCO₃ formation (by either biological or geochemical processes) is a key planetary process returning CO₂ to the atmosphere (Berner *et al* 1983). CaCO₃ dissolution is the reverse process, decreasing atmospheric CO₂.

There are linkages between photosynthesis, respiration and the formation/dissolution of shells by marine calcifiers (figure 1). An individual mollusc, such as an oyster or a mussel, cannot be a sink for CO₂ during its lifespan as it respire, and calcification is also a CO₂ source (equation (1)). Not all the CO₂ released will be returned to the atmosphere (figure 1), since: (i) the seawater may initially be undersaturated with CO₂ (due to photosynthesis); and (ii) some of this CO₂ may become involved in shell dissolution (primarily dead shells), on or within the sediment, running equation (1) in reverse, removing some CO₂, but leaving the system a CO₂ source,



Shellfish aquaculture has been advocated as a climate mitigation action to achieve CO₂ removal (e.g. Lin *et al* 2023, Moore *et al* 2023). Such assertions stem from a fundamental misunderstanding of



chemical reactions and/or using inappropriate system boundaries. If aquaculture were to be used for that purpose, full life cycle assessments (LCA) need to include all associated anthropogenic processes that generate CO₂ such as spat collection and transportation, the use of manufactured material for farming, boats, processing and packaging, distribution and marketing. However, ‘reversing climate change’ cannot be achieved by that approach, as confirmed by Tomasetti *et al* (2023): >70% of short-term measurements on oyster reefs showed that they are CO₂ sources relative to control sites.

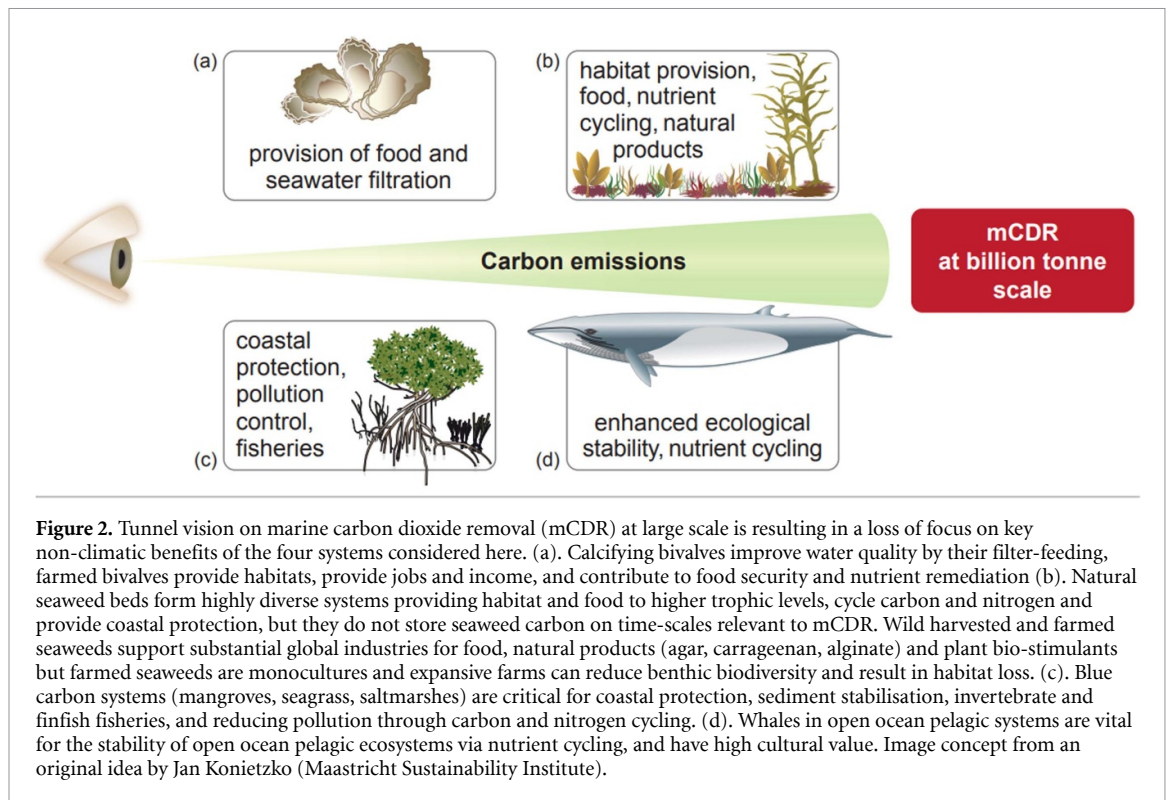
3. Seaweed farming for CDR

Seaweeds are key primary producers of coastal ecosystems globally, forming highly diverse 3D habitats and food for higher trophic levels, and support important fisheries (figure 2). Natural beds of the three seaweed phyla occupy ~6.1–7.2 million km² (Duarte *et al* 2022) and farmed seaweeds (for food, natural products) occupy an additional ~2700 km² (DeAngelo *et al* 2023). Seaweeds have been proposed to play a central role in ocean CDR (NASEM 2022), focusing on kelps (e.g. *Macrocystis pyrifera*, *Saccharina latissima*) and two pelagic *Sargassum* species (Hurd *et al* 2023). However, such a role requires massive expansion of seaweed cultivation, including

into the open ocean. For example, Wu *et al* (2023) model simulations estimate that seaweed farming across 20% of the ocean could remove 0.6 Gt C annually, rising to 1.0 Gt with artificial upwelling (supplying nitrate and iron) and DeAngelo *et al* (2023) analysis indicates that to remove 1 Gt CO₂ (i.e. 0.27 Gt C) by 2030 will require global seaweed farming to expand by 42%–64% per year for nearly a decade. It is unfeasible to sustain such annual upscaling with current farming technologies.

It is likely that many seaweeds are unable to grow in offshore waters. Seaweed farming has focused on nitrogen as the key limiting nutrient for healthy growth, but for *Macrocystis pyrifera* concentrations of biologically available iron (Fe⁺) 50–200 km offshore are 1,000 times lower than required (Paine *et al* 2023). Coastal diatoms have colonised iron-depleted offshore waters over evolutionary timescales by reducing their chloroplast iron requirements (Strzepek and Harrison 2004) but seaweeds have no such adaptation. Therefore, it is likely that many seaweeds will not be suitable for off-shore cultivation, and Paine *et al* (2023) highlight the utility of lab-based experiments to examine growth requirements prior to expensive field deployments.

In terms of CDR, a common misunderstanding is that seaweed ‘forests’ function like terrestrial forests. However, most seaweeds do not directly remove CO₂



from the atmosphere, and nor do they store carbon in living biomass or soil. Instead, biomass enters the detrital and microbial foodwebs as particulate and dissolved organic carbon (POC, DOC; Hurd *et al* 2022). To assess the CDR potential of seaweeds, two coupled measurements are required: track the fate of DOC and POC and determine how much of that is stored in long-term pools (e.g. deep ocean and deep sediments) and mapping the seawater from which CO₂ was removed for weeks-months to determine, mostly via modelling, the degree of atmospheric CO₂ equilibration (Hurd *et al* 2023). These costly, difficult, and specialised measurements will be required for monitoring, reporting and verification (MRV) of any CDR farming proposals including sinking seaweeds to the deep ocean. As for shellfish aquaculture, a full carbon accounting, akin to a carbon budget linked to an LCA for each cultivation system, would be needed to ensure rigorous MRV (Hurd *et al* 2022).

4. Coastal blue carbon

Proposals to use vegetated coastal ecosystems for CDR mostly focus on seagrass meadows, mangrove forests and saltmarshes. Sediments in these ‘blue carbon ecosystems’ accumulate large amounts of organic carbon, with its decomposition slowed by low oxygen and high salinity. The attractiveness of this ‘climate solution’ is summarised by statements such as: ‘Scientific assessments show that blue carbon ecosystems can store two to four times more carbon per hectare and sequester it 30–50 times faster than

terrestrial forests, and thereby can make a significant contribution to global action on climate change’ www.dcceew.gov.au/climate-change/policy/ocean-sustainability/coastal-blue-carbon-ecosystems.

Whilst the quoted comparisons with land forests are correct, carbon accumulation in natural ecosystems does not readily translate into climate mitigation action. Storage *per se* is not actually helpful; fossil fuel reserves are also carbon stores, yet do not provide any climate benefits. Furthermore, mature forests (and their soils) are usually close to carbon balance, with losses matching gains; their potential for net carbon removal, through reforestation or afforestation action, is mainly in their first 10–50 years of growth.

For genuine ‘additionality’ of CDR, large-scale active restoration of blue carbon ecosystems is needed; however there are three major problems associated with such action. First, the socio-economic constraints: in most parts of the world, coastal restoration will direct conflict with either human settlement, agriculture, aquaculture, or other economically-important uses of coastal land. It is therefore unrealistic to estimate potential climate benefits on the basis of full restoration to pre-industrial coverage, which would require a near-doubling of the current area of such ecosystems. Second, there is insufficient appreciation of the relatively small contribution that blue carbon ecosystems naturally make to carbon removal, estimated at ~0.4% of current CO₂ emissions (Taillardat *et al* 2018). Whilst increasing that amount by 10%–20% through restoration might be

achievable, the effect on global climate would be slight.

Third, the quantification of such relatively modest climatic benefits (for carbon accounting) is extremely challenging. There is very high variability in natural carbon removal rates for seagrass, saltmarsh and mangrove ecosystems, and the site-specific factors responsible are poorly understood (Williamson and Gattuso 2022). Complexities include: the counteracting effects of methane and nitrous oxide production (Rosentreter *et al* 2021); CO₂ release through calcification (see above); lateral carbon transport, both as imports and exports; and vulnerability to future climate change (Williamson and Gattuso 2022).

Currently-assumed 'typical' CDR for the three coastal blue carbon ecosystems, as used for carbon offset purposes, therefore seem likely to be overestimates, by tenfold or more (Johannessen and Macdonald 2016, Williamson and Gattuso 2022). Determining more accurate values requires many long-term, site-specific measurements, with implications for the cost-effectiveness of this approach. We do, however, emphasise that the restoration of coastal blue carbon is highly desirable for many other reasons, including coastal protection, pollution control, biodiversity and food security (figure 2).

5. 'Rewilding' whale populations

The ocean faces many challenges including biodiversity loss and over-harvesting. Proposed management mechanisms to overcome these challenges include refugia, and ecosystem restoration aka 'rewilding'. Rewilding has focussed on restoring whale abundances to pre-industrial levels which should bring wide-ranging ecological benefits (figure 2). However, there is a growing concern that these potential benefits could be marginalised or overlooked if the focus of rewilding becomes whale-driven CDR.

Proponents of re-wilding whale populations for CDR suggest that the additional nutrients via excretion will enhance phytoplankton growth and hence the oceanic biological carbon pump, as will sinking whale carcasses. Whales play multiple roles such as acting as ecosystem engineers linking trophic levels and supplying food to deep-sea biota upon their death (whale falls; Pearson *et al* 2022). However, their potential for CDR is questionable (Meynecke *et al* 2023) and lacks quantitative evidence. The results of incubation studies using whale faecal material to explore phytoplankton responses to nutrient enrichment, are highly variable (Meynecke *et al* 2023). Moreover, only a small (and variable) proportion of this additional productivity would translate into CDR.

These fundamental knowledge gaps are compounded by the need to extrapolate scant observations on the various mechanisms including the whale pump (i.e. faecally-mediated CDR to depth)

(Pearson *et al* 2022, Meynecke *et al* 2023) to obtain global pools or fluxes. This extrapolation also requires factoring in losses due to prior persistent harvesting before conservation was introduced (>80%, Pearson *et al* 2022) to explore the potential effect of whale 'rewilding' on the ocean carbon cycle. Pearson *et al* (2022) summarises data on the various fates of whale carbon: stored (biomass), sequestered (>100 years, falls), or exported (<100 years, pump). For the modern era all estimates are 0.001–0.1 Gt C, as are most from the pre-whaling era (cf 2021 Global CO₂ emissions ~40 Gt CO₂, www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2).

6. Discussion and conclusions

The case studies above include methods that have high public interest (>350 media articles on whales and climate since 2013; Meynecke *et al* 2023), are politically well-regarded (coastal blue carbon is the most mentioned marine CDR method in national climate actions; Gallo *et al* 2017) and have attracted substantive investment (for example, >40 companies are investigating seaweed for carbon removal; GESAMP⁵).

Nevertheless, we consider that proponents of these methods have given insufficient attention to basic constraints relating to ecosystem functioning and the ocean carbon cycle (e.g. ignoring the many processes returning CO₂ to the atmosphere), as well as: the challenges of implementation at climatically-significant scale, the (in)security of carbon storage and the many difficulties in reliable quantification of climatic benefits. Such problems strongly indicate that these approaches will be 'dead ends' with regard to meaningful (*sensu* IPCC definitions) mitigation, whilst also being counter-productive to the wider effort to limit warming to <2 °C.

We have three closely-linked concerns. First, the 'opportunity costs'—the resources directed at these approaches could be better invested in other CDR methods (both land and ocean-based) that are inherently more likely to be safe, durable, verifiable, and scalable (IPCC 2022, Boyd *et al* 2023).

Second, the involvement of non-experts in CDR approaches across many parts of the private sector: NGOs have favoured enthusiasm and advocacy at the expense of scientific quality, facilitated by predatory journals with scant regard for academic rigour. The associated over-emphasis on uncertain CDR potential at the expense of other well-established benefits ('tunnel vision'; for example, farmed seaweeds are monocultures whereas restored seaweed ecosystems promote diversity, figure 2) can cause confusion for policy-makers. Whilst expert critiques of specific approaches have been developed (e.g. Pearson *et al*

⁵ GESAMP WG 41; online at link at end of www.gesamp.org/work/groups/41.

2022, Paine et al 2023), they take additional effort. Furthermore, the apparent lack of agreement on fundamental issues, such as the efficacy of CDR, weakens wider scientific credibility.

Third, the on-going commercialisation of these approaches for carbon offsetting (mostly using coastal blue carbon, but also the main driver for open ocean seaweed aquaculture) is, in our opinion, premature and misguided. The uncertainties involved are currently too great for estimates of future carbon accumulation in marine sediment or seaweed biomass to 'excuse' the ongoing release of greenhouse gases from preventable sources, with risks of loopholes and misuse at least as problematic as for terrestrial forest-based carbon credits.

The need is therefore for better communication—through targeted and widely-accessible educational resources—of the basic criteria (Boyd et al 2023) for CDR viability using marine processes. These characteristics (safety, durability, verifiability, scalability) should be used to prioritise relevant R&D funding by Governments, as well as providing checks and balances for policy-makers.

Data availability statement

The data cannot be made publicly available upon publication because they are not available in a format that is sufficiently accessible or reusable by other researchers. The data that support the findings of this study are available upon reasonable request from the authors.

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