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A system-based analysis of carbon fluxes shows that bivalve aquaculture cannot be considered a marine carbon dioxide removal strategy

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Abstract

Marine carbon dioxide removal (mCDR) is gaining momentum as part of the global climate mitigation portfolio. Yet as enthusiasm grows, so does the risk of overstating the carbon removal potential of marine activities that were never designed as climate interventions. Among these, bivalve aquaculture is increasingly framed as a nature-based carbon sink. We critically examine whether bivalve farming meets the scientific and policy criteria to qualify as a valid method of mCDR, emphasizing additionality, permanence, accountability, and the obligation for robust monitoring, reporting, and verification (MRV), including life-cycle assessment and certification frameworks. We demonstrate why bivalve farming does not currently qualify as an mCDR pathway. At the organism level, bivalves are not CO₂ sinks: as heterotrophic and calcifying organisms, they release CO₂ through respiration and calcification. Claims that shell inorganic carbon incorporation constitutes net atmospheric CO₂ removal have been critically examined and refuted. At the ecosystem scale, hypotheses that bivalve aquaculture enhances the biological carbon pump or stimulates organic carbon sequestration in sediments remain highly uncertain. Empirical evidence is sparse, often methodologically limited, and lacking appropriate baselines, temporal resolution, and ecological realism. Critically, questions of scalability, long-term sequestration, and carbon accountability remain unresolved. Given the urgent need to prioritize reliable, scalable and cost-effective mCDR solutions, we argue that it is highly unlikely—and scientifically unjustified—that bivalve aquaculture can ever be used to obtain carbon credits. Bivalve aquaculture remains a model of sustainable food production that should not be distorted by attributing to it unverified virtues of atmospheric CO₂ removal.

Keywords Aquaculture, Bivalve, Blue carbon, mCDR, MRV

Introduction

Limiting global warming below 2°C above pre-industrial levels, as set out in the Paris agreement, involves rapid, deep, and sustained reductions in greenhouse gas emissions. While carbon dioxide removal (CDR) cannot substitute for these emissions reductions, it is widely recognized as necessary to address residual emissions, remove legacy CO₂ from the atmosphere, and counteract the weakening of natural carbon sinks (IPCC 2023a).

The Intergovernmental Panel on Climate Change (IPCC 2023b) defines CDR as: “Anthropogenic activities capturing CO₂ from the atmosphere and storing it durably in geological, land or ocean reservoirs or in products. This includes human enhancement of natural removal processes but excludes natural uptake not caused directly by human activities.” This definition of CDR thus follows three key principles (Smith et al. 2024). First, CO₂ must be removed from the atmosphere, although such removal can occur indirectly, for instance via seawater equilibration. Second, subsequent storage must be durable, preferably on millennial

timescale. Third, the removal must be a result of human intervention, additional to the Earth’s natural processes. A diverse portfolio of proposed CDR methods—across both terrestrial and marine domains—has been advanced with the ambition of achieving removal of 7–9 gigatonnes (Gt) of CO₂ per year within the next 25 years (Smith et al. 2024). For comparison, current anthropogenic CO₂ emissions are on the order of ~40 Gt CO₂ yr⁻¹, while the global ocean carbon sink absorbs approximately ~10 Gt CO₂ yr⁻¹ (Friedlingstein et al. 2025), highlighting the substantial scale at which CDR deployment would need to operate.

CDR must be accompanied by rigorous scientific evaluation to ensure climate benefits are delivered. Key considerations include additionality (whether removals measurably exceed what would have occurred anyway), permanency (the duration and stability of storage), and accountability (clear attribution, quantification, and governance of removals). These principles underpin the obligation for robust monitoring, reporting, and verification (MRV), with associated environmental impact assessment (EIA), life cycle as-

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refuted: it is not supported by either observational or experimental studies (Pernet et al. 2025a). Nevertheless, several studies consider that two moles of CO₂ are used in the form of HCO₃⁻ for each mole of CaCO₃ produced. One mole is incorporated into the shell and the other is released. According to this reasoning, 1 g of CaCO₃ produced is equivalent to the consumption of 0.44 g of CO₂ (Pernet et al. 2025a). Shell carbon production sequesters carbon in the ocean as CaCO₃, but chemical seawater re-equilibration degases CO₂, making it a net CO₂ source for the atmosphere. The (relatively few) observational studies that measured air-sea CO₂ fluxes at bivalve farms and natural reef ecosystems have confirmed that these animals are net CO₂ emitters (Pernet et al. 2025a).

Despite this evidence, many scientific papers still consider calcification to be a net atmospheric CO₂ sink and use the aforementioned incorrect calculation (Pernet et al. 2025a). It is noteworthy that these studies, which rely on bivalve production data to estimate the amount of carbon sequestered in shells converted into CO₂ equivalents, are relatively simple, quick, and inexpensive to conduct compared to those based on direct carbon flux measurements, including air-sea CO₂ exchanges, which are much more complex, time-consuming, and costly. Consequently, the scientific literature is likely to be biased towards the former. This is concerning because it promotes a misconception that misleads not only the scientific community, but also shellfish farmers, professional organizations, NGOs, and governmental policy-makers.

The ecosystem: shellfish farms may provide indirect CO₂ removal but this is variable and uncertain

Classifying a species as a CO₂ sink or source does not accurately reflect its ecosystem-level contribution. Although bivalves are net CO₂ emitters at the organism scale, yet they can improve water clarity and nutrient recycling, creating conditions that favour the growth of seagrass, seaweed, and phytoplankton (Newell and Koch 2004, Wagner et al. 2012, Zhang et al. 2021, Alleway et al. 2025, Chen et al. 2025). In contrast, bivalve farming can cause local declines in seagrass density through increased shading or sediment alteration. The net effect of bivalve aquaculture on seagrass ecosystems varies with environmental conditions, culture methods, stocking density, and hydrodynamics (Ferriss et al. 2019). Additionally, although nutrients released by bivalves may stimulate planktonic primary production in nutrient-limited environments, bivalves can exert strong grazing pressure, reducing phytoplankton biomass and even primary production when filtration losses surpass algal growth rates (Banas et al. 2007, Cloern et al. 2014, Lucas et al. 2016).

It has also been suggested that bivalve farming can promote the sequestration of organic matter in sediments through biodeposition of faeces and pseudofaeces (material rejected after and before digestion respectively), therefore acting as a carbon sink (Feng et al. 2023, Chen et al. 2025, Sun et al. 2025). Biodeposition may indeed increase benthic carbon accumulation and burial under specific depositional and redox conditions, as shown for some oyster reefs (Fodrie et al. 2017, Southwell et al. 2017, Veenstra et al. 2021). However, it may also stimulate microbial remineralization processes, oxygen consumption, and nutrient regeneration. These changes may alter nitrogen cycling pathways and potentially en-

hance fluxes of non-CO₂ greenhouse gases such as N₂O and CH₄ in organically enriched sediments (Gilbert et al. 1997, Hylén et al. 2021). The net climatic effect therefore depends on sedimentation rates, benthic mineralization, sediment redox state, and hydrodynamic resuspension. Under most circumstances, only a small amount is ultimately buried over climate-relevant timescales (i.e. over 100 years) (Chen et al. 2022). Without direct measurements of sediment carbon burial efficiency, long-term stability, and other greenhouse gas fluxes, claims of durable sequestration remain unverified.

Conclusions regarding ecosystem carbon budgets are mostly derived from models that rely on incomplete assessments of relevant processes and unverified assumptions (Pernet et al. 2025a, Pernet et al. 2026). The few empirical studies that establish carbon inventories for bivalve farms reveal that, in comparison to unfarmed control areas, they exhibit a lower capacity to absorb atmospheric CO₂ (Li et al. 2021, Liu et al. 2022, Ye et al. 2022, Chen et al. 2025) as also reported in wild oyster reefs (Fodrie et al. 2017, Tomasetti et al. 2023). That said, empirical evidence is sparse, often methodologically limited, and lacking appropriate baselines, temporal resolution and duration, and ecological realism (Pernet et al. 2025a, Pernet et al. 2026).

Most of all, hydrodynamics is largely ignored despite being the greatest source of uncertainty in coastal carbon budgets. Water movement redistributes carbon across ecosystem boundaries. Organic matter produced elsewhere—such as phytoplankton or biomass from nearby vegetated habitats—can be transported into shellfish farms, where bivalves filter it and convert it into biodeposits that contribute to local sediment carbon burial. In these situations, a shellfish farm may act as a local CO₂ source while storing carbon that originated outside the farm. At the same time, carbon produced within the farm itself, including respired CO₂ or excreted organic matter, can be transported to neighbouring ecosystems, where it may be remineralized or ultimately buried. These cross-boundary carbon fluxes make it difficult to assign carbon sequestration or atmospheric CO₂ uptake to a single habitat and represent, as in other blue carbon ecosystems, a major source of uncertainty in coastal carbon accounting (Santos et al. 2021, Williamson and Gattuso 2022, Williamson et al. 2025).

In conclusion, the net CO₂ contribution of bivalve farm ecosystems vary with farming density and practices, hydrodynamics and depth, nutrient availability and primary productivity, temperature, and oxygen concentration. The shellfish farming ecosystem is not an inherent source or sink of CO₂, this depends on site-specific ecological and management factors.

The human system: The supply-chain and resource use involve CO₂ emission

Life cycle assessment (LCA) is essential for evaluating the holistic effectiveness of atmospheric CO₂ capture because it provides a comprehensive overview of all materials and energy used throughout a production system. The stages and processes included in an LCA depend on the boundaries selected—primarily whether it is attributional (cradle-to-gate or cradle-to-grave) or consequential (including wider, downstream processes and feed-

backs, albeit with greater uncertainties) (Goglio et al. 2020). Most LCAs for mCDR to date have had limited scope, not including consideration of wider environmental impacts (Delval et al. 2025).

Attributional LCA is expected to account for emissions from aquaculture activities such as hatchery, nursery, grow-out, depuration, harvesting, distribution, and end-of-life management, including shell disposal. It can also incorporate emissions from equipment production, vessel fuel use, and other forms of energy consumption. Consequential LCA may additionally include carbon dynamics at the ecosystem level (see previous section), and relating to socio-economic consequences (e.g. whether an increase in marine aquaculture would reduce CO₂ emissions from land-based food production). All inputs and outputs quantified within the defined boundaries are converted into environmental impacts, primarily greenhouse gas emissions as CO₂ equivalents to determine carbon footprints. When combined with the organismal and ecosystem CO₂ emissions, the resulting analysis provides an integrated measure of the overall climate impact of the aquaculture system. In this way, LCA offers the methodological rigour necessary to determine whether bivalve farming reduces carbon emissions (relative to other food production processes) or may even result in net carbon removal.

Farmed bivalves do not require feed and generally have lower environmental impacts than many other forms of aquaculture or land-based animal production (Gephart et al. 2021). Nevertheless, bivalve aquaculture still depends on activities and materials that emit CO₂ and other greenhouse gases. Key sources include vessel fuel use for seeding, maintenance, and harvesting; the manufacture, transport, and replacement of farming gear such as ropes, buoys, poles, and nets; hatchery operations where spat are produced; processing and depuration; and transport of the final product (Aubin et al. 2018, Turolla et al. 2020, Martini et al. 2022, Tamburini et al. 2022, Dias et al. 2025, Domech et al. 2025, Jiang et al. 2026). Shell waste management is another important consideration that can result in either CO₂ emissions (e.g. from incineration) or uptake through long-term weathering (if shells are returned to the ocean, see e.g. Álvarez-Salgado et al. 2022); however, such processes are excluded from most LCAs (except Jiang et al. 2026).

Studies that claim bivalve aquaculture provides net carbon removal typically do not report LCA of the supply-chain and resource use (e.g. Chen et al. 2025). When full accounting is attempted, results are often undermined by the incorrect inclusion of shells, and sometimes flesh, as CO₂ sinks (e.g. Turolla et al. 2020, Martini et al. 2022, Tamburini et al. 2022, Domech et al. 2025). This error substantially alters the balance by offsetting the operational emissions and can lead to the mistaken conclusion that bivalve aquaculture is a net CO₂ sink.

Recalculations of past studies to include CO₂ released during shell formation show that this correction increases the total global warming impact (CO₂-equivalent) in LCA analyses for farmed bivalves by around 80% compared with the originally reported values (Ray et al. 2018). Taking account of calcification effects, emissions averaged 201 kg CO₂ per kg ash free dry weight of tissue for the five studies re-analysed by Ray et al. (2018). However, there was high variability in the percentage increase (range of 1.3%–286.5%) and also in the total emissions (20.1–639 kg CO₂ per kg tissue), showing the difficulty in applying “global values” to specific situations. Furthermore, the importance of such emissions can be reduced over time, if shell waste management does actively favour

return to the ocean with associated shell dissolution and CO₂ uptake (Jiang et al. 2026).

The climate system: the issues of additionality, permanency, accountability, and cost effectiveness of climate mitigation

For shellfish aquaculture to qualify as a mCDR activity contributing to national greenhouse gas inventories or carbon markets, it must generate net atmospheric CO₂ removal that is directly attributable to the farming activity. Beyond demonstrating such additionality (Michaelowa et al. 2019), the removed carbon must also be stored on a “permanent” basis, typically defined in climate mitigation frameworks as at least 100 years—and preferably much longer (Arcusa and Lackner 2025).

In this context, a robust, consistent, and comprehensive MRV framework must be developed to ensure transparent, accurate, and reproducible accounting of net CO₂ removal and potential impacts prior to any carbon removal claims. This framework quantifies net greenhouse gas removals, including CO₂ and non-CO₂ gases, relative to a counterfactual/baseline, assesses the durability of carbon storage, and evaluates uncertainties (Muri et al. 2025, Fennel 2026). A comprehensive MRV also encompasses i) an LCA of supply-chain emissions and resource use, with associated quantification of environmental and ecological impacts using integrated observational and modelling methods across relevant spatial and temporal scales; ii) transparent reporting of results; and iii) the enabling of independent third-party verification to support credible carbon accounting, governance and market mechanisms for mCDR. No mCDR method currently has a MRV protocol that meets such standards (Muri et al. 2025, Fennel 2026).

Although the carbon sequestration mechanisms differ, the uncertainties constraining robust carbon accounting in bivalve aquaculture closely parallel those documented in blue carbon ecosystem restoration (Williamson and Gattuso 2022, Williamson et al. 2025). Both systems are biologically-based approaches facing spatial heterogeneity, hydrodynamic exchanges, climate disturbance risks, and attribution complexity and uncertainty. The MRV requirements for such systems are extremely challenging. Site-specific observational strategies are essential to capture spatial variability, and high-frequency measurements are needed to resolve the strong diel, seasonal, and interannual fluctuations characteristic of coastal ecosystems. These strategies must include carefully selected reference sites located outside farming areas, adequate replication to ensure statistical robustness, and sampling designs capable of capturing both short- and long-term variability. Equally important is a comprehensive assessment of carbon stocks and fluxes across key ecosystem compartments, including bivalves, primary producers, and sediments, along with exchanges with adjacent systems. This requires validated hydrodynamic and biogeochemical models to quantify net carbon balances and air-sea CO₂ equilibration at the regional scale. To date, none of the studies claiming carbon removal from bivalve aquaculture meet these requirements (Feng et al. 2023, Chen et al. 2025, He et al. 2025).

Perspectives

On the basis of the above, we consider that particular attention should be given to the following six issues when evaluating the potential role of bivalve aquaculture as a mCDR approach.

First, additionality needs to be robustly investigated, using control sites to estimate air–sea CO₂ fluxes and sedimentary carbon accumulation outside the aquaculture area, and preferably also before the installation of the farm. Without such baseline information as part of the LCA, the specific influence of aquaculture on local carbon dynamics cannot be isolated, and additionality cannot be established.

Second, the CO₂ equilibration with the atmosphere need to be carefully examined. This is a critical omission in all the studies that have been published so far. Marine CDR does not remove CO₂ directly from the atmosphere but decreases its concentration within seawater. Therefore, any climate benefit depends on subsequent air–sea CO₂ equilibration that may take months or years, or not occur at all (Jones et al. 2014, Bach et al. 2023). Without quantifying this step, no robust claim of atmospheric CO₂ removal can be made.

Third, empirically-derived carbon budgets need to be much improved, avoiding temporal biases. Most field campaigns span only a few months, and longer studies often rely on very low-frequency measurements. Winter periods (when conditions are usually more heterotrophic) have generally not been included to date, and some assessments only record CO₂ fluxes during daylight hours, leading to overestimation of CO₂ uptake and underestimation of emissions. Full year–round monitoring, is essential for producing reliable and unbiased carbon budgets.

Fourth, the permanence of storage needs to be assessed, on a site-specific basis. Sedimentation of organic carbon (near-surface accumulation) is not the same as carbon burial (long-term storage) since it can be highly susceptible to remineralization over decadal timescales (Kristensen et al. 2025). As climate–mitigation strategies require sequestration on multidecadal and ideally centuries or millennials, realistic remineralization rates must be incorporated into carbon budgets, based on a wide range of parameters including bioturbation (Smit et al. 2025): sedimentation alone cannot be used to claim carbon removal.

Fifth, scalability needs to be properly assessed rather than simply claimed (Pernet et al. 2026). This is particularly important given that i) aquaculture is often carried out in spatially restricted and heavily used areas; and ii) bivalves are vulnerable to ocean warming and acidification, which seems likely to limit their potential for large-scale farming and deployment in the future (Pernet et al. 2025b, Froehlich et al. 2018). To what extent, then, can bivalve farming be considered a solution to climate change when it is itself directly threatened by it?

Finally, while low-density bivalve farming generally has a positive environmental impact, the intensification of large-scale farming can have adverse effects (Grant et al. 1995, Newell 2004). For instance, enhanced biodeposition can increase microbial respiration and reduce sediment oxygen content. This can inhibit coupled nitrification-denitrification and cause phosphorus to become unbound and released into the water column. The result is the build-up of hydrogen sulphide, which can be toxic to benthic organisms (Newell 2004). This may impact benthic biodiversity. Therefore, this environmental impact should be carefully assessed and considered to avoid adverse ecological consequences.

Conclusion

Our overall conclusion is that bivalve aquaculture cannot currently be considered an mCDR approach, and is highly unlikely to take on this role in future. Its contribution, if any, to climate mitigation through net CO₂ uptake can only be credibly determined through comprehensive, process–based carbon accounting supported by long–term monitoring and verification on a site-specific basis.

The MRV at the level required for carbon–market applications seems unlikely to be operationally practical for bivalve farming systems. Furthermore, it would significantly decrease the cost-effectiveness of any carbon-credits obtained. Advocates of CO₂–sequestering aquaculture cannot disregard these requirements if meaningful progress is to be made. Carbon markets are adopting increasingly stringent and competitive MRV standards (Mistry et al. 2023): the key question is not whether MRV should be applied, but what form of MRV is appropriate and achievable. As with all mCDR approaches, there are different levels of MRV: what is scientifically ideal, what is operationally feasible, and what is necessary to ensure credible carbon accounting (Delval et al. 2025, Halloran et al. 2025). For bivalve farming, a much more thorough and explicit recognition of the limits, requirements, and overall feasibility of MRV is essential for avoiding unsupported claims of carbon removal.

Although bivalve aquaculture cannot be considered a mCDR strategy, it remains a relatively sustainable mode of food production. Compared with many forms of fed aquaculture and terrestrial livestock farming, shellfish cultivation generally has lower environmental impacts, as bivalves do not require external feed inputs and can improve water quality through their filtration activity. Recognizing these distinct benefits is important to avoid confusing food-production advantages with unverified claims of atmospheric CO₂ removal.

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Author contributions

Fabrice Pernet (Conceptualization [equal], Investigation [equal], Writing – original draft [lead], Writing – review & editing [equal]), Phillip Williamson (Conceptualization [equal], Investigation [equal], Writing – original draft [equal], Writing – review & editing [equal]), Frédéric Gazeau (Conceptualization [equal], Investigation [equal], Writing – original draft [equal], Writing – review & editing [equal]).

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