Filling the monitoring gap: Aquatic ecosystem metabolism as a cost-effective, scalable tool for assessing marine carbon dioxide removal

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Abstract

Marine carbon dioxide removal (mCDR) is an emerging climate mitigation solution increasingly recognized as necessary to supplement greenhouse gas emission reductions. Various mCDR methods, from biotic to abiotic measures, are being piloted, fueled by enthusiasm from governments and the private sector. As companies start to sell carbon credits, standards for monitoring, reporting, and verification (MRV) to assess removed carbon and environmental impacts have begun to lag behind, putting the credibility of mCDR at risk. Currently proposed assessment frameworks require costly, complex measurements that can pose a practical barrier, especially for smaller projects. Although dissolved oxygen is easily measured and often included as a required monitoring parameter, its role in evaluating ecosystem status remains poorly defined—highlighting gaps in MRV interpretation and implementation. To address this monitoring bottleneck, we propose the widespread adoption of aquatic ecosystem metabolism metrics in the MRV pipeline. Ecosystem metabolism, which can be calculated using low-cost, autonomous oxygen sensor measurements, provides real-time, integrative insights into how mCDR interventions affect carbon cycling and ecosystem function. Here, we review how metabolism has been used as an effective tool in environmental management and highlight parallels with mCDR assessment needs. We then present a synthesis of metabolism measurements in coastal ecosystems and describe how scaling these measurements can address key mCDR assessment challenges. We also discuss practical considerations and opportunities for incorporating metabolism into MRV frameworks. By tracking ecosystem responses across mCDR methods and deployment sites, metabolism provides a readily measured and communicated metric that serves as a practical addition to the mCDR monitoring toolkit.

1. Introduction

Record temperatures in calendar year 2024 suggest that the world will likely exceed the Paris Agreement's climate target of 1.5°C within the next 20 years (Bevacqua et al., 2025; Cannon, 2025). In order to keep warming below this threshold, human society must severely limit future carbon dioxide (CO_2) emissions—to have a 50% chance of staying within 1.5°C warming, at the start of 2025 our estimated remaining carbon budget was 130 billion tons (Gt) CO_2 (Forster et al., 2025). This budget is rapidly dwindling: Global CO_2 emissions have steadily increased over the past decades, on average by 2.2% per year since 1960 (Deng et al., 2025), and culminating in an all-time high of 37.4 Gt released during 2024 alone (Friedlingstein et al., 2025).

While efforts should focus first and foremost on reducing current emissions, implementing carbon dioxide removal (CDR) approaches is increasingly recognized as necessary to offset residual emissions and achieve net negative emissions. Indeed, the Intergovernmental Panel on Climate Change (IPCC)'s Sixth Assessment Report emphasized that to achieve the 1.5°C warming target, deploying CDR techniques alongside rapid and substantial emissions reductions is necessary (IPCC, 2023). Until recently, CDR efforts have focused on land-based methods such as biochar carbon removal, afforestation/reforestation, and direct air capture; the former is the dominant CDR method in terms of delivered carbon credits (https://www.cdr.fyi/). Given constraints for terrestrial CDR—notably, competition for land use—over the past decade the ocean has gained renewed attention as a promising source of climate change mitigation solutions (De Pryck & Boettcher, 2024). Such marine CDR (mCDR) approaches involve human interventions to enhance or accelerate natural processes that store carbon in the ocean long term.

Various mCDR methods have been proposed and can be broadly classified into biotic and abiotic approaches. Biotic approaches intentionally modify ecosystems to generate net carbon removal from the atmosphere beyond what would have occurred naturally, and entail enhancing photosynthetic CO_2 uptake in surface waters in contact with the atmosphere (Oschlies et al., 2025). Widely considered biotic methods include fertilizing the ocean with the micronutrient iron to stimulate marine primary production (termed ocean iron fertilization, OIF); farming seaweed, aka macroalgae, and either sinking it to the deep ocean or harvesting it for use in durable products on land (macroalgae sinking or harvesting); pumping nutrient-rich water from the deep ocean to the surface to stimulate phytoplankton growth (artificial upwelling); and restoring or creating new habitats in coastal vegetated ecosystems like mangroves, salt marshes, and seagrass beds, essentially marine reforestation (coastal blue carbon enhancement) (Bach et al., 2024; Oschlies et al., 2025).

In contrast, abiotic approaches enhance the ocean's uptake of CO_2 from the atmosphere by altering seawater chemistry. In general, these approaches aim to reduce the partial pressure of CO_2 in surface waters by either enhancing its alkalinity (a measure of the capacity of a solution to neutralize acids; it determines how much CO_2, a weak acid, can be stored in seawater) or by directly extracting CO_2 from seawater. The former, termed ocean alkalinity enhancement (OAE), can be accomplished by dissolving alkaline materials like basalt or limestone, essentially accelerating natural rock weathering processes, or by removing acids from seawater via electrochemical methods—both of these processes shift the dissolved inorganic carbon (DIC) species present from dissolved CO_2 toward stable forms, namely bicarbonate and carbonate ions. In the latter, termed direct ocean removal (aka direct ocean capture and storage), CO_2 extracted from seawater is sequestered in underground geological reservoirs or utilized in durable products, while the CO_2-depleted seawater is released back into the surface ocean where it can absorb more CO_2.

For a given method to produce high-quality carbon removal, it must be additional—i.e., it removes CO_2 due to deliberate human intervention, above what would have been removed from natural oceanic uptake, and durable—i.e., it keeps carbon out of the atmosphere for a considerable length of time (on the order of centuries to millennia) (Ho et al., 2023). Equally important to quantifying the carbon removed is assessing the ecological and environmental impacts, which could include changes to plankton communities, oxygen levels, pH, and production of other greenhouse gases like methane and nitrous oxide (Buesseler et al., 2024). Systematic assessment of an mCDR method, both in terms of carbon removal efficacy and potential environmental impacts, requires robust monitoring, reporting, and verification (MRV). MRV for carbon accounting involves measuring or quantifying the amount of CO_2 removed over the course of an mCDR project and reporting the results of this monitoring to a third party, which can then independently verify these results (Burke et al., 2024). Evaluating potential ecological and environmental shifts, also known as environmental MRV (eMRV) (Buesseler et al., 2024), similarly requires collecting water quality and ecological data and making it available to regulatory agencies, research partners, and community members (Ebb Carbon, 2024). Detailed, transparent MRV protocols are necessary to demonstrate that an mCDR intervention is either a viable and safe climate mitigation tool, or that it is ineffective or environmentally harmful and should not be pursued.

To date, no proposed mCDR method has a sufficient scientific knowledge base to support its large-scale deployment (Fennel, 2026). While some best practice guidelines have recently been developed for mCDR research (e.g., Oschlies et al., 2023 for OAE), very few MRV protocols exist for testing specific strategies (Ebb Carbon, 2024; Planetary, 2023) and there is no standard MRV framework across methods (Yao et al., 2025). While the overarching goals of MRV are to quantify the amount of CO_2 removed, its durability, and any non-carbon environmental impacts, the exact details of an MRV protocol—a document that outlines methods or sets quality requirements for achieving these goals—depend on the mCDR method. Each method faces specific MRV challenges (**Figure 1**). For instance, MRV for biotic methods that aim to stimulate surface ocean primary production would need to assess the additional biomass created, how much is exported to the deep ocean, and how long the carbon remains sequestered before being mixed back to the surface (Palter et al., 2023). It is also imperative to assess unintended effects, such as whether the additional production at the mCDR project site causes decreased production elsewhere, which would undermine the climate benefits (Palter et al., 2023). MRV for coastal blue carbon enhancement like kelp or mangrove forest establishment is challenging as it requires monitoring impacts over a vast area (Yao et al., 2025). OAE has various potential side effects, such as secondary precipitation of carbonate minerals (if alkalinity is added too quickly), which would release CO_2, or shifts in phytoplankton community structure, which may alter carbon production and flux; tracking these ecosystem changes requires comprehensive environmental monitoring (Ho et al., 2023; Yao et al., 2025)—no easy feat in dynamic marine systems.

Novel mCDR methods are gaining traction among policymakers and companies are already buying carbon removal credits. In the U.S., the National Academies of Science, Engineering, and Medicine recently released a federal research strategy for mCDR that recommended $125 million in federal research funding over the next decade (NASEM, 2022). Meanwhile, Frontier, a $1 billion carbon removal fund backed by Google, Stripe, Shopify, and others is already purchasing carbon credits from several mCDR companies in return for mitigating their carbon footprints. This rapid development necessitates robust and consistent MRV systems and standards for ocean-based CDR, which to date remain underdeveloped compared to terrestrial CDR methods (Oschlies et al., 2025). MRV enables inclusion of mCDR in national greenhouse gas inventories so that it can count toward countries' climate goals—termed nationally determined contributions (NDCs)—under the Paris Agreement, and it allows commercial entities to verify their carbon removal services and seek payment in the voluntary carbon credits market. MRV policy varies by country; for example, the United Kingdom government has prioritized development of CDR standards and guidelines and funds demonstrator projects that must meet quality thresholds (Burke et al., 2024). In the U.S., CDR strategy has focused on rapid commercial scaling of publicly funded methods instead of MRV development (Burke et al., 2024). Consequently, at present no national greenhouse gas inventory guidelines are available, while development of the first protocols only began in the voluntary market in 2022 (Burke et al., 2024; Planetary, 2023) As the need to deploy carbon removal strategies becomes ever more urgent, there is a matching need for well-regulated MRV mechanisms to evaluate promising methods and avoid harmful consequences.

Ecosystem metabolism, a key indicator of ecosystem processes, is gaining traction as a tool for aquatic environmental management and could enhance carbon accounting and ecosystem impact assessment for mCDR MRV frameworks (**Figure 1**). Ecosystem metabolism integrates the total metabolic activity of all organisms in a particular ecosystem and as such is a "common currency" that links organic carbon cycling to environmental change in disparate habitats (Jankowski et al., 2021; Testa & Nidzieko, 2024). The metabolism of an ecosystem is characterized as the sum of autotrophic processes, which synthesize new organic carbon using external energy, and heterotrophic processes, which consume organic carbon to produce energy. Accordingly, at the whole-ecosystem level, metabolism comprises two components: the total rates of organic matter production ("gross primary production," GPP) and organic matter respiration ("ecosystem respiration," ER). Their difference, termed "net ecosystem metabolism" (NEM = GPP – ER), reflects the overall organic carbon balance of the ecosystem (equivalent terms are "net ecosystem production" and, in the oceanographic literature, "net community production"). NEM provides an integrative measure to assess the health of aquatic environments and to quantify the fluxes of organic carbon at regional and global scales (Needoba et al., 2012).

Ecosystem metabolism metrics (GPP, ER, and NEM) can be quantified by tracking changes in any reactant that is consistently involved in primary production and respiration, such as dissolved oxygen (DO), CO_2, or macronutrients. Using oxygen changes over 24-hour cycles to calculate production and respiration was first explored by Sargent & Austin (1949) to study a coral reef; this method was refined and broadly applied by the Odum brothers (Odum, 1956, 1957; Odum & Odum, 1955), leading to the widespread adoption of the open-water diel oxygen method as a technique for measuring metabolism in lakes, streams, and estuaries. "Open-water" refers to the fact that measurements are taken directly in the ecosystem, rather than in closed chambers or bottles, while "diel oxygen" specifies that daily cycles of oxygen concentrations are monitored. The technique calculates daily rates of GPP and ER by accounting for DO produced by photosynthesis during daylight and DO consumed by aerobic respiration over the full diel cycle, correcting for nonbiological gas exchange and advection (for a more detailed description, see Section 4.1 Methodological Considerations). Oxygen-based metabolism rates can be converted to carbon rates using assumed or measured photosynthetic or respiratory quotients (Testa & Nidzieko, 2024). While this method was initially developed for the coastal ocean, it has been expanded to constrain primary productivity in the open ocean using observations obtained using ships, moorings, and autonomous underwater platforms (e.g., Izett et al., 2024; Nicholson et al., 2015).

Measuring DO concentrations has become the most common method to quantify ecosystem metabolism, given advancements in the past two decades that have produced relatively cheap, low-power, and robust DO sensors that can be operated in situ autonomously (Bittig et al., 2018; Needoba et al., 2012; Staehr et al., 2010). The diel DO technique has significant advantages over other oxygen-based methods: traditional bottle incubations provide only a snapshot of pelagic metabolism at a discrete location, leading to scaling issues; similarly, while oxygen isotope measurements from bottle samples can provide sensitive rate estimates, they are integrated over the previous DO turnover timescale and, like incubations, must also be scaled up from a single sample (Loken et al., 2021). With the diel DO technique, in situ DO sensors permit continuous monitoring of whole-ecosystem metabolic activity, providing integrative, dynamic rates. Accordingly, long timeseries of diel DO-derived metabolism have been used as early indicator of environmental change and to detect ecosystem responses to management (Jankowski et al., 2021).

In this review, we evaluate how the diel DO technique offers a practical, low-cost, and scalable approach to quantifying ecosystem metabolism, helping address key MRV challenges across mCDR methods. Because initial mCDR field trials have concentrated in coastal regions—due to favorable conditions and simpler access and permitting—we focus on coastal applications. However, this review lays the groundwork for the integration of metabolism metrics into more complex MRV frameworks, including those that would be required for mCDR in open-ocean settings. In **Section 3**, we describe recent applications of ecosystem metabolism to environmental management in lakes and rivers and highlight parallels with mCDR MRV needs. Using these lessons, we conceptualize how metabolism metrics can complement existing MRV frameworks. We then synthesize published diel-DO-based metabolism estimates from coastal ecosystems worldwide to illustrate where measurements have been made and how they can inform mCDR deployments. In **Section 4**, we discuss key issues to consider when implementing the diel DO technique, and explore how metabolism metrics can be integrated with observational and modeling efforts and eventually scaled to open-ocean settings. Finally, in **Section 5**, we outline priorities for operationalizing metabolism metrics within MRV frameworks. The overarching goal of this paper is to motivate and guide the application of metabolism metrics to advance mCDR assessment.

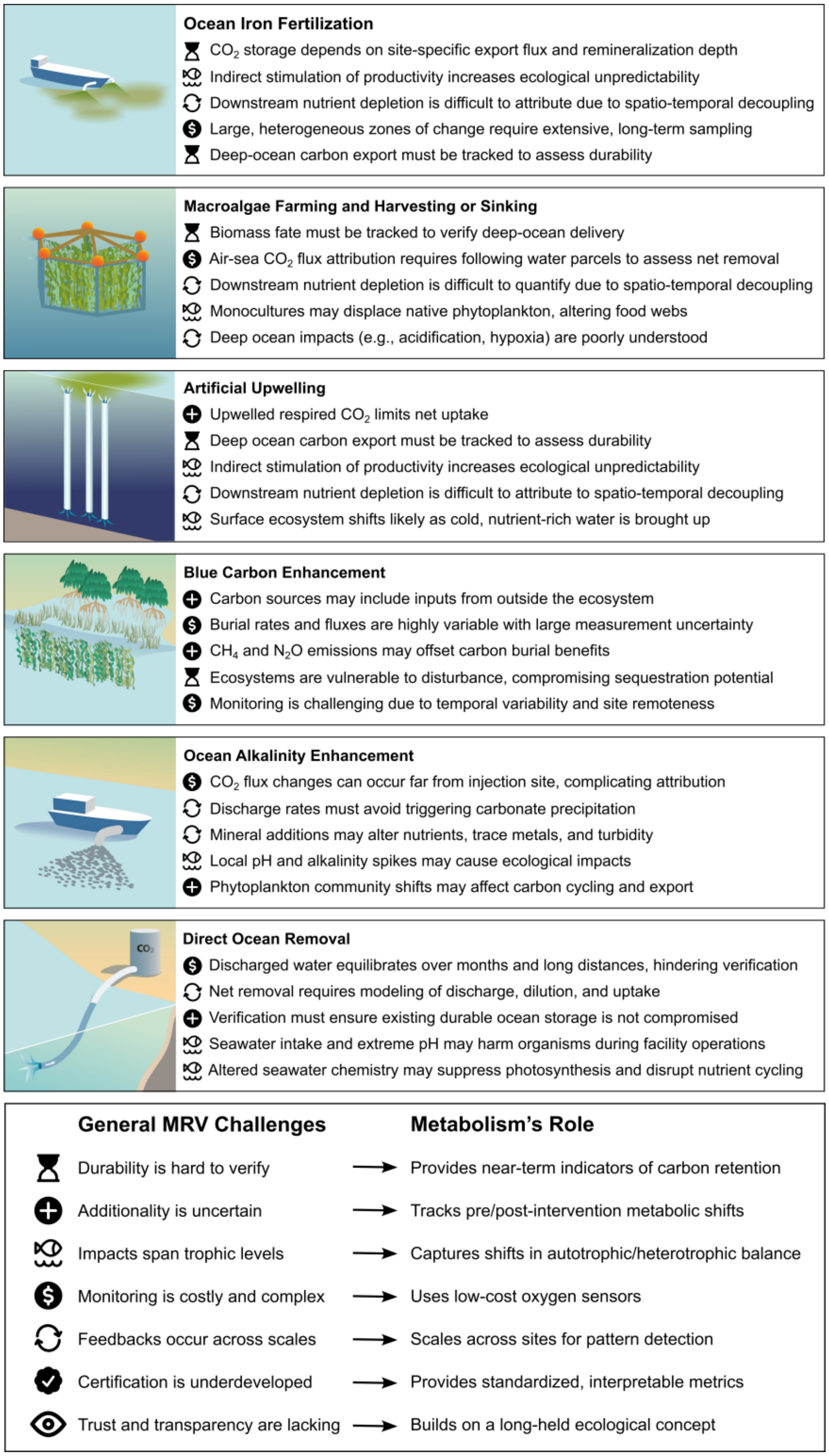
2. Methods

2.1 Overarching Narrative Review

The accelerating development and commercialization of mCDR techniques risks outpacing our understanding of the biogeochemical and ecological changes they may trigger in marine ecosystems. To support informed decision-making about which ocean-based climate interventions to pursue, robust and scalable monitoring frameworks are urgently needed. This topical review synthesizes insights from aquatic ecosystem metabolism research to assess its potential for filling mCDR monitoring gaps. We focus on how metabolism metrics derived from continuous DO measurements can be used to evaluate carbon cycling changes and ecosystem responses in a cost-effective and scalable manner.

Numerous recent reviews and assessments have synthesized the current state of mCDR science (e.g., NASEM, 2022; Doney et al., 2024, 2025; GESAMP, 2025; Oschlies et al., 2025), offering detailed evaluations of technical approaches, feasibility, and environmental risks. Similarly, foundational work on Odum's diel oxygen method and its applications in quantifying ecosystem metabolism is well-covered in several book chapters and articles (Jankowski et al., 2021; Needoba et al., 2012; Staehr et al., 2010; Testa & Nidzieko, 2024). Rather than duplicating these comprehensive reviews, we adopt a narrative approach that bridges disciplinary divides and highlights the underexplored potential of metabolism metrics to strengthen mCDR evaluation frameworks.

This interpretative synthesis aims to support scientists, policymakers, and practitioners by offering both conceptual framing and actionable recommendations. Embedded within the broader conceptual synthesis is a targeted systematic review of studies that quantified coastal ecosystem metabolism using continuous DO data. We aim to update previous compilations of metabolic rates in coastal ecosystems (Caffrey, 2004; Hoellein et al., 2013; Nidzieko, 2018) and identify where diel DO-based metabolism estimates exist in coastal locations that may serve directly as mCDR deployment sites or as analogs.



Ocean Iron Fertilization

- ⌛ CO_2 storage depends on site-specific export flux and remineralization depth
- 🐟 Indirect stimulation of productivity increases ecological unpredictability
- ↻ Downstream nutrient depletion is difficult to attribute due to spatio-temporal decoupling
- $ Large, heterogeneous zones of change require extensive, long-term sampling
- ⌛ Deep-ocean carbon export must be tracked to assess durability

Macroalgae Farming and Harvesting or Sinking

- ⌛ Biomass fate must be tracked to verify deep-ocean delivery
- $ Air-sea CO_2 flux attribution requires following water parcels to assess net removal
- ↻ Downstream nutrient depletion is difficult to quantify due to spatio-temporal decoupling
- 🐟 Monocultures may displace native phytoplankton, altering food webs
- ↻ Deep ocean impacts (e.g., acidification, hypoxia) are poorly understood

Artificial Upwelling

- ⊕ Upwelled respired CO_2 limits net uptake
- ⌛ Deep ocean carbon export must be tracked to assess durability
- 🐟 Indirect stimulation of productivity increases ecological unpredictability
- ↻ Downstream nutrient depletion is difficult to attribute to spatio-temporal decoupling
- 🐟 Surface ecosystem shifts likely as cold, nutrient-rich water is brought up

Blue Carbon Enhancement

- ⊕ Carbon sources may include inputs from outside the ecosystem
- $ Burial rates and fluxes are highly variable with large measurement uncertainty
- ⊕ CH_4 and N_2O emissions may offset carbon burial benefits
- ⌛ Ecosystems are vulnerable to disturbance, compromising sequestration potential
- $ Monitoring is challenging due to temporal variability and site remoteness

Ocean Alkalinity Enhancement

- $ CO_2 flux changes can occur far from injection site, complicating attribution
- ↻ Discharge rates must avoid triggering carbonate precipitation
- ↻ Mineral additions may alter nutrients, trace metals, and turbidity
- 🐟 Local pH and alkalinity spikes may cause ecological impacts
- ⊕ Phytoplankton community shifts may affect carbon cycling and export

Direct Ocean Removal

- $ Discharged water equilibrates over months and long distances, hindering verification
- ↻ Net removal requires modeling of discharge, dilution, and uptake
- ⊕ Verification must ensure existing durable ocean storage is not compromised
- 🐟 Seawater intake and extreme pH may harm organisms during facility operations
- 🐟 Altered seawater chemistry may suppress photosynthesis and disrupt nutrient cycling

	General MRV Challenges		Metabolism's Role
⌛	Durability is hard to verify	→	Provides near-term indicators of carbon retention
⊕	Additionality is uncertain	→	Tracks pre/post-intervention metabolic shifts
🐟	Impacts span trophic levels	→	Captures shifts in autotrophic/heterotrophic balance
$	Monitoring is costly and complex	→	Uses low-cost oxygen sensors
↻	Feedbacks occur across scales	→	Scales across sites for pattern detection
✓	Certification is underdeveloped	→	Provides standardized, interpretable metrics
👁	Trust and transparency are lacking	→	Builds on a long-held ecological concept

Figure 1. Key monitoring, reporting, and verification (MRV) challenges across six marine carbon dioxide removal approaches. The intervention-specific panels summarize major issues identified from the literature (Bach et al., 2024; Buesseler et al., 2024; Halloran et al., 2025; Ho et al., 2023; Hurd et al., 2024; Mengis et al., 2023; NASEM, 2022; Oschlies et al., 2025; Troell et al., 2024; Yao et al., 2025). General MRV challenges and the potential role of metabolism measurements in providing standardized, scalable indicators of CO_2 removal and ecosystem impacts are shown at the bottom. Intervention-specific issues are categorized according to the broader MRV challenge they represent, as indicated by the symbols. Artwork modified from Rita Erven, GEOMAR (CC BY 4.0).

2.2 Systematic Review

For the systematic review component, we compiled published diel oxygen metabolism measurements in coastal environments worldwide. By synthesizing existing metabolism data, we aimed to provide an overview of the location and the extent of baseline data to inform mCDR deployments in nearby or similar coastal sites. While mCDR is envisioned to be deployed in the open ocean as well, we restricted our scope to the coastal zone because nearly all mCDR field trials to date have occurred in coastal and estuarine sites (**Figure 2**). Initial deployments have focused on coastal sites as they provide favorable oceanographic conditions for efficient mCDR, including rapid gas exchange, upwelling, and greater air-sea pCO_2 differences (Ebb Carbon, 2024). Moreover, capitalizing on locations with existing wastewater outfalls or industrial infrastructure—e.g., shore-based industrial facilities with seawater intakes—lowers costs, accelerating demonstration projects and scaling up of technology (NASEM, 2022); similarly, easy access to inputs (e.g., alkaline materials for OAE) lowers transportation-related costs and greenhouse gas emissions. For instance, in the first proof-of-concept OAE field trial, wastewater was enhanced with alkalinity and discharged to the coastal ocean in north Cornwall, UK (Kitidis et al., 2024). Another important consideration in determining real-world implementation is governability—mCDR activities attract less international concern if they are contained within territorial waters, ensuring more localized environmental impacts and easier monitoring (Bach et al., 2024). Sites like estuaries are promising candidates for mCDR pilots as they have limited spatial transport and are easier to monitor.

Ideally, sites are selected with ample historical, publicly available data to help understand natural variability and baseline conditions pre-deployment. We therefore conducted a systematic review of the peer-reviewed English-language literature to synthesize studies that used continuous dissolved oxygen measurements to calculate NEM rates in coastal ecosystems. We targeted studies that reported either NEM or both GPP and ER, as in the latter case, NEM can be calculated by difference. We conducted this search in Scopus and Web of Science using the following keyword combination: ("ecosystem metabolism" OR "net ecosystem production" OR "net community production" OR ("primary production" AND "respiration")) AND (coast* OR estuar* OR nearshore OR bay) AND ("diel oxygen" OR "open water" OR "free water" OR "continuous dissolved oxygen" OR "high frequency dissolved oxygen" OR "dissolved oxygen dynamics"). Articles from any point until December 1, 2025 were included, yielding 81 publications combined from both databases after removing duplicates. Furthermore, relevant articles based on the authors' personal knowledge were included, adding 14 publications and one preprint. To validate our search string, we conducted a cross-check with other studies (e.g., Caffrey et al., 2014, 2014; Gomez-Castillo et al., 2023; Hoellein et al., 2013) to confirm that well-known, relevant articles were included in our synthesis.

Next, we manually screened the compiled articles to ensure their relevance to our synthesis by reviewing each title and abstract. Articles were only included if they were original studies that reported NEM rates derived from high-frequency dissolved oxygen measurements in estuarine or coastal systems. We excluded studies that reported only GPP or ER, or that used an alternative method (e.g., bottle incubations or oxygen isotopes) to estimate metabolic rates. Additionally, we required numeric NEM (or GPP and ER) values to be reported in text or tables. Applying these criteria yielded a final set of 30 articles.

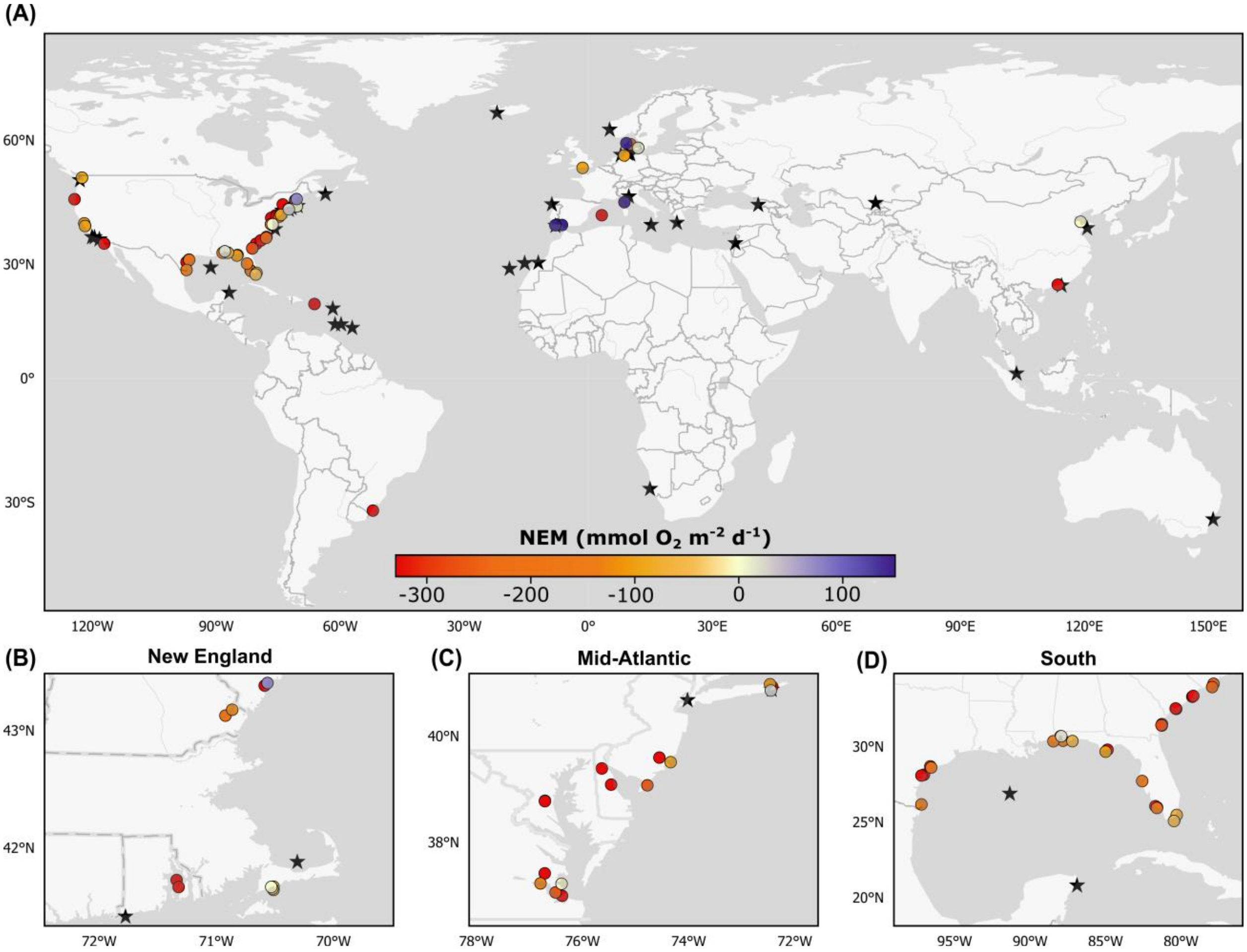


Figure 2. Published annual mean net ecosystem metabolism (NEM) rates estimated using the diel oxygen method across **(A)** global coastal oceans, with insets showing U.S. east coast regions: **(B)** New England, **(C)** Mid-Atlantic, and **(D)** South. One site in the Pearl River Estuary (Humen outlet, China) had an exceptionally low NEM rate of -1,207 mmol O_2 m^{-2} d^{-1} and was excluded from the map. Black stars indicate locations of past and current mCDR pilot sites, obtained from Ocean Visions (https://oceanvisions.org/mcdr-field-trials/). Detailed NEM, GPP, and ER rates (in both original and converted units), along with site metadata, are provided in **Table S1** of the Supplemental Information.

3. Results & Synthesis

3.1 Lessons from Freshwater Management

3.1.1 Case Studies

Aquatic ecosystem metabolism has proven valuable as a monitoring tool in freshwater environmental management, providing early indicators of anthropogenic impacts and restoration success. Here, we highlight case studies illustrating how metabolism metrics have been used to track ecosystem responses to environmental degradation and functional recovery from management efforts in rivers and lakes worldwide. These applications offer critical insights for incorporating metabolism into MRV frameworks, particularly regarding sensitivity to environmental change, scalability, and integration with existing monitoring infrastructure.

In a recent synthesis, Zhang et al. (2023) extracted two decades of metabolism data across China's major rivers and coastal zones, which have experienced significant changes associated with population growth. Their analysis revealed that aquatic metabolism varies in response to spatiotemporal gradients in land cover and nutrient inputs. In the Pearl River Estuary, which receives most of the wastewater from the mega-metropolis of Guangzhou, rapid urban growth and subsequent increases in nutrient loading between 2000–2010 drove large decreases in NEM and increased ER, signaling ecosystem stress (Jiang et al., 2015). Zhang et al. (2023) also found that large riverine inputs of nutrients during certain seasons often drove estuarine NEM below zero, turning coastal zones like the East China Sea and Bohai Sea into CO_2 sources and placing them at risk of hypoxia (oxygen depletion) and acidification. Conversely, wetland restoration was linked to increased NEM; in the Liao River Basin, expansion of wetland area corresponded with peak NEM values in 2015 (Xi et al., 2018), suggesting that wetlands are crucial in river productivity and that proper management can protect ecological function.

In Spain's polluted Oria River, Arroita et al. (2019) demonstrated how metabolism can be used as an early indicator of recovery following implementation of a wastewater treatment plant. They leveraged DO data collected for long-term water quality monitoring to derive a 20-year daily metabolism record. Their analysis showed that following sewage abatement, GPP and ER gradually decreased—ER more than GPP—resulting in a shift in NEM from highly heterotrophic to nearly balanced. This functional shift improved oxygen conditions and increased the amount of algal-derived carbon available for higher trophic levels, enabling recolonization by invertebrates and fish. Notably, metabolic trends emerged years before visible biological recovery, demonstrating metabolism's value as an early diagnostic. While structural indicators (i.e., water quality parameters like oxygen levels, nutrient concentrations, and biological diversity) describe ecosystem condition, functional metrics like metabolism reveal the underlying dynamics of key biophysical processes (Palmer & Febria, 2012). In other words, while structural metrics can indicate that something is wrong with an ecosystem, functional metrics can help illustrate why. In this case, reduced metabolic rates reflected less extreme daily oxygen fluctuations, lowering hypoxia risk and creating a more hospitable environment for aquatic life.

Other riverine studies further illustrate metabolism's sensitivity to management. In the Kootenai River, which spans Canada and the U.S., Chowanski et al. (2020) observed that flow regulation and habitat restoration significantly elevated GPP and ER, reflecting increased biological activity. Flow regulation downstream of Libby Dam reduced turbidity and bed mobility, enhancing light availability and algal persistence; habitat restoration further boosted metabolism, likely through increased macrophyte abundance and floodplain connectivity. Similarly, Huang et al. (2018) studied the Ohyama River in Japan, where historically low environmental flows had degraded downstream habitats. Following flow restoration to more natural conditions, they documented increases in GPP and ER, a shift toward autotrophic conditions (higher GPP/ER ratio), and greater algal species richness. These functional changes signaled ecological recovery and improved water quality.

Lake restoration efforts demonstrate metabolism's sensitivity to engineered interventions. Dunalska et al. (2014) tracked metabolism responses to hypolimnetic withdrawal—a technique that removes nutrient-rich bottom waters—in Poland's Kortowskie Lake. Using metabolism metrics calculated from vertical DO profiles, they found the intervention successfully weakened stratification and shifted the lake toward net autotrophy by boosting primary production in the upper layers, highlighting metabolism's ability to detect vertical changes in carbon processing from physical interventions.

Metabolism's sensitivity to environmental gradients is further illustrated by Morant et al. (2024), who examined Mediterranean saline shallow lakes—ecosystems that share key characteristics with coastal environments, including variable salinity and hydrological regimes. Saline lakes in this region have experienced widespread ecological degradation from land reclamation, pollution, freshwater overuse, and intensive agriculture. Through measurements of metabolism in 19 lakes of varying ecological status, they found that the well-preserved and restored lakes exhibited the highest carbon retention rates and functioned as autotrophic systems. In contrast, more degraded lakes—affected by hydrological changes like excess freshwater or wastewater inputs, and trophic disturbances like nutrient enrichment—displayed heterotrophy and reduced carbon storage capacity.

Collectively, these case studies demonstrate metabolism's value as a functional monitoring tool across diverse aquatic systems and management contexts. Metabolism metrics consistently detect both ecosystem degradation and recovery responses, and potentially reveal changes before structural indicators. Importantly, metabolism responds to environmental gradients (e.g., in nutrient loading) and tracks interventions ranging from wastewater treatment to wetland expansion to engineered lake restoration. These capabilities establish a strong foundation for extending metabolism monitoring to coastal marine environments, where clear communication of metabolic status can aid in assessing mCDR interventions (**Box 1**, point 6).

3.1.2 Metabolic Regimes and Fingerprints

Tracking metabolism over seasonal time scales enables definition of a metabolic regime—the characteristic temporal pattern of GPP and ER within an ecosystem (Bernhardt et al., 2018; **Figure 3A**). Similar to phenology for terrestrial ecosystems, which describes seasonal patterns of biological activity, metabolic regimes integrate responses to interacting drivers such as light, temperature, water clarity, nutrient supply, organic matter availability, and hydrologic variability (Testa & Nidzieko, 2024). Bernhardt et al. (2018) also introduced the concept of the metabolic fingerprint as a complementary diagnostic tool. A metabolic fingerprint depicts the entire distribution of daily GPP and ER values for a site over a defined time period, visualized as a kernel density plot (**Figure 3B**). Beyond summary metrics such as mean GPP or ER, it conveys the range and frequency of metabolic rates and their relative balance between autotrophy and heterotrophy. In the Oria River case study, following installation of the wastewater treatment plant, the river's metabolic fingerprint shifted from a broad, heterotrophic-dominated space to a contracted, near-balanced state, reflecting reduced daily DO fluctuations and improved water quality conditions (Bernhardt et al., 2018). Similarly, Jarvie et al. (2022) applied metabolic fingerprints to visualize ecosystem responses in the Grand River in Canada, showing that enhanced wastewater nitrification treatment led to a pronounced contraction of metabolic space and a shift from net heterotrophy to net autotrophy.

Metabolic fingerprints provide a concise visual representation of metabolism patterns, enabling direct comparison of ecosystem function across sites, seasons, and years, while summarizing complex dynamics in an accessible format. As metabolism datasets expand, fingerprints can help classify clusters of metabolic regimes and improve mechanistic understanding of how coastal metabolism responds to climatic and anthropogenic change. For mCDR interventions, metabolic fingerprints offer a scalable and intuitive diagnostic for cross-site comparison and conveying ecosystem functional responses to mCDR interventions (**Box 1**, points 2 and 6).

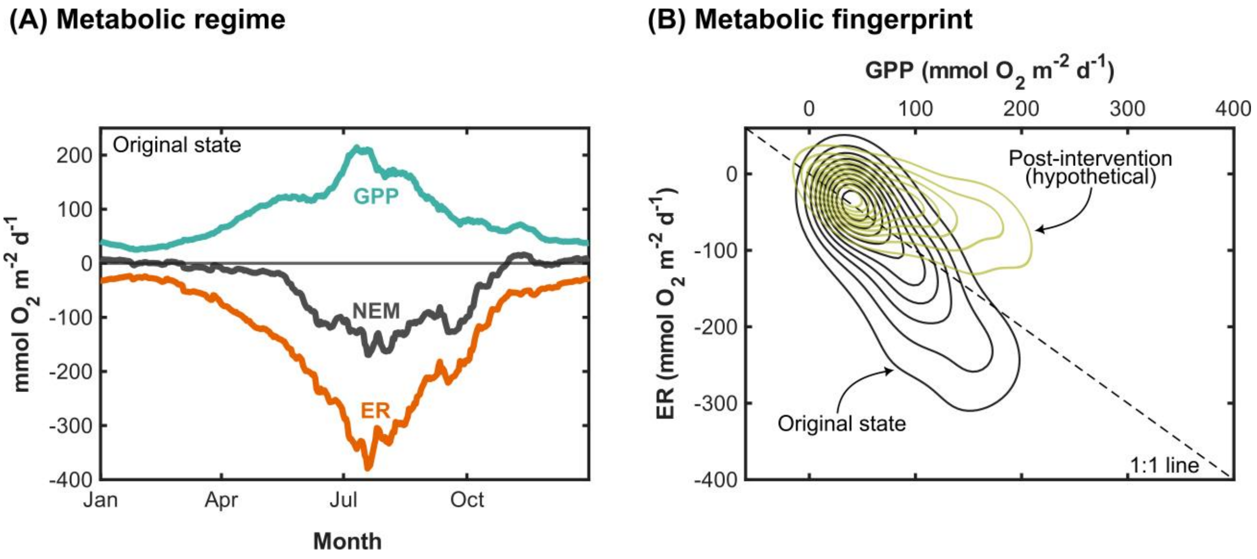


Figure 3. Conceptual illustration of metabolic regimes and fingerprints. **(A)** Seasonal dynamics of gross primary production (GPP) and ecosystem respiration (ER) over an annual cycle for a net heterotrophic ecosystem (a marsh tidal channel in southern New Jersey; reference removed for anonymous review), illustrating a characteristic metabolic regime. **(B)** Metabolic fingerprints, visualized as kernel density plots of daily GPP and ER values. The original state, which corresponds to the data in (A), occupies a broad heterotrophic space. The post-intervention fingerprint represents a possible shift following a hypothetical mCDR deployment; this shape and trend is schematic and does not represent empirical data.

3.2 Scaling Metabolism for MRV

Despite growing interest in mCDR, robust MRV frameworks remain in their infancy. Existing efforts to develop method-specific protocols—particularly for OAE—vary widely in scope and detail. For example, Ho et al. (2023), as part of an OAE best practices guide (Oschlies et al., 2023), outline foundational principles for validating carbon removal, advocating for MRV systems that combine tailored numerical models with targeted observations of ocean currents, air-sea gas exchange, and carbonate chemistry. Meanwhile, Isometric, a voluntary carbon removal registry, has introduced protocols for five mCDR methods, including alkalinity enhancement and direct ocean capture and storage (https://registry.isometric.com/protocols). These protocols require monitoring DO to assess ecosystem health and, for direct ocean capture, to ensure restoration of safe DO levels after CO_2 extraction, yet provide little guidance on implementation. Terms such as “high” and “low” frequency monitoring remain undefined, and no interpretation framework or ecological thresholds are specified. Notably, Isometric protocols avoid prescribing ecological stop triggers (predefined thresholds to halt deployment when exceeded), citing challenges in establishing baselines and attributing ecological changes.

Two mCDR companies—Planetary Technologies and Ebb Carbon—have released MRV protocols that comply with ISO 14064-2, an international standard that facilitates accurate and transparent greenhouse gas accounting. Planetary's (2023) protocol for mineral-based OAE emphasizes collecting baseline data that captures seasonal variability and monitoring control sites with similar tidal and water column characteristics to isolate intervention effects. Their ecological monitoring plan focuses on lower trophic level organisms and includes post-operational follow-up monitoring to detect long-term impacts. They also describe tracking potential restorative effects, such as reduced local acidification, using pH and carbonate saturation state. Ebb Carbon's (2024) protocol, which supports electrochemical OAE, similarly outlines pre-deployment site assessments using historical and sensor data, and post-deployment monitoring to ensure the site is left in a “stable and ecologically sound condition.” During deployments, they describe collecting ecological data, such as visible shifts in habitat conditions or marine life, to monitor potential impacts and to address them as needed. DO is included as an indicator of general ecosystem health and for regulatory compliance, but again, no specific metrics or thresholds are provided.

These protocols lay important groundwork for operationalizing MRV for mCDR, but they also highlight key gaps related to scalability, credibility, and policy integration. Most notably, while DO is frequently listed as a required parameter, its role in assessing ecosystem status—both in terms of carbon and ecological impacts—is poorly defined. For instance, the Isometric protocols do not define what "high" and "low" frequency measurements are, nor how these measurements can be used to indicate ecosystem health. Meanwhile, Oschlies et al.'s (2023) OAE best-practices guide does not mention monitoring DO in its chapter on MRV for carbon impacts, nor in other chapters considering ecosystem impacts. While both Planetary and Ebb Carbon's protocols outline ecological monitoring plans, only Ebb's mentions DO, and neither describe exactly how they will assess ecological impacts, e.g., what parameter-specific metrics and thresholds they will use. This lack of clarity risks creating inconsistent standards among projects and undermines the credibility of MRV systems. Moreover, if ecological changes are only detected once they become visibly apparent—such as shifts in habitat or marine life—it may be too late to mitigate them.

Metabolism metrics provide a pathway to filling crucial gaps in current MRV protocols (**Figure 1**). Building on the freshwater management case studies presented in Section 3.1 Lessons from Freshwater Management, we outline how metabolism can strengthen MRV frameworks for mCDR, organized around four themes: enhancing data coverage across space and time, establishing baselines and detecting disturbance, supporting modeling efforts for carbon accounting, and providing standardized metrics with policy relevance.

3.2.1 Data Coverage Across Space and Time

Robust MRV must capture dynamic ecosystem responses to mCDR interventions across a range of spatial and temporal scales. The diel oxygen method enables derivation of metabolism metrics from daily oxygen cycles. This method has become increasingly widespread due to the availability of low-cost, autonomous DO sensors—for example, Zhang et al. (2023) found that 79% of metabolism studies that used the diel oxygen method in China's waterways were published in the last five years of their study period, reflecting growing adoption of the technique. The U.S. Geological Survey's National Water Information System provides real-time DO data from thousands of sites, which Appling et al. (2018) used to estimate daily metabolism for 356 rivers, covering nearly 500,000 site-days. These data now underpin StreamPULSE (https://data.streampulse.org/), an open-source platform that aggregates high-frequency river data and provides metabolism estimates. Similar opportunities exist in coastal environments through the National Estuarine Research Reserve System (NERRS)'s System-Wide Monitoring Program (SWMP), which operates 29 estuary monitoring sites spanning the coastal bioregions of the U.S. and provides year-round continuous records of environmental parameters, including DO (Kennish, 2019). SWMP data has been used to estimate metabolic rates in a variety of estuarine sites across the country (**Figure 2**; Beck et al., 2015; Bruesewitz et al., 2013; Caffrey, 2004; Caffrey et al., 2014). These examples underscore the value of coordinated data streams (**Box 1**, point 1).

Within mCDR projects, DO sensors can be deployed across multiple sites at relatively low cost, facilitating replication and long-term monitoring. For example, a network of moored sensors deployed within and surrounding the alkalinity mixing zone in an OAE deployment could provide daily NEM estimates. By enhancing the spatial coverage and temporal resolution, DO-based metabolism can detect transient responses and broader system changes.

3.2.2 Establishing Baselines and Detecting Disturbance

Determining whether mCDR interventions result in net carbon removal or induce ecological shifts requires clear baseline measurements (**Box 1**, point 2). NEM reflects the dynamic balance between autotrophic production and heterotrophic respiration, and deviations from pre-intervention conditions can indicate changes in carbon retention or ecosystem stress. Deploying sensors at targeted downstream sites also enables evaluation of potential nutrient robbing effects. As demonstrated in freshwater systems, metabolism metrics can detect underlying shifts in trophic status before biological disturbances become visibly apparent, serving as early warning indicators.

Given the affordability of DO sensors, they could be installed well before deployment to capture natural seasonal variability and establish site-specific baselines, as well as support high-frequency follow-up monitoring to detect long-term ecological impacts. Data from existing networks like the NERRS SWMP can be leveraged to detect long-term ecological trends. Planetary's protocol describes development of a feedback loop in which environmental data collected downstream automatically tunes their alkalinity dosing rate, with continued addition dependent on whether impacts are detected. Incorporating metabolism metrics into this feedback loop—e.g., adjusting dosing if NEM exceeds a threshold—could improve responsiveness and ecological safety (**Box 1**, point 5).

Estimating daily DO-based metabolic rates permits broadscale assessment of general carbon cycling trends in near-real-time and can inform more comprehensive carbonate system determinations. For example, a shift in NEM from negative to positive values following a macroalgae sinking project may indicate increased carbon uptake via a system-wide shift from net heterotrophy to net autotrophy. Conversely, elevated ER could signal microbial decomposition or ecosystem stress. Continuous metabolism monitoring would facilitate early detection of leakage in carbon storage, which can occur due to both natural and anthropogenic disturbances and results in the loss of stored CO_2 to the atmosphere (Mengis et al., 2023). Sustained, long-term monitoring before and after interventions enables assessments of additionality and helps distinguish mCDR project impacts from natural variability.

3.2.3 Model Support for Carbon Accounting

Verifying that an mCDR project is responsible for removing CO_2 is inherently challenging, as it involves quantifying a small perturbation relative to the ocean's large background uptake. Physical circulation further dilutes this signal, making it difficult to isolate the effects of a specific intervention (Fennel et al., 2022). Consequently, evaluating net carbon uptake and potential ecosystem impacts cannot solely rely on direct observations but requires biogeochemical models tailored to the unique characteristics of each mCDR method, such as the scale, regional environment, and process used (Fennel et al., 2023).

To reliably simulate carbon sequestration and ecosystem feedbacks, these "fit-for-purpose" models must be constrained by real-world observational data. However, many models lack routine biogeochemical and ecological monitoring data, which are required to calibrate, validate, and iteratively improve model performance. Metabolism metrics, which integrate biological activity across trophic levels, can be used to parameterize or validate biogeochemical models (**Box 1**, point 5). For instance, NEM could inform the direction and magnitude of net carbon fluxes. In blue carbon ecosystems, metabolism rate data could be used to calibrate carbon budget models that estimate long-term sequestration under different blue carbon enhancement scenarios. This would strengthen model-data integration, increasing the accuracy and credibility of carbon accounting frameworks.

3.2.4 Standardization & Policy Relevance

As mCDR protocols emerge, standardized and interpretable metrics are needed to ensure consistency between and across projects and facilitate policy integration. Currently, there is little to guide consistency—for example, Isometric's protocols simply list DO as a required parameter without specifying monitoring frequency and duration, thresholds, or interpretation strategies. This lack of standardization is particularly problematic for more complex mCDR methods (**Figure 1**), which have less predictable CO_2 sequestration and higher potential for unintended side effects, making them less readily accepted by policymakers and the public (Bach et al., 2024).

Ecosystem metabolism offers a long-held ecological framework with clear definitions and interpretation. In the U.S., metabolism metrics have been explored as functional indicators of stream nutrient enrichment—the state of Utah has formally established metabolic standards, specifying thresholds for GPP and ER that distinguish between good or fair ecological condition (Jankowski et al., 2021). Applying similar standards to mCDR could support certification schemes, with metabolic rates evaluated relative to baseline conditions for each ecosystem to assess carbon removal durability and ecosystem stability (e.g., **Figure 3**).

Metabolism's relevance to both carbon cycling and ecosystem health makes it a compelling candidate for inclusion in mCDR certification frameworks. For instance, Planetary's (2023) protocol mentions developing a dashboard to visualize project data and statistics, as well as an annual report that shares data metrics. Incorporating metabolism metrics into these tools would provide a clear, integrative indicator of ecosystem status (**Box 1**, point 6). By increasing transparency and facilitating cross-project comparisons, metabolism metrics could help build public and stakeholder trust in mCDR initiatives.

3.3 Metabolism in Coastal Ecosystems

Published diel oxygen-based metabolism estimates are concentrated in temperate estuaries of the U.S. east coast, with some data coverage on the U.S. west coast and Europe, and virtually no data from the southern hemisphere and high-latitude regions (**Figure 2**). This uneven distribution underscores significant gaps in regions that may host future mCDR deployments. Across compiled studies, nearly 80% of sites were net heterotrophic on an annual basis, reflecting the tendency of many coastal systems to consume more organic carbon than they produce. These annual means, however, mask substantial seasonal variability at each site, with metabolic rates typically following pronounced seasonal cycles (e.g., see a representative seasonal metabolic regime for a marsh-adjacent site in **Figure 3A**). While some monitoring networks provide continuous long-term records, particularly in the U.S., many regions globally lack baseline metabolism data, limiting our ability to assess natural variability or detect intervention impacts (see **Table S1** in Supplemental Information for compiled rates and site metadata). Addressing these gaps will be critical for developing scalable MRV frameworks that can support responsible mCDR implementation.

4. Discussion

4.1 Methodological Considerations

Implementing the diel oxygen method for metabolism monitoring requires careful attention to data quality and physical processes that influence DO dynamics. Although modern DO sensors are relatively low cost and robust, sustained quality assurance (QA) and quality control (QC) are essential to ensure reliable estimates (**Box 1**, point 3). QA involves routine sensor calibration and maintenance—particularly in high-productivity coastal environments prone to biofouling—while QC focuses on screening and validating collected data prior to analysis and dissemination. Recommended QC procedures for real-time coastal DO data are outlined by the Integrated Ocean Observing System (IOOS, 2018).

Accurate metabolism estimates depend not only on high-quality data but also on robust analytical frameworks. The widely used diel oxygen method applies a mass balance framework to a defined water body to partition observed changes in DO concentration into biological and physical components. This approach assumes that temporal DO concentration variations (e.g., mmol O_2 m^{-3} d^{-1}) reflect the combined effects of biological production and consumption, as well as physical transport and exchange:

$$\begin{aligned} &\text{Time rate of change of DO} \\ &= \underbrace{\text{Primary production rate } - \text{Respiration rate}}_{\text{Biological processes}} \\ &+ \underbrace{\text{Sediment-water flux } - \text{Air-sea flux } - \text{ Horizontal advection}}_{\text{Physical processes}} \end{aligned} \tag{1}$$

This equation can be rearranged to estimate metabolic rates—namely, GPP and ER—from observed DO time series, provided the physical terms are properly addressed.

In shallow systems, it is assumed that the water column is well mixed and in frequent contact with the sediment interface. As a result, observed DO fluxes include contributions from both submersed primary producers and benthic heterotrophs (organisms living in or on the seafloor that consume organic matter). Consequently, metabolism estimates derived from this method incorporate processes occurring in both the pelagic (water column) and benthic (bottom) zones (Caffrey et al., 2014), and the sediment-water gas flux term can be ignored (Testa & Nidzieko, 2024).

While the air-sea gas flux can be measured directly using floating chambers or eddy covariance methods, in metabolism studies it is typically estimated using empirical relationships with wind speed and/or water velocity (Needoba et al., 2012; Testa & Nidzieko, 2024; Wanninkhof et al., 2009). Determining gas flux is often the largest source of uncertainty in metabolic rate estimates using the diel oxygen method. In low-flow environments, wind speed is the dominant driver of gas exchange, making it a practical proxy for estimating gas flux in coastal and open-ocean systems. Therefore, wind speed alone—readily available from in-situ and satellite observations—is often used to estimate gas exchange (Needoba et al., 2012; Wanninkhof, 2014). Air-sea gas flux is modeled as the product of a gas-exchange coefficient and the difference between the calculated DO saturation concentration (the equilibrium concentration based on temperature and salinity) and the measured DO concentration. Various parameterizations exist to estimate the gas-exchange coefficient. Most were developed from open-ocean data, such as that of Wanninkhof (2014), which is widely used in marine studies. For smaller systems such as lakes and reservoirs, Vachon & Prairie (2013) introduced a parameterization that includes fetch (the maximum distance of open water wind can travel), which has also been shown to perform well in shallow salt marsh ponds (E. M. Howard et al., 2018). In coastal habitats, the parameterization of Ro & Hunt (2006), as described in Thebault et al. (2008), has been commonly applied. Other formulations account for bubble-mediated gas exchange, which becomes significant in high-wind regions (wind speeds >8–10 m s^{-1}), particularly at latitudes greater than 40° (Deike, 2022; Deike et al., 2025; Emerson et al., 2019).

In tidal systems, horizontal advection can introduce water masses with different DO concentrations, potentially biasing metabolism estimates and producing implausible values such as negative primary productivity or positive respiration rates. Because diurnal tidal cycles (~24 hours) overlap with diel biological cycles, distinguishing between these signals is challenging. Beck et al. (2015) addressed this issue by developing a weighted regression model that filters tidal signals from the DO time series. This method, implemented as an R package, improved metabolism estimates across several U.S. tidal bays and sloughs (Beck et al., 2015) and in the Sacramento River Deep Water Ship Channel (Loken et al., 2021). It is most effective in systems with dominant semidiurnal tides but performs less well when tidal and solar cycles are highly correlated. An alternative approach was proposed by Roberts et al. (2022), who accounted for advective effects in a tidal slough by pairing measurements from flood and ebb tides. Salinity was used as a conservative tracer to identify water parcels, and the difference in DO between paired samples was interpreted as net biological activity.

Applying these approaches to estimate the role of physical processes, Equation (1) can rearranged as:

$$\begin{aligned} &\text{Primary production rate} - \text{Respiration rate} \\ &= \underbrace{\text{Time rate of change of DO}}_{\text{Measured}} - \underbrace{\text{Air-sea flux} - \text{Horizontal advection}}_{\text{Estimated}} \end{aligned} \tag{2}$$

This formulation enables the calculation of GPP, ER, and NEM following procedures outlined by Caffrey et al. (2014). DO fluxes, corrected for physical effects, are averaged separately over day and night periods to compute the daytime production rate and nighttime respiration rate, respectively. Assuming respiration rates are constant during night and day, ER is calculated by multiplying this rate by 24 hours. Since primary production only happens during daylight hours, GPP is then calculated as the difference between the daytime production and respiration rates, scaled by daylength. These volumetric rates are typically converted to areal rates (mmol O_2 m^{-2} d^{-1}), by multiplying by the mean water depth. Finally, NEM is calculated as the sum of GPP and ER.

Most recently, Beck et al. (2024) introduced a Bayesian framework for estimating estuarine metabolism from high-resolution DO time series. This method improves upon Odum’s traditional method by eliminating physically impossible results, quantifying uncertainty, and accommodating missing data. Available as an open-source R package (https://fawda123.github.io/EBASE/), it provides an accessible means to leverage long-term monitoring data in estuarine environments.

An important consideration with diel oxygen-based metabolism estimates is the spatial domain over which water originated during each 24-hour period. Unlike lakes and rivers, estuaries lack clear boundaries, and water depths can vary with tidal cycles. For heterogeneous coastal systems, the areal footprint captured by diel oxygen-based metabolism estimates can therefore be difficult to define. Water masses from distinct habitats may mix and cause irregularities in DO measurements and metabolism estimates. Different habitats may also have different tidal phase relationships, complicating efforts to remove tidal signals from the observed DO time series. One solution is to deploy DO sensors in a spatial network to account for spatial heterogeneity and tidal phases. For example, Loken et al. (2021) estimated metabolism across a 7-km stretch of a tidal estuary using a stationary array of DO, temperature, and conductivity sensors. They compared temporally averaged and spatially aggregated diel oxygen estimates to those derived from bottle incubations and oxygen isotopes, finding general agreement among the three methods. This sensor network approach is likely essential in systems with complex morphometry and hydrodynamics and diverse habitats.

Although metabolism is commonly measured via changes in DO due to the ease of O_2 monitoring, researchers are often interested in carbon cycling. To estimate carbon-based rates of GPP and ER, oxygen-based values are frequently converted using photosynthetic quotients (PQ) and respiratory quotients (RQ), which represent the molar ratio of O_2 released to CO_2 assimilated during photosynthesis, and CO_2 released to O_2 consumed during respiration, respectively. In the open ocean, the traditional Redfield ratio of 138 O_2 : 106 CO_2 is often assumed, reflecting tightly coupled nutrient cycling, and marine researchers typically apply PQ values of 1.1–1.4, acknowledging some variability (Trentman et al., 2023). However, RQs have been found to vary widely along latitudinal and regional gradients in the open ocean (Moreno et al., 2022). Similarly, coastal ecosystems often exhibit even greater departures from assumed ratios due to processes like anaerobic respiration and anoxygenic photosynthesis, which can cause seasonally varying deviations (Wang et al., 2018). A recent literature synthesis by Trentman et al. (2023) demonstrated that biological and environmental drivers can lead to far greater variation than commonly assumed, with PQ values ranging from 0.1 to 4.2 in marine systems, and emphasized the importance of obtaining site-specific data or applying a range of plausible values from the literature tailored to local conditions. Because obtaining site-specific PQs and RQs is beyond the scope of this study, we report our systematic review results in oxygen units and do not convert to carbon.

Because the diel oxygen method relies on several key assumptions, metabolism rate estimates should always be accompanied by clear descriptions of site characteristics and analytical choices (**Box 1**, point 3).

4.2 Integration Opportunities

Monitoring is a critical component of mCDR projects, providing observations before, during, and after deployment that can be reported to a certified authority for verification. Effective monitoring aims to: 1) detect and quantify the magnitude and durability of CO_2 removal; 2) attribute the fraction of carbon sequestration to specific interventions; and 3) assess side effects to ensure ecological impacts remain within acceptable limits (Boyd et al., 2023). Achieving these objectives requires integrating diverse observational platforms—such as fixed platforms (moorings, buoys), autonomous moving platforms (surface and underwater vehicles), and satellites—into an operational monitoring network. Data streams from these platforms support real-time evaluation of interventions and also feed into models for validation and optimization, creating a feedback loop between observation and prediction. In this section, we highlight opportunities to integrate metabolism-based monitoring with existing observatories, sediment archives, remote sensing, and modeling frameworks to build a scalable, multi-platform MRV system.

Many observatory networks already collect the parameters needed to estimate ecosystem metabolism—such as dissolved oxygen, salinity, temperature, water depth, atmospheric pressure, wind speed, and water velocity—making them well suited for integration into mCDR monitoring frameworks (**Box 1**, point 4). As demonstrated in Section 3.3, the three-decade-old NERRS SWMP exemplifies how existing long-term networks can be leveraged to calculate metabolic rates in estuaries across the U.S., accounting for half of all rate estimates in our systematic review (**Figure 2**; **Table S1**). Its broad geographic distribution spans diverse habitats, including phytoplankton-dominated water and salt marsh, seagrass, macroalgal, and mangrove estuaries. Habitat type strongly influences metabolic balance: Caffrey (2004) found sites adjacent to mangroves or salt marshes were predominantly heterotrophic, while those adjacent to submerged aquatic vegetation (eelgrass or macroalgal beds) were autotrophic or near balance.

Other observatory systems provide similar opportunities. The Coastal Observing System for Northern and Arctic Seas (COSYNA) deploys FerryBox systems that measure high-frequency dissolved oxygen and other biogeochemical parameters at fixed locations or aboard ships of opportunity, with data transmitted via satellite and made publicly available. For example, a COSYNA station at the Elbe Estuary outflow into the German Bight has collected continuous measurements since 2010; a year-long dataset was used to quantify metabolism (Rewrie et al., 2025). Similarly, the Brazilian Coast Monitoring System (SiMCosta) operates a network of fixed autonomous platforms providing oceanographic and meteorologic variables. Although metabolism relies on parameters like dissolved oxygen that can be measured with relatively low-cost sensors, deploying and maintaining automated observatory systems can be cost prohibitive, reflected in the scarcity of metabolism studies in the Southern Hemisphere. SiMCosta data were recently used to provide metabolism estimates for the Patos Lagoon Estuary (Bordin et al., 2024), filling a gap where previous studies relied on chlorophyll-a as a proxy for primary production and did not quantify ER or NEM.

Integrating metabolism metrics with sediment archives offers another pathway to strengthening MRV frameworks, particularly in coastal wetlands. Mangroves, tidal salt marshes, and seagrass meadows store substantial carbon in their belowground biomass because plant material accumulates in oxygen-poor sediments, slowing decomposition. To fully capture the role of these blue carbon ecosystems in carbon sequestration, monitoring must combine CO_2 flux-based metrics with stock-based measurements of sediment carbon (J. Howard et al., 2014). The diel oxygen method provides real-time flux data (with conversion to carbon units requiring site-specific photosynthetic and respiration quotients), while collecting sediment cores enable quantification of long-term carbon storage. The belowground carbon pool, comprising living and decomposing roots, rhizomes, and leaf litter and is termed sediment or soil carbon, is typically the largest reservoir in vegetated coastal ecosystems. Quantifying this pool involves collecting soil cores (≥1 m), subsampling, and determining soil depth, dry bulk density, and soil organic carbon content. While specialized equipment is needed for carbon analysis, samples can be processed in commercial laboratories, and standardized protocols are widely available (e.g., J. Howard et al., 2014). Pairing continuous metabolism monitoring with soil carbon pool measurements strengthens MRV by linking short-term flux changes to deliberate interventions (additionality) and providing baselines for assessing long-term storage (durability), creating a complete carbon inventory for mCDR projects.

Scaling metabolism-based monitoring to the open ocean is crucial for evaluating large-scale mCDR. Open-ocean deployments introduce additional challenges to MRV efforts, including monitoring over vast horizontal domains, tracking deep-water carbon storage and potential leakage, and sustaining long-term observations (Bach et al., 2024; Boyd et al., 2023). Traditional approaches—such as bottle incubations, tracer-based techniques, instrumented moorings, and ship surveys—provide valuable insights but are limited by spatial and temporal resolution. Autonomous technologies, including profiling floats and gliders, now enable year-round, depth-resolved estimates of primary productivity from diel upper-ocean oxygen oscillations or particulate organic carbon concentrations (see Izett et al., 2024 for a synthesis of recent applications). The BGC-Argo program exemplifies this potential: its global array of floats routinely measure oxygen, pH, and other key variables, and planned expansion to 1,000 floats under OneArgo will dramatically increase coverage (Thierry et al., 2025). There have also long been efforts to develop satellite remote-sensing algorithms to estimate metabolism in the open ocean (as reviewed by Jönsson et al., 2023), and more recently, in estuarine waters (Xu et al., 2022). Advances in modern satellites such as PACE (Plankton, Aerosol, Cloud, ocean Ecosystem), enable the ability to distinguish phytoplankton functional types rather than just total biomass, offering insights into ecosystem responses to mCDR interventions. Integrating site-specific metabolism data with spatially extensive observations improves detection, attribution, and scalability. For example, NEM trends can be compared with satellite-based phytoplankton shifts to assess intervention impacts across scales. Leveraging these platforms offers a scalable pathway to integrate metabolism monitoring into open-ocean MRV frameworks (**Box 1**, point 4).

These integrated observations also support emerging efforts to develop digital twins of the ocean—dynamic, data-driven virtual replicas of marine systems (Boyd et al., 2023; Hochberg et al., 2025; Mengis et al., 2023; Van Dam et al., 2024). Digital twins continuously assimilate real-time data from satellites, autonomous platforms and observatories, and other model outputs, enabling rapid assessment of intervention impacts and scenario testing (Hochberg et al., 2025). For mCDR, incorporating metabolism time series derived from continuous dissolved oxygen measurements can strengthen attribution and support adaptive management (**Box 1**, point 5). Centralized and standardized data repositories will be essential to ensure comparability and transparency between projects (**Box 1**, points 1 and 3; Van Dam et al., 2024), enabling digital-twin frameworks to scale with increasing mCDR deployment activity.

5. Conclusions

Continuous dissolved oxygen data are increasingly available, enabling construction of metabolism records that can inform mCDR projects. This review synthesizes lessons from freshwater management and highlights current MRV needs, while evaluating metabolism's potential role and key methodological considerations. It also outlines pathways for integrating metabolism metrics into coastal monitoring networks. Six priorities can guide implementation (**Box 1**), providing a roadmap for operationalizing metabolism into MRV frameworks.

Box 1: Vision for Implementation

Priorities for implementing metabolism-based indicators into mCDR monitoring, reporting, and verification frameworks.

1. **Shared data infrastructure**
   Build centralized repositories for routinely collected metabolism estimates and underlying high-frequency data (e.g., DO, temperature, salinity) with site metadata, modeled on open data projects like StreamPULSE.
2. **Baselines, thresholds, and metrics**
   Establish site-specific metabolism baselines across seasonal and interannual timescales to capture natural variability. Define thresholds for metabolism regime shifts and adopt intuitive metrics such as metabolic fingerprints for within- and cross-site comparison.
3. **Best practices, uncertainty, and standardization**
   Follow established best practices for DO sensor deployment, including routine calibration and maintenance and implement near-real-time data QA/QC. Require uncertainty estimates and clear documentation of methods (e.g., gas exchange coefficient parameterization; oxygen–carbon conversion assumptions). Standardize reporting formats and include essential site metadata.
4. **Scaling monitoring systems**
   Leverage existing observatory networks, autonomous platforms (e.g., gliders, BGC-Argo), and remote-sensing capabilities to scale metabolism estimates across coastal systems and into the open ocean.
5. **Model integration and feedback**
   Use metabolism data to parameterize and validate biogeochemical models and digital twins and evaluate durability, additionality, and side-effects under realistic scenarios to inform adaptive mCDR deployments. Incorporate feedback loops where metabolism indicators inform dosing or operational decisions.
6. **Visualization and communication**
   Mandate accessible reporting through online project dashboards and periodic reports, using clear diagnostics (e.g., metabolic fingerprints) to communicate ecosystem metabolic status to regulators, stakeholders, and the public.

Attaining gigaton-scale CO_2 removal to meet climate targets is no easy feat. Evaluating the efficacy of emerging mCDR methods—and equally, their ecological impacts—is a critical challenge. Ecosystem metabolism metrics, already widely applied in aquatic science, offer a practical addition to the MRV toolkit. By adapting existing MRV frameworks and harnessing continuous DO measurements, metabolism can complement other approaches to improve understanding of mCDR feasibility and trade-offs, supporting more informed and responsible deployment.

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