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Perspective

Big Decisions from Small Experiments: Observational strategies for biomass-based marine carbon storage

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Abstract

Biomass-based CO_2 removal (CDR) with marine storage aims to harness photosynthesis to remove excess CO_2 from the atmosphere and sequester that fixed carbon in a long-lived marine reservoir. To guide decision-making around testing, deploying, and regulating CDR as part of a portfolio of climate mitigation strategies, we need to better understand how the deep sea and broader Earth system would respond to increased biomass addition. The central processes driving this response are sensitive to choices about biomass type and storage site, and they span spatial and temporal scales from microns to kilometers and from minutes to millennia. To organize this interdisciplinary challenge, we define five generalizable phases for biomass-based marine carbon storage projects: inputs, placement, short-term response, long-term response, and functional stability. Each phase is associated with observational needs with characteristic spatial and temporal scales that could be met through direct field measurements, investigations of analog sites, experiments, and/or models. Predicting the effects of potential interventions over global and centennial scales will require the strategic integration of diverse observational types into process-based Earth System models that can be used to support planning. Beyond assessing carbon storage and ensuring regulatory compliance, future research should therefore prioritize generating the data required to improve models for impacts of biomass-based marine carbon storage at climatically-relevant scales.

1. Introduction

With every year of continuing anthropogenic CO_2 emissions, humanity's need for atmospheric CO_2 removal (CDR) grows. Current models estimate that, by the end of the century, approximately 10 Gt CO_2e ("atmospheric CO_2 equivalents") removal per year will be needed to limit global average temperature increases to 2.0° C and avoid the most catastrophic impacts of climate change; CO_2 emissions reductions alone are insufficient.[1] This gargantuan effort will require a suite of coordinated technologies that are compatible with the decarbonization of energy systems. Biomass-based CDR approaches leverage photosynthesis to convert atmospheric CO_2 to organic carbon that can be physically stored away from the atmosphere in geologic reservoirs, on land, or in the ocean.[2,3] Excluding "conventional CDR" by forestry management, nearly all biomass-based CDR in 2023 was achieved through bioenergy with carbon capture and storage (BECCS, –0.51 Mt CO_2e/yr) or biochar addition to soils (–0.79 Mt CO_2e/yr), both of which occur on land; bio-oil storage in geologic reservoirs has been reported at the pilot scale.[4] However, ocean-based biomass storage may have capacity to operate at scales of at least 0.1 to 1.0 Gt CO_2e/yr,[2,5,6] which could allow it to make a significant contribution to global removal goals.[7,8] Here, we focus specifically on biomass C storage in marine reservoirs, recognizing that future decisions about limited biomass resources will need to weigh the relative benefits and risks of geological, terrestrial, and marine storage as well as other biomass uses. Such approaches include, for example, macroalgae (e.g., kelp) cultivation or harvesting with deep-sea storage, marine anoxic carbon storage of terrestrial biomass (MACS), or certain approaches to enhance microalgal surface productivity and sinking, as detailed in several recent reviews [3,7,8]. For the purposes of evaluating impacts on deep marine environments (e.g., ≥200 m depth), we consider any pathway that uses photosynthesis to produce organic carbon and then stores that carbon in a marine reservoir (e.g., deep water, sediments) to be "biomass-based CDR with marine storage."

The CDR field currently operates within a structure where companies aim to sequester CO_2 at some minimum threshold for durability and risk. Those companies then sell that sequestration value in units of tonnes CO_2e to a buyer in either a voluntary or regulated carbon market for a commodity price.[4] Brokering this exchange is typically a third-party verification organization, which can serve as a *de facto* approver of carbon credit quality.[9] Recent initial quantification frameworks by biomass-based CDR providers[10–12] identify pathways for carbon loss and accounting, but they so far lack specific approaches to assess longer-term processes or deep-sea impacts. None yet address the central challenge of scaling monitoring, reporting, and verification (MRV) from benchtop experiments to gigatonnes.

To begin to fill these gaps, we present a generalizable framework for ocean biomass storage projects that defines the types of observations that are needed to understand each of the five phases of a biomass deployment cycle: inputs, placement, short-term response, long-term response, and functional stability (Fig.

1). Within each of these phases, we consider groups of processes that have similar spatial and temporal scales, illustrated in Fig. 2. After introducing these processes in section 2, we describe how they align with potential observational strategies in section 3. Together, different observational strategies can provide insights into the likely outcomes of ocean biomass storage over global and centennial scales. Our aim is to provide practical guidance for process-based CDR research and MRV standards that will improve our ability to model the outcomes of potential interventions at climatically-relevant scales relative to the no-action alternative.

2. Ocean Storage of Biomass: Project phases and important processes

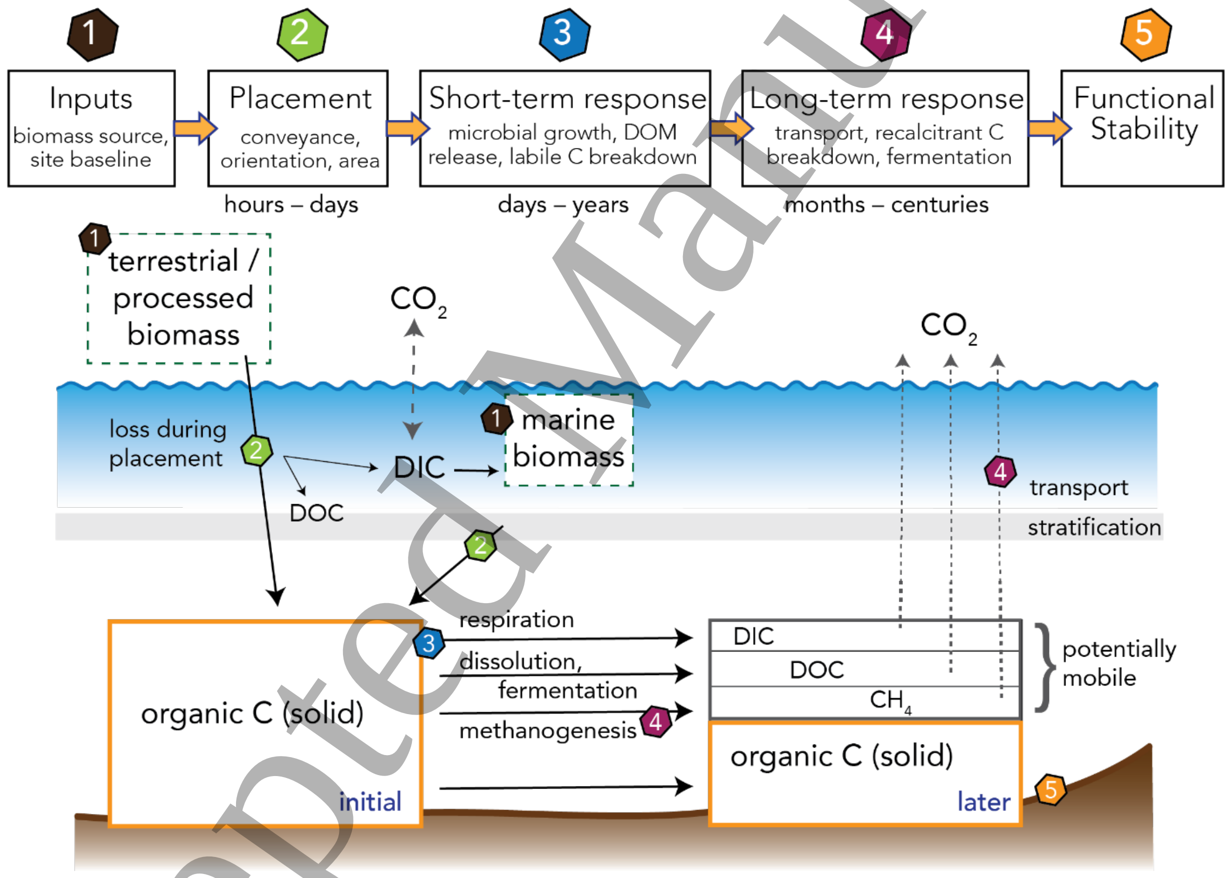

Figure 1. The biomass life cycle during marine carbon sequestration. Time progresses from left to right. DIC = dissolved inorganic carbon; DOC = dissolved organic carbon. Stratification may reflect the base of the surface mixed layer or any deeper boundary that limits mixing. Solid carbon is shown sitting on the seafloor but could also be buried in a layer of sediment (not shown). Not to scale.

The life cycle of an ocean biomass deployment can be divided into five phases, each associated with different physical, chemical, and biological processes that can transfer carbon between reservoirs and influence the surrounding environment (Fig. 1).

Phase 1 (Inputs)

Prior to placement, projects need to establish initial conditions for the biomass source and sequestration site.

Biomass source characterization Potential biomass sources span huge ranges of chemical and physical properties that give them different breakdown rates in marine environments. Generally speaking, fresh macro- and micro-algal biomass is rich in relatively labile molecules like sugars, proteins, and other metabolites that can be consumed within minutes to days by marine microbial communities – a process that allows ~84% of global marine primary production (at sites ≥200 m) to be recycled in the surface ocean rather than being exported to depth.[13] Alternatively, terrestrial materials like agricultural or forestry wastes contain large amounts of structural polymers (e.g., lignins) that can be relatively resistant to breakdown in marine environments.[14,15] Engineering choices about biomass processing and packaging will also impact overall biomass recalcitrance.

Accounting for the initial composition of deployed biomass requires characterizing the amounts of carbon, nutrients, and any regulated chemicals of concern (e.g., pesticides) at the time of processing and then tracking changes throughout transport and handling, especially loss of biomass carbon to CO_2 or methane. A complete biomass source characterization includes a life cycle assessment (LCA) of cultivation, handling, and transportation as well as embedded impacts associated with the supply chain. Some initial LCAs and accounting protocols have been released for terrestrial biomass sources, building on work in biofuels and related industries.[16,17] Marine biomass cultivation poses additional challenges related to the release of dissolved organic carbon (DOC),[5,18] ecological competition,[6] and air-sea gas exchange[19,20] that would need to be addressed through research and eventually an equivalent standard for marine biomass.

Site baseline Calculating actual, long–term additional CO_2e removal requires attributing observed biogeochemical changes to a specific intervention rather than natural variability or future climate change.[7] Although deep ocean sites can be more buffered against rapid changes than surface waters, they still evolve in response to natural cycles and climate.[21,22] Extrapolating a dynamic site baseline into the future will require a concerted effort to describe and parameterize deep ocean and benthic processes and to integrate them into prognostic Earth System models.

Phase 2 (Placement)

Placement involves the physical transport of biomass carbon to the deep ocean floor.

Loss during sinking The importance of biomass loss during sinking depends strongly on the delivery method chosen: the placement of containerized, high-density materials might occur over an hour, while free-sinking algae might reach the deep ocean after days or weeks, if at all. Especially for slow-sinking materials, early breakdown can divert a substantial fraction of initial, solid biomass C to mobile phases (DIC, DOC, suspended particulate OC) that may not meet standards for durable carbon credits. Potential consequences of released dissolved and particulate organic matter (DOM and POM) on "downstream" ecosystems need assessment.

Seafloor distribution The spatial distribution of biomass on the seafloor influences the environmental effects of a deployment. For projects that disperse biomass in the surface ocean, projecting the movement of biomass packages and their final coverage on sediments with different properties represents a major area of research,[23] while projects with rapid sinking times may be able to precisely locate seafloor packages. In any case, the orientation, extent, and potential mobility of biomass on the seafloor will impact the design of appropriate MRV for later phases.

Phase 3 (Short-Term Response)

During the first days and months after delivery to the seafloor, biomass experiences a wide range of biogeochemical and ecological interactions that may drive the most acute effects of intervention on the deep-sea environment.

Rapid breakdown Biomass added to benthic environments represents a windfall of potential food for heterotrophic organisms and may inspire strong responses by in-situ ecosystems.[24,25] Grazers and other heterotrophic organisms will first degrade and metabolize particularly labile or physically accessible components of the biomass, producing DIC along with other metabolic products.[26] The highest rates of respiration are expected during breakdown of these materials and thus the highest production of DIC (and mobilization of otherwise sequestered C; Fig. 1). However, there may be a lag between placement and maximum rates of breakdown due to the slow growth rates and long doubling times associated with many deep-sea organisms.[24] Depending on local biogeochemical conditions, biomass respiration may release nutrients, acidity, oxygen depletion, sulfide, and/or methane to seawater. Overall breakdown rates are sensitive to biogeochemical conditions at the sequestration site. For example, macroalgal biomass is typically broken down within weeks in oxic waters,[27] but it can persist for millennia in anoxic brines.[28]

Biomass addition to the seafloor may also impact rates of microbial processes in underlying sediments due to reduced exchange with seawater, changes in porewater pH, or priming with labile organic matter.[29]

Additionally, some fraction of biomass carbon can dissolve, either abiotically or due to heterotrophic breakdown, and potentially impact downstream environments.[5,30] The DOC pool represents a complex mixture of individual molecules with a wide range of chemistry and reactivity, which would need to be evaluated for any proposed biomass type.[31,32]

Dilution and mixing Products of leaching and biological breakdown are released into a dynamic fluid environment experiencing turbulence, currents, and eddies. The choice of sequestration site – specifically its "openness" or connectivity to the open ocean – will determine the effective volume into which these products are diluted and thus affects the potential sampling locations and detection limits of an MRV program. Isolated (e.g., hypersaline) marine basins can act as relatively closed systems, which allows the monitoring area to be both fixed and small.[33] On the other end of the spectrum, some practitioners have proposed biomass delivery approaches that widely disperse materials through the open ocean. Uncertainties related to fluid dynamics will need to be considered when designing sampling strategies that use concentration data (e.g., DIC or DOM in seawater near a biomass placement site) to estimate carbon retention and environmental impacts.

Phase 4 (Long-Term Response)

Depending on biomass type and properties of the sequestration site, the "long-term" breakdown of biomass and the transport of breakdown products throughout the Earth system can last several weeks to several centuries.

Slow breakdown The rates of respiration and fermentation will change over time due to ecological adaptation and the preferential removal of biomass components.[34,35] In sediments, models that effectively reproduce consumption rates of organic C with depth are classically referred to as multi-G models[36,37] and commonly have two or three organic carbon fractions with first-order rate constants spanning several orders of magnitude.[14] In the current framework, the labile organic fraction is broken down in phase 3 (rapid breakdown), and the semi-labile fraction is broken down in phase 4 (slow breakdown). Accurately parameterizing the breakdown rates of distinct fractions of organic matter under project-specific conditions will be crucial for simulating large scale biomass deployments and projecting durability into the future.

Regional to global circulation The long-term impacts of an intervention over regional to global scales will depend on the transport and mixing of breakdown products into downstream water masses and their eventual interactions with the atmosphere. For relatively "open" regions of the deep ocean (i.e., not isolated brines), the timescale for transport and return of a water mass and its dissolved compounds to the surface ocean ranges from tens to thousands of years.[38] Knowledge of the immediate and regional-scale flow regimes will be critical for the development of MRV programs that integrate larger-scale transport models with discrete sampling and observational programs that operate over smaller scales.

Phase 5 (Functional Stability)

Functional stability entails the effective stabilization or exhaustion of biomass materials.

Biomass stabilization Remaining biomass solids in phase 5 correspond with the "unreactive" pool in multi-G models: sedimentary organic matter that persists for hundreds to millions of years.[36] Functionally stable organics are effectively resistant to breakdown under site conditions, and rates of carbon mobilization approach zero. The well-preserved wood materials remaining in 4,600-year-old shipwrecks in the deep Black Sea are one charismatic example of functionally stable biomass.[39] Quantifying and describing this durable carbon storage is a top priority for the management and valuation of biomass-based CDR.

Net environmental impact In addition to calculating a final amount of durably stored carbon, research programs are tasked with defining a "final" Earth System impact from an intervention on a centennial to millennial scale. This assessment can only be achieved through modeling, as informed by research and observations from all prior phases.

Table 1. Important types of observations by deployment phase. Columns indicate different research strategies that may be well suited to investigating processes within each phase. Observational strategies marked with X's align with the scales needed for each type of observation, also illustrated in Figure 2.

Types of Observations	Observational Strategies			
Phase	**Field Data**	**Analog Sites**	**Experiments**	**Models**
E.g.: .	seawater samples, sensors	aged organics, paleo-records	lab + in-situ bottle incubations	circulation, multi-G kinetics
1: Inputs				
Biomass source characterization	<external modules>			
Sequestration site baseline	x	x		x
2: Placement				
Loss during sinking			x	x
Seafloor distribution	x			x
3: Short-term response				
Rapid breakdown	x		x	

Dilution and mixing: benthic boundary layer flows, eddy turbulent diffusion, local circulation	x		x	x
4: Long-term response				
Slow breakdown		x	x	x
Regional to global circulation				x
5: Functional stability				
Biomass stabilization		x		x
Net environmental impact				x

3. Scales and goals of process-based MRV

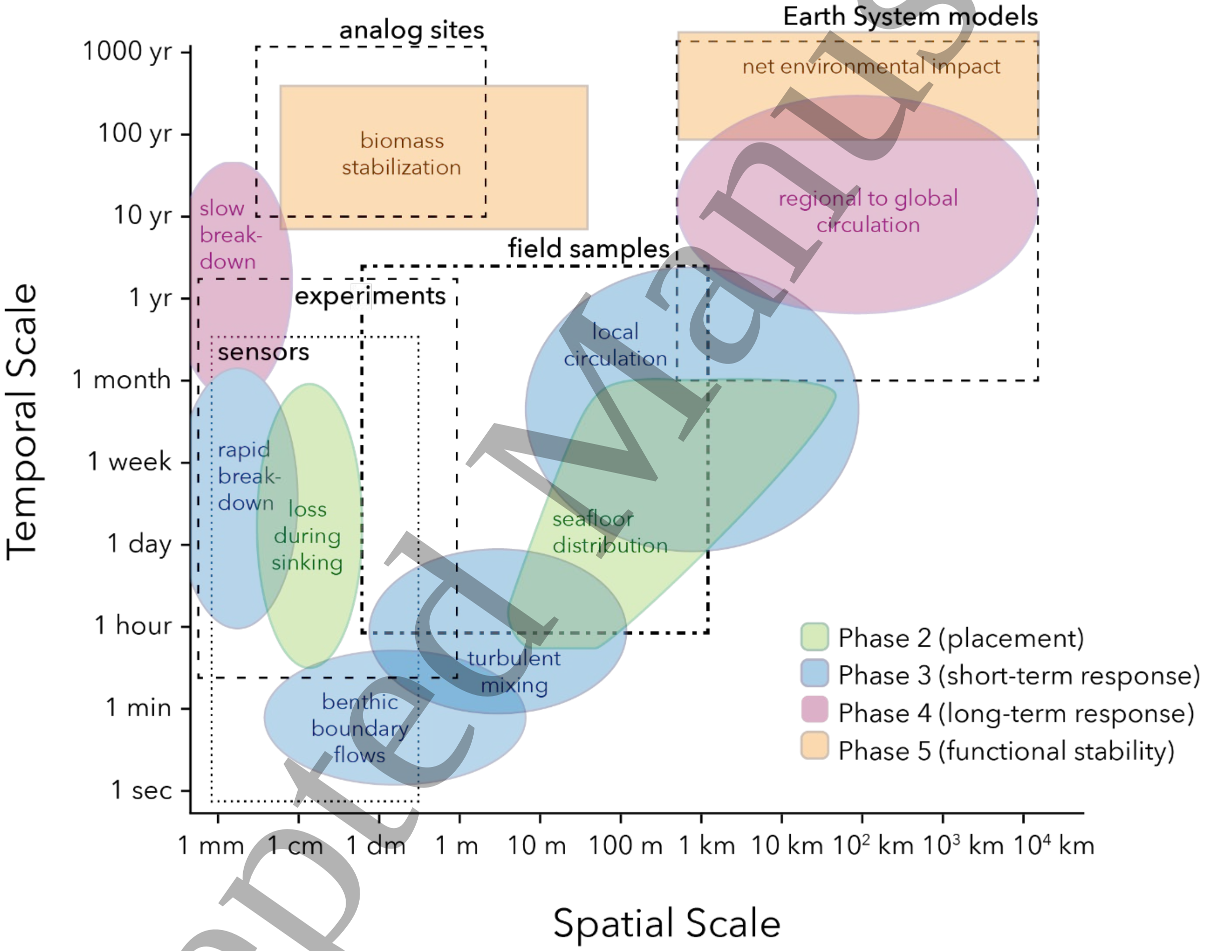

Figure 2. Spatial and temporal scales of key phenomena (shaded regions) and observational strategies (dashed boxes). Modified after Wilson et al. (2020) and others. Phase 1 (site baseline) processes are not shown but overlap with processes in phases 3, 4, and 5.

Central processes associated with deployment phases are displayed schematically in Figure 2. Even within a single phase of a deployment, multiple processes work in concert to transfer impacts from a relatively localized (point) source to the global Earth system. Specific choices about biomass type and deployment site will impact where a specific project falls within the shaded regions on Figure 2 and by extension the temporal and spatial scales over which signals can be measured.[7]

As one example, DIC is first produced by primarily biological mechanisms at the scale of a microbial biofilm (μm to mm). The microorganisms responsible for DIC production only “feel” and respond to their immediate environment within the biomass package, necessitating small-scale measurements to understand their behavior. Next, DIC will diffuse away from the site of its formation and may be entrained in benthic boundary layer (laminar) flows that mix the signal into the surrounding water. At some distance from the boundary, typically within minutes or hours, molecules can enter an eddy turbulent diffusion regime and mix over the dm-to-100-m scale. Over days to months, dissolved signals may be transported by currents over hundreds of kilometers, depending on the regional circulation. Each of these processes can be observed through observational strategies that align with their temporal and spatial scales.[40,41] Sensors can be effective at assessing the microbial environment on biomass surfaces, while circulation models can be effective for assessing regional transport. To account for the wide ranges of temporal and spatial scales required to assess project outcomes, regulators, verifiers, and MRV practitioners will benefit from integrating information gained from a spectrum of research strategies, including field data, experiments, models, and comparisons with analog sites.

Long-term processes over small spatial scales, found in the upper left corner of Fig. 2, are particularly important for understanding the functionally stable form of residual biomass after hundreds or thousands of years. The relevant scales for this question overlap with the scales of information that are available in sedimentary records from analogous sites, such as woody organic matter or algal debris buried in the sediments of anoxic fjords or marine basins. The organic matter that has been stored and naturally aged in these sediments can provide insights into the functionally stable form of some comparable biomass materials over long timescales.

Processes occurring over intermediate scales in Fig. 2 can be observed by field samples, sensors, and experiments, which have complementary strengths and caveats. Laboratory experiments are well-suited to target individual processes throughout phases 2, 3, and 4 that can be observed in micro- or meso-cosms (e.g., up to meter scale). Targeted experiments can be a more effective way to achieve certain monitoring objectives than field tests, especially when frequent or controlled sampling is required, and they provide valuable data to guide the design of more resource-intensive field expeditions. Still, especially for biological processes, the utility of ex-situ incubations can be limited because deep-sea microbial communities can be disrupted by depressurization and handling. Seafloor bottle incubations, on the other hand, can minimize this disruption to the microbial community while still avoiding the open-system challenges of seawater mixing and tracer dilution. In both the lab and the field, careful consideration of the length of the experiment and the appropriate amount of biomass to incubate, given expected rates of transformations and bottle volumes, is critical to ensure that conditions inside the incubations remain similar to the target environment. Both lab and field experiments are thus useful as components of verification standards and early method validation.

Carbon removals provide the greatest climate benefit when they are durable for ideally thousands of years[42]. A key challenge facing research into biomass-based CDR with marine storage is therefore bridging the practical observations made at the sensor or experimental scale to the models that are essential to explore the outcomes of alternative proposals over these long timescales. Early and regular communication between model developers and field oceanographers is essential to identify data that can provide the greatest enhancements in model ability and prioritize MRV targets. Advances in coupled empirical-theoretical approaches will allow scientists to more confidently extrapolate findings from field and lab experiments to forecast and manage environmental impacts of biomass CDR at climate-relevant scales.

5. Conclusions

Biomass-based CDR with marine storage may be able to contribute to global climate mitigation goals, but only if the outcomes of such interventions can be predicted, compared with the no-action baseline, and used to make informed choices for the future. Therefore, beyond reporting the outcomes associated with a specific small-scale experiment, research programs for CDR will be most effective if they target process-based understanding and prioritize data types with the greatest value for model improvement. To structure this effort, generalizable types of observations can be defined for the five phases of a biomass-based marine carbon storage project. This framework aims to subdivide open-system MRV development into tractable targets with similar scales that can be aligned with the scales of various observational strategies, from lab experiments to field samples and investigations of analog sites. To use these interdisciplinary observations to project CDR outcomes, a substantial community effort is needed to build models and process-intensive modules for the deep ocean that include interactions with sediments and benthic processes. The challenge ahead is to design relatively small experiments that can answer urgent questions about the ability of ocean biomass storage to contribute to global climate mitigation at scale.

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