State of Monitoring, Reporting, and Verification for Carbon Removal



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Co-founder | CEO

[C] Worthy

NASEM Marine Carbon Dioxide Removal Standing Committee: Meeting 2

15 September

We are

[C] Worthy

Our work is rooted in public benefit, scientific integrity, and building open source infrastructure; our tools aim to invoke consensus standards and promote trust through transparency, reproducibility, & auditability.



Product Driven

We are pursuing an engineeringheavy effort to develop and deliver modeling and data infrastructure to support high-integrity MRV for earlystage ocean CDR companies.



Scientifically Oriented

While the need to rapidly scale CDR is urgent, we are keenly aware that science continues to evolve—we're building an R&D community to ensure our tools track the best available science and computing technology over time.



Committed to Open Science

The scientific codes at the core of our tools are open source & community developed; our workflow engines support accessibility, transparency, and reproducibility; we engage in empowerment activities through targeted capacity building.

Our Products



C-Star

Standardized open-source modeling for quantifying ocean-based CDR

Ensures ease of use, transparency, reproducibility, & auditability of model calculations



Ocean CDR Atlas

Multiscale public datasets for ocean CDR

Metrics relevant for deployment design, technoeconomic analysis, permitting, policy &lowcost MRV



C-Star Ocean Network

A growing constellation of oceanographic models adhering to common standards

Serves research & carbon crediting needs; facilitates cross-sector communication, international collaboration, standards & capacity building



[C]Worthy Funders & Partners



Philanthropic Support















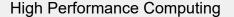








Competitive Federal Grants















Industry & Academic Partnerships





(carbon)plan





















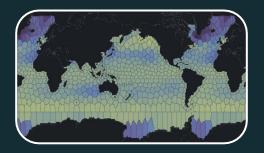




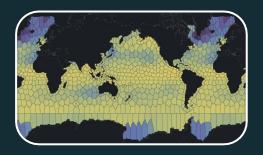
Ocean CDR Atlas Multiscale Public Datasets for Ocean CDR



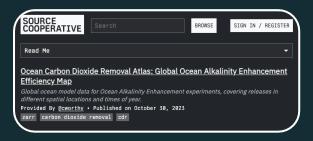
Current Datasets & Dashboards



Ocean Alkalinity Enhancement Efficiency Map



Direct Ocean Removal Efficiency Map



Research Grade Data





What is an Effective Climate Intervention?

CDR must remove CO₂ from the atmosphere

- High integrity
 - Based on Accurate & Transparent Quantification
 - Acknowledged, discussed, and accepted by society (social license)
 - Quantifiable & acceptable ecosystem impacts
- Equitable
 - Costs and benefits are collectively understood and accepted
- Efficient, fundable, & sustainable



Accurate & Transparent Quantification

We are perturbing the Global Commons, the burden of proof is high

- Causal impact is considered knowable
- Truth is a product of consensus
 - Transparency &peer-review norms ensure vetting
- Standards codify consensus
- The market mechanism can operate effectively with effective quantification & accounting standards, and relational enforcement mechanisms
- Standards must track evolving science



Building the Plane as We Fly It

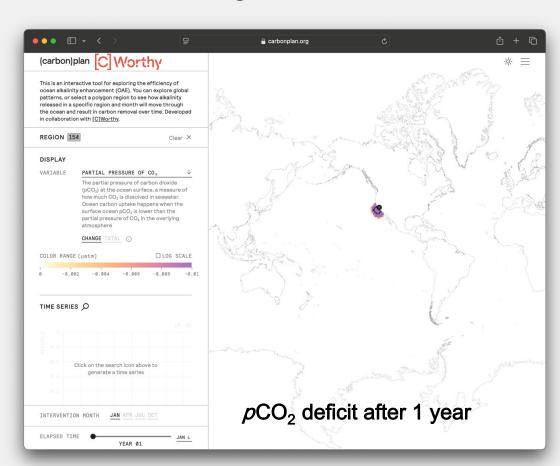
A network of R&D hubs?

- Collective ownership (e.g., government[!], public utilities)
- Centralized planning & execution
 - Public asset portfolio
 - Governance & engagement
 - Funding for prioritized R&D initiatives
- Private sector investment
- Market structure
- Civil society

Context Setting: Ocean MRV

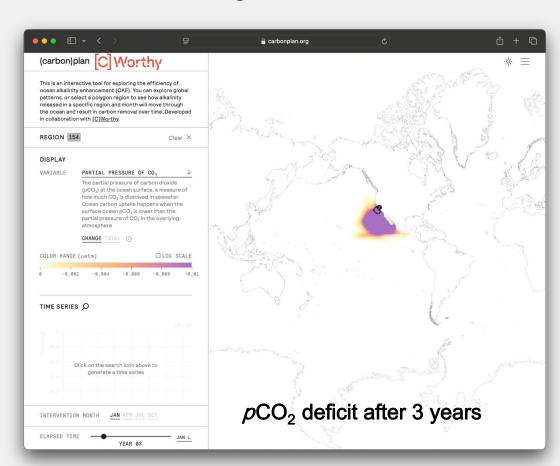
Large spatiotemporal scales Slow CO₂ equilibration timescales leads to basin-scale signals that cannot be monitored in-situ.

Unfavorable signal-to-noise High intrinsic background variability relative to signal size makes signal detection beyond the near-field impossible.



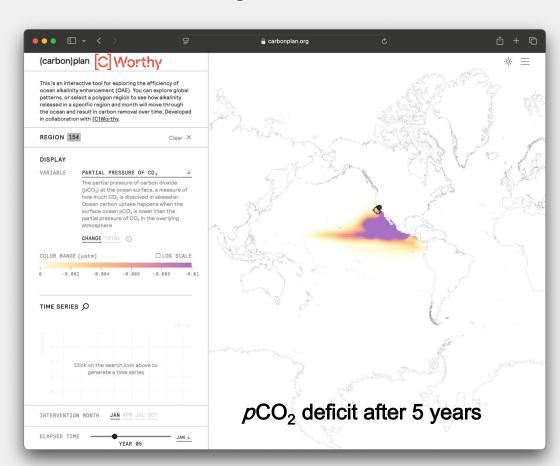
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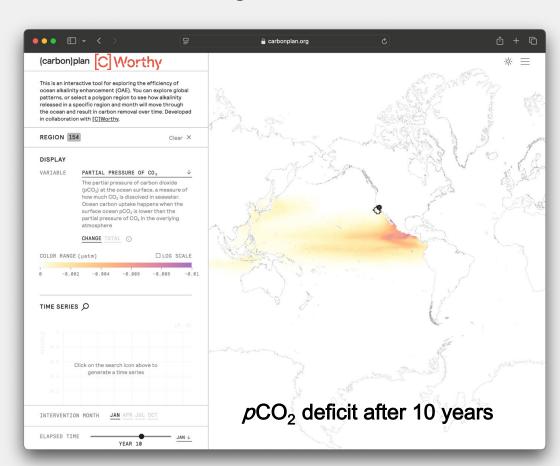
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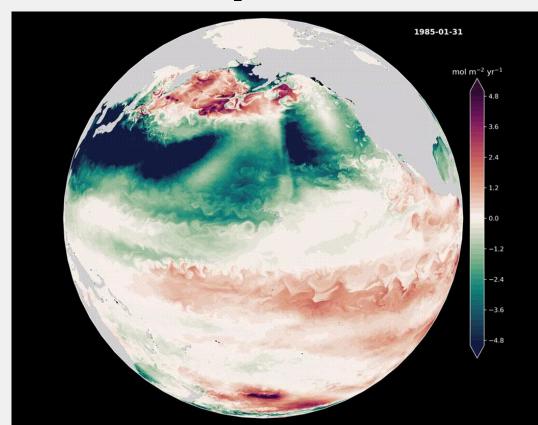


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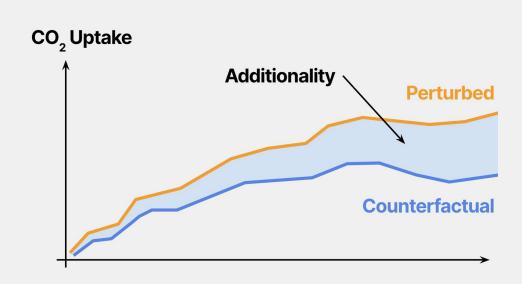
Complex baselines Counterfactual baselines are needed to assess additionality.

Sea-to-air CO₂ flux simulated at 0.1



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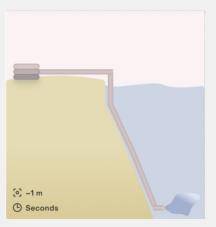
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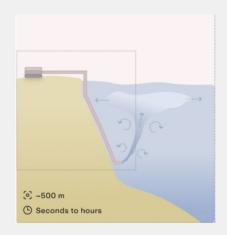


Context for CDR quantification: Spatiotemporal scales

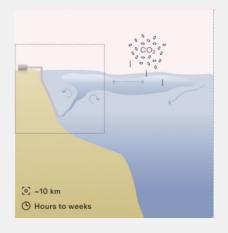
Dosing Location



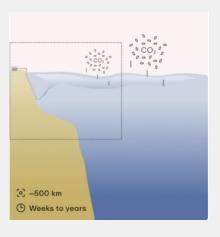
Mixing Zone



Coastal Domain

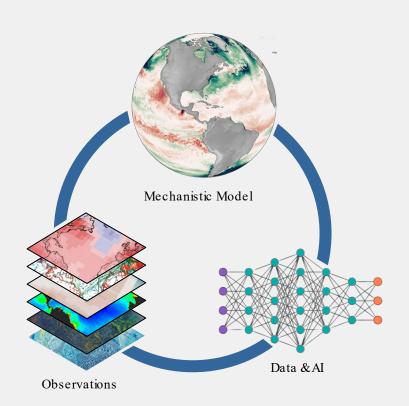


Open Ocean





Context for CDR quantification: Epistemology



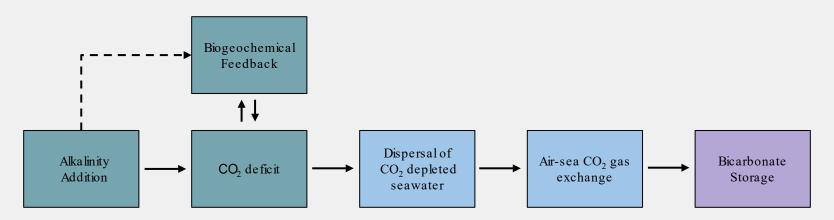
The Earth System is complex

- O Geophysical fluid dynamics
- o Scale interaction, heterogeneity
- Metabolism, biogeochemical cycles
- o Ecological interactions

Behaviors:

- o Deterministic, but chaotic
- Complex, adaptive, & emergent
- Nonlinear feedback

Framing OAE quantification



Near field — bespoke observations & models

What rates maintain compliance with permitted limits?

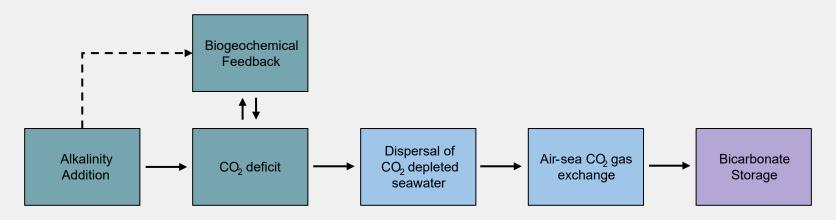
What are the alkalinity production rates from mineral feedstocks?

What are the thresholds and loss patterns associated with mineral precipitation?

Are the thermodynamic coefficients to solve carbon chemistry system correct?

How do natural fluxes of alkalinity from sediments change? Biogenic

Framing OAE quantification



Far field — models & backbone observational networks

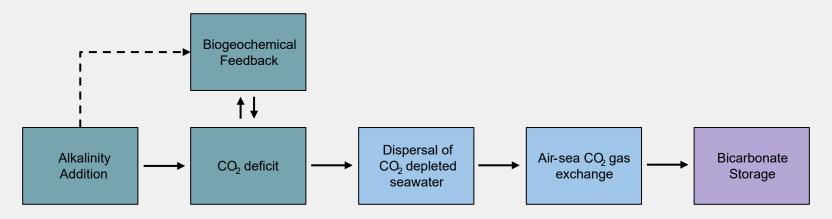
How can we upscale from near-field to far-field effectively?

What are the resolution requirements for accurately representing circulation?

Upon what key features of models does uncertainty hinge?

How can it be demonstrated that a model is scientifically credible?

Framing OAE quantification



Storage

What is the residence time of ocean dissolved inorganic carbon?

Mobilization

Carbon Market Mechanisms



Individuals and companies voluntarily choose to purchase carbon credits that finance projects which avoid or sequester emissions, e.g. nature-based solutions, clean cookstoves, or renewable energies



Compliance carbon markets

Government regulations require certain industries to limit their carbon emissions through financial incentives – these can take the form of a tax or an emissions trading system, whereby companies can trade emissions credits to comply with these regulations



International trading of carbon credits through Article 6

Nations sign bilateral agreements under Article 6 of the Paris Climate Agreement to trade carbon credits (called ITMOsⁱ), where the acquiring country can use the credits towards their climate targets (NDCsⁱⁱ)

i. Internationally Transferred Mitigation Outcomes. | ii. Nationally Determined Contributions.

Carbon Market Mechanisms

The past year's slowing market has been driven by 2 main setbacks...

Increased media scrutiny of credits' integrity:



- Suppliers: Concerns that carbon projects that do not reflect real emissions reductions and lack transparency
- Buyers: Concerns businesses use credits to greenwash and avoid decarbonising their own operations



Slowing macroeconomic growth has reduced the demand for carbon credits through squeezed corporate budgets

...but 4 major market advantages will help carbon markets unlock 10-30x growth over the next decade

A renewed focus on integrity and transparency:



- Suppliers: Landmark integrity frameworks (e.g. ICVCM's CCPs) and major anti-fraud institutions support higher integrity and transparency
- Buyers: Studies show that credit buyers decarbonise 2x faster; the VCMI Claims Code of Practice and EU Green Claims Code increase integrity among buyers



Increased trading of carbon credits under Article 6 of the Paris
Agreement, with the total **number of signed bilateral agreements rising by 47%** in the last year



More ambitious climate targets among companies, with ~1,100 companies validating their targets in 2022, more than in the 7 previous years combined



Favourable regulations by governments help companies use carbon markets to achieve emissions reductions





The Benefits of Innovation: An Assessment of the Economic Opportunities of Highly Durable Carbon Dioxide Removal

January 14, 2025

Authors:

Galen Bower Nathan Pastorek John Larsen

Carbon Markets: Benefit Sustainable Development Goals

	Benefit category	SDGs supported	Explanation and evidence
	Income and jobs	9 MONTH MANAGEM ***********************************	Global carbon markets were worth ~\$2 bn in 2022 alone, generating incomes for millions of people – in well-designed projects, a large share of this can go to local people ¹
			Carbon projects create jobs across the carbon credit value chain: From direct jobs in developing projects to jobs in monitoring, reporting, and verification (MRV), and further jobs through upstream demand for manufactured products like decentralised renewable technologies
		7 streams and 12 streams on 12	The green investments that carbon projects facilitate create many more jobs than unsustainable investments: Per \$ invested, ecosystem restoration creates 3.7x as many jobs as oil and gas production, and investments in solar energy create ~1.5x more jobs than investments in fossil fuels ⁱⁱ
V III	Food security	2 and substitute of the substi	Carbon credits can improve food security by incentivising farmers to adopt sustainable agriculture practices that can improve soil health and increase yields by up to 20% ⁱⁱⁱ
6 3	People's health	3 contracts one 6 constants	Cookstove projects can reduce household air pollution by roughly 30-45% iv,v, providing benefits to the roughly 4 billion people who suffer from household air pollution, particularly women and children v
		., ,	Nature-based solutions can protect crucial ecosystems which improve air quality and provide sources of food, water, and medicine ^{vi}
			By improving climate resilience, carbon credit projects can also reduce health issues caused by climate change , which is projected to cause 250,000 deaths a year between 2030-50 ^{vii}
	Climate resilience	3 DOS STATES 13 STATES	Nature-based projects, particularly wetland restoration and forest conservation, help communities adapt to changing climates by preserving natural barriers against disasters that will be exacerbated by climate change ^{viii}
	Biodiversity	14 min some 15 min some	Nature-based projects can boost plant and animal species numbers, especially projects that avoid deforestation or restore indigenous habitats ^{ix}



MRV Requirements Hinge on Markets

What ocean -based CDR pathways are candidates for "pay for practice"?



Market - Based Crediting Frameworks

- Precision MRV
 - Project-specific system boundaries
 - Removal "assets" require monitoring as carbon credit
 - Registry &traceability



Public "Pay for Practice"

- Activity evidence, not ton metering
- Less granularity in MRV
 - Ongoing monitoring & state estimation
 - Centralized registry & traceability

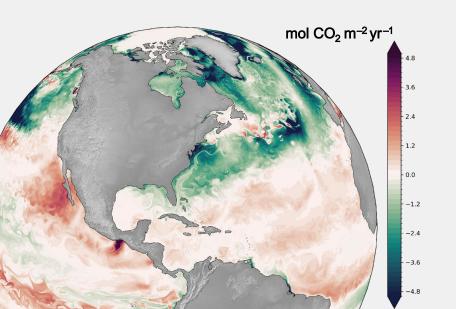


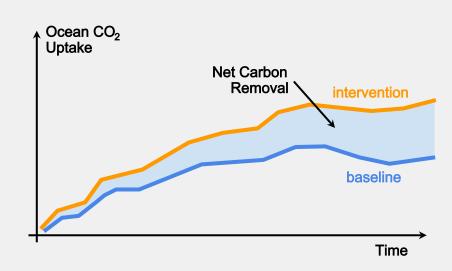


Computations systems for quantification

Simulated airsea CO₂ Flux

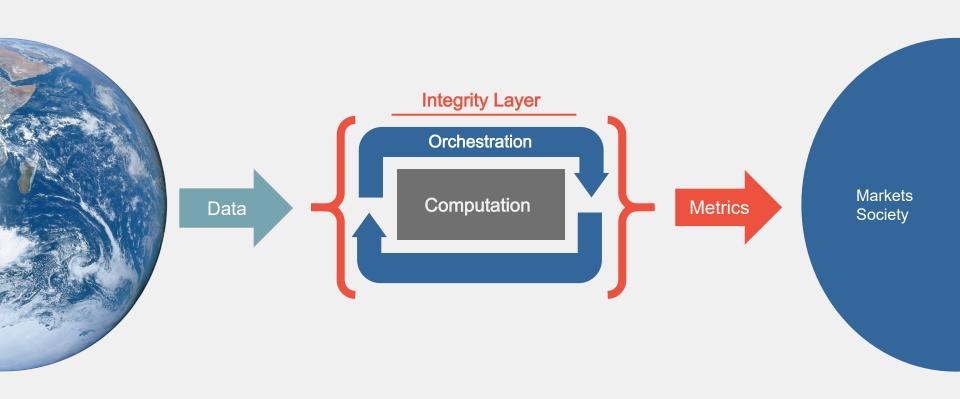
Metrics of Net Carbon Removal





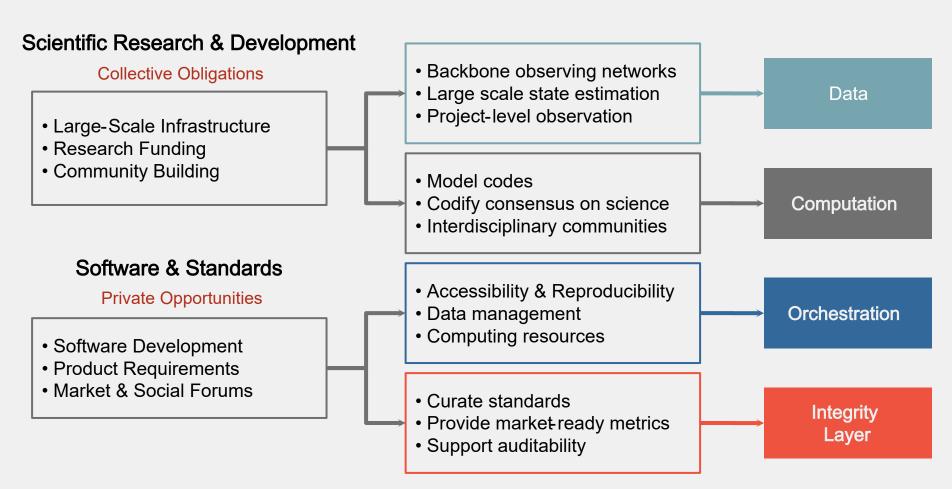
MRV Engines





MRV Investment Needs

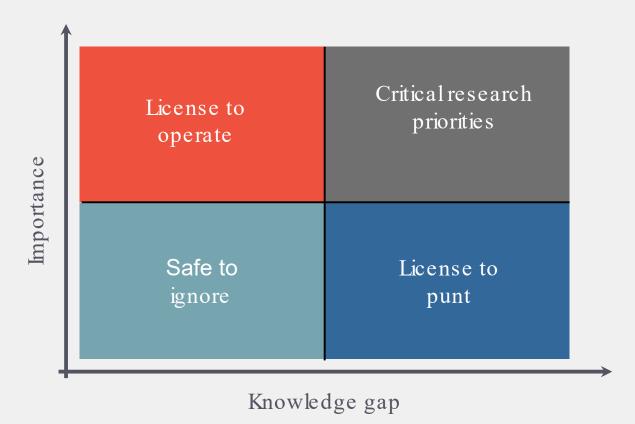






Knowledge Taxonomy

Where can we enable markets to operate?





Uncertainty Taxonomy

Which sources of uncertainty are most important?

Sampling

Statistically under sampled process preventing precise determination of a summary statistic (e.g., an average)

Empirical

Lack of measure ments of complex, diverse, or hetero geneous process

Ontological

Lack of conceptual understanding of the underlying process (or model)

Intrinsic

Uncertainty arising due to a fundamental property of the system (e.g., chaos, complexity)

Epistemic Aleatoric

Reducible Irreducible



Knowledge Gap Taxonomy

What type of knowledge blocks scaling for each pathway?

Social Challenges

Public ownership & engagement—informed assessment to inform equitable decision making

Engineering Challenges

Design technology for safe & effective deployment including robust MRV

Science Challenges

Discover new knowledge of natural phenomenon

Market Challenges

Establish effective quantification & accounting standards & enforcement mechanisms



Effective standards can create a flywheel for innovation

Iterative deployment tracking the best available science

