captura

Update on Captura's Ocean Health and MRV Protocol

V2.0

02/14/2025

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1. Overview

In October 2023, Captura published our Carbon Dioxide Removal Pathway, detailing our approach to safeguarding ocean health and establishing Monitoring, Reporting, and Verification (MRV) protocols for our marine carbon dioxide removal (mCDR) solution. Building on the foundational practices and protocols introduced in the Pathway, this report offers a progress update on our ongoing research. Through this work, we aim to evaluate and minimize any potential environmental impacts of our Direct Ocean Capture (DOC) process and generate operational data for precise carbon accounting.

This update provides an overview and preliminary results from our collaborations with external experts on ocean modeling and biological impact studies. These activities include:

1) regional-scale modeling simulations to quantify the atmospheric carbon dioxide (CO_2) drawdown of a 20kt/yr DOC system in collaboration with the Southern California Coastal Water Research Project (SCCWRP)

2) biological impact studies with Holdfast Aquaculture (HFA) and Nautilus Environmental (formerly Enthalpy Analytical) to assess the potential effects of Captura's effluent on mussels, fish, and kelp.

This work is ongoing and continuously expanding. Following this update, we plan to share further research findings via open-access, peer-reviewed journals.

Captura is encouraged by the substantial progress made over the past year in advancing MRV and ocean health research within the mCDR space. This momentum has been driven by advancements in academia, government, and industry. We aim for Captura's ocean health and MRV research program to contribute meaningfully to this growing body of knowledge and support the broader mCDR field.

2. Regional Scale Carbon Drawdown Modeling

A regional-scale physical-biogeochemical numerical ocean model is being used to determine the DIC depletion resulting from direct ocean capture installations, and the subsequent air-sea equilibration to quantify atmospheric carbon drawdown. This research is conducted in collaboration with the Southern California Coastal Water Research Project (SCCWRP; sccwrp.org).

2.1 Model Description

The Regional Ocean Model System (ROMS, Shchepetkin and McWilliams, 2005) is a physical model that has widely used open-sourced code for U.S. coastal waters and elsewhere. ROMS is coupled to the Biogeochemical Elemental Cycling model (BEC, Moore et al., 2020, Deutsch et al., 2021) to simulate physical and biogeochemical properties of the US west coast (Fig. 1).

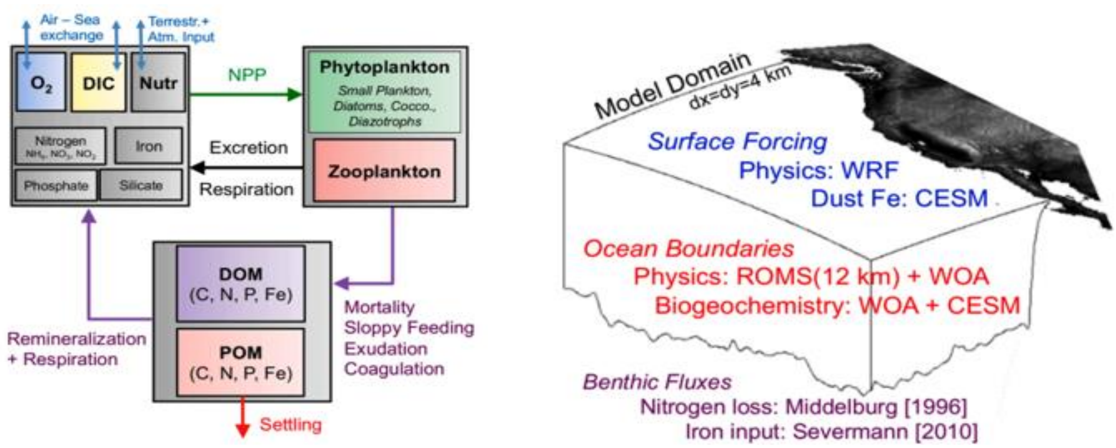

Fig 1. Model schematic for ROMS-BEC. Representation of the ecosystem state variables and fluxes, geographic scale, sources of surface forcing, open boundary condition data, and benthic nutrient fluxes. (Figure adapted from Deutsch et al. 2021).

For this work, model domains are nested and scale from 4-km resolution for the entire California Current System to a 1-km grid for much of the California coast, and a 0.3-km grid in the Southern California Bight (Kessouri et al., 2021). This configuration allows for the domain used in this work to be submesoscale resolving (Fig. 2).

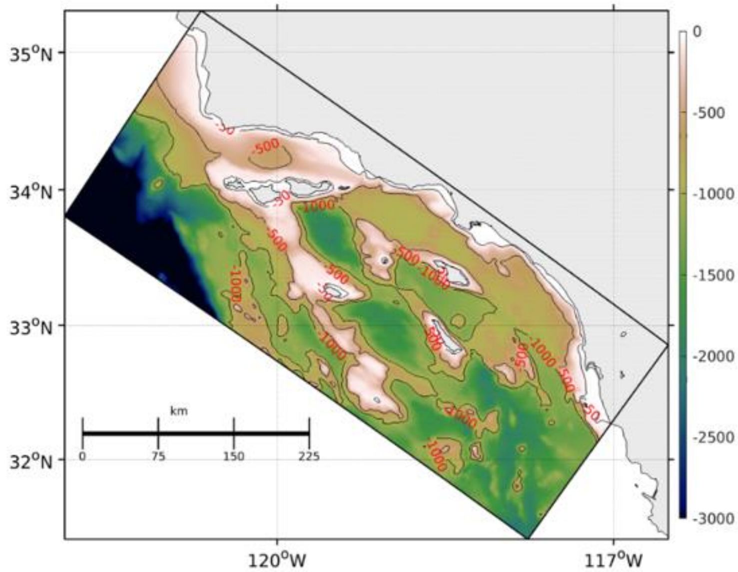

Fig 2. Grid model domain used in this project with a horizontal resolution of 300 m. Seafloor depth (m) is represented by colormap and topographical contouring.

2.2 Determination of Net Carbon Dioxide Removal (CDR)

The CDR quantification methodology is based on the evaluation of two ROMS-BEC scenarios: the scenario with direct ocean capture relative to the baseline scenario. CO_2 removal from direct ocean capture is quantified as the difference in the air-sea gas exchange of CO_2 (ΦCO_2) between the two (Eq. 1).

$$\Delta\Phi\_CO_2 = \Phi(CO_2\text{-Direct Ocean Capture}) - \Phi(CO_2\text{-Baseline}) \quad \text{Eq. 1}$$

Where, **$\Delta\Phi\_CO_2$** represents the total net change in CO_2 that changes across the air-sea boundary for the time period of the scenario. It does not include CO_2 emissions associated with the process. **$\Phi(CO_2$-Direct Ocean Capture)** represents the total air-sea CO_2 gas exchange, in tonnes of CO_2, as a result of direct ocean capture. **$\Phi(CO_2$-Baseline)** represents the total air-sea gas exchange from the counterfactual scenario, in tonnes of CO_2.

2.3 Model Scenarios and Sensitivity Tests

The baseline simulation includes terrestrial and atmospheric forcing of freshwater, nutrients, and carbon (see Kessouri et al. 2021), thus capturing both natural oceanic cycle of nutrient, carbon, and oxygen, with the effects of atmospheric deposition and global CO_2 superimposed, as well as inputs from terrestrial sources of nutrients, C and Fe. Resolving sub-mesoscale eddies with the 0.3-km grid dramatically increases the variability of vertical fluxes of biogeochemical tracers, including

DIC (Kessouri et al. 2021). This counterfactual scenario represents the natural background oceanic uptake and outgassing of CO_2.

The direct ocean capture process is parameterized into the 3-dimensional model with a forcing function developed for wastewater application (Eq. 2; Kessouri et al. 2021). Scenarios are of a hindcast time period, beginning in August 2013.

Short-term scenario testing (5 days to 3 months) is being performed to optimize volume flux rates to the regional setting (ranging from 1 – 47 $m^3\ s^{-1}$) and test combinations of intake and discharge locations. Sensitivity analysis is being performed to maximize DIC extraction rates and minimize high pH conditions.

Long-term scenario testing (1 year – 3 years) is being performed to assess the fate of DIC-depleted waters and $\Delta\Phi\_CO_2$ over necessary time and space scales for Captura systems in the 10^3 – 10^4 tonnes CO_2 removal per year range. Preliminary results (Fig. 3) show $\Delta\Phi\_CO_2$ over the first year of running a direct ocean capture process for a ~20 kton/year system. Model assessments find that oceanic uptake of atmospheric CO_2 is in the range of 65-98% of the direct ocean capture extraction rate.

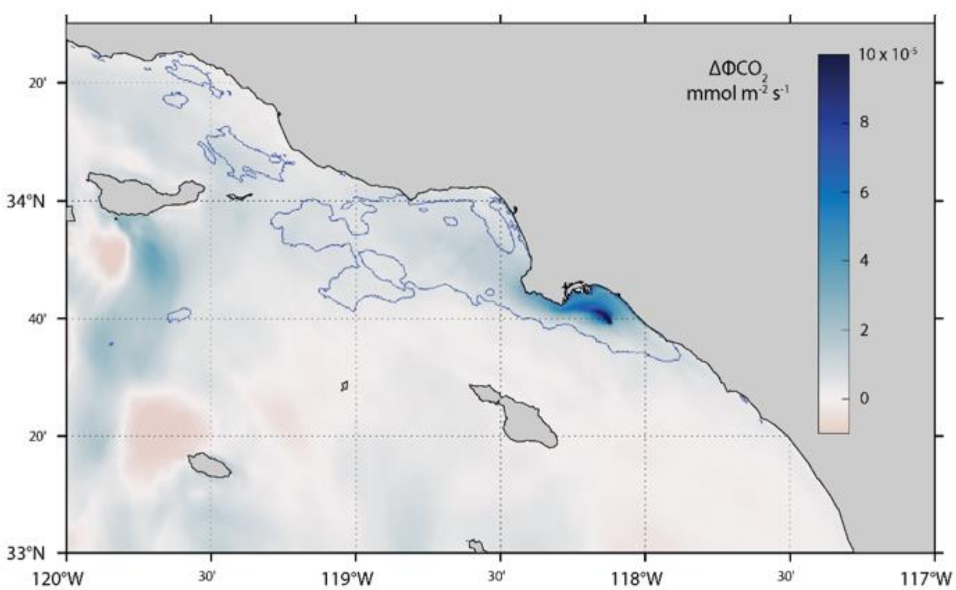

Fig. 3. CO_2 additionality attributable to direct ocean capture assessed as the change in air-sea CO_2 flux ($\Delta\Phi\_CO_2$; mmol $m^{-2}\ s^{-1}$) between a modeling scenario with direct ocean capture (10 $m^3\ s^{-1}$) and a counterfactual scenario. Shown is the monthly average after 11 months of continuous direct ocean capture. Areas contoured (solid blue line) represent those changes that are identified as attributable to direct ocean capture and beyond the noise of model intrinsic variability. Positive values represent an increase in air-sea CO_2 flux into the ocean.

2.4 Model Uncertainty and Validation

There are multiple types of model uncertainty that can contribute to carbon removal quantification. One of these is that the inputs, boundary conditions, and forcings applied to the model are based on imperfect and incomplete observations. Within the ROMS-BEC model, the counterfactual scenario is performed multiple times where the initial ocean state and/or atmospheric forcing is slightly perturbed. Evaluating variability attributable to intrinsic variability will help determine when the signal of direct ocean capture emerges from the noise of model uncertainty.

ROMS-BEC has been validated coast-wide for atmospheric forcing, physics, and biogeochemistry, including O_2, DIC, primary productivity, and hydrographic parameters (Deutsch et al., 2021; Renault et al., 2021). It has also been validated in the Southern California Bight for investigating wastewater outfall impacts on coastal eutrophication, ocean acidification, and oxygen loss (Kessouri et al. 2021, 2024).

3. Biological Impact Studies

3.1 Study Description

To understand what potential effects our process may have on marine organisms, Captura has tested exposure of our effluent on a range of local marine species. Results will help design our technology to minimize impacts on marine ecosystems and inform which topics of research should be further explored to safely and responsibly reach gigaton-scale carbon removal. For our commercial scale systems to generate an extraction efficiency of 90%, which results in a DIC of ~200 umol/kg and pH of ~10.4, with slight variations depending on local conditions. Note that these higher pH levels would be diluted either within the system or in the mixing zone to comply with local regulations. For these studies, we used effluent compositions resulting in pH 9.8-10.1 to quantify potential impacts. Using standardized acute and chronic whole effluent toxicity (WET) testing procedures (ASTM, 1999; USEPA, 1995), we have tested the potential for lethal and sublethal effects of the effluent generated from Captura's technology on the following species:

1) adult stage of commercially farmed mussel, *Mytilus galloprovincialis*

2) larval stage of Pacific Topsmelt, *Atherinops affinis*

3) germination of dominant native seaweed species, *Macrocsytis pyrifera*

Mussels are known for their sensitivity to environmental changes and therefore used as a sentinel species in toxicity testing. Mussel experiments were carried out by Holdfast Aquaculture (HFA, https://www.holdfastaq.com/), a shellfish aquaculture business based in San Pedro, California.

HFA specializes in producing high-quality seed for sustainable seafood growers, including seaweed and bivalves like oysters and mussels. In addition to invertebrates, we were also interested in testing a vertebrate and plant species common to Southern California. Pacific topsmelt and giant kelp chronic toxicity tests were conducted by Nautilus Environmental (formerly Enthalpy Analytical), an environmental analysis laboratory accredited by the California State Water Board in toxicology testing for environmental regulatory compliance (https://nautilusenvironmental.com/). These biological impact studies were primarily funded by Department of Energy ARPA-E DE-AR0001662 and Climate Intervention Environmental Impact Fund (https://cieif.org/current-grants/). Ongoing studies are designed to characterize the biological effects, if any, of Captura's effluent on these marine aquaculture species, while also exploring opportunities of co-industrialization between direct ocean capture and aquaculture.

Fig. 4. Experimental setup of the second trial of mussel experiments with young adult mussels.

3.2 Methods

For adult mussels, mussels were exposed to varying concentrations of effluent during two separate experiments (Fig. 4). In the first trial, dilutions were made with treated seawater (UV-sterilized, 0.2-micron filtered, buffered with sodium bicarbonate, which is standard procedure at HFA). There were 6 mussels per treatment replicate and 6 treatment replicates with a total of 36 mussels assayed per experimental group for 3 effluent concentrations (0, 50, 100% effluent). In the second trial, dilutions were made with unbuffered, filtered seawater. There were 10 mussels per treatment replicate and 3 treatment replicates for a total of 30 mussels per experiment group for 5 effluent concentrations (0, 25, 50, 75, 100% effluent). Each replicate was gently aerated and maintained in a water bath at 18°C. Animals were inspected at 96 hours for survival (determined by responsive adductor muscles) and presence of byssal thread formation.

For Pacific topsmelt, 13-day post hatch larval fish were used for the experiment. There were 5 larval fish per container, 5 replicates per treatment, and 6 effluent concentrations (0, 6.25, 12.5, 25, 50, 100 % effluent). The larval fish were exposed to effluent for 7 days in static conditions. They were fed twice daily. The water was renewed daily and maintained at 20°C. Live larvae were counted daily, and at the end of the test, the organisms were dried and weighed.

For giant kelp, zoospores released from the sporophyll blades were collected with 7,500 spores/mL per container, in 5 replicates. The spores were allowed to settle onto microscope slides and germinate. Water was maintained at 18°C. After 48 hours, germination success was determined and germ-tube length was measured.

3.3 Preliminary results

Expt. 1: Large adult mussels (6-10 cm, *n* = 108) all survived and developed byssal threads. Expt. 2: Young adult mussels (2-4 cm, *n* = 150) all survived and developed byssal threads. Overall, the results (Table 1, *n* = 258) show no significant impact of effluent on adult mussels survival or byssal thread formation.

In the WET tests for larval Pacific topsmelt, there were high rates of fish survival across all effluent concentrations with no significant impact on the growth (Table 1). Similarly for giant kelp, all spores had high germination rates and there was no significant impact on their growth (Table 1).

	Adult Mussel Trial #1		Adult Mussel Trial #2		Larval Pacific Topsmelt		Giant Kelp	
Conc. (% effluent)	Survival (%)	Byssal formation (%)	Survival (%)	Byssal formation (%)	Survival (%)	Biomass (mg/org)	Germina-tion (%)	Mean Tube Length (um)
0	100 (0)	100 (0)	100 (0)	100 (0)	88 (8)	0.97 (0.1)	95.6 (0.7)	12.4 (0.16)
6.25	-	-	-	-	100 (0)	1.01 (0.05)	94.4 (1.2)	12.3 (0.13)
12.5	-	-	-	-	92 (5)	0.93 (0.05)	93.4 (1.2)	12.2 (0.14)
25	-	-	100 (0)	100 (0)	88 (5)	0.89 (0.06)	93.4 (0.7)	11.8 (0.24)
50	100 (0)	100 (0)	100 (0)	100 (0)	96 (4)	0.95 (0.08)	93.2 (1)	12.1 (0.39)
75	-	-	100 (0)	100 (0)	-	-	-	-
100	100 (0)	100 (0)	100 (0)	100 (0)	92 (5)	0.96 (0.1)	93.6 (1)	12.2 (0.44)

Table 1. Preliminary results from mussel, fish, kelp effluent exposure tests. Standard error is shown in parentheses.

Collectively, these preliminary results support the hypothesis that Captura's technology will have minimal impacts on nearby marine ecosystems; however, further long-term, increased scale exposure studies with full effluent composition are necessary. Future work with HFA will include larger and longer trials, additional testing on the sensitive larval life stage of mussels, as well as other marine species such as phytoplankton, oysters, and sea urchins. Captura will also continue to explore potential synergies between direct ocean capture and low-trophic aquaculture. This work will provide valuable data to ensure Captura's process adheres to environmental standards and supports the continued development of safe and responsible mCDR deployment.

4. References

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