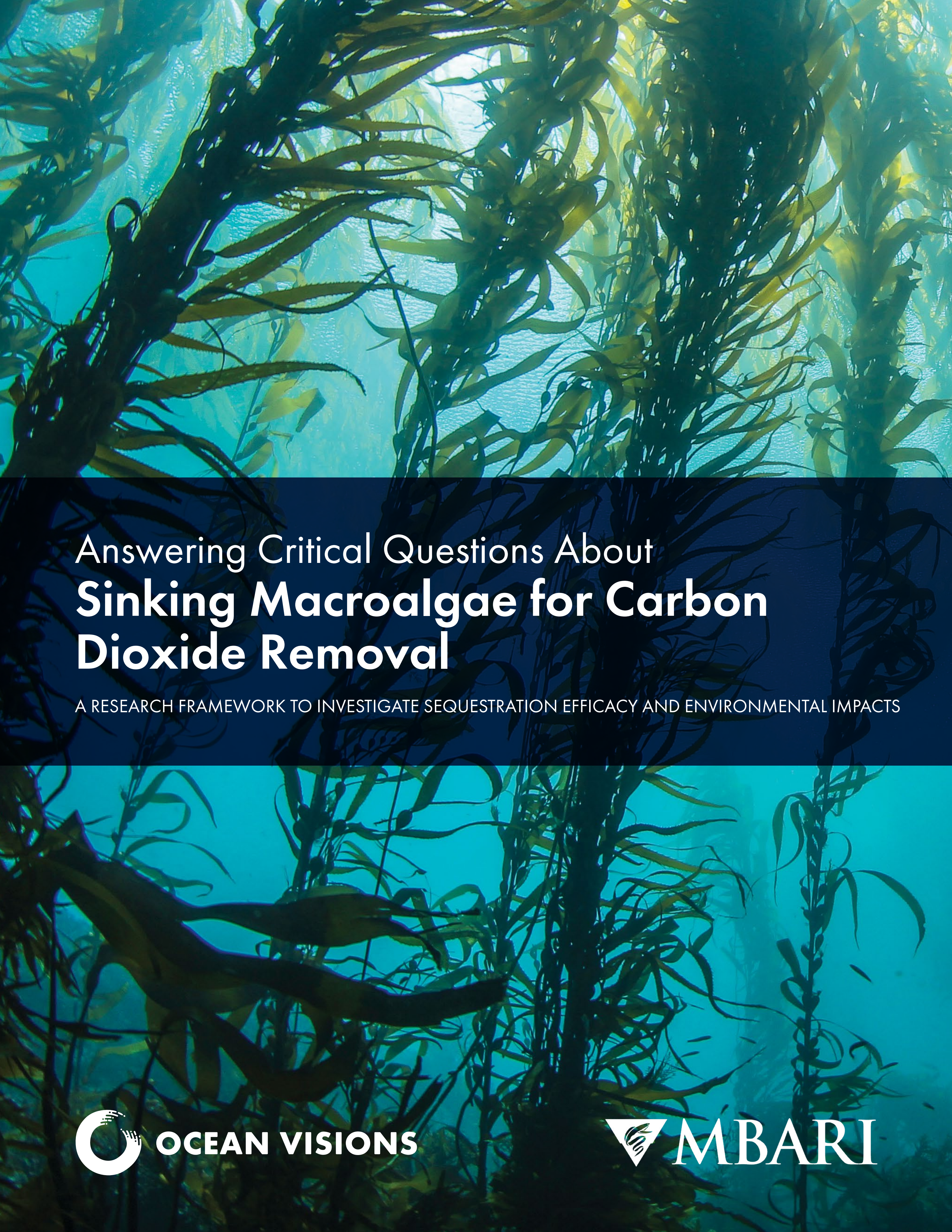

Answering Critical Questions About

Sinking Macroalgae for Carbon Dioxide Removal

A RESEARCH FRAMEWORK TO INVESTIGATE SEQUESTRATION EFFICACY AND ENVIRONMENTAL IMPACTS

OCEAN VISIONS

MBARI

Front Matter

Coordinating Institutions and Individuals

This report is a collaboration between Ocean Visions and the Monterey Bay Aquarium Research Institute. Outcomes and findings herein are at the discretion of Ocean Visions and the Monterey Bay Aquarium Research Institute.

Lead responsibilities for the writing, drafting, editing, and final approval of this report lie with the following individuals: David Koweek (Ocean Visions), Jim Barry (Monterey Bay Aquarium Research Institute), and Sarah Mastroni (Ocean Visions).

Expert Working Group

This report was informed by the activities and input of a working group comprised of experts from diverse backgrounds and geographies. Members are listed below.

The working group met eight times between October 2021 and July 2022.

Name	Organization	Country
Joan Alfaro-Lucas	University of Victoria	Canada
Dror Angel	University of Haifa	Israel
Mark E. Capron	OceanForesters	USA
Meg Chadsey	Washington Sea Grant	USA
Max Chalfin	Running Tide Technologies	USA
Stephen Crooks	Silvestrum Climate Associates	USA
Kristen Davis	University of California Irvine	USA
Colleen Durkin	Monterey Bay Aquarium Research Institute	USA
Mar Fernández-Méndez	Alfred Wegener Institute Helmholtz Center for Polar and Marine Research	Germany
Jordan Hollarsmith	NOAA Fisheries, Alaska Fisheries Science Center	USA
Gi Hoon Hong	East China Normal University	China
Nico Julian	Phykos, PBC	USA
Amanda Kahn	Monterey Bay Aquarium Research Institute	USA
Lisa Levin	Scripps Institution of Oceanography, University of California San Diego	USA
Matthew Long	National Center for Atmospheric Research	USA
Alyson Myers	Fearless Fund	USA
Chioma Nwakanma	Michael Okpara Federal University of Agriculture Umudike	Nigeria
Morgan Raven	University of California Santa Barbara	USA
Aurora M Ricart	Bigelow Laboratory for Ocean Sciences	USA
Neil Sims	Ocean Era, Inc.	USA
Tanja Stratmann	Royal Netherlands Institute for Sea Research (NIOZ)	The Netherlands
John Taylor	University of Cambridge, Centre for Climate Repair at Cambridge	United Kingdom
Chris Vivian (observer)	Group of Experts on the Scientific Aspects of Marine Environmental Protection	United Kingdom
Brian von Herzen	Climate Foundation	Australia
Marc von Keitz (observer)	Grantham Environmental Trust	USA

External Reviewers

We are thankful to the following individuals for their review of an earlier draft of this report and for their helpful comments: Freya Chay (CarbonPlan), Jamie Collins (Environmental Defense Fund), Sarah Cooley (Ocean Conservancy), and Anu Khan (Carbon180).

Acknowledgements

This report was made possible through generous support from the Grantham Environmental Trust, ClimateWorks Foundation, The Builders Initiative, and Fremont Bank Foundation.

How to Cite This Report

Ocean Visions and Monterey Bay Aquarium Research Institute (2022). Answering Critical Questions About Sinking Macroalgae for Carbon Dioxide Removal: A Research Framework to Investigate Sequestration Efficacy and Environmental Impacts. Available online at: oceanvisions.org/seaweedresearch

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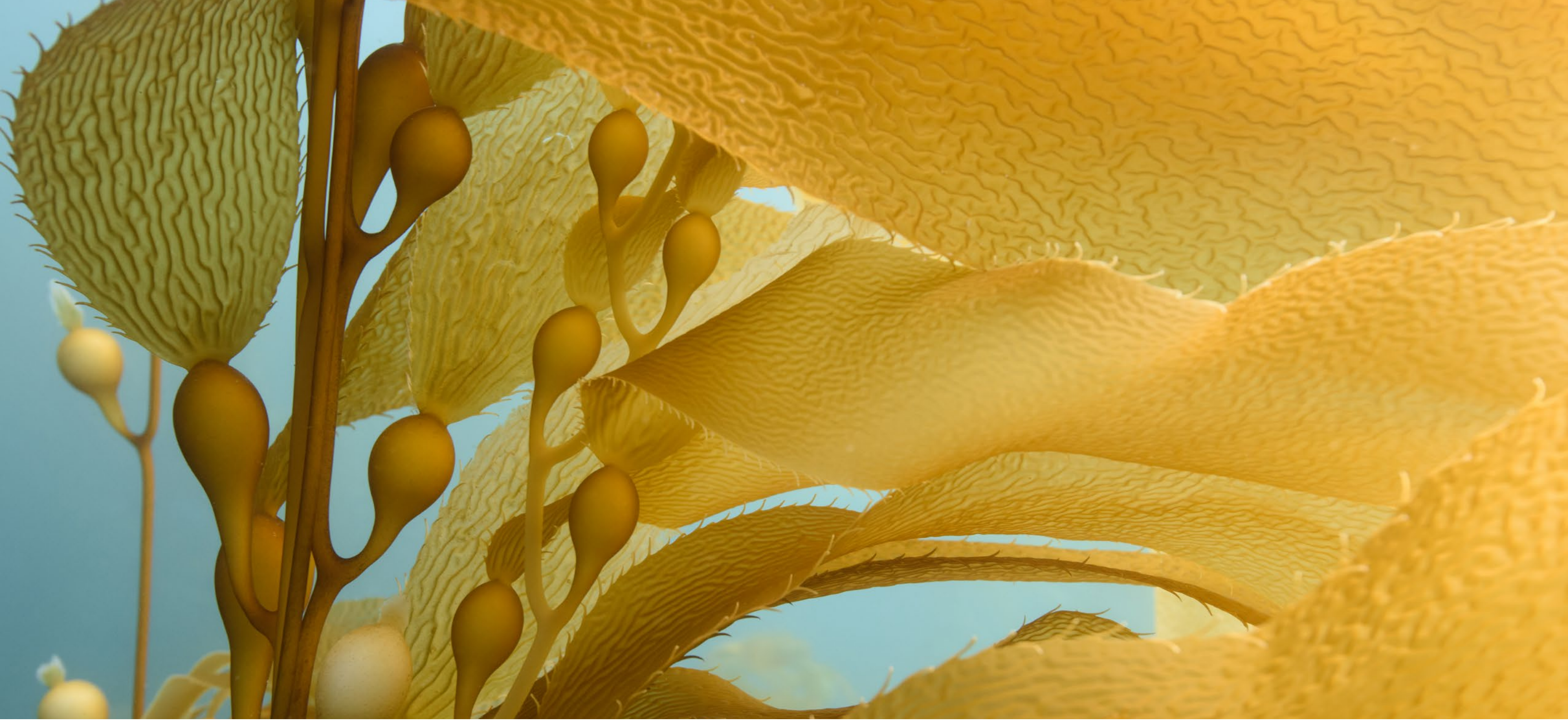


Executive Summary

This report presents a framework for a coordinated global research effort dedicated to investigating the efficacy and environmental impacts (positive and negative) of growing and sinking macroalgae into the deep ocean as a carbon dioxide removal strategy. This report is motivated by two ideas:

- Carbon dioxide removal from the atmosphere is now recognized as an imperative alongside elimination of carbon emissions (decarbonization) to stabilize, and ultimately reverse, climate change. Ocean-based pathways for carbon dioxide removal hold promise due to the size of the ocean, its natural carbon sequestering capacity, and the potential for highly durable pathways of ocean carbon sequestration.
- Growing macroalgae at large scales and sinking it into the deep ocean has received attention as a potential strategy to sequester carbon dioxide at climate-relevant scales (hundreds of megatons-to-gigatons of carbon), but this strategy lacks a body of evidence from which to evaluate its efficacy, risks to ecosystems, and any co-benefits that may accrue.

The framework for research presented in this report offers a path forward to fill the information vacuum about macroalgae sinking as a carbon dioxide removal strategy by presenting:

- 23 fundamental scientific questions spanning physical and biological sciences, along with recommended principal and secondary scientific approaches for answering these questions
- Detailed guidance on the design and execution of controlled field trials that can be completed in approximately two to five years. Guidance is focused on the surface ocean ecosystems where the macroalgae would be grown, and deep-sea ecosystems where the macroalgae would remain.
- Estimates of the cost of a single controlled field trial, as well as the recommendation for approximately 10 coordinated field trials at an estimated total cost of ~$1 billion USD. An associated budgeting tool for developing cost estimates of controlled field trials is shared alongside this report.
- A compilation of global oceanographic assets that can be used to facilitate the research activities described in this report, alongside a list of pilot projects underway or in the planning stages

This report is intended to facilitate reproducibility and intercomparison among the global research community.

Adherence to the guidance in this report is intended to accelerate the production of actionable information for policy about efficacy, costs, and benefits of sinking macroalgae into the deep sea as a carbon dioxide removal strategy, and more broadly, as part of the set of solutions for solving the climate crisis.

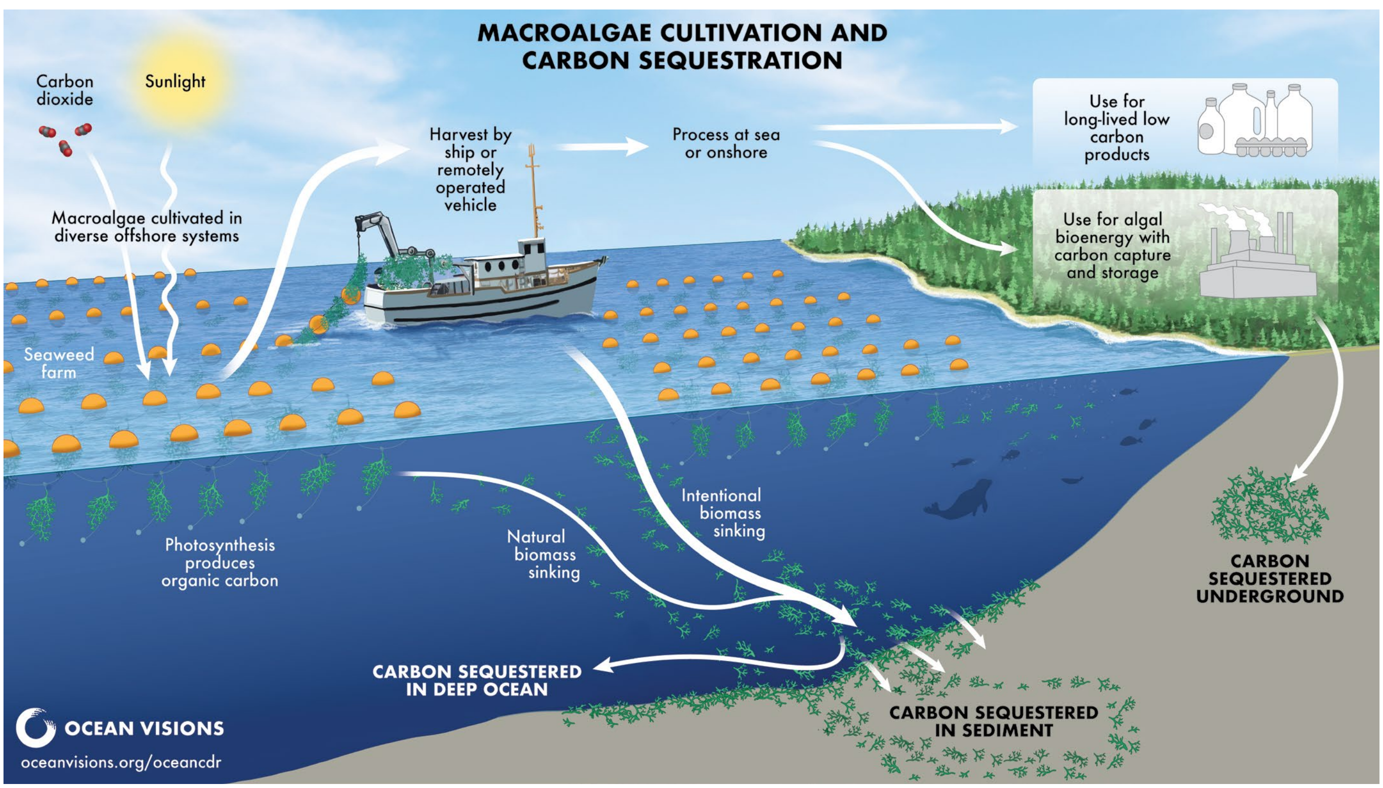
Introduction

Background and Scope

The need for solutions to the climate crisis has never been more urgent. Wildfires, droughts, heatwaves, food insecurity and resulting migration, and climate-related conflict threaten us all. Seas are rising, warming, acidifying, and losing oxygen, all of which threaten the health and structure of marine ecosystems and the communities around the world that rely on them[1]. Continued emissions of greenhouse gases, especially carbon dioxide, are likely to cause increasingly severe consequences for humans and the environment[2]. Halting, and eventually reversing, the impacts of climate change requires that we both stop emitting carbon dioxide *and* remove past carbon dioxide pollution from the atmosphere and ocean. The quantity of carbon that must be removed to meet temperature targets depends upon the date these targets are reached and will likely range from hundreds to a thousand gigatons of carbon dioxide removed by 2100[3,4]. For context, 39 gigatons of carbon dioxide were emitted in 2021 from fossil fuel usage and land use changes[5]. Thus, removal targets represent 2.5 to 25 years of current carbon emissions, underscoring the need to develop scalable carbon removal solutions.

Ocean-based pathways offer high potential for contributing to carbon dioxide removal goals for several reasons. First, the ocean covers ~70% of the surface area of the planet, providing substantial scalability for effective solutions. Second, the ocean is already incredibly effective at sequestering carbon through natural processes. The ocean holds about 50 times more carbon than does the atmosphere and has sequestered about 30% of anthropogenic carbon dioxide emissions since the start of the industrial era[6]. Third, the durability of ocean-based pathways may be greater than for many land-based carbon storage options which may be subject to climate-driven disturbances (e.g., wildfire & erosion), or changes in societal priorities for land use.

Macroalgae, or seaweed, are fast growing marine autotrophs that incorporate carbon from seawater in their living tissue. Macroalgae flourish in coastal and some pelagic environments, and a portion of the seaweed produced is exported naturally to the deep-sea where it may be buried or remineralized by marine food webs[7]. Slow turnover times in most deep ocean environments will sequester carbon released to bottom waters for centuries or longer[8].



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Recently, proposals have emerged to cultivate macroalgae and then sink that algal biomass to the deep ocean to sequester carbon from the atmosphere, amplifying natural seaweed carbon sequestration. In theory, this would promote additional carbon dioxide removal from the atmosphere to replace the sunken algal carbon[9,10,11]. While still in its infancy, this technology has attracted serious attention, and early-stage public[12] and private[13,14] investment in a number of organizations exploring various approaches and at various stages in the commercialization process. However, large knowledge gaps remain that hinder our collective ability to make well-informed decisions about the feasibility, suitability, and risks of this approach. These gaps fall into two categories: questions regarding the efficacy and duration of carbon sequestration across the full life cycle, and questions regarding the environmental impacts (both beneficial and detrimental) of cultivating and sinking large quantities of macroalgae into the deep ocean. Beyond a small number of modeling studies[15,16,17,18], and studies of natural organic carbon burial in the deep sea from macroalgae[7,19] and wood[20], we collectively lack the information on both efficacy and impacts necessary to make well-informed decisions about the benefits and costs, for both ocean ecosystems and climate change mitigation potential, that will affect any decisions about potential deployment of this technology. Generating such information will require multiple approaches including additional modeling, laboratory studies, comprehensive literature reviews, and controlled field trials.

This report lays out a road map to fill information gaps concerning macroalgal carbon sequestration that require field experimentation. It presents the framework of a comprehensive global research program centered on controlled field trials to generate information to support decisions concerning the risks and benefits of utilizing macroalgae sinking as a carbon dioxide removal strategy. Risks include the potential negative ecological effects on marine ecosystems due to the production of macroalgae and its sinking to the seafloor. Potential benefits are meant here as avoided global warming and related consequences due to sequestration of carbon in macroalgae. In addition to new information concerning the fate and effects of sinking macroalgae, results from field trials will be important inputs for models estimating the scaled-up consequences and efficacy of a climate-relevant (hundreds of megatons-to-gigatons) macroalgae carbon sequestration program.

This report builds on the 2022 National Academies of Science, Engineering, and Medicine report: *A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration*[10], which highlights the need for field trials of emerging ocean-based carbon dioxide removal approaches. This report responds to the National Academies of Science, Engineering, and Medicine's call for "tailored implementation planning for specific ocean carbon dioxide removal approaches" and focuses on filling critical knowledge gaps by detailing an actionable research agenda.

Diverse Uses of Cultivated Macroalgae

While this report is solely focused on the efficacy and impacts of macroalgae sinking as a carbon dioxide removal strategy, macroalgae cultivation is a fast-growing industry that may play a multitude of roles in meeting emissions reduction and carbon removal targets.

Macroalgae cultivation has a long history in Asia, which currently produces 99.5% of cultivated seaweed globally[21]. However, macroalgae cultivation is expanding globally and there are a growing number of industries around the world exploring seaweed cultivation for many purposes and end-uses. Cultivated seaweeds provide:

- A low carbon source of high-value bioproducts, such as food, feed, nutritional supplements, and fertilizers[21]
- A low carbon source for biofuels[21] and bioenergy[22], which when combined with carbon capture[23], can create carbon-negative sources of energy
- Macroalgae can also be pyrolyzed to create algal biochar[24,25]
- Finally, macroalgae can be processed for use as industrial feedstocks into long-lived bioproducts, such as bioplastics[26], as a means to sequester the embedded carbon and decrease reliance on carbon-pollution heavy industrial feedstocks for chemical processes.

Due to the vast array of uses and applications for cultivated macroalgae, it is likely there will be many meaningful ways in which macroalgae will contribute to combatting the climate crisis.

Contents of This Report

This report is intended to catalyze a comprehensive research effort engaging a global community of government representatives, policymakers, scientists, engineers, and technologists. It neither advocates for nor against large-scale cultivation and sinking of macroalgae as a carbon dioxide removal strategy. The research outlined in this report is focused solely on generating information concerning the efficacy and impacts of a large-scale macroalgal cultivation and sinking program, to enable well-informed decisions concerning the value and risks of macroalgal carbon dioxide removal.

In the following sections, this framework is presented in four parts:

1. The foremost scientific questions concerning the efficacy and impacts of large-scale cultivation and subsequent sinking of macroalgae for carbon dioxide removal. This section of the report also identifies principal and secondary scientific approaches most appropriate for answering each question.
2. Template experimental designs for controlled field trials to assess:
    - the carbon sequestration efficacy, and biogeochemical and ecological impacts of sinking macroalgae to deep seafloor (benthic) environments
    - the potential for removal of atmospheric carbon dioxide, and biogeochemical and ecological impacts of cultivating macroalgae in the upper layers (epipelagic) of new open ocean locations
3. Cost estimates for a global scale research program that include multiple controlled field trials across a number of macroalgal taxa and oceanographic environments. Accompanying this global scale estimate, we are releasing an experimental design budgeting tool that can aid in experimental planning and understanding cost drivers of this research.
4. A compendium of existing oceanographic assets, infrastructure, and pilot projects that can facilitate the science described above

This report is intended to increase intercomparison and reproducibility of field trials and their results among the global scientific community. Information gained from this approach will enhance our ability to make informed decisions concerning macroalgae cultivation and sinking as a carbon dioxide removal strategy.

This report recommends that all research activities, and especially controlled field trials, adhere to a research code of conduct that ensures the activities are transparent, inclusive, ethical, and just[27,28,29].

Audiences and Outcomes

This report is designed to advance a concerted global effort to answer key scientific questions about the efficacy and impacts of growing and sinking macroalgae for carbon dioxide removal. It is primarily intended for individuals in positions that:

- Advance research and development through allocation of time, energy, or money (e.g., program officers in public, philanthropic, and private organizations)
- Develop policies to support scientific innovation, technology development, and climate solutions (e.g., policy makers, analysts, and regulators)
- Conduct and/or facilitate research (e.g., scientists, engineers, technologists, marine operations professionals)

Execution of the type of research program outlined in this report is intended to yield actionable information about the carbon sequestration efficacy and environmental impacts of sinking macroalgae as a carbon dioxide removal strategy. The set of questions and activities recommended in this report, while not exhaustive, represent priorities for catalyzing research progress in the field. As with all areas of scientific inquiry, we expect that initial investigations will yield new questions as well as answers.

Fundamental Scientific Questions Regarding the Efficacy and Impacts of Large-Scale Cultivation and Sinking of Macroalgae for Carbon Dioxide Removal

Substantial scientific uncertainties exist regarding the efficacy of growing and sinking macroalgae to the deep ocean for carbon dioxide removal, and its associated environmental impacts (both beneficial and detrimental). This section of the report articulates a categorized set of scientific questions necessary for developing a foundational base of information. Alongside each question, this report recommends principal and, often, secondary scientific approaches appropriate for addressing the question. Assigned principal and secondary approaches are somewhat subjective and may change; in some cases, the prioritization of scientific approach(es) for answering a question may deviate from the recommendations in this report. Nonetheless, they provide a starting point for a thorough investigation of the key physical, chemical, and biological questions concerning the growing, harvesting, and sinking of macroalgae for carbon dioxide removal.

Note: There are a number of information needs that must be addressed alongside, or following, the fundamental physical and biological sciences questions articulated in this report. While it is beyond the scope of this report to address these information needs in detail, they are listed below. They include, but are not limited to:

- *Sociological and psychological questions related to social acceptance, risk perception, and risk-risk tradeoffs*
- *Questions of environmental justice and equity*
- *Life cycle assessments*
- *Technoeconomic analysis*

Summary Questions for Policy Makers

The fundamental scientific questions detailed in the table below can be summarized as:

1. What happens to macroalgae once it sinks to the bottom of the ocean?
2. How does sinking macroalgae impact seafloor (benthic) and mid-water column ecosystems?
3. How does growing large quantities of macroalgae in new open ocean locations impact upper ocean ecosystems?
4. How much total carbon dioxide removal is possible if this technology can be scaled?

Answering each of these questions requires one or more scientific approaches. For many questions, multiple scientific approaches may be useful.

Scientific Approaches

Controlled Field Trials: the intentional perturbation of the marine environment for the purposes of observing, characterizing, and quantifying the causal relationship between an activity (in this case, sinking macroalgae) and its effects (biogeochemical, ecological, etc.)

Observational Field Studies: studies where researchers collect data from a marine environment without perturbing it for the purposes of understanding ecosystem function, characterizing a site, and/or collecting baseline data

Laboratory and/or Mesocosm Experiments: an experimental set-up (either indoors or outdoors) that simulates a natural environment and allows for observation under controlled conditions. These types of experiments allow for precise manipulation and are used to model a larger ecosystem

Numerical Modeling: mathematical modeling to represent and simulate physical, chemical, and biological conditions and dynamics

Synthesis of Existing Scientific Literature: the systematic and transparent collection, categorization, and analysis of existing data and scientific literature to develop new knowledge

Principal Approach   Secondary Approach

Theme	Key Question	Scientific Approaches				
		Controlled Field Trials	Observational Field Studies	Laboratory and/or Mesocosm Experiments	Numerical Modeling	Synthesis of Existing Scientific Literature
What are the impacts to benthic ecosystems from sinking macroalgae?	Are there thresholds in density and spatial extent of deposited macroalgae that trigger biological and/or biogeochemical responses?	Principal Approach	Principal Approach	Secondary Approach	Principal Approach	Secondary Approach
	What are the remineralization and consumption rates of seaweed in different benthic environments?	Principal Approach	Secondary Approach		Secondary Approach	Secondary Approach
	How will sinking seaweed affect benthic and benthopelagic organismal assemblages and biodiversity?	Principal Approach	Principal Approach	Secondary Approach		Secondary Approach
	How will sinking seaweed affect benthic microbial assemblages?	Principal Approach	Principal Approach	Principal Approach		Secondary Approach
	How will sinking seaweed affect biogeochemical patterns and processes near (bottom waters), on, and beneath the seabed?	Principal Approach	Secondary Approach	Secondary Approach	Secondary Approach	Secondary Approach
	What is the spatial extent of benthic impacts for a climate-relevant seaweed sinking program?	Secondary Approach	Secondary Approach		Principal Approach	Secondary Approach

Theme	Key Question	Scientific Approaches				
		Controlled Field Trials	Observational Field Studies	Laboratory and/or Mesocosm Experiments	Numerical Modeling	Synthesis of Existing Scientific Literature
What are the impacts to upper ocean ecosystems from cultivating macroalgae?	How does cultivating macroalgae modify upper ocean biogeochemical cycles in the vicinity of a farming area and downstream of it?					
	How does cultivating macroalgae modify upper ocean ecological interactions in the vicinity of a farming area and downstream of it (including the introduction of invasive species and spread of pathogens)?					
	How does cultivating macroalgae modify the biological carbon pump in the vicinity of a farming area and downstream of it?					
	What are the spatial and temporal bounds of physical, geochemical, and ecological influences from a farming area?					
	How may the introduction of "new" nutrients to support seaweed cultivation from, e.g., artificial upwelling, affect biogeochemical processes?					
	How will cultivating macroalgae affect air-sea exchange of carbon dioxide?					
	Will macroalgae cultivation affect migration patterns of vertebrates (e.g., fish, sea birds, sea turtles, mammals)?					
	How do large-scale cultivation and sinking operations affect radiative transfer between the sun and upper ocean? What are the relevant spatial scales?					

Theme	Key Question	Scientific Approaches				
		Controlled Field Trials	Observational Field Studies	Laboratory and/or Mesocosm Experiments	Numerical Modeling	Synthesis of Existing Scientific Literature
What is the fate of carbon in macroalgae sunk to the deep ocean?	How much seaweed is converted to dissolved organic carbon?					
	How much seaweed is preserved as particulate organic carbon?					
	How much seaweed is remineralized to dissolved inorganic carbon?					
	What are the physical, chemical, geological, and biological factors controlling the distribution of carbon that is a) remineralized in the water column, b) remineralized in the benthos, c) converted to dissolved organic carbon, or d) preserved as organic carbon in the benthos?					
What are the impacts to mid-water column ecosystems?	How will sinking seaweed affect midwater biogeochemical patterns and fluxes?					
	How will sinking seaweed affect mid-water column microbial assemblages?					
	How will sinking seaweed affect mid-water column organismal assemblages and abundance?					
Scaling Considerations	How does location affect estimates of sequestration timescales?					
	What is the global-scale geophysical limit for carbon dioxide removal by sinking macroalgae? How would yield variations and uncertainty from macroalgae farms affect this estimate?					

Guidance for Seafloor-Focused Controlled Field Trials to Assess Efficacy and Impacts of Macroalgae Sinking for Carbon Dioxide Removal

Controlled field trials[i] are necessary to assess the fate of macroalgae carbon sunk into the deep ocean for the purposes of ocean-based carbon dioxide removal. These same experiments should also assess the environmental effects of large-scale macroalgae sinking on deep sea benthic ecosystems. While all other scientific approaches (models, experiments, observations of natural systems, and literature syntheses) can inform our understanding of the important questions related to macroalgae sinking, **controlled field trials are the only means to establish cause-effect relationships in real world, complex marine environments. As such, they are a core and irreplaceable component of evaluating proposed ocean-based climate solutions, including macroalgae sinking.**

Here we provide guidance on the design and execution of controlled field trials focused on the fate and impacts of sinking macroalgae into the deep ocean. Multiple controlled field trials, spanning different oceanographic regions and with multiple species will be necessary for developing a more complete understanding of the potentials and risks associated with intentionally sinking macroalgae in the deep sea. The data resulting from these field trials should adhere to FAIR principles to ensure data transparency and reproducibility[ii].

In this section of the report, guidance is categorized as "Key" and "Additional". Recommendations that are considered essential to the proper design of a controlled field trial are labeled "Key" and recommendations considered beneficial, but not essential, to the proper design of a controlled field trial are labeled "Additional". Within each section, information presented is not ranked by priority of importance.

Note: Controlled field trials to characterize the fate and impacts of sinking macroalgae into the deep ocean may be conducted separately or jointly with controlled field trials focused on the efficacy and impacts of large-scale cultivation in new open ocean locations.

Location(s) for Field Trials

Key Site Considerations for an Experiment

The overarching consideration when selecting site(s) for field trials is that the sites should be as analogous in all ways possible to sites under consideration for full-scale deployments.

Oceanographic Criteria

- Site(s) with bottom depth > 1,000 meters
- Sediment covered, largely homogeneous seabed
- Baseline information available concerning physical, chemical, and biological characteristics of the site(s)
- Sufficiently distant from all protected areas (e.g., sensitive or vulnerable marine ecosystems, marine protected areas, other effective area-based conservation measures), including hydrothermal vents, seeps, seamounts, and habitats for critically endangered species to avoid unintended impacts
- Locations with a low probability of episodic disturbance that could disrupt the planned field trials
- Include sites with low and with high bottom water dissolved oxygen concentrations to characterize the effects of sunk macroalgae on deep sea dissolved oxygen concentrations, and of dissolved oxygen concentration on the fate of macroalgae deposited in the deep sea.
    - » Experiments could exploit natural dissolved oxygen gradients on continental margins.
- Treatment site(s) and/or control site(s) are unaffected by advection and dispersion from one another

Logistical

- Proximity to shore-based support services (e.g., seaweed sources, monitoring logistics) practical for experimental budget (e.g., less than approximately five days steam from port)

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i Here we define "controlled field trial" as the intentional perturbation of the marine environment for the purposes of observing, characterizing, and quantifying the causal relationship between an activity (in this case, sinking macroalgae) and its effects (biogeochemical, ecological, etc.).

ii https://www.go-fair.org/fair-principles/

Social Criteria

- Adherence to appropriate permitting, regulation, and governance frameworks
- Research teams work with local communities, including indigenous groups, and stakeholders (fishers, shippers, mariners, offshore industries) to:
  - » Identify sites and plan experiments
  - » Identify potential conflicts and develop conflict mitigation plans

Additional Site Considerations for an Experiment

Oceanographic Criteria

- Experiments are, collectively, conducted in hydrographically diverse regimes, including upwelling systems as well as highly stratified systems.
- Experiments, collectively, feature locations with low and with high benthic consumer abundances.

Logistical Criteria

- Positioned near science-ready submarine cable (i.e., electrical power and communications)
- Hydrodynamics well understood and suitable for a control volume approach to quantify the fate of the seaweed carbon
  - » Low rates of lateral and vertical mixing
  - » Predominant advection sluggish, unidirectional
  - » Low advection and diffusive fluxes of tracers relative to biogeochemical reactions (e.g., seaweed remineralization)

Locations to Avoid

- Protected sites including marine protected areas, world heritage sites, culturally significant areas and treaty-protected resources, ecologically or biologically significant marine areas, vulnerable or sensitive marine ecosystems
- Areas with seabed mining or other infrastructure (e.g., telecom cable, oil and gas pipeline)
- Steeply sloped areas where seaweed deposited on the seafloor may move (e.g., sites that experience turbidity flows)

Quantity and Frequency of Sinking in Field Trials: How Much and How Often?

Key Considerations

- Sinking experiments should be designed to assess both one-time (pulse) and repeated (continuous) deposits of seaweed to the seafloor. These need not be elements of a single experiment but could be part of a larger network of experiments, possibly in the same large area.
  - » **Pulse** experiments are performed as a single treatment event. In pulse experiments, a single application of macroalgae to the seafloor environment is monitored and tracked for resulting changes in biological, physical, and chemical responses. This experimental design is likely most useful for assessing efficacy and impacts of a sinking program **at the onset of the program.**
  - » **Continuous** experiments maintain a perturbation throughout an experiment. In this case, seaweed would be repeatedly deposited with continued monitoring across all treatments. Deposition frequency could range from several months to annually. **This design is likely to be more representative of an actual sequestration program.**
- Experiments utilize various seaweed delivery methods (e.g., baled, release point, etc.) optimized for intended seafloor seaweed dispersion and thickness of macroalgae deposited on seafloor. Baling and sinking strategies should not include the use of plastics.
- Seaweed should sink rapidly to the seafloor to ensure that any biogeochemical fluxes in the water column due to macroalgae decomposition and slow seaweed sinking do not confound the results of benthic-focused experiments.

Additional Considerations

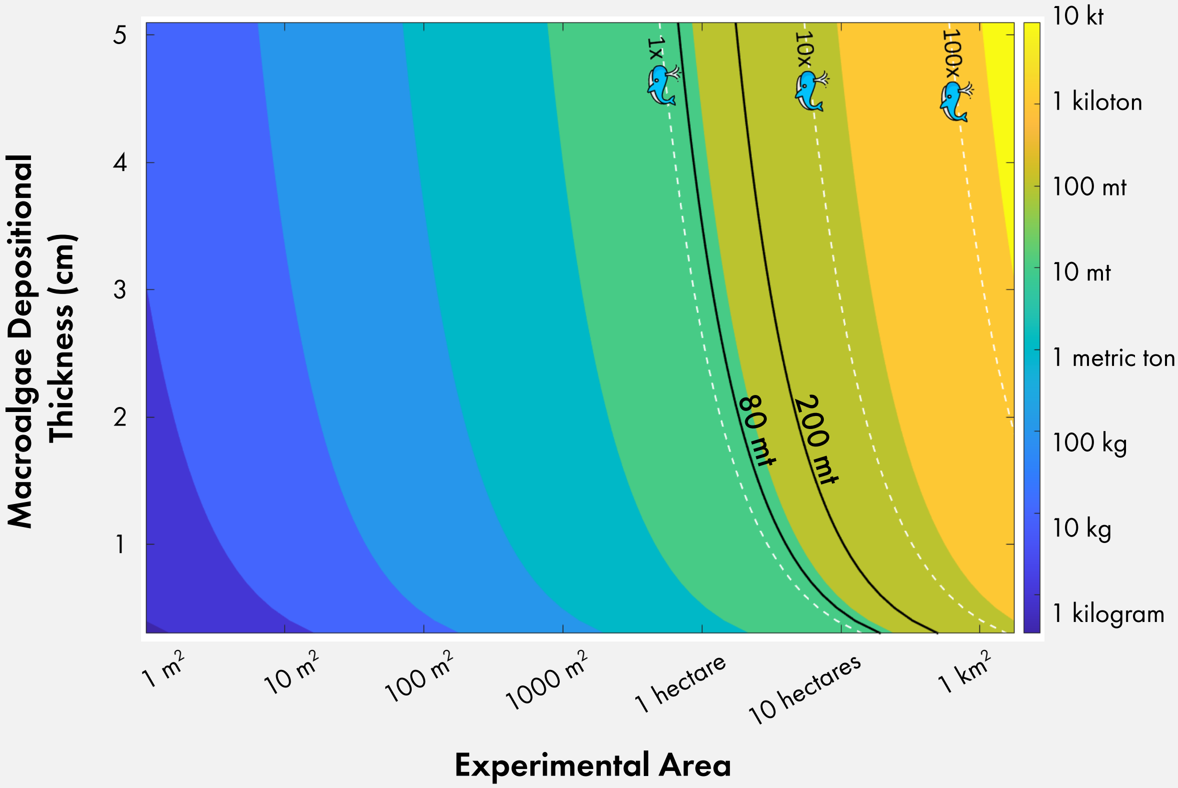
- Controlled field trials should incorporate multiple treatment levels (e.g., quantities and densities of seaweed sunk) to enable robust estimates of the direction and magnitude of ecosystem responses, which will best support subsequent numerical model studies of scaled-up operations.

Modeling Sinking of Macroalgae

We developed a simple model to illustrate the quantities of macroalgae necessary for controlled field trials, and how the quantity of macroalgae sunk might spread across an experimental area.

This model shows the tradeoff in areal extent and depositional thickness (uniform height of deposited macroalgae above the seafloor) for a given quantity of macroalgae sunk into the deep ocean. The x-axis and color are on logarithmic scales to consider a wide range in areal extents and quantities of macroalgae deposited.

To provide some context for the mass (wet) handling of seaweed needed for a controlled field trial, solid black isolines show the upper (200 metric tons) and lower (80 metric tons) bounds of expected annual yields from a one hectare farm cultivating *Macrocystis pyrifera*[30,31,32]. For further context, we also show the mass of 1, 10, and 100 whales as dashed white isolines (assuming that a whale has a mass of about 50 metric tons[33]). For example, a controlled field trial that aims for an area of 10 hectares with macroalgae deposited at an average thickness of one centimeter will require approximately 200 metric tons of seaweed, the upper bound on expected annual yield from a hectare-sized *M. pyrifera* farm.



Measurements Before, During, and After Controlled Field Trials

Overview

Measurements before, during, and after a controlled field trial should focus on understanding:

1. Fate of sunken seaweed and its associated carbon through various pathways (e.g., decomposition, conversion to dissolved organic matter)
2. Related responses of organisms spanning the range of microbes to megafauna
3. Biogeochemical effects of seaweed deposition on underlying sediments and in the overlying water column

Measurements of physical, chemical, and biological parameters in control and treatment areas will span a wide range of sensors, samplers, and observations. Current technological limits on the performance of sensors in deep sea environments (e.g., pH) may necessitate the use of discrete sampling. Use of imaging systems, such as those found on remotely operated vehicles, autonomous underwater vehicles, event-triggered camera systems, time-lapse camera systems, towed camera systems, and sediment profile imaging may be especially helpful to document ecological and biogeochemical responses to macroalgae deposition on and above the seafloor.

This report recommends that a control volume design[34] (used to quantify fluxes of materials across boundaries) would be informative for both treatment and control sites. This approach may provide more accurate estimates of biogeochemical and ecological responses than spot measurements alone. However, this report also recognizes that executing a control volume design in the deep sea may be difficult and, in some cases, not possible.

Recommendations Regarding Measurement Frequency and Duration

The density and frequency of measurements depends on a number of factors including access to vehicles for on-site operations (e.g., ships, ROVs), availability of sensors and platforms to maintain *in situ* sampling without human presence, and the pace and magnitude of environmental responses to seaweed deposition.

Controlling Factors for Sampling Frequency

- For measurements requiring onsite presence (e.g., ships, ROVs), observations should initially be frequent enough to monitor the emerging effects of seaweed deposition, followed by a decreasing frequency (e.g., 0.5, 1, 3, and 6 month intervals, annual thereafter). Changes in the observational frequency may be required after considering the pattern and rate of treatment effects identified from early results.
- For *in situ* sensors, including time-lapse camera: sampling frequency determined by battery capacity and maintenance schedule
- Spatial sampling in each treatment plot in a controlled field trial should extend radially outward from the experimental center to characterize the spatial extent of the experiment. Note: In trials where the experimental signal decays moving radially outward from the center of the experiment, regression-style analyses may be possible to quantify experimental effects in the absence of one or more dedicated control sites.

Factors Controlling Experimental Duration

The responses of faunal communities or seaweed driven changes in biogeochemistry of the seabed or bottom waters could be apparent within 2-5 years. Therefore, **recommended experimental durations are in the range of 2-5 years.** Variations in experimental design (e.g., pulse vs. continuous) might affect the emergence of actionable information from the experiment, with pulse designs anticipated to yield key experimental results sooner. Long-term monitoring of experimental sites after the conclusion of the experiments may be useful for gaining an understanding of any long-term effects to organisms and ecosystems but should not come at the expense of generating actionable information in the first several years of an experiment.

Key Recommended Measurements at Treatment and Control Sites

Site characterization

- Depth
- Bathymetry
- Substratum composition

Water Column Oceanographic and Biogeochemical Conditions

- Temperature
- Salinity
- Suspended sediment concentrations and turbidity
- Macronutrients
    - » Nitrate and nitrite
    - » Ammonia
    - » Phosphate
- Carbonate system parameters (at least two of the following four parameters)
    - » Dissolved inorganic carbon
    - » Total alkalinity
    - » pH
    - » pCO_2
        - – *Note that organic acid concentrations may become elevated in these experiments, and would need to be measured to complete carbonate system characterizations.*

- Dissolved oxygen
- Particulate organic carbon (total amount, elemental composition, and size distribution)
- Dissolved organic carbon
- Assays to measure major biogeochemical rate processes, including remineralization of organic matter and transformation of particulate organic matter into dissolved organic matter
  - » Natural abundance isotopes (e.g., ^{13}C, ^{15}N), and chemical biomarkers such as phenols and pigments may serve as useful tracers for tracking decomposition related to these biogeochemical reactions
- Three-dimensional, vertically resolved currents (i.e., as produced from an acoustic Doppler current profiler)

Benthic faunal abundance and diversity

- Infauna
- Epifauna
- Demersal and mesopelagic zooplankton
- Fish
- Strength and interactions of food webs, potentially tracked using stable isotopes
- Sediment cores to ascertain:
  - » Biogeochemical profiles
  - » Rate processes (e.g., methane production and consumption, nitrous oxide production and consumption)
  - » Microbial assemblages: abundance, diversity

Sites of Macroalgae Deposition Only

- Thickness of seaweed deposited on seafloor
- Areal extent
- Macroalgal composition (e.g., weight percent carbon)
- If deposited in bales or otherwise tightly packaged:
  - » Pore water chemistry (pH, dissolved oxygen, nutrients, sulfides, dissolved inorganic carbon, redox chemistry)
  - » Microbial activity (sulfate reduction rates, carbon dioxide production rates)
- Relative mass loss over time

Fail Safe: Stopping a Planned or In-Progress Field Trial

Key criteria for terminating a planned or in-progress field trial include, but are not limited to:

- Regulatory non-compliance
- Harm to protected species, sensitive or vulnerable marine ecosystems, or treaty-protected resources in the area
- Danger to the health and/or safety of the people conducting the field trial or to other stakeholders in the area of a field trial
- Disturbances (e.g., turbidity flows) that compromise the capacity to generate actionable information from the field trial
- Negative impacts to adjacent or compatible managed resources (e.g., development of a hypoxic zone affects nearby fishery)
- Other termination criteria jointly decided with local communities during field trial planning phases

If a controlled field trial is terminated before its completion, non-invasive monitoring of the site should continue if it can be done safely to maximize the acquisition of actionable information.

Guidance for Upper Ocean-Focused Controlled Field Trials to Assess Efficacy and Impacts of Large-Scale Macroalgae Cultivation

Cultivating macroalgae is a necessary requirement to sink macroalgae. While macroalgae cultivation has many diverse uses and potential pathways to contribute to ocean-based climate solutions beyond sinking (as described in the Introduction), a comprehensive evaluation of the sinking pathway must include an evaluation of the capacity for cultivated macroalgae to remove carbon dioxide from the atmosphere (for later sequestration in the deep ocean), as well as the biogeochemical and ecological impacts of large-scale cultivation. These information needs must be satisfied by controlled field trials because **controlled field trials are the only means to establish cause-effect relationships in real world, complex marine environments.**

Controlled field trials of macroalgae cultivation should take place in offshore (>50 meters deep) habitats to best reflect the likely move from coastal areas into offshore waters that would need to accompany macroalgae cultivation for climate-relevant (hundreds of megatons-to-gigaton) scales of cultivation and carbon sequestration.

Here we provide guidance on the design and execution of controlled field trials focused on the efficacy of carbon drawdown and environmental impacts of large-scale macroalgae cultivation in the upper ocean. Multiple controlled field trials, spanning different oceanographic regions and with multiple species will be necessary for developing a more complete understanding of the potentials and risks associated with cultivating macroalgae at large-scale in offshore habitats. The data resulting from these field trials should adhere to FAIR principles[iii] to ensure data transparency and reproducibility.

This report recommends that upper ocean field trials commence at the scale of a square kilometer or larger. While field trials at smaller spatial scales may be useful for improved scientific understanding, larger-scale trials are necessary for providing robust information about efficacy and impacts of macroalgae cultivation at scale. Regardless of the size of the field trial, they must inform how effects might integrate to regional-to-global scales if deployed at scale.

In this section of the report, guidance is categorized as "Key" and "Additional". Recommendations that are considered essential to the proper design of a controlled field trial are labeled "Key" and recommendations considered beneficial, but not essential, to the proper design of a controlled field trial are labeled "Additional". Within each section, information presented is not ranked by priority of importance.

iii https://www.go-fair.org/fair-principles/

Note: Controlled field trials to characterize and quantify upper ocean (here defined as the epipelagic zone) carbon dioxide uptake and environmental impacts may be conducted separately or jointly with controlled field trials focused on the fate and impacts of depositing macroalgae on the seafloor. If conducted jointly, sites would need to be in waters substantially deeper than 1,000 meters following the recommendations for benthic experiments in this report.

Location(s) for Field Trials

Key Site Considerations for an Experiment

The overarching consideration when selecting site(s) for field trials is that the sites should be as analogous in all ways possible to sites under consideration for full-scale deployments.

Oceanographic and Ecological Criteria

Sites for field trials should:

- Include regionally appropriate species (i.e. tropical species in tropical systems, temperate species in temperate systems).
- Have environmental conditions (e.g., ambient temperature, light, and nutrients) appropriate for the species of interest.
  - » Approaches that introduce nutrients (e.g., artificial upwelling or direct fertilization, are options in nutrient-depleted regions) may introduce biogeochemical or ecological consequences that could require further study or carbon accounting.
- Have oceanographic and meteorological conditions (e.g., waves, currents, winds) suitable for the macroalgae species under investigation and for ocean research. A low-energy environment will also make it easier to observe biogeochemical fluxes.
- Be in close proximity to suitable control sites. For gradient-monitoring experimental approaches, field trial sites should have sufficient space for optimal gradient sampling.

Social Criteria

- Adherence to appropriate permitting, regulation, and governance frameworks.
- Research teams work with local communities, including indigenous groups, and stakeholders (fishers, shippers, mariners, offshore industries) to:
  - » Identify sites and plan experiments
  - » Identify potential conflicts and develop conflict mitigation plans

Additional Site Considerations for an Experiment

Oceanographic and Ecological Criteria

- Co-locate upper ocean and benthic experiments to maximize efficient use of resources and potential for process-based understanding of cultivation and sinking in the same location (*If conducted jointly, sites would need to be in waters deeper than 1,000 meters following the recommendations for benthic experiments in this report)*
- Site(s) where an experiment can be conducted and monitored over an entire year, starting before the growing season and finishing after (where applicable)
- Proximity to, without interference in, long-term monitoring areas
- Sites that already have existing well-developed physical-biogeochemical models

Logistical Criterial

- Economically feasible distance from ports and/or logistics centers
- Sites with hazard buoys, AIS (automatic identification system) beacon, etc.

Locations to Avoid

- Major shipping lanes
- Centers of commercial fishing activity
- Heavily polluted areas or areas with low biological activity
- Systems with high potential for herbivory of cultivated macroalgae during the experiment
- Locations subject to ecological disturbance (e.g., harmful algal blooms) that may confound interpretation of experimental results
- Dominant migratory routes of marine mammals (e.g., whales)
- Major seabird feeding grounds
- Protected sites including marine protected areas, world heritage sites, culturally significant areas, treaty-protected resources, ecologically or biologically significant marine areas, sensitive or vulnerable marine ecosystems, marine protected areas, and other effective area-based conservation measures

Assessing Impacts of Macroalgae Cultivation in New Habitats on Upper Ocean Ecological and Biogeochemical Processes

General Measurement Guidance

- Measurements and samples from fixed moorings should be coupled with those from autonomous or remotely operated vehicles to provide higher spatial resolution observations between moorings.
- Where oceanographic conditions permit, control volume experimental designs that quantify all fluxes entering and exiting treatment and control sites are preferred.
- Measurements should be of sufficiently high spatial and temporal resolution to capture the ecological process of interest. For processes that occur quickly (e.g., phytoplankton growth), measurements may need to be made on sub-daily timescales. For processes that unfold over seasonal timescales (e.g., shifts in phytoplankton composition), daily-to-weekly or longer measurements may be sufficient.
- Data-assimilative models can also help fill in data gaps during experiments by providing reanalysis-style products that interpolate between observations in space and time.

Key Recommended Measurement at Treatment and Control Sites

Spatially (horizontally and vertically) and temporally resolved measurements should be made inside a seaweed cultivation experiment and in the corresponding control sites.

Oceanographic and Biogeochemical Conditions

- Water temperature
- Salinity
- Bio-optical properties including
  - Surface irradiance
  - Albedo
  - Vertical light attenuation
- Relevant oceanographic and meteorological variables including
  - Currents
  - Waves
  - Wind
  - Tides
- Marine carbonate system parameters
  - pH
  - pCO_2
  - Dissolved inorganic carbon
  - Total alkalinity
- Nutrient availability and ratios for major macronutrients including
  - Nitrate
  - Ammonia
  - Phosphate
  - Dissolved silica
- Nutrient availability and ratios for major micronutrients (e.g., iron)
- Dissolved oxygen concentrations and estimations of fluxes
- Particulate organic matter concentrations and fluxes (e.g., particulate organic matter to dissolved organic matter)

- Dissolved organic matter concentrations, fluxes, and characterization of labile and recalcitrant components
- Net primary production and net community production, as well as the contributions of both phytoplankton and macroalgae to these flux estimates

Ecosystem Impacts Measurements

- Phytoplankton
  - » Community composition
  - » Overall abundance
  - » Primary productivity rates
  - » Presence of harmful algal bloom-causing species
  - » Associated biomass proxies, such as chlorophyll a
- Microbial community composition
- Zooplankton composition and abundance across life histories
- Fish community abundance and diversity
- Large herbivores (e.g., sea turtles) abundance and behavior changes
- Changes in composition and/or abundance of macroalgae-associated fauna (e.g., epiphytes)
- Bird abundance, diversity, and behavior changes
- Marine mammal abundance, diversity, and behavior changes

Additional Measurement Needs

- Stable isotopic of major elements (carbon, nitrogen, sulfur) for tracking energy flow through food webs
- Production and fate of:
  - » Halogenated compounds (bromoform and other halomethanes)
  - » Dimethyl sulfide
  - » Methane, nitrous oxide, and other potentially hazardous gases produced by cultivated macroalgae

Measurement Approaches and Tools

- Aerial drones for localized air-side passive and active (e.g., LIDAR) remote sensing of the field experiment and control site(s).
- *In situ* imaging devices such as the Underwater Vision Profiler, imaging FlowCytobot, profiling cameras, and/or time lapse cameras
- Acoustic doppler profilers for measuring the hydrodynamics
- eDNA for community-level composition questions of biological species
- Optical sensors (backscatter, fluorescence)
- Nutrient sensors
- pCO2 and pH sensors
- CTD (conductivity, temperature, depth)
- Discrete surface water samples (e.g., using bottles)
- Satellite/micro-satellite observations

Quantifying Additional Uptake of Carbon Dioxide

Macroalgae cultivation in surface waters creates a localized deficit in carbon dioxide that can be replenished through uptake of carbon dioxide from the atmosphere. Quantifying the uptake of carbon dioxide in these field trials is critical to assessing the efficacy of macroalgae as a carbon dioxide removal strategy.

Key Measurements

- pCO_2 in the atmosphere
  - » Use drones for spatially resolved, near surface estimates
- Spatially-resolved pCO_2 in the surface water
  - » Consider profiling floats and/or unmanned surface vehicles (e.g., Saildrones), especially for large-scale experiments
- Spatially-resolved sea surface temperature and salinity
- Methods to appropriately model gas transfer velocities, including wind speeds (U_{10}), dissipation of turbulent kinetic energy, and/or tracer releases (e.g., ^3He / SF_6)
- Direct measurements of air/sea gas fluxes using eddy covariance and/or other technologies
- **Counterfactual estimates of air/sea exchange of carbon dioxide (what would have happened without a field experiment) from models validated with observational data and/or gas exchange rates measured at control site(s)**
- Primary production, and seaweed's contribution to primary production (to know the upper bound on the potential for additional uptake of atmospheric carbon dioxide)
- Effects of macroalgal production on surface phytoplankton and zooplankton communities to understand synergistic or antagonistic effects of macroalgae cultivation on surface ocean pCO_2

Key Expected Outputs

- Spatially resolved, and spatially integrated, estimates of air/sea carbon dioxide exchange in the vicinity of a field experiment along with associated uncertainty
- Relationship between experimental variables (seawater pCO_2 anomalies, gas transfer velocities, etc.) and uncertainty in air/sea gas flux that can answer:
  - » What are the set(s) of conditions that lead to more (or less) reliable air/sea gas flux estimates?
  - » When do the estimates of gas flux rise above the measurement uncertainty?

Estimating the Cost of a Research Program

The Cost of a Field Trial

The cost for a single controlled field trial to study the efficacy of carbon sequestration and associated environmental impacts of sinking macroalgae to the deep sea depends on the size and duration of the experiment. Factors dictating the cost include (but are not limited to):

- The size of the controlled field trial
- The number of treatment sites and control sites
- The duration of the experiment
- The duration, frequency, and intensity of monitoring before, during, and after the experiment
- The operating costs for research vessels, remotely operated vehicles, and other scientific instrumentation
- Cultivation or acquisition costs of macroalgae
- Labor costs

To demonstrate how cost varies with the scale of the experiment, we have modeled costs for an example small (one hectare), medium (10 hectares), and large field trial (one square kilometer). Modeled costs for the small, medium, and large field trials were $17 million, $47 million, and $105 million USD, respectively. Details of these examples are available in the Appendix.

Note that these costs estimates do not consider any fees necessary to obtain applicable permits to conduct the research.

From Field Trials to a Global Research Program

This report recommends approximately **10** controlled field trials, spanning **three** to **five** different locations, and using between **one** and **five** macroalgae species, are necessary for a well-developed global research program that permits assessments of the efficacy and impacts of both growing and sinking macroalgae across a range of oceanographic, ecological, and biogeochemical factors. The majority of these field trials should be at larger scales (~one square kilometer), while several medium (10 hectares) and small (one hectare) field trials will also be necessary to build an empirical understanding of the scale-dependence for key questions about efficacy of carbon sequestration and environmental impacts.

Given the lack of purposeful experiments into macroalgae sinking as a carbon dioxide removal strategy, it is impossible to *a priori* know exactly how many field trials will be needed to validate or invalidate the various hypotheses articulated in this report. Instead, this assessment of the number of experiments and diversity of macroalgal taxa should be considered as the collective assessment by the group of experts who contributed to this report.

Collectively, this report recommends that a global research effort to conduct the field trials necessary to make informed assessments about the efficacy and impacts of sinking macroalgae as a strategy for carbon dioxide removal would likely cost **approximately $1 billion USD in total**. These costs can be shared by the global set of funders, and need not be the responsibility of any one single funding entity. The budget would include more than five large field trials at the scale of $100 million USD each, along with a set of accompanying medium and small field trials. This budget projection is subject to uncertainty in the range of ±10-20% that reflects the many decisions that would go into designing each field trial, and the cost implications of those decisions. This report recommends a more ambition research budget than the $385 million USD over five-to-ten years called for in the National Academies of Science, Engineering, and Medicine (NASEM) report[10], a difference that can be attributed to the recommend number of field trials. This report calls for multiple field trials of macroalgae cultivation and sequestration in the deep sea to characterize the range of expected outcomes, in contrast to NASEM's call for a single "demonstration-scale seaweed cultivation and sequestration system".

Budgeting Tool

Our cost estimates were developed using a custom-made budgeting tool. We are releasing a budget planning tool alongside this report, intended to help individuals allocating resources for field experiments and individuals planning to conduct field trials. It provides detailed information about the cost drivers of controlled field trials. Interested users can explore various scenarios of field trials, examine budget assumptions, review budget relationships (formulas in the model), and even modify for their specific needs.

Note: Given the number of decision variables and parameters required for the user, baseline cost estimates using this tool may be coarse, especially for larger experiments.

Relevant Oceanographic Resources to Support Controlled Field Trials

This section of the report provides a non-exhaustive list of oceanographic assets to support the design and execution of controlled field trials. The list of assets in this table should be considered a starting point for the assets developed and maintained by the global oceanographic community. Expanded engagement with the global community of interested researchers, engineers, and technologists will continue to expand the set of assets available to support controlled field trials.

Asset Class	Examples
Research Vessel	Japan Agency for Marine-Earth Science and Technology Fleet
	University-National Oceanographic Laboratory System Fleet
	E/V Nautilus
	R/V Thomas G. Thompson
	Rachel Carson
	David Packard
	R/V Falkor (TOO)
	Alfred Wegener Institute Fleet
ROV (Remotely Operated Vehicle)	Seaeye Falcon
	Ventana
	Jason
	Medea
	Hercules
	Doc Ricketts
AUV (Autonomous Underwater Vehicle)	Mesobot
	Sentry
	Orpheus
Sensor	Argo Fleet
	BIOMAPPER – II (The BIo-Optical Multi-frequency Acoustical and Physical Environmental Recorder)
	IMET (Improved Meteorological Packages)
	Sediment Profile Imaging
	Instrument Development Group
Camera	TowCam (Towed Camera System)
Cabled Observatory	Ocean Observatories Initiative
	MARS (Monterey Accelerated Research System)
	NEPTUNE (North East Pacific Time-series Undersea Networked Experiments)
Non-cabled Observatory	EMSO-Azores (European Multidisciplinary Seafloor and water column Observatory)
	Integrated Ocean Observing System

Pilot Projects

A small number of macroalgae sinking small-scale pilot projects have already commenced. Projects are listed here along with primary points of contact. This list is not intended to be exhaustive of all sinking trials taking place globally, but reflects the most up-to-date knowledge from the report's authors. Points of contact for each project are listed in order to facilitate communication and sharing of lessons learned for future field trials.

Institution	Point of Contact	Location	Project Status	Notes
Fearless Fund	Alyson Myers (alysonmyers1@gmail.com)	North Atlantic Ocean	Ongoing	Kilogram-scale *Sargassum* sinking experiments
Climate Foundation	Brian von Herzen (brian@climatefoundation.org)	Camotes Sea, Philippine archipelago	Ongoing	Measurement of seaweed detrital flux falling from deep-water platforms during growth and sinking quickly to deep seafloor. Currently at approximately one ton with plans to ramp up.
Running Tide Technologies	Max Chalfin (max@runningtide.com)	Akranes, Iceland	In preparation	Ocean transport platform pilot experiment with prototype scale macroalgae seeding
Seafields	Richard Wills (richard.wills@seafields.eco) Franziska Elmer (franziska.elmer@seafields.eco)	Atlantic abyssal plain	In preparation (Tentative deployment November 2022)	~30 bales of Sargassum, one cubic meter each
Oceanwise / Ocean Networks Canada	Andrew Wong (Andrew.LangWong@ocean.org)	Barkley Canyon Node and Barkley Canyon Mid-east, NE Pacific	Not yet started	Kilogram-scale sinking experiments
University of California Santa Barbara	David Siegel (david.siegel@ucsb.edu)	Southern California Bight	Initiated July 2022	Ton-scale sinking experiments planned
National Institute of Water and Atmospheric Research (NIWA; New Zealand)	Scott Nodder (Scott.Nodder@niwa.co.nz)	Kaikoura and Cook Strait canyon systems, New Zealand	Ongoing	Studying natural deep-sea burial of macroalgae from natural macroalgae beds

Appendix: Cost Estimates of Controlled Field Trial Scenarios

Experiment 1: Small-scale ($17 million USD)

Experimental Details

Areal extent: One hectare (10,000 m^2)

Replicates: Three treatment sites and three control sites

Duration of Field Trial: Three years

Thickness of macroalgae on seafloor: Average thickness of 1 cm spread across the study site

Frequency of macroalgae deposition: Two times per year in year 1 only

Monitoring setup:

- Oceanographic moorings with sediment traps & profiling sensor packages located at each treatment and control sites
- Seafloor platforms deployed at each site equipped with various sensors and samplers
- Remotely-operated vehicle sampling plans for benthic surveys and sampling for each site

Monitoring Frequency: Three monitoring/sampling visits in the first year followed by one monitoring/sampling visit per year in the two following years.

Comments:

This is a relatively small macroalgal sinking experiment compared to the scale required for significant climate mitigation. The major expense estimates are for salaries ($7.5 million USD), ship use ($4 million USD), instruments and other hardware ($4.4 million USD). Of 92 ship-days estimated for the entire experiment, 28 are required for seaweed deployment.

Supporting budget tables for Experiment 1

Experimental Details	Number	Units	Comment
Seaweed plot area	10,000	square meters	Defines the size of the experiment
Seaweed thickness	1	cm	
Number of treatment sites	3	sites (=replicates)	
Number of control sites	3	sites	
Pulse or Continuous seaweed application?	Continuous	treatment	Pull down menu (click on cell to show pull-down)
Frequency of Continuous Applications (#/year; 0 if "Pulse")	2	#/year	How many seaweed applications per year if "Continuous" is selected above
Duration of Continous Applications (years)	1	years	Only used for "continuous"—how many years will seaweed application continue?
Experiment Duration (years)	3	years	Total length of experiment
Frequency of Monitoring year 1	3	#/year	Number of visits to site during year 1
Frequency of Monitoring year 2+	1	#/year	Number of visits to site during year 2+
Continency Fund percentage	1	Percentage	What percent of the project cost subtotal should be added for contingencies?

Ship Days	92	days
Ship / ROV Costs	$4.0	$M
Seaweed	$0.2	$M
Instruments & Moorings	$4.4	$M
Analyses	$0.9	$M
Labor	$7.5	$M
Project Subtotal Cost	**$16.9**	**$M**
Contingency fund	$0.08	$M
Total Project Cost	**$17.0**	**$M**

SUMMARY	Year 1	Year 2	Year 3	Year 4	Year 5	Experiment Total	
Cost ($ Millions)	**10.3**	**3.4**	**3.4**	**0.0**	**0.0**	**Grand Total ($M)**	**17.0**
Total Seaweed Mass req. (tonnes wet)	203	0	0	0	0	metric tonnes	203
Seaweed Cost ($K)	$203K	$0K	$0K	$0K	$0K	$K	$203K
Packaging cost ($K)	$20K	$0K	$0K	$0K	$0K	$K	$20K
Total Seaweed Cost ($K)	**$223K**	**$0K**	**$0K**	**$0K**	**$0K**		**$223K**
Ship days for seaweed transport	3	0	0	0	0		3.0
Shipdays for seaweed application	25.0	0.0	0.0	0.0	0.0		25.0
Total seaweed deployment ship days	**28.0**	**0.0**	**0.0**	**0.0**	**0.0**	**days**	**28.0**
Instrument Deployment and Sampling							
Number of Sites (Treat + Control)	6	6	6	6	6	30.0	
Number of Visits per year	3	1	1	0	0	5.0	
Number of Site visited for moorings, rov per year	18	6	6	0	0	30.0	
Ship Days for Mooring activities	**6**	**6**	**6**	**0**	**0**	**days**	**18.0**
ROV Sampling							
Ship days for ROV monitoring	18.0	6.0	6.0	0.0	0.0	days	30.0
Ship days for ROV inst deployment / recovery	18.0	6.0	6.0	0.0	0.0	days	30.0
Ship Transit days	6	2	2	0	0	10.0	
Comination factor (1 to 2)	1	1	1	1	1	days	
Ship Days for ROV Activities	**24**	**8**	**8**	**0**	**0**	**days**	**40**
Total Ship days (seaweed + sampling)	**60**	**16**	**16**	**0**	**0**	**days**	**92**
Ship Costs							
Ship Costs per year (no ROV)	$1,400K	$280K	$280K	$0K	$0K	$K	$1,960K
Ship Costs per year (with ROV)	$1,199K	$400K	$400K	$0K	$0K	$K	$1,998K
Ship Costs by year	**$2,599K**	**$680K**	**$680K**	**$0K**	**$0K**	**$K**	**$3,958K**
Instrument Cost (all sites)	**$4,383K**	**$0K**	**$0K**	**$0K**	**$0K**	**$K**	**$4,383K**
Sample Analysis Costs/y	**$531K**	**$177K**	**$177K**	**$0K**	**$0K**	**$K**	**$885K**
Continency funds	**$51.1K**	**$16.8K**	**$16.8K**	**$0.0K**	**$0.0K**	**$K**	**$85K**
Labor							
Total Salaries	**$2,494K**	**$2,494K**	**$2,494K**	**$0K**	**$0K**	**$K**	**$7,481K**

Experiment 2: Medium-scale ($47 million USD)

Experimental Details

Areal extent: 10 hectares (100,000 m^2)

Replicates: Three treatment sites and three control sites

Duration of Field Trial: Four years

Thickness of macroalgae on seafloor: Average thickness of 1 cm spread across the study site

Frequency of macroalgae deposition: Once per year during years 1 and 2

Monitoring setup:

- Oceanographic moorings with sediment traps & profiling sensor packages located at each treatment and control sites
- Seafloor platforms deployed at each site equipped with various sensors and samplers
- Remotely-operated vehicle sampling plans for benthic surveys and sampling for each site

Monitoring Frequency: Three monitoring/sampling visits during year 1, followed by monitoring once per year for three years.

Comments:

This moderate sized experiment would require 6000 cubic meters of seaweed (2028 metric tons wet weight) applied over two years. Seaweed deployment alone would use ~100 ship-days for each year of macroalgal application. The major expense estimates are for salaries ($17 million USD) and ship use ($21 million USD).

Supporting budget tables for Experiment 2

Experimental Details	Number	Units	Comment
Seaweed plot area	100,000	square meters	Defines the size of the experiment
Seaweed thickness	1	cm	
Number of treatment sites	3	sites (=replicates)	
Number of control sites	3	sites	
Pulse or Continuous seaweed application?	Continuous	treatment	Pull down menu (click on cell to show pull-down)
Frequency of Continuous Applications (#/year; 0 if "Pulse")	1	#/year	How many seaweed applications per year if "Continuous" is selected above
Duration of Continous Applications (years)	2	years	Only used for "continuous"—how many years will seaweed application continue?
Experiment Duration (years)	4	years	Total length of experiment
Frequency of Monitoring year 1	3	#/year	Number of visits to site during year 1
Frequency of Monitoring year 2+	1	#/year	Number of visits to site during year 2+
Continency Fund percentage	1	Percentage	What percent of the project cost subtotal should be added for contingencies?

Ship Days	504	days
Ship / ROV Costs	$21.7	$M
Seaweed	$2.2	$M
Instruments & Moorings	$4.4	$M
Analyses	$1.1	$M
Labor	$17.4	$M
Project Subtotal Cost	**$46.8**	**$M**
Contingency fund	$0.23	$M
Total Project Cost	**$47.1**	**$M**

SUMMARY	Year 1	Year 2	Year 3	Year 4	Year 5	Experiment Total	
Cost ($ Millions)	**21.2**	**11.8**	**7.0**	**7.0**	**0.0**	**Grand Total ($M)**	**47.1**
Total Seaweed Mass req. (tonnes wet)	1,014	1,014	0	0	0	metric tonnes	2,029
Seaweed Cost ($K)	$1,014K	$1,014K	$0K	$0K	$0K	$K	$2,029K
Packaging cost ($K)	$101K	$101K	$0K	$0K	$0K	$K	$203K
Total Seaweed Cost ($K)	**$1,116K**	**$1,116K**	**$0K**	**$0K**	**$0K**		**$2,232K**
Ship days for seaweed transport	1.5	1.5	0	0	0		3.0
Shipdays for seaweed application	103.0	102.5	0.0	0.0	0.0		205.5
Total seaweed deployment ship days	**104.5**	**104.0**	**0.0**	**0.0**	**0.0**	**days**	**208.5**
Instrument Deployment and Sampling							
Number of Sites (Treat + Control)	6	6	6	6	6		30.0
Number of Visits per year	3	1	1	1	0		6.0
Number of Site visited for moorings, rov per year	18	6	6	6	0		36.0
Ship Days for Mooring activities	**6**	**6**	**6**	**6**	**0**	**days**	**24.0**
ROV Sampling							
Ship days for ROV monitoring	180.0	60.0	60.0	60.0	0.0	days	360.0
Ship days for ROV inst deployment / recovery	18.0	6.0	6.0	6.0	0.0	days	36.0
Ship Transit days	6	2	2	2	0		12.0
Comination factor (1 to 2)	1	1	1	1	1	days	
Ship Days for ROV Activities	**132**	**44**	**44**	**44**	**0**	**days**	**264**
Total Ship days (seaweed + sampling)	**244**	**156**	**52**	**52**	**0**	**days**	**504**
Ship Costs							
Ship Costs per year (no ROV)	$4,078K	$3,920K	$280K	$280K	$0K	$K	$8,558K
Ship Costs per year (with ROV)	$6,593K	$2,198K	$2,198K	$2,198K	$0K	$K	$13,187K
Ship Costs by year	**$10,671K**	**$6,118K**	**$2,478K**	**$2,478K**	**$0K**	**$K**	**$21,744K**
Instrument Cost (all sites)	**$4,383K**	**$0K**	**$0K**	**$0K**	**$0K**	**$K**	**$4,383K**
Sample Analysis Costs/y	**$531K**	**$177K**	**$177K**	**$177K**	**$0K**	**$K**	**$1,062K**
Continency funds	**$105.3K**	**$58.8K**	**$35.0K**	**$35.0K**	**$0.0K**	**$K**	**$234K**
Labor							
Total Salaries	**$4,350K**	**$4,350K**	**$4,350K**	**$4,350K**	**$0K**	**$K**	**$17,400K**

Experiment 3: Large-scale ($105 million USD)

Experimental Details

Areal extent: One square kilometer (1,000,000 m^2)

Replicates: One treatment site and one control site

Duration of Field Trial: Five years

Thickness of macroalgae on seafloor: Average thickness of 1 cm spread across the study site

Frequency of macroalgae deposition: Once per year during years 1 and 2

Monitoring setup:

- Oceanographic moorings with sediment traps & profiling sensor packages located at each treatment and control sites
- Seafloor platforms deployed at each site equipped with various sensors and samplers
- Remotely-operated vehicle sampling plans for benthic surveys and sampling for each site

Monitoring Frequency: Three monitoring/sampling visits in the first year followed by one monitoring/sampling visit per year in the four subsequent years.

Comments:

Experiment 3 is a large-scale experiment that would be a significant undertaking and would represent a fairly large carbon removal action in itself (>160 metric tons C sunken as macroalgae). It would require the cultivation or procurement of over 6,600 metric tons of macroalgae (wet weight). A small fleet of ships would be required for macroalgae transport and deployment (~339 ship days per year in years 1, 2 for seaweed deployment alone). Ship support is by far the major expense ($72 million USD), followed by labor (~$23 million USD).

There are many uncertainties in estimates concerning components of the total experimental costs. Particularly for larger experiments (e.g., Experiments 2 and 3), cultivation or otherwise procuring macroalgae to support the sequestration study will require considerable planning that is beyond the scope of this budget tool (which only uses a cost per ton as an estimate). Ship-time required for harvesting and transporting macroalgae may also have large uncertainty. Labor required for Experiments 1, 2, and 3 was increased with the scale of each experiment but will require closer consideration in relation to the activities planned (e.g., the scope and detail of biological or oceanographic sampling) to develop labor estimates with high confidence.

Supporting budget tables for Experiment 3

Experimental Details	Number	Units	Comment
Seaweed plot area	1,000,000	square meters	Defines the size of the experiment
Seaweed thickness	1	cm	
Number of treatment sites	1	sites (=replicates)	
Number of control sites	1	sites	
Pulse or Continuous seaweed application?	Continuous	treatment	Pull down menu (click on cell to show pull-down)
Frequency of Continuous Applications (#/year; 0 if "Pulse")	1	#/year	How many seaweed applications per year if "Continuous" is selected above
Duration of Continous Applications (years)	2	years	Only used for "continuous"—how many years will seaweed application continue?
Experiment Duration (years)	5	years	Total length of experiment
Frequency of Monitoring year 1	3	#/year	Number of visits to site during year 1
Frequency of Monitoring year 2+	1	#/year	Number of visits to site during year 2+
Continency Fund percentage	1	Percentage	What percent of the project cost subtotal should be added for contingencies?

Ship Days	92	days
Ship / ROV Costs	$71.7	$M
Seaweed	$7.4	$M
Instruments & Moorings	$1.5	$M
Analyses	$0.4	$M
Labor	$23.6	$M
Project Subtotal Cost	**$104.7**	**$M**
Contingency fund	$0.52	$M
Total Project Cost	**$105.2**	**$M**

SUMMARY	Year 1	Year 2	Year 3	Year 4	Year 5	Experiment Total	
Cost ($ Millions)	**42.7**	**27.4**	**11.7**	**11.7**	**11.7**	**Grand Total ($M)**	**105.2**
Total Seaweed Mass req. (tonnes wet)	3,381	3,381	0	0	0	metric tonnes	6,763
Seaweed Cost ($K)	$3,381K	$3,381K	$0K	$0K	$0K	$K	$6,763K
Packaging cost ($K)	$338K	$338K	$0K	$0K	$0K	$K	$676K
Total Seaweed Cost ($K)	**$3,720K**	**$3,720K**	**$0K**	**$0K**	**$0K**		**$7,439K**
Ship days for seaweed transport	0.5	0.5	0	0	0		1.0
Shipdays for seaweed application	340.0	339.5	0.0	0.0	0.0		679.5
Total seaweed deployment ship days	**340.5**	**340.0**	**0.0**	**0.0**	**0.0**	**days**	**680.5**
Instrument Deployment and Sampling							
Number of Sites (Treat + Control)	2	2	2	2	2		10.0
Number of Visits per year	3	1	1	1	1		7.0
Number of Site visited for moorings, rov per year	6	2	2	2	2		14.0
Ship Days for Mooring activities	**2**	**2**	**2**	**2**	**2**	**days**	**10.0**
ROV Sampling							
Ship days for ROV monitoring	600.0	200.0	200.0	200.0	200.0	days	1400.0
Ship days for ROV inst deployment / recovery	6.0	2.0	2.0	2.0	2.0	days	14.0
Ship Transit days	6	2	2	2	2		14.0
Comination factor (1 to 2)	1	1	1	1	1	days	
Ship Days for ROV Activities	**404**	**135**	**135**	**135**	**135**	**days**	**942**
Total Ship days (seaweed + sampling)	**748**	**479**	**139**	**139**	**139**	**days**	**1642**
Ship Costs							
Ship Costs by year	**$32,377K**	**$18,767K**	**$6,867K**	**$6,867K**	**$6,867K**	**$K**	**$71,744K**
Instrument Cost (all sites)	**$1,484K**	**$0K**	**$0K**	**$0K**	**$0K**	**$K**	**$1,484K**
Sample Analysis Costs/y	**$177K**	**$59K**	**$59K**	**$59K**	**$59K**	**$K**	**$413K**
Continency funds	**$212.4K**	**$136.4K**	**$58.3K**	**$58.3K**	**$58.3K**	**$K**	**$524K**
Labor							
Total Salaries	**$4,725K**	**$4,725K**	**$4,725K**	**$4,725K**	**$4,725K**	**$K**	**$23,625K**

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