OCEAN IRON FERTILIZATION

Assessing its potential as a climate solution

EXOIS
EXPLORING OCEAN IRON SOLUTIONS

Ocean iron fertilization: assessing its potential as a climate solution

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Cover image courtacy of NASA Ocean Ecology

ACRONYM TABLE (those used in more than one paragraph)

BCP	biological carbon pump
C	carbon (can be in many forms—inorganic, organic, dissolved, particulate)
CDR	carbon dioxide removal
CO_2	carbon dioxide
Fe	iron
GHG	greenhouse gasses
Gt	gigaton, or one billion metric tons
MRV	monitoring, reporting, and verification, used here to include not only C tracking but MRV of ecological and non-C impacts
OIF	ocean iron fertilization
OSSE	Observing System Simulation Experiment

EXECUTIVE SUMMARY

The continued warming of the Earth is pushing many ecosystems and components of the climate system beyond their tipping points, resulting in irreversible damages to our planet as we know it. To stem the tide, we need to aggressively shift away from our fossil fuel-based economies and actively pursue methods of removing existing carbon dioxide from the atmosphere. Only with this combined approach can we limit global warming to within 2ºC and attempt to roll back the effects of our unintended geoengineering of the planet from centuries of fossil fuel dependence.

The ocean has an enormous capacity for storing carbon and already takes up about one-third of the carbon dioxide released by human activities. In parts of the ocean where biological activity is limited by a lack of iron in seawater, adding iron could help spur phytoplankton growth and increase both the ocean's uptake of atmospheric carbon dioxide and the amount of carbon that gets sequestered at depth.

Tens of gigatons per year of carbon dioxide need to be removed from the atmosphere in the coming decades and no single carbon dioxide removal (CDR) approach is likely to reach that capacity. But adding iron to the ocean may be a responsible and effective way to make a significant contribution. Analyses of natural and deliberate ocean iron fertilization (OIF) field experiments have suggested that large-scale OIF could potentially remove gigatons of atmospheric carbon dioxide per year. However, experiments to date were not designed to, nor can they, adequately quantify how effective, durable, or wise iron addition may be as a CDR approach.

We need new, deliberate research led by international scientific collaborations to provide the greatest possible insight into both the intended and unintended consequences, as well as the long-term effectiveness, of adding iron to the ocean. Any ocean CDR must be done following an ethical path and with guidelines and a governance framework that protect the environment (including the ocean commons), advance equitable and just outcomes, and appropriately account for other social dimensions. The consequences of OIF must be weighed against other climate intervention approaches and the broad spectrum of harmful impacts brought on by human-induced climate change.

EXploring Ocean Iron Solutions (ExOIS; http://oceaniron.org) is a consortium of scientists who came together in early 2022 to share ideas and move ahead on studies to consider OIF as one way to address our climate crisis. We follow five guiding principles that: 1) prioritize activities for the collective benefit of humans and the environment; 2) establish clear lines of responsibility; 3) commit to open and cooperative research; 4) assess results in an open, iterative and independent manner; and 5) engage the public in consideration of CDR options.

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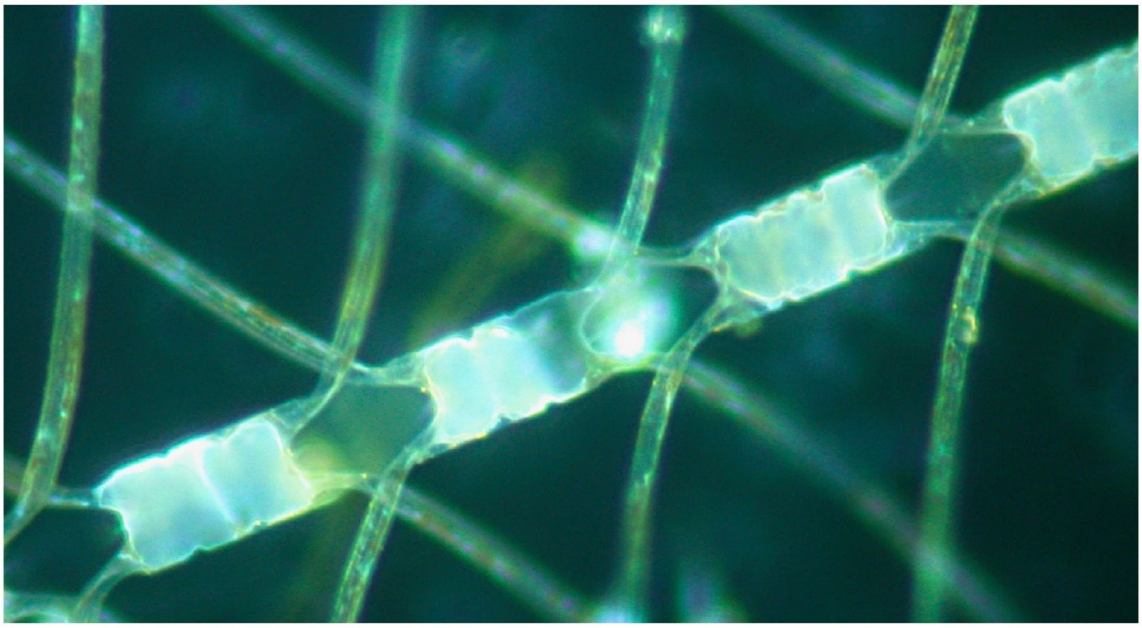

Photo of a diatiom, *Chaetoceros sp.*, that commonly respond to iron additions. Credit. M. W. Silver

Together, we have laid out the needs and priorities required for a comprehensive assessment of OIF for ocean CDR. The research and development activities include planning and executing large lab, field, and modeling studies over a period of five to seven years, assessing public acceptance and improving public understanding of ocean CDR and OIF in particular, advancing development and adoption of international governance structures for open ocean field studies and large-scale CDR efforts, and providing training opportunities for future scientists, engineers, and policy experts.

This transformative R&D program would result in a detailed understanding of OIF as a CDR approach, including whether it is scalable and reproducible, has known deployment costs that can be transparent and accurate in terms of carbon accounting, and has known and acceptable ecological consequences. It would help to build a governance framework and clearly establish a set of responsibilities for large-scale deployment efforts.

No single institution or country can accomplish all of these scientific goals. Moving ahead with a coordinated OIF research program will require philanthropic, corporate, and private sources of funding support, along with national and international partnerships. But with the growing investment in commercial CDR markets, interest in ocean CDR is increasing rapidly. We have the opportunity to invest in the knowledge necessary to ensure that we can make scientifically and ethically sound decisions for the future of our planet.

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1 OVERVIEW

The continuing warming of the Earth is pushing many ecosystems and components of the climate system (ice sheets, coral reefs, etc.) beyond their tipping points, resulting in irreversible damages to our planet as we know it [1]. To stem the tide, agreements aimed at limiting global warming to within 2ºC [2] need both climate mitigation (emissions reduction) and intervention (carbon dioxide removal) in order to achieve "net negative emissions" [3, 4] [Fig. 1]. All options to remove carbon dioxide from the atmosphere need to be considered, as we simultaneously and aggressively shift away from our fossil fuel-based economies and attempt to roll back the effects of our unintended geoengineering of the planet from centuries of dependence on fossil fuel energy.

Several ocean-based carbon dioxide removal (CDR) approaches have been proposed given the ocean's huge storage capacity for carbon, containing more than 50 times the carbon found in the atmosphere and 15-20 times more than is found in all land plants and soils. With this capacity comes the ability to naturally take up carbon dioxide. In fact, the oceans already take up about one-third of the carbon dioxide released by human activities [5].

Enhancing the ocean's natural biological carbon pump may be one responsible and effective way to help control increases in atmospheric carbon dioxide. We are encouraged by analyses of natural and deliberate ocean iron fertilization (OIF) field experiments conducted in regions high in the major nutrients, such as nitrogen and phosphorus, but low in iron [6-8]. These studies have suggested potentially high global capacity of OIF, up to gigatons (Gt) of CO_2 per year, and even higher if a wider range of settings are considered [9]. There is no single solution for CDR, as 10's of Gt's per year of CO_2 need to be removed in the coming decades, but OIF may be able to make a significant contribution.

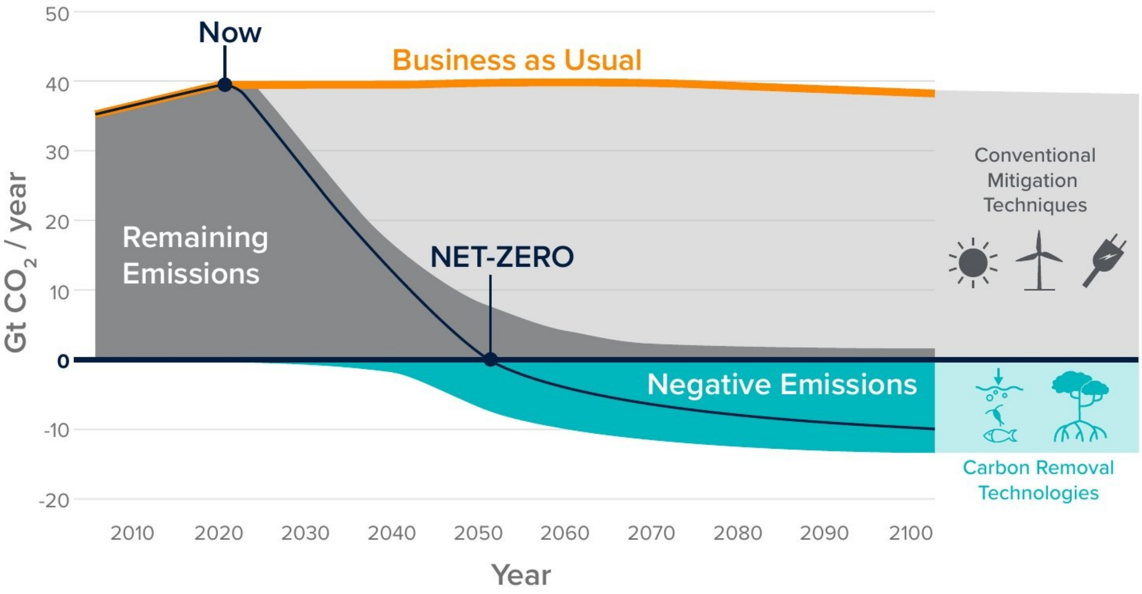

Figure 1. Projected CO_2 emissions and combined reductions in emissions and CDR needed to keep warming below 1.5° C targets. Adapted World Resources Institute from IPCC reports.

We need to advance the development and adoption of international governance structures that permit scientific field studies in the open ocean in the short term, ensuring they occur in a safe, responsible, and scientifically sound manner.

However, many questions and uncertainties remain about the efficiencies and permanence of enhanced carbon sequestration, its ecological consequences, and whether OIF is a practical approach to provide quantifiable climatic benefits [8, 10]. There is ample evidence that changes in ocean iron levels have had a major role in altering earth's paleoclimate, so what is being considered here is whether the deliberate use of OIF is an acceptable approach to speed up natural processes that cool the planet.

Any ocean CDR approach must meet the challenges for monitoring, reporting, and verification (MRV) of its effectiveness and durability [9]. And all ocean CDR approaches must be done following an ethical path and with guidelines and a governance framework that protect the environment (including the ocean commons), advance equitable and just outcomes, and appropriately account for other social dimensions of ocean CDR. Science needs to lead the way through international collaborations by providing the greatest possible insight into both the intended and unintended consequences, as well as the long-term effectiveness of adding iron to the ocean.

This document is designed to lay out the needs and priorities for research and development required for a comprehensive assessment of OIF for ocean CDR. The activities include those leading up to and completing large international field and modeling studies over a period of 5-7 years. The research needs and priorities go beyond just an understanding of the natural science and engineering aspects of OIF. Activities need to include programs to assess public acceptance and improve public understanding of ocean CDR in general and OIF in particular. In addition, we need to advance the development and adoption of international governance structures that permit scientific field studies in the open ocean in the short term, ensuring they occur in a safe, responsible, and scientifically sound manner, while looking ahead at governance of CDR in general if deployed at climatically relevant scales.

2

MOVING FORWARD WITH OCEAN IRON FERTILIZATION

OIF has been proposed for ocean CDR in several key parts of the ocean, where biological activity is limited by a lack of iron in seawater [11, 12]. Adding iron could, therefore, help spur growth of phytoplankton and increase both the uptake of atmospheric carbon dioxide by the ocean and the amount of C that gets sequestered at depth [Fig. 2]. There is ample evidence that adding iron increases phytoplankton growth in some regions of the ocean [7, 8], but experiments to date were not designed to, nor can they, adequately quantify how effective or wise iron addition may be as a CDR approach [9].

Moving ahead requires deliberate field studies that are both guided by and inform mechanistic models to demonstrate the efficacy and potential risks of OIF at scale. Philanthropic, corporate, and private sources of funding are needed for support, along with national and international partnerships. Existing support would be leveraged into an investment reaching \$50-100 M/yr, a scale too large and ambitious to be launched by a single traditional funding mechanism.

We will follow five guiding principles for ocean CDR that: 1) prioritize activities for the collective benefit of humans and the environment; 2) establish clear lines of responsibility; 3) commit to open and cooperative research; 4) assess results in an open, iterative and independent manner; and 5) engage the public in consideration of CDR options. The consequences of OIF must be weighed against other climate intervention approaches and the broad spectrum of harmful impacts brought on by human-induced climate change.

The end result of this transformative R&D program would include a comprehensive assessment of OIF as an ocean CDR approach and whether it is scalable and reproducible, has known deployment costs that can be transparent and accurate in terms of carbon accounting, and has known and acceptable ecological consequences with a governance framework and set of responsibilities clearly established.

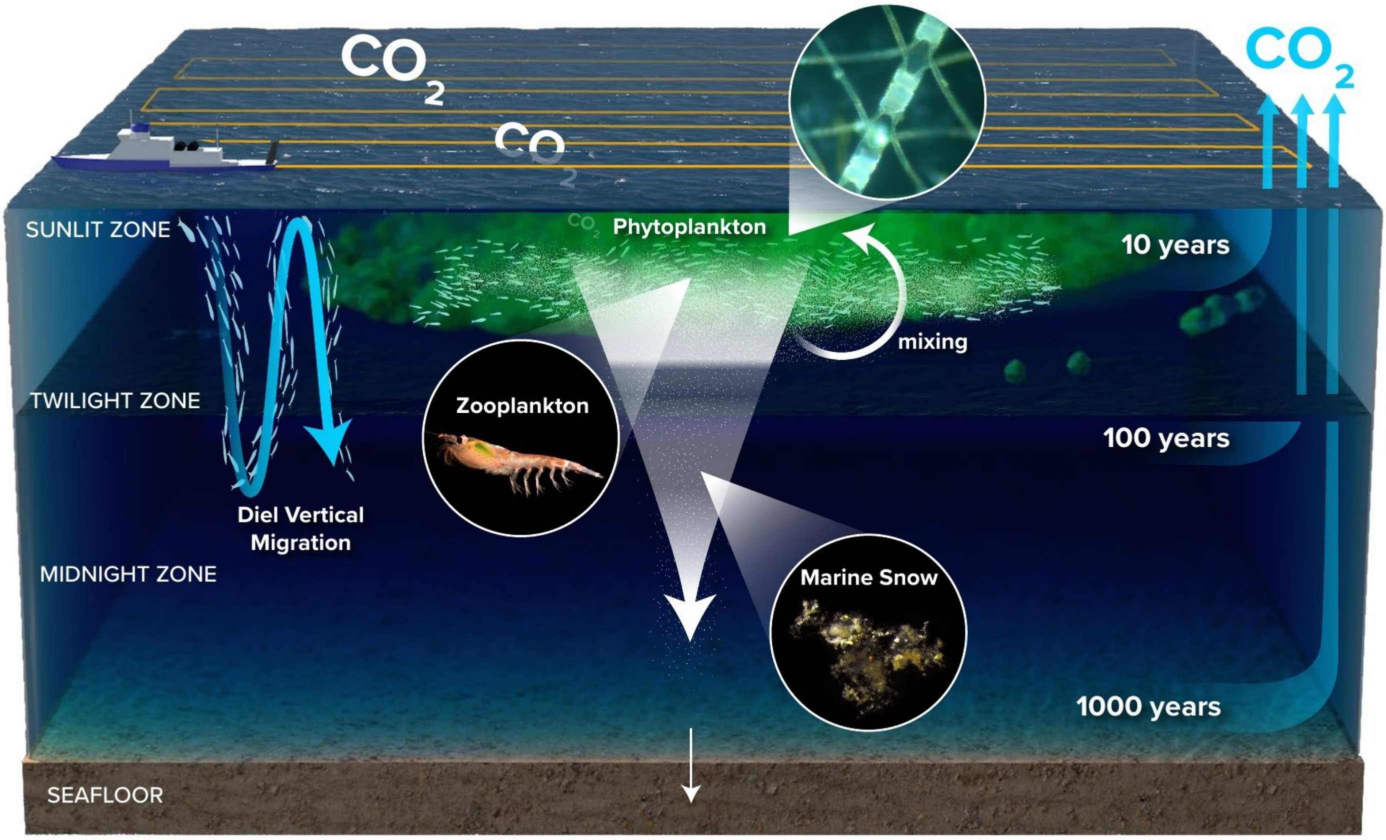

Figure 2. Schematic of enhanced C removal via the biological carbon pump due to iron additions. Phytoplankton growth is enhanced leading to zooplankton grazing, and formation of sinking marine snow particles. Note that the efficiency of the BCP varies, and transformations between sinking and dissolved forms of C at depth limit the amount of durable C sequestration.

3 EXPLORING OCEAN IRON SOLUTIONS SHORT HISTORY

EXploring Ocean Iron Solutions (ExOIS; http://oceaniron.org) is a consortium of scientists who came together in early 2022 to share ideas and move ahead on studies to consider ocean iron additions as one way to address our climate crisis. Resolving the impact of enhanced iron fertilization on marine ecosystems and quantifying its efficiency for removing atmospheric carbon dioxide are key. Central to ExOIS are activities leading up to field experiments that resolve these remaining questions (#1-6 below). The outcome of this knowledge would be used to have sufficient information to consider OIF relative to other climate mitigation options, including its effectiveness, durability, and scaling potential and costs. This information is essential to deploy fully and/or regulate and limit OIF deployments to certain areas or scales.

ExOIS is not a funding agency and currently its members are using a range of resources to make progress, though we hope through this consortium and document to encourage new and coordinated support of individual projects and solicit group support for larger field activities. Through a series of monthly forums (https://oceaniron.org/our-plan/#forums), we are building a consensus on research priorities, codes of conduct, and sharing knowledge regarding individual, national, and international research programs.

4 OVERALL GOAL OF OIF FOR OCEAN CDR

The overall goal of ocean iron fertilization as a CDR approach would be to reduce atmospheric CO_2 by achieving net increases in durable (>100 years) carbon storage in the deep sea on a scale that can reach Gt CO_2/yr levels at a cost less than $100 per ton of CO_2 sequestered.

5 SCIENCE QUESTIONS TO MEET THIS GOAL

SQ1. What controls the efficacy and durability of OIF as a CDR strategy?
SQ2. How can OIF efficacy for CDR be efficiently and accurately monitored and validated?
SQ3. What are the intended and unintended environmental and ecological consequences of OIF, and how can these be monitored?
SQ4. What are the regulatory and governance frameworks needed to facilitate responsible OIF research and furthermore be needed for conducting OIF CDR at scale?
SQ5. What are the societal benefits and impediments for conducting OIF CDR experiments, and if conducted at scale?
SQ6. Is OIF an effective CDR approach with acceptable costs and economic value, and how does OIF compare to other ocean and land-based CDR approaches?

6 OVERALL REQUIREMENTS TO ANSWER THESE QUESTIONS

OIF studies will require enabling technologies and models to conduct field experiments (SQ1) to demonstrate, using accepted MRV (monitoring, reporting, verification) approaches, the effectiveness of OIF to durably remove CO_2 from the atmosphere (SQ2). MRV also is needed to measure intended and identify unintended geochemical and ecological consequences when deploying OIF under varying ocean conditions and at larger and longer scales than prior studies (SQ3).

Along with the science and technological advances for OIF, we need to help develop a robust international governance framework for ocean CDR building upon work already done under the auspices of the London Convention, London Protocol, and Convention on Biological Diversity (SQ4). Accountability and environmental risk assessments are needed. In addition, the social acceptance of ocean CDR and OIF needs to be cultivated, identifying stakeholders and using public engagement tools to build trust while considering social justice and other equity issues (SQ5). Ultimately, the research must inform on the efficacy—effectiveness of CDR relative to the environmental consequences—of OIF in comparison to other ocean and land-based CDR approaches (SQ6).

7 LINKS BETWEEN SCIENCE QUESTIONS AND R&D PRIORITIES

We have tried to graphically link (Fig. 3) the six main science questions (SQs) to the information needed to answer these questions and then priority activities required as listed in Table 1 and discussed further below. For example, to address OIF effectiveness and durability (SQ1), we require information on both field sites and season (I1), while considering the types, scales, and rates of iron inputs (I2). Several priority activities are needed to provide this information (columns) including field studies (A1), studies on Fe delivery (A2), new technologies for measuring, reporting, and verification of C sequestration (A3), experimental design using OSSE models (A5), models to incorporate field data and extrapolate to regional and global scales (A6), field studies synthesis (A7), system costs/benefits modeling (A8), and site-specific permitting (A10). Activities and information needs which address multiple SQs are also represented.

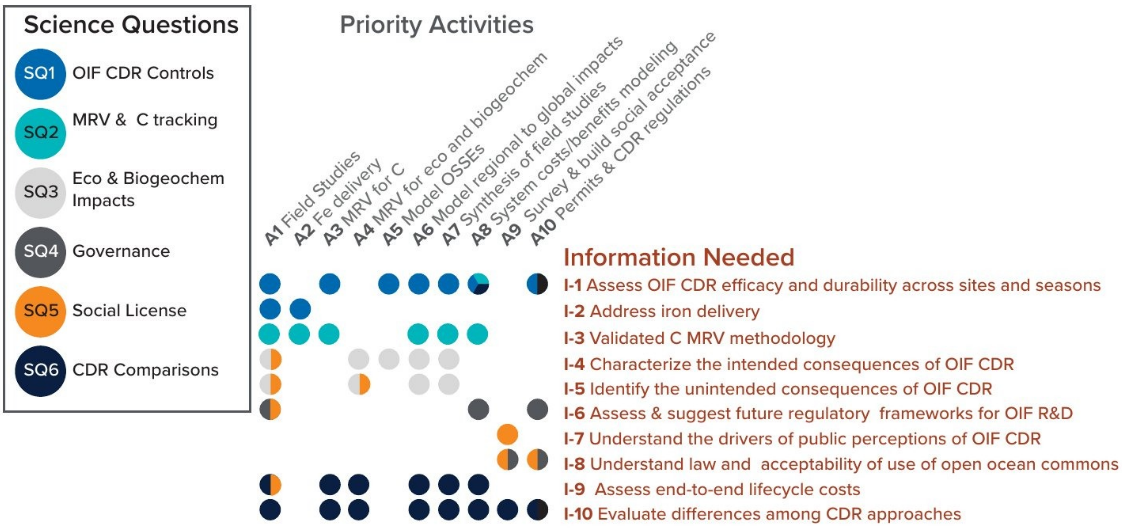

Figure 3. This diagram highlights the multiple interlinkages between the 6 main science questions (SQs, color coded on left and applied to dots throughout) and the information needed to address these SQs (I# rows right side) which require the priority activities listed in Table 1 and discussed in text (A# columns along top). Multiple colored dots indicate information needs which address multiple SQs.

8

KNOWLEDGE BASE AND R&D PRIORITIES

Consideration of OIF as a CDR strategy benefits from foundational knowledge derived from numerous mesoscale iron enrichment studies as well as observations from natural iron enrichments arising from islands (the wake effect) and aerosol deposition events (dust storms; volcanic ash; forest fires). These studies demonstrate that iron addition dramatically increases phytoplankton production in the Southern Ocean and equatorial and subarctic Pacific waters. This rich knowledge base has advanced 13 new priority activities (Table 1) put forward in the remainder of this document to help understand the potential outcomes if using iron as a tool for carbon sequestration. All of these activities are interrelated and need to be advanced in parallel (see Timeline and costs below), but are separated here to introduce where we are at for each topic today and what are the priorities for the future.

TABLE 1. PRIORITY ACTIVITIES

Field studies	A1	C, non-C, and eco impacts	Field experiments at 100 ton and 1000 km^2 deployment areas - from single to multi sites; assess C, non-C, and ecological impacts in response to Fe
	A2	Fe delivery	Design/test better ways to deliver Fe for bioavailablity and tracking of Fe and C using lab, field experiments
Monitoring, Reporting, Verification	A3	Technologies for C accounting	Technologies and models to quantify C impacts - transparent accounting from atmosphere to durable storage at depth
	A4	Technologies for ecological impacts	Technologies and models to remotely/autonomously track changes to upper ocean, mid-water, and deep ocean ecosystems in response to Fe
Modeling	A5	Experimental planning	Model OSSEs for site-specific planning of OIF field work - specific design of experiments and monitoring
	A6	Regional and global impacts	Models to predict larger scale impacts - durability, downstream, fisheries, GHG budgets, uncertainties
	A7	Field study synthesis and modeling	Synthesis and modeling of field experiments (prior/new) and compare to nature & other ocean CDR approaches
	A8	Systems approach/ costs	Systems models for OIF with end-to-end costs, including accounting for GHG impact of operations
Social engagement and legal frameworks	A9	Social engagement	Assess public support and concerns and build social acceptance via public engagement; partnership building
	A10	Governance	Applications for open ocean field work, building policies and governance structures and alliances including with other ocean CDR approaches
Organization, data management, and training	A11	Program Office	Funds for program office, meeting organization, workshops, steering committee, build web materials, etc.
	A12	Data Management	New and existing data management structures will be needed for open access and long-term stewardship of OIF study results
	A13	Capacity building	Fund for competitive awards for Postdocs (multiple awards; 2-3 yr), PhD students (5 yr, build up to 10-20), and undergraduate research projects (summer interns)

9 FIELD STUDIES

9a Carbon impacts

There have been 13 small-scale, deliberate open-ocean OIF studies between 1993 and 2009 [Fig. 4] resulting in 100's of manuscripts, reports, and reviews [7, 8, 13]. Considered as a whole, OIF has demonstrated a significant increase in CO_2 uptake in response to enhanced phytoplankton growth due to the addition of iron. Many of these experiments were designed primarily to study the planktonic ecosystem's response to OIF, not as a tool to reduce atmospheric CO_2 inventories [14]. Larger (>10 km^2) and longer duration (>30 days) experiments with increased emphasis on C tracking at depth are needed to address key unknowns related to the removal and sequestration of that C at depth.

Nevertheless, there are strong indications of the efficacy of OIF for carbon sequestration. For example, the addition of 1.3 tons of iron during SOFeX-South, led to a C export associated with sinking particles at depth (100 m) on the order of 2,100 tons C over a 28 day period [15]. In natural systems in the Southern Ocean those $Fe:C_{export}$ efficiencies are much higher. For example, $Fe:C_{export}$ efficiencies of greater than 100,000 were found in iron-rich waters surrounding islands in the Southern Ocean [6, 16].

A key experimental variable in the application of OIF to CDR is the durability of C export. There are two factors to consider. First, on average, only 10% of the sinking particulate organic C flux leaving 100 m reaches 1000 m [17], but this rate of remineralization of sinking C is highly variable [18]. OIF strategies that encourage diatom blooms, for example, have less attenuation vs depth due to the rapid

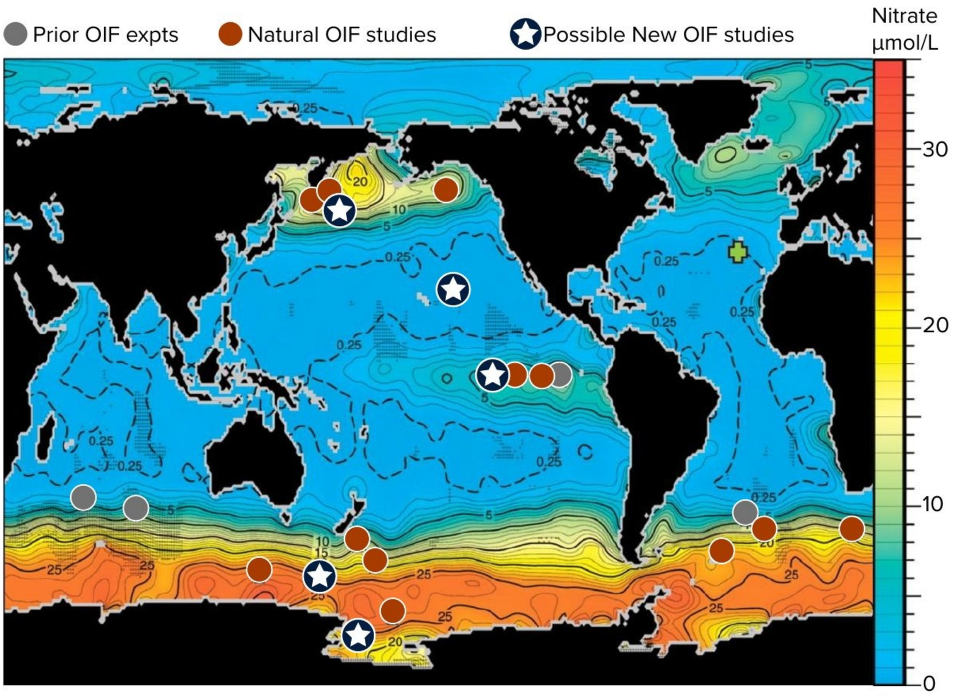

Figure 4. Location of prior artificial OIF experiments (white crosses) and natural OIF studies (red crosses) overlain on surface nitrate map. Possible sites of larger/longer OIF experiments noted by stars. Modified from Boyd et al., 2007 by NASEM 2021.

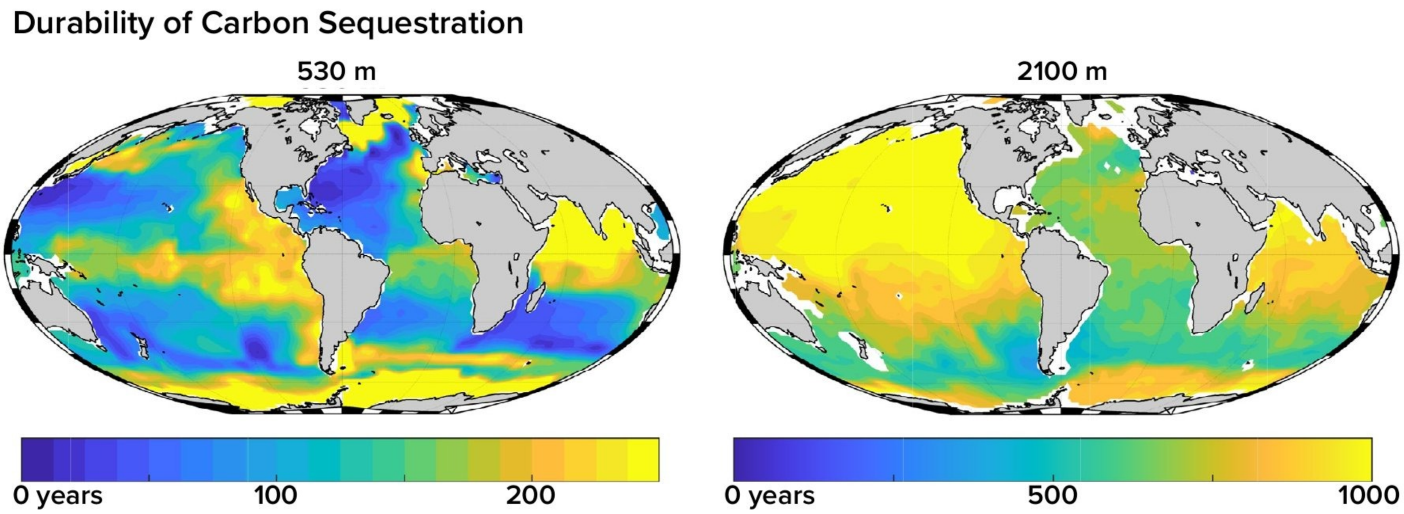

Figure 5. Durability of C sequestration as illustrated for two injection depths calculated for purposeful enhancements of the biological pump. Colors are meidan sequestration times from Siegel et al., 2021.

sinking of large diatom aggregates. Secondly, for durable C sequestration, storage of C on time scales of >100 to >1000 years is readily achievable if sinking C can reach depths of deeper than 500 to 2000 m depending upon location [19](Fig. 5). The value of OIF for CDR to C markets will depend upon both the magnitude of C exported and its durability. There may still be value to climate mitigation and CDR markets, even if durability is <100 years or if only a small fraction of a large surface bloom reaches deep ocean depths.

From prior studies, there is clear evidence that the magnitude and dynamics of iron addition can lead to dramatically different outcomes. Ultimately the cost of OIF will depend greatly on increasing efficiencies for Fe uptake by phytoplankton, CO_2 draw down and long term C sequestration, with potential costs ranging from <$1 per ton CO_2 removed to >$100 ton CO_2 depending upon these efficiencies [9, 20].

In addition to C export efficiencies, another important issue with respect to the use of OIF for CDR is the response time for the surface ocean to absorb carbon dioxide from the atmosphere and how quickly this air-sea gas exchange happens relative to the rate at which surface waters are mixed vertically, and thus, removed from contact with the atmosphere. These equilibration time scales vary from a few weeks to a year due to variations in mixed layer depth, wind speed, temperature, and dissolved inorganic carbon concentrations [21]. This rate of gas exchange versus the vertical mixing of waters will vary widely across the ocean and depend on local conditions as well as large-scale phenomena such as El Niño and monsoons.

Obvious target study areas include the Southern Ocean and equatorial and subarctic Pacific waters, but also low-nutrient sites though logistics and permitting will need to be considered as well in the selection of initial field trials.

The design and development of scalable experimental test beds will be essential to facilitate the needed replication and comparisons among investigations evaluating the geochemical and biological outcomes of different OIF scenarios. The test-bed designs should be functional in a wide range of target ocean regions, thereby accelerating scientific assessment of OIF as a CDR approach. Obvious target study areas include the Southern Ocean and equatorial and subarctic Pacific waters, but also low-nutrient sites [Fig 4] though logistics and permitting will need to be considered as well in the selection of initial field trials.

PRIORITY ACTIVITIES

Larger (100's tons Fe over 1000's km^2) and longer field work (seasons-years) is an essential R&D goal for the assessment of OIF's potential for CDR. Replication and studies in both high- and low-nutrient conditions are needed. Field studies should be open to multiple participants thus serving as test beds for deploying new MRV technologies and for verification of outcomes by independent groups. For each experiment, Fe uptake, CO_2 exchange, and durable/deep sequestration all need to be quantified (see MRV). Enhancing iron bioavailability and increasing C export efficiencies are high priority research areas that likely involve lab or near-shore studies prior to full open ocean deployments. Integration of tasks using observations and models as detailed below under modeling synthesis is essential for the success of this program.

9b Non-Carbon and other ecological impacts

In addition to its impact on CO_2 and C sequestration, field studies need to consider non-C impacts, both potential negative and positive consequences. For example, non-CO_2 greenhouse gasses (GHGs) are produced by breakdown of sinking organic C which could have a negative impact on C sequestration potential. Thus far, the measured and modeled impacts of two of these GHGs in prior field studies were less than a few percent for methane to 6-12% nitrous oxide relative to the climate impacts of the observed reduction in CO_2 [22, 23]. Increased, though variable, production of dimethyl sulfide (DMS) has been observed in previous OIF studies which can lead to the formation of cloud condensation nuclei, potentially providing additional reduction of global temperatures (e.g. [22]). Changes in subsurface oxygen related to the remineralization of sinking organic C also need to be considered [24, 25]. Observations of all of these non-CO_2 impacts are required to build up predictive capabilities.

In the past, concerns arose as a class of toxic diatoms, *Pseudo-nitzschia*, have been found to increase in abundance after some OIF experiments, and they can be responsible for coastal HABs (harmful algal blooms) [26, 27]. The presence of *Pseudo-nitzschia* does not necessarily mean elevated levels of HAB-causing toxins. Research to date showed that the amount of toxin (domoic acid) produced per cell in response to iron addition has not exceeded levels found in non-fertilized areas, nor has it led to any documented HABs. But this would need to be carefully monitored.

Increased phytoplankton production will have ramifications across the food web, including potential increases in fish production. Some groups have proposed OIF as a means of ocean fisheries restoration (e.g., ocean pastures), analogous to land-based farming. However, there presently is insufficient scientific evidence to assess the impacts of iron additions higher up the food chain beyond the initial phytoplankton and zooplankton responses and over multiple years required to demonstrate fisheries impacts. While ecosystem restoration of fisheries and higher predators would enhance C stocks, removal of biomass for food does not lead to durable removal of CO_2. Reliable quantification of these food chain effects and modeling are needed.

It should also be noted that an enhanced ocean biological carbon pump would reduce surface acidification through the drawdown of atmospheric CO_2, but would speed up transfer of CO_2 to the deep sea, increasing acidity at depth and thus of possible concern for some deep sea ecosystems. Iron-enhanced productivity would lead to depletion of major nutrients (N, P, Si) which, in turn, will influence ecosystems downstream of the enrichment zone. The degree of these impacts, both in surface and deeper waters, can be investigated with models (see below), but will remain a critical factor for study in field experiments. Key questions are what thresholds of influence are acceptable, and could offsetting regulations in governance be considered to address any ecological, fisheries, or other societal impacts?

PRIORITY ACTIVITIES

Any field study must consider more than just consequences to the C cycle. Measurement of non-CO_2 gases is important and intended and unintended consequences to marine ecosystems must be quantified to a sufficient degree to parameterize in climate and fisheries models. Potential negative and positive impacts need to be given equal consideration.

10

MONITORING, REPORTING AND VERIFICATION

Prior OIF studies were largely academic-led, involving individual experts and their teams to measure the ecosystem and biogeochemical impacts of adding iron to the surface ocean during two-week to month-long field studies. These were largely based upon ship-based observations with possibly a few profiling floats with relevant sensors or sample collectors. The ship-based observations were augmented by remote sensing and models. Most often, cruise planning was part of the preparation of proposals to national science agencies, and a combination of scientific presentations, peer reviewed manuscripts, and reports were used to disseminate individual findings. Local or national databases were commonly used for long term access to data, though this process was not always complete, nor were data always readily available to all.

CDR requires a more deliberate monitoring, reporting, and verification (MRV) system. More broadly speaking, MRV can be defined as a system for producing trustworthy, quantifiable estimates of real world outcomes and communicating those findings and methods in a consistent and transparent manner. The ultimate goal of MRV for OIF as a CDR approach is to quantify the efficacy and the durability of C storage and to quantify environmental impacts. This includes tracking the lifecycle of removed C (i.e. C accounting), assessing the net drawdown of atmospheric CO_2 due to OIF, and using numerical models to extrapolate to larger/longer scales (durability, additionality, and downstream effects, see Modeling). Standardized methods will become especially important if and when C markets develop to purchase ocean CDR credits with a given durability. And MRV needs to move away from ship-based observations to autonomous platforms,

Figure 6. Instruments for MRV of OIF might include: (top left, clockwise) 1. profiling float with underwater vision profiler (UVP) camera; 2. neutrally buoyant sediment trap (NBST); 3. ocean glider; 4. Twilight Zone EXplorer (TZEX); 5. MINiature IsOpycNal floats (MINIONS); 6. deep ocean time-series sediment trap; 7. long range glider with particle and plankton camera; 8. saildrone surface vehicle.

sensors, and samplers that can more accurately quantify OIF impacts, not just for C accounting but for intended and unintended ecological consequences. Development of reliable predictive models is needed to incorporate observations into larger scale impacts (i.e., durability) and C lifecycle estimates.

It is important to remember that substantial advances have been made since those early OIF experiments in autonomous vehicles (AVs), floats, gliders, sensors, and samplers [28, 29] [Fig. 6]. Along with advances in satellite observations of the surface ocean [30], this means that OIF observations will now be amenable to upscaling and larger scale MRV. Many of those technologies are commercially available, though a large part of this new R&D effort needs to include investment in the development of new sensors and platforms for MRV of essential ocean variables. Data assimilation models need to be developed and tested that assimilate these data and provide actionable MRV information.

Ultimately a transparent and publicly accessible MRV system is required. This is important for designing robust certification schemes that are accessible and trusted by multiple user communities.

PRIORITY ACTIVITIES

In this document we divide MRV needs into the development of field-sampling technologies needed for C tracking, those related to measuring ecological impacts and GHG emissions associated with OIF, and modeling systems to assimilate these observations to quantify the efficacy and impacts of OIF as a CDR strategy. This is not to ignore non-C impacts and other critical biogeochemical measurements that are essential in field experiments, but acknowledges that advances in MRV technologies to track ecosystem dynamics are key to building up certifiable C results within a framework of acceptable environmental impacts.

11 MODELING

Advanced ocean physical-biogeochemical models are powerful tools to complement field studies. Well-tested models can provide quantitative evaluations of the efficacy and the durability of carbon sequestration and storage of ocean-based CDR, such as OIF. They also provide a dynamic framework for synthesizing prior studies of OIF including observational data and identified mechanisms and impacts, which can be used to guide new OIF experiments and predict future roles of the ocean in modulating atmospheric CO_2 under different fossil fuel/climate scenarios. Most biogeochemical models can simulate carbon and nitrogen cycles as well as oxygen dynamics. So, they can provide insight into the effect of OIF on carbon removal as well as associated effects on marine ecosystems (e.g., nutrient drawdown, oxygen depletion at depth, ocean acidification, etc.). However, providing reliable predictions of carbon sequestration and durability will depend on quantitative estimates for carbon export pathways via the food web, particle aggregation, and sinking flux; how these processes are modulated by mesoscale and sub-mesoscale physics; and the rates and degrees of remineralization processes in euphotic and mesopelagic waters. Modeling will be a key aspect of any OIF CDR efforts and essential for identifying and quantifying the resultant short- and long-term consequences.

11a Designing field studies using Observing System Simulation Experimental models

Numerical models are the core of the newly developed Observing System Simulation Experiments (OSSEs; [31]). The goal of OSSEs is to optimize the design of OIF experiments through evaluating different observational strategies and networks to achieve maximum carbon sequestration while minimizing any unintended consequences. It includes model-simulated experiments to evaluate broad aspects of OIF, including but not limited to the impacts of OIF in space and timing, different modes of iron delivery, and the optimal placement of observing assets. Advances in high-resolution data-assimilative circulation models [32-34] enables the study of physical-biogeochemical interactions across sub-mesoscale to regional spatial scales, incorporating processes associated with mesoscale eddies, fronts, and strong ocean currents.

The high-nutrient, low-chlorophyll (HNLC) ocean regions—the equatorial Pacific, subarctic Pacific Ocean, and the Southern Ocean—all have been shown to respond quickly to iron additions [7, 8] so they are an obvious first place to consider for OSSE OIF study [Fig 4]. But subtropical gyres, where both nitrate and phytoplankton are low in abundance (LNLC), are rich in potential for N-fixing phytoplankton (diazotrophs) that also are limited by iron [35]. OSSE research can better quantify iron effects on carbon transfer as well as ecosystem and social structures in these two disparate ocean systems. OSSE studies also can help to optimize regional placement of OIF demonstration projects along with iron delivery strategies to maximize the amount and durability of CDR.

Modeling will be a key aspect of any OIF CDR efforts and essential for identifying and quantifying the resultant short- and long-term consequences.

Carbon export pathways via the food web, particle aggregation, and sinking flux – modulated by mesoscale and small-scale physics as well as the remineralization process in the water column – are essential parameters needed to provide reliable predictions of carbon sequestration.

11b Extrapolation of regional impacts to global scales

Mesoscale OIF experiments over the past three decades were logistically restricted to small scale (10's of km^2) and monitoring over near-area (~100 km^2) and short-term (weeks to months) scales. Findings from these experiments have led to simulations of OIF in regional models that have the advantage of high spatial resolution capable of resolving mesoscale (10-100 km) or even sub-mesoscale (1-10 km) oceanic features [36]. Among other findings, these studies show that patch size affects not only the physical dispersion of added Fe but also influences the efficacy of carbon sequestration.

CDR-inspired OIF studies would be done at much larger scales and over longer periods of time, for which current high-resolution physical-biogeochemical models are now well suited. These larger-scale experiments require more intensive monitoring to track fertilized waters, quantify the timing and spatial distribution of ecosystem and biogeochemical outcomes in both euphotic and mesopelagic waters, and verify the magnitude and durability of CDR. This monitoring would require autonomous vehicles (e.g., gliders, biogeochemical profiling floats, etc; Fig. 6.) and real-time integration of these data into basin- and global-scale three-dimensional high-resolution models that could estimate both direct, near-field effects as well as the "downstream" biogeochemical and ecological effects. The integration of real-time multiple platform-based observational data into models would yield unprecedented understanding of the ocean response to iron fertilization, refine conceptual models for future OIF experiments and other ocean-based CDR approaches, and constrain regional and global models to better quantify the efficacy and durability of OIF as a CDR strategy.

11c Field study synthesis and iron cycling models that include impacts on ecosystems

Iron cycling is the key component of OIF experiments, therefore, its sources, sinks, cycling dynamics, and links with carbon cycle need to be well represented or parameterized in the current biogeochemical model. The robustness of the iron cycle in the model determines the model's capability in simulating iron distribution and concentration levels and predicting carbon drawdown and sequestration during OIF experiments. A previous model comparison study has shown large uncertainties in iron cycling in 13 global biogeochemistry models [37]. New iron model parameterizations and more field observational data to constrain parameters are thus needed. For example, including both soluble iron and ligand iron dynamics in the model can constrain the iron residence time and availability for phytoplankton uptake [38]. In terms of the biological carbon pump, key phytoplankton species (e.g., diatoms, picoplankton, diazotrophs) and their response to iron level and forms should be explicitly represented in the model. Carbon export pathways via the food web, particle aggregation, and sinking flux — modulated by mesoscale and small-scale physics as well as the remineralization process in the water column — are essential parameters needed to provide reliable predictions of carbon sequestration.

11d System modeling approach/costs

Conducting OIF field and modeling experiments needs to be considered at global earth system level to evaluate long-term (10 to 100 years) and global impact. Global ocean models with targeted regional high-resolution configuration can be embedded in global earth system models or end-to-end models, which have the advantage of long-term simulations with carbon feedbacks between land, atmosphere, and ocean. These system models will provide a platform not only for comparing the efficacy of CDR by OIF at different target sites and seasons [39], but also for refining patch size, modes, and timing of iron addition (e.g., iron substrates, continuous or pulse frequency, etc.), as well as optimizing for costs of iron delivery per unit carbon sequestered and the durability of carbon sequestration. Integrated with global models, these findings will provide insight into long-term atmospheric CO_2 trends and changes in biogeochemical and ecological processes [40, 41], which can inform on the potential for socioeconomic and cultural effects. The costs for delivering iron as well as the amount and durability of C sequestration can be estimated with the end-to-end global models.

PRIORITY ACTIVITIES

Advanced high-resolution (~10 km) physical-biogeochemical modeling studies are needed. Regional well-tested models should be used for Observing System Simulation Experiments (OSSE) to design OIF field experiments. Different model-simulated experiments need to evaluate the impacts of OIF both in space and time, especially near- and far-fields responses and short- and long-term consequences. Data-constrained high-resolution models need to address the different ways of delivering iron (fixed locations, different size of the iron patch, multiple, pause, continuous releases, etc.) and placement of different observing assets. The synthesis and modeling of prior and new OIF experimental observations and remote sensing information will need to be integrated with regional high-resolution models, especially for improving iron and carbon cycle components in the biogeochemical model. Model intercomparisons will be valuable to understanding uncertainties. End-to-end systems models needed to evaluate costs per ton CO_2 and full GHG balances.

12 SOCIAL ACCEPTANCE

We accept at the outset that social acceptance of OIF is not something we can 'engineer' but is instead a function of pre-existing values and perceptions across target social groups, which may also come to be influenced by positions taken by environmental NGOs, the nature of language of debates across the scientific community, as well as the conditions of OIF's trial and roll out. By conditions we refer to principles of responsible innovation, among other features.

In the early stages, we expect positions to be 'upstream' — that is, very sensitive to initial framing of OIF. For example, the analogues people use to make sense of fertilization, and the environmental and social risks and benefits they ascribe to it, will be key. We also anticipate that social acceptance will not 'exist' in a vacuum, but will likely be higher if OIF co-exists with meaningful reductions in fossil energy, if OIF does not assign impacts to already vulnerable communities, and if OIF is managed and monitored (i.e., governed) by widely trusted parties.

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Perceptually, a few psychological and social variables are also consistently predictive of perceived risk and might apply in this case. Specifically, OIF may be more likely to be seen as risky if its widespread use as a carbon-drawdown solution is temporally distant (e.g., people are increasingly expressing climate urgency), if it is seen as 'unnatural', if the receiving marine environment is regarded as fragile or easily susceptible to impacts, or if any consequences of the trial of OIF are regarded as irreversible. It is also historically difficult to communicate and elicit views on problems of scale to the extent that study participants can become 'numb' to the sheer volume of CO_2 removal needed and thus unable to evaluate technologies on this point without some tutorial assistance.

Social, climate, and environmental justice issues need to be embedded in how we pursue CDR and consider who benefits and where the impacts of CDR deployments may be highest. OIF is largely an open-ocean approach, but potential real and perceived impacts to downstream coastal communities need to be considered. Ultimately, "who controls the thermostat" of the globe impacts not just coastal communities but agricultural practices inland, and these impacts are far removed from the interests of the groups conducting OIF research and commercial interests that seek to gain financially from CDR. Engaging underrepresented groups in OIF training and studies would be one important step in building trust.

Overall, our plan is to investigate social acceptance through a few empirical steps. First, we will establish a citizen advisory panel to conduct routine meetings and open discussions as to any concerns held or conditions suggested for OIF. A subset might also be tasked with accompanying the scientific team on field trials if able. Such groups are most likely to be effective when the composition of the group is diverse, not homogenous, from a knowledge point of view and is also highly representative of regional interests.

Secondly, with input from the citizen advisory panels, effort would be spent to produce educational materials to explain the need for CDR, why the oceans should be considered, and why OIF is a CDR option worth exploring. This would be done via production of materials for the web, articles in popular media outlets, social media promotion through publicly known "ambassadors" who support our goals, convening virtual and in-person events/panels, and creating content on ocean and climate themes for education that includes CDR and OIF.

PRIORITY ACTIVITIES

Form citizen advisory panels to investigate social acceptance. Such panels would: 1. participate in deliberative-engagement focus groups and surveys; 2. elicit context-specific views about physical and social risks and benefits as well as views regarding the financial mechanisms that support CDR markets; and 3. engage in the transparent release of information as new knowledge unfolds. Activities under these themes would include production of educational materials for the public, including web-based products, organizing events, maintaining social media and blogs, producing public-facing articles, and developing diverse course materials for teaching.

13 GOVERNANCE

The governance of OIF has received significant attention from the international community. In 2008, the parties to the Convention on Biological Diversity and the London Convention and Protocol adopted resolutions which establish an initial framework for governing OIF. Both resolutions acknowledge the need for further research to fully evaluate OIF and establish criteria for the approval of research projects. While the resolutions are not legally binding, they have wide support within the international community and thus the criteria they establish can be thought of as accepted "best practice" for OIF research.

There is an ongoing effort to create a legally binding international governance framework for OIF research. In 2013, the parties to the London Protocol adopted an amendment which, if and when it enters into force, will establish binding rules for certain the conduct of "marine geoengineering activities." OIF is currently the only activity covered by the amendment. In this respect, then, OIF could be said to be ahead of other ocean CDR approaches for which there is no established international governance framework. It is, however, important to note that the 2013 OIF amendment has not yet entered into force. Under the terms of the London Protocol, for an amendment to enter into force, it must be ratified by two-thirds of the parties to the Protocol. To date, of the 53 parties to the London Protocol, only six have ratified the 2013 OIF amendment. The slow pace of ratification raises questions about whether the regime established in the 2013 OIF amendment will prove workable and effective.

There is a need for research to evaluate the adequacy of the existing international governance framework and possible alternatives that might be more effective in terms of (1) enabling necessary OIF research and (2) ensuring that research occurs in a manner that is scientifically-robust, environmentally-responsible, socially-acceptable, just, and equitable. This necessarily requires consideration of how the international governance framework is implemented, for example, via its incorporation into the domestic laws of different countries. Engagement with governments and other relevant actors at the international and domestic levels is imperative to inform the design, and further the adoption of, new frameworks.

In addition to research on the overarching governance framework for OIF, work is also needed on the permitting and regulation of individual research projects. This is primarily a matter of domestic law. In the U.S., the Environmental Protection Agency (EPA) is likely to have primary authority over OIF research projects, though other government agencies may also be involved. The EPA has not published any guidance on how it will approach the permitting and regulation of OIF research. Engagement with the EPA and other agencies will thus be important, both to educate agency staff about OIF generally and to advance specific research projects.

Engagement with governments and other relevant actors at the international and domestic levels is imperative to inform the design, and further the adoption of, new frameworks.

PRIORITY ACTIVITIES

Research is needed to evaluate existing, and develop possible alternative, governance frameworks for OIF. The research must include consideration of both international and domestic law and involve engagement with relevant actors at both levels. A high priority would be to build relationships with key U.S. government agencies with authority to permit open ocean field studies and, working with advice of the scientific teams, move forward on applications for site-specific field studies.

14

ORGANIZATION AND PLANNING, DATA MANAGEMENT, AND TRAINING THE NEXT GENERATION

An organizational structure or Program Office (PO) would be needed to facilitate the activities described above through coordination of workshops, regular meetings, facilitating contacts among participants, and interacting with potential sponsors. As envisioned, though the final model could differ and be more distributed, some of the centralized PO functions would include responsibility for maintaining and building out the ExOIS website (http://oceaniron.org). Early experience in ExOIS has shown that involvement and communication within the group is key, as in any large project. Currently, materials for public engagement are also managed by the ExOIS PO staff, bringing in professional writers, graphics, and web help for specific tasks as needed. This outreach activity is thus informed by, and not separate from, the social acceptance activities mentioned above. And depending upon the form of support that comes in, the PO may serve in a management role and certainly would be the liaison between funders and practitioners of OIF studies (see Management discussion below).

Data management (DM) needs must be considered up front and it is likely that an ExOIS-like PO would not directly hire staff, but take advantage of and select an existing DM group(s) for coordination of building systems to handle the diverse observational data and model results that would be collected. One of the first tasks would be to identify end-users, from academics to policy makers, US federal agencies, NGOs, and commercial entities. Most likely this activity will take several DM groups to curate data (remote sensing, genetics, biogeochemistry, etc.), considering international restrictions, in order to come up with user-friendly, publicly accessible products. Any system will need to be aligned with FAIR data principles (Findable, Accessible, Interoperable, Reproducible Data) and open source code. A goal would be a streamlined and professionally maintained set of interfaces for data aggregation, manipulation, and visualization. A subgroup within the program participants will be needed to serve as a DM steering committee under coordination by the PO.

A final pair of recommended activities are for the PO to manage support for students and postdoctoral-level candidates working on ocean iron CDR projects. A solicitation for applications for support, selection by non-conflicted panels, and progress reporting could be managed by the PO. Ultimately the future of ocean CDR requires we build up the number of scientists and practitioners working in this area and there is no better way to ensure this than by supporting a strong cadre of PhD and PD candidates, not limited to one activity, institution, or country, but distributed over all of the partners who are part of the larger ocean iron activities described in this document. Shorter term undergraduate opportunities should also be considered to grow the base of future ocean CDR scientists, practitioners, entrepreneurs, and regulators.

PRIORITY ACTIVITIES

A program of this scale and complexity requires formation of a Program Office that has expertise in program development, systems engineering, supporting robust and effective communication between participants and with funding sources. It will engage outside group(s) for data management who are responsible for field and model data and create user-friendly products for stakeholders. Public engagement would be managed by the PO with collaborators. Included in these PO responsibilities would be management of training and mentoring opportunities to support the OIF community. Steering committees would advise PO on organizing meetings, creating web materials, building international relationships, etc. Capacity building for an emerging ocean CDR industry and governance is needed through academic training programs.

15

TIMELINE AND COSTS

It is important to note that we anticipate support will come from multiple sources as no single institution or country can accomplish all of the science goals set out in this plan, hence the organization of this document around priorities and goals, not specific logistics or management. There is no single model for funding or distribution as these will vary for different national, international, philanthropic, and possibly commercial support models.

In Figure 7, we group the 13 priority activities into three time frames: those activities that need rapid/seed funding now, or soon, and should not require a lengthy review processes; those activities that are ready to be started in the next 6-12 months in 2023 and would be better suited for at least a 3-year funding cycle; and then how this would build out to a larger program with multiple field experiments running in parallel (by year 5 and beyond). These funds are likely to come from different sources, either as single awards or, for example, as an agency-announced request for proposals. They could also be managed more centrally if large philanthropic gifts are provided to a central Program Office that has financial responsibility for management with an external process for selecting participants (see possible management plan below). Some of these early activities are already being supported or planned.

Of high priority for the initiation of the research goals in the first 6-12 months would be support for: 1. modeling specific to the design of field experiments (A5, table 1); 2. researching and making inroads into the permitting process under the London Protocols (in US, this includes US EPA and State Department for international waters; A10); 3. furthering lab work and testing of new forms/methods for introduction of iron that are more readily taken up by marine phytoplankton, easier to track, and preferentially lead to high C export efficiencies (A2); and 4. funds to organize this collective effort out of a program office (A11). Parts of this are happening already, but these early investments, mostly likely distributed as individual $100-$500K projects, are necessary to launch the larger goals of this program.

The rollout of a coordinated OIF research program would require all 13 activities described in the text and summarized in Table 1 and Figure 3. The activities are intimately connected and need to be coordinated. The support levels for individual activities would range on the lower end from $100-$500K/yr to up to $10M/yr for the first field experiment which would need to secure ship time, purchase autonomous assets, and mobilize lab groups (Table 1, A1), as well as design improved Fe delivery systems (A2). To support those field experiments, significant investments in new MRV technologies are needed (A3 & A4) that could be field ready in two years for deployment as part of the first field experiment. In support of the field work, modelers are needed to work on detailed site-specific OSSE-based field plans (A5) and models need to be optimized for regional and global extrapolations of OIF durability, downstream impacts, and climate impacts (A6). Synthesis and modeling can begin by looking at prior OIF field work, and should be fully pursued by multiple groups as data are collected and predictive models of C efficiencies and ecological impacts are assessed against field observations (A7). Systems models are needed for determining end-to-end costs and GHG budgets (A8). All of these modeling activities will serve an important role in comparing OIF to other ocean CDR approaches.

No matter how strong the OIF science, we need to invest early on in the social sciences, to form citizen groups to survey current views about the necessity for ocean CDR and OIF and advise on the best ways and methods to reach broader audiences (A9). Experts on governance are needed to initiate a formal permitting process, which requires impact assessments and later-on, legal expertise (A10). To support the organization of these activities, a program office needs to be stood up and hosted by an entity that can play multiple roles including project management, financing, communications, and team building (A11). The PO is not a data-management center but, with advice from its steering committees, would

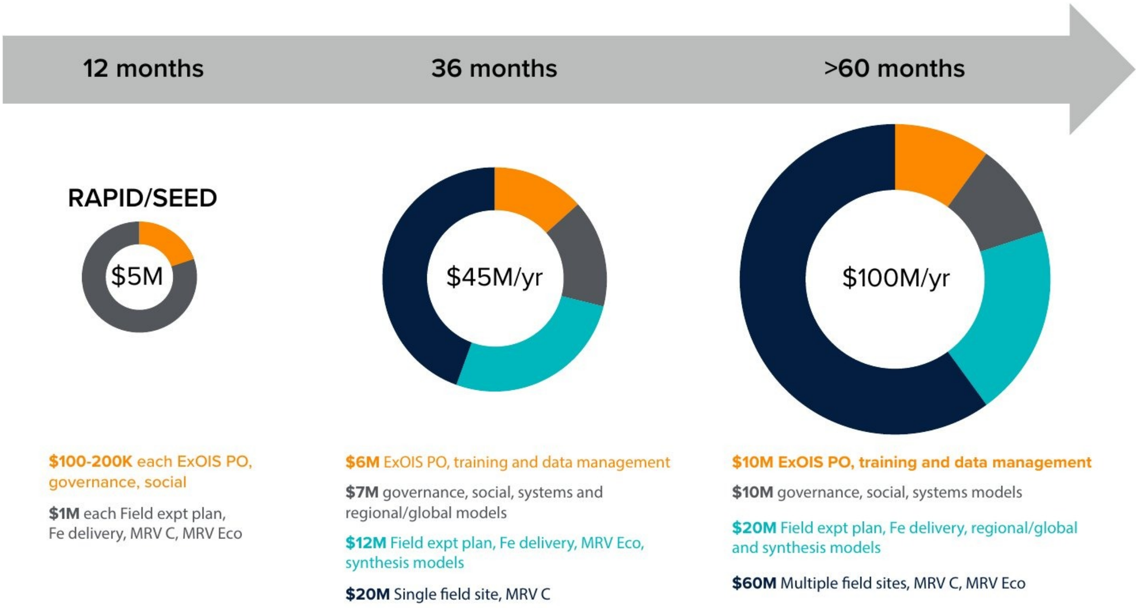

Figure 7. Schematic of timeline and activities and rough cost estimates for a fully viable OIF CDR research portfolio to meet the goals outlined in this document.

With the growing interest in commercial CDR markets, support for ocean CDR is increasing rapidly. This is evidenced by a small number of individual efforts that are already being supported by a range of sources, mostly from philanthropies.

select and direct several data-management teams to build up systems for data aggregation, manipulation, and visualization (A12). Finally, the future of our planet requires CDR and thus support for the next generation of scientists, engineers, social scientists, legal experts, and policy administrators (A13) and fellowship programs for postdocs, PhD students, and undergrads would be administered through the PO.

With the growing interest in commercial CDR markets, support for ocean CDR is increasing rapidly. This is evidenced by a small number of individual efforts that are already being supported by a range of sources, mostly from philanthropies. On the national level in the US, the proposed ARPA-E investment in a $30-50M 3-year program related to developing C and CDR sensors, platforms, and models is a good example of a national agency response to this growing need (and overlaps here with activity A3). By the end of the 2nd or into the 3rd year the sum of these efforts would total on order $45M/yr, reaching double that and more as additional field sites are brought on line (Fig 7).

16 POSSIBLE MANAGEMENT STRUCTURE

As of the writing of this document, there is a small group at the Woods Hole Oceanographic Institution organizing the ExOIS website and monthly forums with assistance from a scientific steering committee. As additional support is secured, there will be a need for a management team and structure, or ExOIS Program Office (PO). There are several models for this and suggested here is one such model based largely on similar-scale programs and with a US-centric model, though parallel POs and international collaboration would be integral to the pursuit of OIF activities as described in this White Paper (Fig. 8).

Key elements of the structure would ultimately include a central PO with several professional staff to manage overall coordination, planning, and organization (Org); meetings/conferences and other virtual, in-person and hybrid gatherings (Mtgs); subcontracts (Subs) lead in community engagement; and coordination of any training programs such as for postdocs (PD), PhD candidates (PhD) or undergrads (UG). Staffing would need to include a lead scientist familiar with OIF and large programs and a full time co-lead with program management experience. Staff with expertise in systems engineering, financial management, software development, fund raising, outreach and engagement, and legal advice are needed. Depending upon the host institution/entity, in-house finance, accounting, human resources, legal, information services, and ship operations management would be entrained. As envisioned, the PO would seek funding from multiple sources (green arrows in), which at different times would support specific priority activities (see Table 1).

In some cases, activities such as the anticipated ARPA-E MRV studies would be completely externally managed, selected, and funded, and would require only coordination with the PO. In other cases, incoming funds (green arrows out) would be dispersed to multiple institutions via subcontracts managed by professional financial staff within the PO.

To avoid conflicts, any request for proposals (RFPs), would be externally announced and selected by a non-conflicted entity (e.g. NGO such as Ocean Visions) brought in for each RFP (broken arrows). The majority of funds would be used for successful projects managed as subcontracts by the central PO. With advice from the Steering Committees (SC), some funds may flow directly to chosen groups such as for one or more Data Management Offices (DMOs). Contracts would be used to manage website (Web) and engagement activities (Social) within the main PO and with external collaborators. As needed, SC would be stood up with different foci, for example a data management SC, a SC for field studies, etc. Several of the activities may require their own external POs, and coordination would be needed with several international programs and their respective POs.

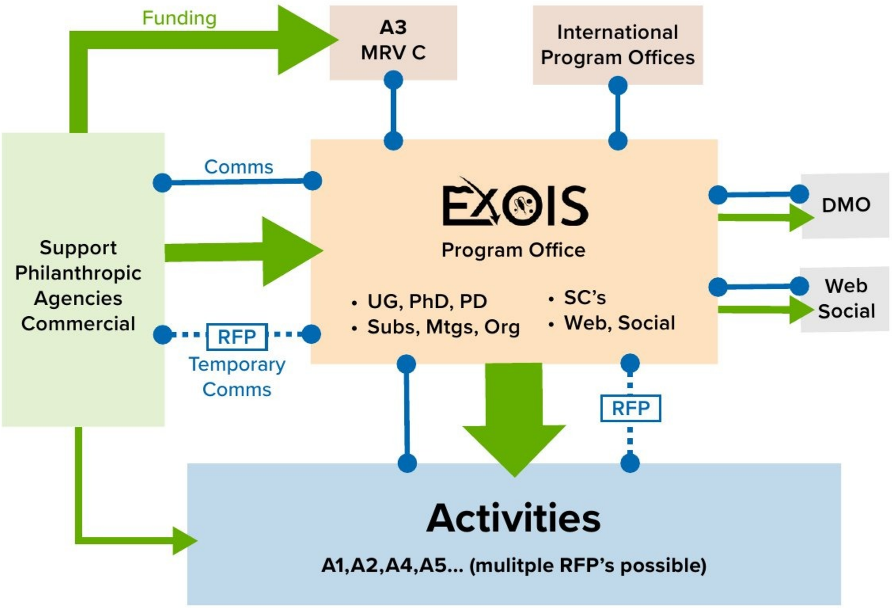

Figure 8. A notional management structure for an OIF research program with a central Program Office that has multiple funding sources coming in (green arrows) and parallel projects operated by many groups (activity circles). Double ended arrows in blue indicate communication paths, with dashed arrows indicating temporary paths such as might be needed for a specific RFP (request for proposals). Note that a more distributed PO structure is also an option but not included for simplification of the plan.

17 SUMMARY

With the climate crisis at hand, we cannot ignore the ocean's current role and potential for enhanced removal of atmospheric CO_2. We need to be considering ocean CDR and its potential beyond coastal blue carbon to include "Big Blue Carbon", i.e. the capacity of the larger ocean commons to reliably and durably remove atmospheric CO_2 with acceptable consequences. We are encouraged by analyses of natural and deliberate ocean iron fertilization field experiments that OIF may be an ocean CDR approach worth considering.

Outlined in this document are research priorities and a structure of a transformative OIF program that would include a comprehensive assessment of OIF as an ocean CDR approach and address the many remaining questions and uncertainties about the efficiencies and permanence of enhanced carbon sequestration, its intended and unintended ecological consequences, and whether OIF is a practical and cost-effective approach to provide quantifiable climatic benefits.

International scientific collaborations need to lead the way, though the priorities go beyond just an understanding of the natural science and engineering aspects of OIF; we must include assessments of public perceptions and build tools to improve public understanding of ocean CDR in general and OIF in particular. In addition, we need to advance international governance structures for OIF following an ethical path and with guidelines that protect the ocean environment, prioritize equitable and just outcomes, and appropriately account for other social dimensions of ocean CDR. We also need to build workforce capacity and grow the community through training of the next generation of CDR scientists, practitioners, and regulators. With this comprehensive research program, we have the opportunity to invest in the knowledge necessary to ensure that we can make scientifically and ethically sound decisions for the future of our planet. ■

With this comprehensive research program, we have the opportunity to invest in the knowledge necessary to ensure that we can make scientifically and ethically sound decisions for the future of our planet.

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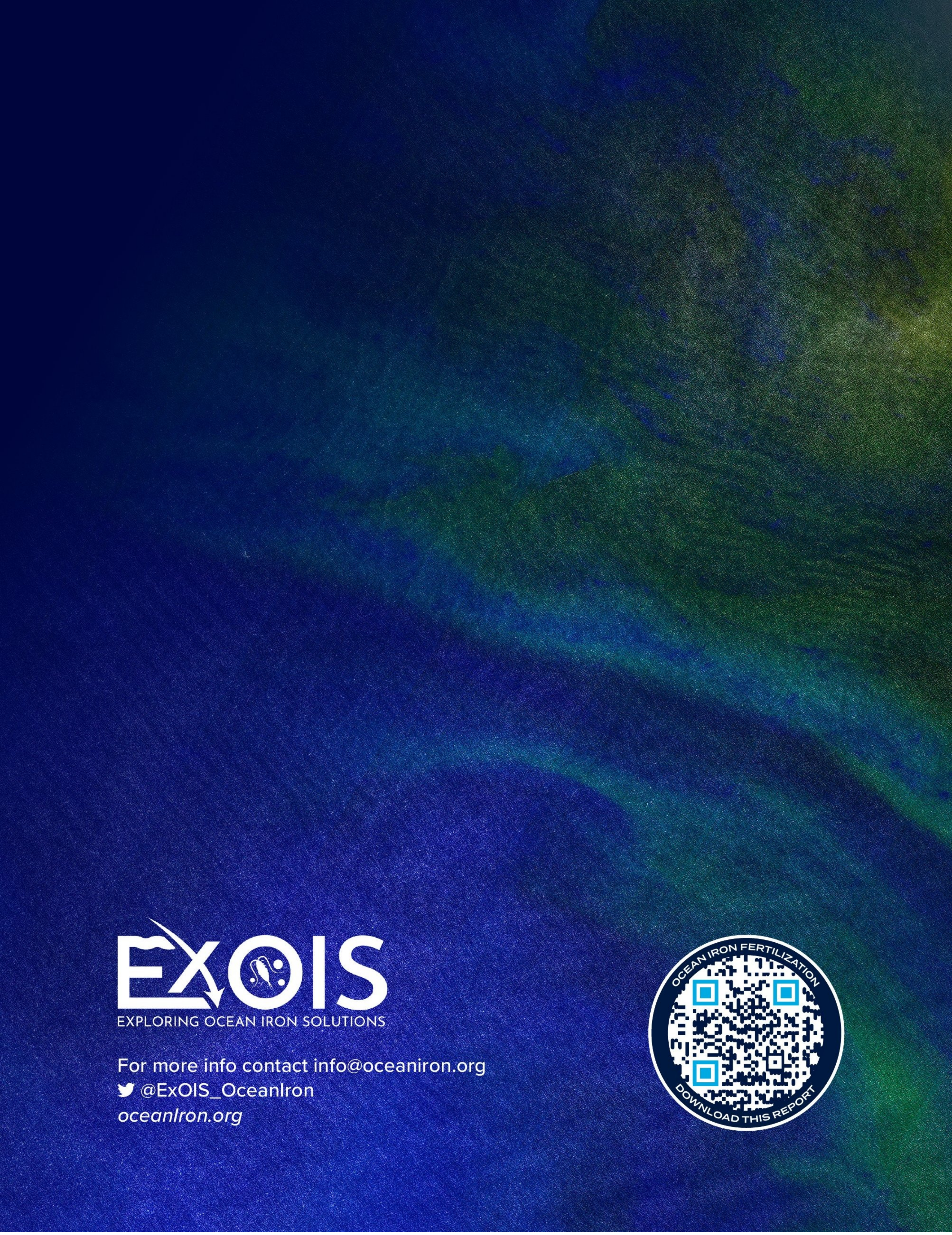
CARBON ACCOUNTING:

C is used for stocks of different forms of carbon in the ocean, whereas CO_2 is specific to the gas carbon dioxide. The atomic weight of carbon is 12 atomic mass units, while carbon dioxide is 44 (CO_2 includes two oxygen atoms that each weigh 16). To calculate the mass of C contained in a mass of CO_2, multiply the mass of CO_2 by the fraction 12/44. More easy to remember is that 1 ton of C equates to 3.7 tons of CO_2. In common CDR terms, humans release about 10 Gt of C each year, which is the equivalent to the release of 37 Gt CO_2.



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